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Proceedings of the Workshop on Program Options in Intermediate-Energy Physics

Summary and Panel Reports

Held at the Los Alamos Scientific Laboratory

Los Alamos, New Mexico

August 20-31, 1979

University of California

...IS UNLIMITED

LOS ALAMOS SCIENTIFIC LABORATORY
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CONTENTS

PROCEEDINGS OF THE WORKSHOP ON

PROGRAM OPTIONS IN INTERMEDIATE-ENERGY PHYSICS

Vol. I: Summary and Panel Reports

Compiled and edited by

John C. Allred and Beverly Talley

ABSTRACT

A Workshop on Program Options in Intermediate-Energy Physics sponsored by the U.S. Department of Energy was held at Los Alamos Scientific Laboratory, August 20-31, 1979. The scope of the Workshop included all laboratories in intermediate-energy physics, worldwide, and all of these sent representatives to the Workshop.

The Workshop addressed itself to the critical questions on nuclear and particle physics and how they can best be investigated by intermediate-energy accelerators. Among the questions that the Workshop members considered were:

1. What are the important physics topics which might be understood through research on these accelerators in the next 10 years? These topics include, but are not restricted to, fundamental interactions and symmetries in particle physics, and nuclear modes of motion, structure, and reaction mechanisms.
2. What experiments should be undertaken to carry out the program? What are the kinematical conditions, accuracies, resolutions, and other parameters required to obtain the desired knowledge?
3. Which accelerators are best suited for each experiment? What work at other laboratories (low-, intermediate-, or high-energy) could be undertaken to complement and/or supplement the proposed LAMPF program?
4. What new facility capabilities should be explored for the long-term future?

The Workshop was divided into small panels in order to promote effective interchange of ideas. After reports to other panels and plenary sessions, the panelists prepared reports stating the results of their deliberations. These reports comprise the principal part of Volume I.

Keynote addresses were given by G. E. Brown (State University of New York, Stony Brook) and Maurice Jacob (CERN). Volumes II and III report these addresses. During the time of the Workshop, Murray Gell-Mann gave the J. Robert Oppenheimer Memorial Lecture, which is published separately from these Proceedings, and is available from the J. Robert Oppenheimer Memorial Committee, P.O. Box 220, Los Alamos, NM 87544.

I. INTRODUCTION

Ernest M. Henley
University of Washington

Chairman of the Workshop on Program Options in Intermediate-Energy Physics

I. GENERAL REMARKS

The Workshop on Program Options in Intermediate-Energy Physics was held at the Los Alamos Scientific Laboratory from August 20-31, 1979. Its purpose was to raise critical questions in nuclear and particle physics and to recommend how they best can be addressed in the next few (~5) years by intermediate-energy accelerators. Although it is clear that some crucial questions cannot be raised at any one time because they rest on future developments, there are important issues which *can* be addressed.

The workshop was organized by a Steering Committee consisting of Earle L. Lomon (Massachusetts Institute of Technology), Chairman; John C. Allred (University of Houston/LASL); Robert L. Burman (LASL); Ernest M. Henley (University of Washington); Peter Herczeg (LASL); Vernon W. Hughes (Yale University); George J. Igo (University of California); Darragh E. Nagle (LASL); Louis Rosen (LASL), John P. Schiffer (Argonne National Laboratory); Richard R. Silbar (LASL); and Richard C. Slansky (LASL).

The steering committee outlined some topics to be discussed: fundamental interactions and symmetries, nuclear modes of motion, structure, and reaction mechanisms. Panel members were asked to outline experiments that should be undertaken, together with the necessary kinematics, resolution, accuracies, and other parameters in order to obtain the desired knowledge. They were also asked to recommend which accelerator is best suited for each experiment or program, and what new facility capabilities should be explored for the long-term future.

The interest in the workshop can be judged by the willingness of the 183 participants to spend almost two weeks of intense work and discussions at the Los Alamos Scientific Laboratory.

The workshop was divided into eight nuclear panels and four particle panels. The topics for the 12 panels were chosen to cover broad areas of physics accessible at medium-energy facilities. Although such a division is bound to be somewhat arbitrary, it was felt important to address questions in nuclear structure as well as in basic interactions and reaction mechanisms. Some overlap was therefore unavoidable and even was felt to be desirable.

In addition to the 141 panelists (including 12 students) there were 42 members at-large (selected by a committee consisting of Earle L. Lomon, Darragh Nagle, and Ernest M. Henley).

The steering committee made valiant attempts to obtain a balanced membership for the workshop: it was limited in this endeavor by the desire to keep the number of participants sufficiently small to allow thorough discussions and strong interactions within each panel, and by the availability of chosen members. The recommendations undoubtedly are colored by the membership of the various panels. However, the steering committee hopes that the membership is sufficiently representative of the broader nuclear (intermediate-energy) physics community to make the recommendations of this report meaningful.

The program of the workshop is given in Appendix B. Two keynote addresses were given by M. Jacob (CERN) on "New Directions in Elementary Particle Physics, $p\bar{p}$ from Very Low to Very High Energies," and by G. E. Brown (State University of New York, Stony Brook) on "New Directions in

Intermediate-Energy Nuclear Physics." P. Debevec reported on the Boulder Future Directions workshop held in Boulder, Colorado earlier this year. The workshop members also heard M. Gell-Mann deliver the J. R. Oppenheimer Memorial Lecture on "Quarks and Other Fundamental Building Blocks of Matter." These talks are published separately. Furthermore, there were talks on possible future facilities by D. E. Nagle, W. Turchinetz (Massachusetts Institute of Technology), and E. M. Henley, who reported on the TRIUMF Kaon Factory workshop held in Vancouver, British Columbia, Canada, August 13-15, 1979.

After all panel reports had been heard in plenary sessions, a panel was organized for the purpose of discussing major facilities, equipment, and instrumentation needs at various intermediate-energy facilities. The panel, chaired by Maurice Goldhaber (Brookhaven National Laboratory), included John Domingo (SIN, Villigen), Vladimir Lobashev (INR, Moscow), Louis Rosen (LAMPF), Jack Sample (TRIUMF), and Jacques Thirion (CEN, Saclay). This panel presented and discussed plans at their own laboratories, and the recommendations made by the 12 panels; the presentation was followed by discussion with workshop participants.

During the workshop, Roy Glauber (Harvard University) introduced the subject of summer schools for intermediate-energy physics. The panel chairpersons discussed this matter. They suggested that summer schools should not be restricted to intermediate-energy physics, but that such schools in nuclear physics in general were a good idea. They should be aimed at senior graduate students and research associates. Near the end of the workshop, Professor Glauber formally introduced the subject at a plenary session. A show of hands indicated overwhelming support for such summer schools.

The reports that are attached are the work of the various panels, but were prepared by the chairpersons with the assistance of the co-chairpersons. Although the usefulness of the workshop can be evaluated only after some time, whatever success can be ascribed to it should be credited in large measure to the chairpersons of the 12 panels. In many cases, they made preparations and were in touch with their members long before the workshop. They worked long and hard during the workshop itself and were able to finish their writing prior to their departure from the workshop so that this report could be published in a timely fashion. (Our apologies are offered to the reader if the prose suffers as a consequence.) It should be noted, furthermore, that illustrations and examples in the various reports are used to clarify the discussion and are not intended to give credit. The chairpersons were forced by time constraints to use material that was readily available or was familiar to them or to members of their panels.

Although the reports stand "on their own feet," I believe that it is worthwhile to summarize some salient features. In doing so it should be noted that at this writing I have not had access to the reports, but only have listened to some of the discussions and have heard the oral presentations made by chairpersons (or co-chairpersons) at the workshop. Since I am a theorist, my comments undoubtedly will do even less justice to the equipment and facilities recommendations that were made than to the other recommendations. For this and for other omissions, I apologize beforehand. In the short space allotted to me, I only have managed to pick out some highlights of the reports which follow.

I have divided the recommendations into three main categories: "Strong Interactions," both outside and within the nucleus; "Nuclear Properties;" and "Electro-Weak Interactions." In addition, I have tried to categorize the recommendations as near term ($\lesssim 2$ years) and longer term ($\gtrsim 2$ years). Both these divisions are somewhat arbitrary. Panel reports overlap the three areas, and short-term recommendations may not be implemented for a number of years. The cuts were made to help me organize the material presented below.

There are a number of features of the recommendations which cannot be divided or categorized. One of these is a general characteristic of hadronic interactions. There often is no single or crucial experiment to test a theory or model, or even to deduce an important property of the nucleus. Examples are pion condensation and high-momentum components or short-range correlations in nuclei. The isolation and elucidation of such properties or theories generally require experimental and theoretical programs with several probes. It is only when various approaches and attacks can be interpreted consistently in terms of the desired theory or property that the result is accepted by the community of physicists.

In the case of hadronic probes there is the further difficulty of isolating and understanding the reaction mechanism so that the desired structure or other property can be deduced. For this reason the reports contain many recommendations which use very light (e.g., nucleon number $A \lesssim 4$) nuclei, or selected heavier ones (e.g., ^{208}Pb, ^{40}Ca) as targets, because it is felt that the structure of these systems is understood reasonably well. Another suggested technique is to use inclusive reactions for which detailed structure aspects are less important.

Another message which was heard consistently at the workshop is that an increased theoretical effort is required to keep up with experimental findings and to guide future experiments.

II. STRONG INTERACTIONS

A. Short-Term Recommendations for Studies of Basic Interactions

Although the subject of the nucleon-nucleon (NN) interaction is a very old one, recent developments have revived interest in it. These developments are related to the underlying structure of the nucleons themselves. What is the number and nature of dibaryon resonances? The answer to this question may give us insight into underlying bag and quark models of nucleons *and* nuclei. Medium-energy ($E \gtrsim$ 500 MeV) scattering experiments with polarized beam and polarized targets are emphasized to help answer this question and to pin down phase shifts in this energy region. For instance, $\Delta\sigma_L = \sigma(\rightleftarrows) - \sigma(\rightrightarrows)$, where arrows indicate spin directions, shows resonance behavior. High-quality polarized beams of protons and deuterons (at Saturne in France), of reasonable intensity, and (frozen) polarized targets are required for this work. Indeed, in order to take advantage of nucleon probes of nuclear densities, it is recommended that at least both spin-independent and spin-spin NN isoscalar amplitudes be determined in the region $0° \lesssim \theta \lesssim 35°$ at energies around 800 MeV.

At energies above ~450 MeV, where pion production becomes an important inelasticity, it is recommended that complete kinematical experiments be done at several energies for the pion channels which are coupled to the NN system (N ≡ nucleon), i.e., for the reactions NN → πd and NN → πNN.

For the πN interaction, further low-energy experiments to test the accuracy of PCAC, and higher energy experiments with polarized targets to tie down phase shifts are recommended. At the higher energies the inelastic channel πN → $\pi\pi$N must be considered, and detailed experiments are required to delineate the properties of the πN interaction. What is the πN form factor? Is the pion a useful probe to test bag models? In the small bag model the pion plays a special role, so that details of πN interaction and form factor, and of excited nucleon (N^*) states, may help to test quark models of hadrons. Such experimental studies are recommended.

The Δ is perhaps as "fundamental" as the N. Properties of the ΔN interaction can be obtained from reactions such as πd → ΔN and γd → ΔN; these and other such reactions with polarized beams/targets are proposed.

B. Longer Term Studies of Basic Interactions

Not all of the recommendations in the previous section are short-term ones; it may take some time to develop (frozen) spin targets at some of the medium-energy facilities. I have classified kaon (K and $\bar{K}$) and antinucleon ($\bar{N}$) proposals as longer term ones, even though some of the recommendations may be able to be carried out on a shorter time scale.

Detailed properties of $K^{\pm}$-N interactions are still not well known. The limitations on the applicability of PCAC to the low-energy K-N system are unknown. The couplings which connect a K^- and nucleon to hyperons (Λ or Σ) remain to be studied. Better quality kaon beams are required for these investigations.

The antinucleon nucleon ($\bar{N}$N) system is rich in information. Closely connected to QCD and quark models is the necessity of studying the existence and properties of bound and unbound baryonium states. The number of such states and their energies and spins may give clues to the underlying quark structure of nucleons and nuclei. It is recommended that nuclear physicists make use of the low-energy $\bar{p}$ beam at Fermilab to carry out some of this work, and I endorse this proposal. Detailed investigations will probably have to wait for the Low-Energy Antiproton Ring (LEAR) to begin operations at CERN.

C. Strong Interactions in Nuclei; Short-Term Recommendations

Continued off-the-energy-shell experiments of the NN and πN interactions are recommended to test theory. Theoretical calculations of pion production which include *both* the single- and two-nucleon mechanisms are needed to compare with experiment. Further elucidation of the pion interaction in nuclei requires isolating the various absorption channels [e.g., (π,N), $(\pi,2N)$, . . .], especially at energies below and above the Δ resonance, and the various contributions to the total cross section.

A joint effort of studies of pionic x rays and pion-nucleus scattering to probe the low-energy interaction of pions with nuclei is recommended. Systematic investigations are called for.

It is urged that investigations of N and π scattering studies be carried out in nuclei with $A \lesssim 4$ and in selected heavier ones with polarized beams and/or targets to test our theoretical understanding of the scattering and reaction mechanisms. For instance, what is the *quantitative contribution of ρ exchange* in pion scattering and production? Such tests are important if nucleons and pions are to be used to probe nuclear densities and structure.

In order to understand further the interaction of pions with nuclei, the role of the Δ-nucleus interaction, the propagation of the Δ through the nucleus, and the Δ-hole interaction need to be investigated. This subject is presently receiving considerable attention and further investigations are recommended.

D. Strong Interactions in Nuclei; Longer Term Recommendations

Investigations with kaons, especially K^- to form hypernuclei and Y^* resonances in nuclei, were recommended. Better quality and lower energy kaon beams are required to take full advantage of theoretical proposals. At low energies the strangeness double-charge-exchange reaction can be used to form $\Lambda\Lambda$-hypernuclei. Simple and naive applications of QCD predict a strongly bound $\Lambda\Lambda$ state.

III. NUCLEAR PROPERTIES

One of the more intriguing and challenging studies that is possible with intermediate-energy accelerators is an investigation of the possible existence of *pion condensation. This phenomenon does* not occur at normal nuclear densities, so that the challenge is to find experiments which can give evidence for or against its existence. Convincing evidence requires a coherent picture with theoretical predictions and experimental verifications of a variety of precursor phenomena. A signature is the enhancement of excitation modes that can be reached by a pion; in even-even nuclei these modes are isospin 1, $J^P = 0^-, 1^+, 2^-, \ldots$ states at momentum transfers $q \sim (2\text{-}3)\ m_\pi$. Recommended experiments involve (e,e'), $(e,e'\pi)$, (γ,π), (π,γ), $(\pi,\gamma\gamma)$, (π,e^+e^-), (N,N'), and $(\pi,2\pi)$ reactions. Considerable theoretical as well as experimental work is required to determine best attacks on this fascinating and provocative problem.

The electron is a choice probe to investigate nuclear charge densities (ρ) and currents $(\mathbf{j})$, especially when used in conjunction with muonic atom studies. *The recommendation is that an accuracy of* 1% in the determination of these parameters be sought in electron scattering up to momentum transfers $q \sim 4\ fm^{-1}$. This would allow a mapping of charge and current densities and would determine nuclear charge radii to better than 0.01 fm. Indirect evidence for quark structure or bag properties may appear. The importance of exchange currents is stressed. The use of high-resolution N and π scattering experiments to determine nuclear densities is recommended.

Intermediate-energy accelerators allow one to probe simple modes of motion (elementary excitations) of the nucleus at high excitation energies. There remain giant resonances yet to be discovered and properties of known resonances to be elucidated. For the determination of partial widths and decay channels the use of a yet-to-be-constructed electron accelerator is recommended, as are polarized p probes to determine spin properties. The investigation of the properties of high-spin simple particle-hole stretched modes with pions, protons, and electrons is recommended; such studies require high-momentum transfers (~600 MeV/c) and good energy resolution.

An elusive property of nuclei is the short-distance behavior or the presence of short-range correlations (SRC). It is emphasized that an understanding of the formation and interaction of the Δ is required to understand these nuclear properties. A program of experimental and theoretical investigations of elastic scattering, inclusive reactions, quasi-elastic (knockout) reactions, two-nucleon knockout reactions, high-momentum mismatch [e.g., (γ,p)], and other reactions is recommended to explore SRC. The importance of considering post-scattering NN interactions in addition to prescattering ones is emphasized. The importance of determining whether high-momentum transfer reactions are primarily one- or multiple-step processes is recommended.

A program of inelastic-scattering processes at high-momentum transfers is recommended to determine transition densities. The suggested program incluc'^s a comparison of the excitation of selective high-spin states with (e,e'), (NN'), and (π,π') reactions.

An improved low-energy kaon beam is recommended for longer term detailed investigations of Λ-hypernuclei through (K^-,π^-) and ($K^-,\pi^- \gamma$) reactions. Such a beam would also allow the study of Σ-hypernuclei, of ΛΛ-hypernuclei, and the determination of the presence or absence of strangeness analog states in heavier Λ-hypernuclei. In addition, it would allow improved studies of kaonic x rays to determine the kaon-nucleus optical potential and probe the nuclear surface.

IV. ELECTROMAGNETIC AND WEAK INTERACTIONS

Because the electromagnetic interaction is well understood, very high-precision measurements of nuclear and particle properties are possible. Some of these studies already have been mentioned. Higher quality beams are recommended (e.g., line-narrowing, pulsing) in order to continue such studies. Muonium remains a rich source of information, and continued investigations of this system are recommended.

The advent of polarized electron beams opens up a new horizon for probing weak interactions. A program to determine completely the weak neutral nucleon currents is recommended, as are investigations of selected inelastic scatterings of longitudinally polarized electrons to determine the nonleptonic parity-violating interaction in nuclei. Improved polarized electron beams (higher polarization and flux) are recommended for this purpose. Parity-violation experiments in muonic atoms are suggested, as are higher energy experiments in polarized pp and perhaps np scatterings.

The capture of μ^- in hydrogen, with separation of the two hyperfine states, is recommended but would require a higher flux stopped muon channel. The helicity of the muon neutrino can be determined.

Continued efforts to detect $\mu \rightarrow e\gamma$ and/or $\mu \rightarrow e$ conversion are recommended as tests of gauge theories. The present discrepancy between theory and experiment in the ratio of the decay rates for

$$\frac{\pi^- \rightarrow e\nu + e\nu\gamma}{\pi^- \rightarrow \mu\nu + \mu\nu\gamma}$$

needs to be resolved or understood.

Continued searches for CP violation are urged in order to determine whether more than one Higgs doublet is required by the theory or whether the superweak interaction model is correct.

Longer term recommendations include an ultracold pulsed-neutron (n) source for higher precision (one to two orders of magnitude) searches of an n electric dipole moment. Studies of selected rare-decay modes are suggested.

It is highly recommended that the forthcoming proton storage ring (PSR) at LAMPF be used for ν scattering experiments and for other studies. Neutrino oscillation experiments be‹ome possible ai d can set lower limits on neutrino masses.

Improved measurements of low-energy $\nu_e e^- \rightarrow \nu_e e^-$ scattering are recommended. This cross section is sensitive to both neutral and charged weak currents. The interference tests weak-interaction theory, such as the description in terms of a single neutral gauge boson (Z^0).

Elastic- and inelastic-scattering experiments of ν's on nuclei would allow one to isolate isoscalar and isovector axial and vector interactions of neutrinos with nucleons. Large detectors would be required.

In this introduction I have only been able to give a broad perspective of the workshop recommendations. If the summary sounds like a long program, it is because that is my impression of the recommendations. The field of strong interactions does not lend itself to simple clear-cut and highly specific recommendations. Nevertheless, I am sure that all of us hope that the attached reports will be useful to researchers, advisory committees, and laboratory directors. As I stated at the beginning, the recommendations are the result of hard work for a short time by dedicated individuals. Although we hope that they will serve as guidelines, I don't think that any of us believe that they should be followed slavishly. Indeed, new findings and discoveries may well make some of the recommendations obsolete before they can be pursued. The recommendations should certainly be re-examined a few years hence in the light of new insights which have been gained in the meantime.

Finally, for the steering committee, I would like to thank all participants for your efforts during the workshop. We hope that it was a rewarding experience. We are particularly grateful to the chairpersons and co-chairpersons for the additional work entailed in planning, organizing, and finally distilling the discussions and work that took place. We are also grateful to John Allred for his organizational skill and help throughout the planning and execution of the workshop.

Finally, I'm sure I speak for all workshop participants in thanking Louis Rosen, the conference staff, and other LAMPF personnel for the gracious hospitality and help they have provided.

II. PANEL P-1

STRONG INTERACTIONS

Chairman: **Richard Silbar**
Co-Chairman: **Peter Carruthers**

Participants: B. E. Bonner, D. Calloway, F. H. Cverna, B. Dieterle, D. C. Dodder, C. A. Dominguez, H. W. Fearing, P.A.M. Gram, L. Heller, E. Henley, R. Hess, M. B. Johnson, V. M. Lobashev, E. L. Lomon, G. C. Phillips, G. A. Rebka, Jr., J. T. Sample, M. D. Scadron, H. Schmitt, J. Simmons, J. Thirion, and A. Yokosawa.

I. INTRODUCTION

In the last few years one important aspect of strong interactions at intermediate energies — the nucleon-nucleon problem — has enjoyed a considerable rejuvenation. This has been in large part because of the possible discovery of dibaryon resonances in certain measurements of spin-dependent observables. On the other hand, the equally fundamental pion-nucleon interaction has for some time been in a state of neglect, the richness of the πN resonance region having been recognized 15 or 20 years ago.

The reasons for this "ho-hum" attitude by many physicists regarding the πN and, in the past before the dibaryons, NN interactions are hard to understand. One possibility is that, in spite of great efforts by leading theorists, there was no striking success in the πN and NN problem for many years, in contrast to the situation in weak and electromagnetic interactions. Furthermore, experimental investigations following the discovery of the πN resonances did not lead to surprising new effects but rather to a gradual improvement in our knowledge of the interactions. Further progress in our understanding of these systems will require yet more hard work. Are the rewards worth it?

We feel the answer to that question is "yes," and that the present and past states of neglect in the πN and NN interactions have been undeserved. Understanding these fundamental hadronic interactions both elucidates strong-interaction particle physics and has important applications in nuclear physics.

Moreover, in very recent times a new prospect for what we may learn from πN and NN seems to be emerging — can we learn about the underlying quark structure of hadrons with intermediate-energy data and its analysis? The questions that can be addressed are:

- Is NN scattering, for example, the scattering of two bags of colored quarks, or can it still be described beyond some range by the single and multiple exchanges between the nucleons of pions and other mesons?
- Are the present quark models adequate for describing the πN resonances extracted from the scattering data?
- Is the pion something special in quantum chromodynamics (QCD)?
- How big is a nucleon bag (or, how big is its quark core)?
- What are the quark contributions to the short-range forces between hadrons?

We will return to, and expand upon, these questions below.

Another recent development is that we have now entered a new era of technological opportunities in strong interactions at medium energies. Because of the high-intensity, good-quality beams now available, the phase shifts and inelasticity parameters describing NN elastic scattering will very likely be much better known in the near future. The πN phase-shift analyses can also be considerably sharpened, at least to 600 MeV, though this will require some improvements in detectors and instrumentation. Finally, there is now the possibility for the study of inelastic reactions like $pp \to np\pi^+$ or $\pi^+p \to \pi^+\pi^0p$, in which all the kinematic variables are completely determined.

In the report of the P-1 panel which follows, we will discuss in turn the status and the opportunities for progress for a number of strongly interacting systems — NN, KN, and $\bar{K}$N, as well as the above-mentioned NN and πN cases. This will be followed by a discussion of the theoretical implications of such studies. Finally, we indicate briefly the kinds of new facilities that will be needed to pursue them.

II. THE NUCLEON-NUCLEON INTERACTION

A. Elastic Scattering and Phase-Shift Analyses

Phase-shift analyses of NN data represent an intermediate step between experiment and fundamental theory. At LAMPF energies there are about 26 elastic phases and 12 inelasticity parameters that cannot be neglected. Thus it is not surprising that progress has sometimes been slow in obtaining meaningful phase-shift solutions.

Impressive progress has recently been made in this field. As a result of the recent analyses of the BASQUE group's triple-scattering data from TRIUMF and the Geneva group's polarization data from SIN, unique I = 1 and I = 0 solutions exist up to 500 MeV. There is an extensive program at LAMPF energies (500-800 MeV) using polarized proton beams and targets. The Virginia Polytechnic Institute and Saclay energy-dependent analyses (still preliminary for I = 0) now go up to 800 MeV. At the ZGS, currently in its last days of operation, an impressive program of proton-proton measurements has led to a unique amplitude analysis at 6 GeV and to the suggestion that dinucleon resonances exist at lower energies. The Kyoto group and Karlsruhe-Wuppertal group have been especially prominent in analyses of these data and the resonance interpretation.

We break our discussion of what further improvements would be desirable in the data and its analysis into separate pp and np cases for various energy ranges.

1. For pp scattering below 500 MeV, we need precise differential cross sections and a reduction in the errors of the triple-scattering parameters. There may be a residual problem with the determination of the forward values of the imaginary amplitudes. Further work is recommended.
2. For pp scattering from 500 to 1000 MeV, the data can be described as qualitative. An exception is the energy point near 650 MeV, where a body of earlier data from Dubna exists. At LAMPF, the Case Western Reserve group has made precision measurements for pp differential cross sections ($d\sigma/d\Omega$), analyzing power (P), and the spin-correlation parameter A_{NN}. Further experiments will take advantage of the variable-energy H^- beam, polarized beams, polarized targets, and polarimeters that will soon be available. These experiments should improve the state of knowledge at these energies considerably.

   Even so, there remains the problem of inelasticity. Single pion production increases rapidly to large values from 500 to 800 MeV. This generates imaginary parts in all phase shifts. The elastic observables are not very sensitive to these parameters, which make their determination difficult. It would be very useful to include suitable differential pion production data directly in the phase-shift analysis. This would require a coupled-channel approach, which has been much discussed but not yet attempted. It is highly desirable that a start be made in this direction, since there already exists a body of pion production data that could be usefully employed.
3. For pp scattering above 1 GeV there are substantial scattering and polarization data from a number of groups. A significant new element was measurement of transverse and longitudinal spin-dependent total cross sections ($\Delta\sigma_T$, $\Delta\sigma_L$) as a function of energy by Michigan-ANL-Rice University groups and the Yokosawa group. These have led to the conjectured dibaryon resonances discussed below. The nature of these resonances remains unclear, and one of the objectives of the LAMPF NN effort is to clarify their origin.
4. For np scattering up to 500 MeV, an important milestone has been recently achieved. The analysis of the BASQUE np triple-scattering data, combined with the pp analysis mentioned above, has resulted in a unique set of I = 0 phase shifts in the 200- to 500-MeV range. Further improvements can be expected from small-angle np $d\sigma/d\Omega$ measurements; such experiments are in progress at TRIUMF. The np spin-correlation observable A_{NN} would further constrain the phase shifts.
5. Regarding np scattering at LAMPF energies, the I = 0 amplitudes are relatively poorly known (see Fig. II-1 for one example). In the

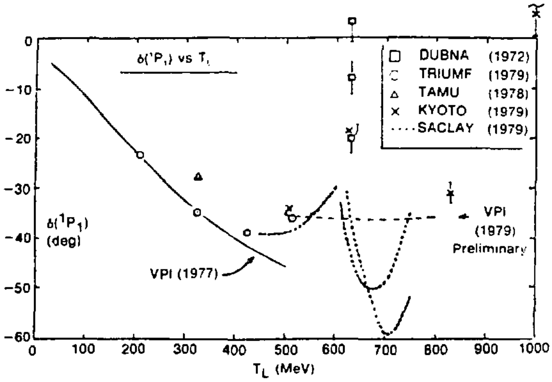

Fig. II-1.
The $I = 0$, ${}^1P_1$ NN phase shift, as a function of energy, as determined by various different analyses.

last few years $d\sigma/d\Omega$ has been measured by LASL and Texas A&M University at a number of energies, including a small-angle measurement at 800 MeV. P and A_{NN} data are in the process of being analyzed. Experiments are being planned or proposed for further small-angle $d\sigma/d\Omega$ and quasi-free pn triple-scattering measurements. The latter should be pursued in free np scattering as well. Spin-correlation observables are also clearly desirable. Here LAMPF finds itself at a distinct disadvantage *vis-a-vis* polarized neutron beams presently at TRIUMF or soon to be available at Saturne II. A more intense polarized proton ion source is needed.

6. Above 800 MeV a rather small amount of np data exists, mainly charge-exchange $d\sigma/d\Omega$ and P. There are, however, some very interesting quasi-tree np $\Delta\sigma_L$ experiments (polarized deuteron target) which have been performed at Argonne by the Yokosawa group. Extracting $I = 0$ information using the $I = 1$ $\Delta\sigma_L$ pp data indicates possible structure as a function of energy there as well. If this is an $I = 0$ dibaryon, it would be very interesting. It would be extremely valuable to confirm this structure by independent experiments in free np scattering. We also note that a program of np polarization and spin-correlation experiments will be carried out at Saturne at energies up to 3 GeV.

B. Inelastic Channels

The NN system at intermediate energies is strongly dominated by the inelastic pion production channels. For example, in the energy region from pion production threshold (near 300 MeV) to 1 GeV, the total pp cross section approximately doubles, while the total elastic cross section monotonically decreases. Thus it is of importance to study the inelastic reactions $NN \to d\pi$ and $NN \to NN\pi$, which account for about one-half of the total NN cross section. (Below 2 GeV the reaction $NN \to NN\pi\pi$ is, for $I = 1$, relatively unimportant. However, it may be more important in $I = 0$ np channels, in which single Δ production is forbidden.)

The interest in inelastic reactions is heightened by the possible effects on these channels due to dibaryon resonances (or, *vice versa*, the effects of inelastic reactions in producing the resonance-like structures). Study of the NN system at intermediate energies must include spin-dependent, variable-energy measurements in *all* reaction channels, so that unique amplitudes can be derived. Clearly, a parameterization only in terms of elastic phase shifts and partial-wave inelasticities is inadequate, and a coupled-channels approach of some kind is called for. This combined program of experiment and analysis is formidable, but we have hope that a careful selection of experiments with tasteful theoretical guidance will shorten an otherwise very long job.

The usual picture of the $NN \to NN\pi$ inelasticity in this energy region is that of the isobar model (Fig. II-2). We note that in the last two years it has become possible to calculate the isobar amplitudes $NN \to N\Delta$, $NN \to NN'$ in a unitary way, i.e., in a way which goes beyond the Born approximation.

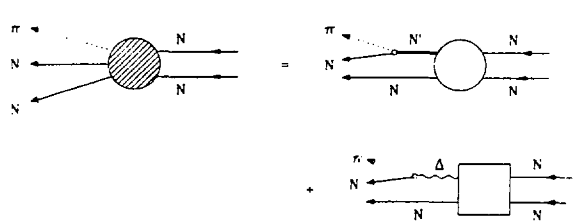

Fig. II-2.
The reaction $NN \to NN\pi$ in the isobar model.

The reaction $pp \to d\pi^+$ has just begun to be studied as a function of energy with polarized beams and targets at all three meson factories. This reaction is simpler than the unbound three-body state $NN\pi$ experimentally, but may be more difficult to deal with theoretically. There have also been the beginnings of two-armed spectrometer studies of the $pp \to np\pi^+$ and $pp \to pp\pi^0$ reactions by the Rice University/University of Houston group. In fact, one of these "complete kinematics" experiments has taken data with a polarized beam, and the spin-dependence of the reaction seems to be large. (A similar dependence on spin is seen by the LASL-Texas A&M group in the spin transfer to the forward neutron in polarized $pp \to np\pi^+$.)

We expect, and wish to encourage, that other "kinematically complete" pion production experiments be done in the near future. To facilitate data acquisition it may be necessary to consider experiments with large solid-angle acceptance (streamer chambers? time projection chambers?). Also because of the small cross sections for kinematically complete differential cross sections, we encourage the installation of an intense polarized H^- source to make spin-dependent pion production experiments feasible.

C. Dibaryons?

As mentioned in the Introduction, the discovery of strong energy dependence in spin-dependent total cross-section differences, such as $\Delta\sigma_L = \sigma(\rightleftarrows) - \sigma(\rightrightarrows)$, has led to considerable new interest in the nucleon-nucleon problem. We review the evidence for these dibaryon resonances briefly:

1. $I = 1$, $^3F_3$, with a mass around 2.23 GeV, has been seen as a dip in $\Delta\sigma_L$ near 800 MeV. Associated with this are a fast rise in the polarization, a peak in the total elastic cross section, and a sharp change in A_{LL} ($\theta_{c.m.} = 90°$) at this energy. A dispersion relation analysis and several phase-shift analyses show resonance-like counterclockwise motion on the Argand plot of the $^3F_3$ partial-wave amplitude.
2. $I = 1$, $^1G_4$, with a mass around 2.43 GeV, has been suggested by $\Delta\sigma_T$ and possibly $\Delta\sigma_L$ peaks. The $A_{LL}(90°)$ data indicate this is resulting from rapid change in the $^1G_4$ partial-wave amplitude.
3. $I = 1$, $^1D_2$, with a mass around 2.16 GeV, is suggested by a sharp peak in $\Delta\sigma_L$ and three phase-shift analyses.
4. $I = 0$, $^3F_3$, with a mass around 2.20 GeV (near 800 MeV), is suggested by the smooth behavior of $\Delta\sigma_L$ for pd scattering. There is some support for a resonance interpretation from a forward dispersion relation analysis and one $I = 0$ phase-shift analysis.
5. Resonance-like behavior seen in the proton polarization from deuteron photodisintegration.
6. Possible $p\Lambda$ and $\Lambda\Lambda$ enhancements at 2.13 and 2.35 GeV may have been observed in low-statistics invariant mass plots by groups at CERN and Dubna.

It is fair to say that among the P-1 panelists there was a range of acceptance of this evidence for dibaryon resonances that went from enthusiastic advocacy to skepticism. We all feel that new experiments under way, to check the earlier measurements and to extend them to particular reactions, should clarify this matter in a few years. If these exotic objects really exist, there are profound theoretical implications.

There are at present two common views of how the resonance-like structures might arise. The conventional meson theory approach, which includes the attractive potential due to the opening of inelastic channels (e.g., the $NN \to N\Delta \to NN$ "box diagram"), may already provide a dynamical explanation. Figure II-3 shows the prediction for the $^1D_2$ partial-wave amplitude by Kloet and Silbar, using such a

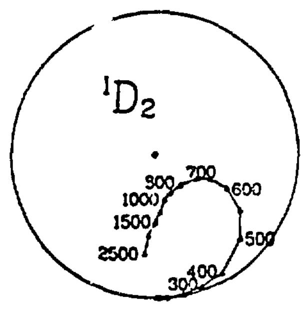

Fig. II-3.
The Argand plot of the $^1D_2$ NN partial-wave amplitude, as calculated by W. M. Kloet and R. R. Silbar in the isobar model.

model. This is a unitary calculation using one-pion-exchange forces between nucleons and isobars, and it has no adjustable parameters. The highly inelastic resonance-like behavior in this partial wave may even be exaggerated. There are similar counter-clockwise loops in the $^3P_1$, $^3F_3$, and $^1G_4$ partial waves in this model, but they are slower and are not by themselves able to fit, say, the $\Delta\sigma_L$ or $\Delta\sigma_T$ data. With some adjustments of transition potentials in a similar model, however, Lomon *is* able to reproduce most of the energy dependence of the experimental phase shifts.

The other popular suggestion is that these dibaryons are in fact six-quark bound states, all in one bag (big or small), perhaps temporarily separated into two halves, each with color. The QCD-bag model approach predicts many such resonances. If it turns out that there is in fact an I = 0 $^1F_3$ resonance with nearly the same mass and width as the better established I = 1 $^3F_3$, it may be the only explanation for them is such a bag model picture; the conventional meson theory approach would be at a loss in such a case.

In this regard, it might be most amusing to check to see if lower energy s- and p-wave dibaryons (around 400 MeV) might also show up as narrow peaks in precision total cross-section measurements.

III. NUCLEON-ANTINUCLEON INTERACTIONS

The important news in this field is that the Low-Energy Antiproton Ring (LEAR) is looming on the CERN horizon. The LEAR will begin producing, around 1984, very high-quality antiproton beams that are 10^3 times more intense than those, say, of the LESB-II channel at the Brookhaven AGS. The experimental program for LEAR is well thought out and well documented, and there appears to be little activity in planning and building such a cooling and storage ring anywhere else. Because of this virtual monopoly by CERN on future low-energy antiproton physics, the P-1 panel did not dwell too much on the NN problem, so this section will be relatively short.

The antiproton physics that has received the most attention in recent years has been whether narrow (or broad) bound states and resonances exist in the NN system. The experimental situation is chaotic, with even the "well-established" S(1937) meson now in a state of doubt. Theoretically, there has been a fair bit of hoopla claiming that such "baryonium" states can arise (or not) in either the conventional meson-exchange picture of the NN potential, transformed to an NN potential by a simple G-parity argument, or in bag model like that described above for dibaryon resonances ("color chemistry"). It may well be that we shall have to await the results of LEAR before we know whether and how much baryonium exists in the world.

Other aspects of the NN interaction are also interesting. It has been suggested by D. Underwood of ANL that the storage ring more or less naturally brings the antiprotons into a state of polarization. Scattering experiments measuring spin correlations would then give us interesting new information. We may eventually be able to obtain the NN elastic-scattering phases, just as we now do for the NN problem. The NN case is much more complicated (and interesting) because of the very important annihilation channels. Indeed, the annihilation process, NN → pions, is poorly understood and is ripe for exploitation. It may be that, if the nucleon is described as a collection of three quarks in a large (MIT) bag, the branching ratio for some NN → 3π reactions is predictable. On the other hand, if the small (Stony Brook) bag picture holds, NN → $4\pi, 5\pi, \ldots$ may be more important because of the spectator pions in the clouds about the bags.

Other applications of antiprotons, such as to exotic atoms and to nuclear physics, may need more study.

As to the question of whether the United States or others should consider building a low-energy storage ring in a future competition with LEAR, there was some mixture of opinion among the P-1 panelists. The majority felt that a wait-and-see attitude was appropriate.

IV. PION-NUCLEON INTERACTIONS

A. Elastic Scattering and Phase-Shift Analyses

The amplitudes for πN elastic scattering are better known than those of any other hadron-hadron reaction. This is largely because there are only four independent invariant amplitudes and some 35 000 data points. Nonetheless, the present knowledge of the $\pi N \to \pi N$ process is not satisfactory for many applications. There are fairly large discrepancies between different data sets and considerable gaps in the data.

An improved determination of the πN amplitudes is of interest for the following applications:

- The excited states of the nucleon (the πN resonances) are often the most important data with which calculations of the excited states of a three-quark system (bound in a bag or by some single- or multi-channel potential) can be compared. The parameters of these resonances are determined in πN phase-shift analyses, but the present experimental accuracy is not sufficient to determine reliably the level splittings and weakly coupled members of multiplets. Since the structure of the nucleon is one of the fundamental problems of physics, interest in the πN resonance parameters will increase in the next decade.
- Accurate results for the πN amplitudes at low energies (and for extrapolation to unphysical, subthreshold regions) are needed to test predictions of PCAC (see Sec. VII) and various dynamical models. These models are of interest in that they give off-shell extrapolations of πN amplitudes needed for applications to nuclear physics (e.g., pion-nucleus scattering, pion condensates, three-body nuclear forces, etc.).
- By analytic continuation of $\pi N \to \pi N$ amplitudes, we can obtain $\pi\pi \to N\bar{N}$ information that is useful for extending one-boson-exchange models of the NN force beyond one-pion exchange. At present the accuracy of the continuation for $t \geq 10\ \mu^2$ is not yet satisfactory; it requires more accurate low-energy πN data and resolution of problems with $\pi\pi \to \pi\pi$ phase shifts at low energies. The $\pi\pi \to N\bar{N}$ amplitudes are also useful in our understanding of the nucleon's isovector electromagnetic form factor.

The methods used in πN phase-shift analyses today are considerably augmented by theoretical constraints. These include not only consistency with isospin conservation, but also with fixed-t and other sorts of dispersion relations, and other uses of analyticity (such as conformal mapping to put singularities in the amplitudes "far away"). This is not the place to go into details of this well-developed machinery. (We do comment, however, that many of these techniques might also be useful in carrying out NN phase-shift analyses; it might be worthwhile to have a special topic workshop to which practitioners of both arts get together for an exchange of information.)

Since the incorporation of many of the above-mentioned constraints in phase-shift analyses requires much effort, it has been accomplished up to now only by two groups, Karlsruhe-Helsinki (KH) and Carnegie-Mellon-Berkeley (CMU-LBL). These two analyses use considerably different methods.

The CMU-LBL group starts with a careful amalgamation of the πN data at 35 momenta in the range of 0.43 to 2.0 GeV/c. The Ansatz for the partial-wave amplitude at fixed-s contains "Born terms" which include Regge expressions with absorption corrections for the exchange of the Pomeron, meson resonances, the nucleon, and Δ isobars. Presumably this introduces only a weak model dependence. The application of constraints from dispersion relations along five hyperbolae in the Mandelstam plane finally leads to a unique set of phase shifts.

The KH group did not use such Born terms, and the effort for the amalgamation of the data, for error estimates, and for random searches was smaller. Instead, much stronger analyticity constraints were used. Fixed-t analyticity was imposed at 45 t-values up to $t = -1\ (\mathrm{GeV})^2$, as was fixed center-of-mass angle analyticity at 18 $\cos\theta$ values. This made it necessary to analyze simultaneously all data from threshold to 200 GeV/c. The analysis would not have been possible without Pietarinen's expansion method. The solution was checked for compatibility with fixed lab angle ("interior") and, for s-waves, s-channel partial-wave dispersion relations. "Zero trajectories" were also studied for invariant and transversity amplitudes.

A detailed comparison of the CMU-LBL and KH analyses will soon be available. There are differences, of course, in many of the partial waves. For example, the imaginary part of the D_{35} amplitude shows a distinct bump in the CMU-LBL case at 1900 MeV, whereas the KH only shows a shoulder. If there is a D_{35} resonance, however, it represents evidence for a state which is not predicted in the simplest quark models. Thus it is of some importance to clarify the nature of this bump or shoulder.

In comparing with earlier phase-shift analyses, one should remember that a good fit to all data solves only the simpler part of the problem. The main question is whether the phases of the amplitudes are compatible with fixed-t and other dispersion relations. To now this has not been checked for the older solutions.

We turn now to the experimental situation and the gaps in the data that need to be filled. We consider, for convenience, two energy regions: "low," from 0 to 600 MeV, accessible at the present meson factories; and "high," above 500 MeV, accessible at other high-energy accelerators. In the low-energy region we could identify only two active groups, working at SIN and LAMPF. There is a problem in the "high" region in that many facilities for carrying out πN experiments are disappearing rapidly. The advent of a πN program at the Japanese KEK facility is encouraging, however. In addition to active groups, there is a fair bit of πN data extant, not yet available in final published form. We continue to eagerly await the results from the LAMPF and Saclay low-energy $\pi^{\pm}p$ elastic cross sections ($\lesssim$70 MeV) and the extensive Nimrod data at higher energies.

In the "low" region, it would be most useful to have $\pi^- p \to \pi^0 n$ charge exchange cross sections below 200 MeV. A good absolute normalization for that process is necessary in the region where $d\sigma/d\Omega$ is flat (s-wave dominance). In the region of the (3,3) resonance, the main problems are the determination of the Δ^{++}-Δ^0 mass splitting and the $I = 1/2$ phases. We need $d\sigma/d\Omega$ in larger angular intervals for all three $\pi N \to \pi N$ reactions and at more energies than measured in the benchmark experiment of Bugg, Carter, and Carter. New $\pi^- p$ elastic and charge-exchange polarization data would give important constraints on the S_{11} amplitude. This partial wave is not well determined as yet because its contribution to the $I = 1/2$ total cross section is comparable to the effect of the Δ-mass splitting. Above the first resonance there are gaps and discrepancies between different data sets.

In the "high" region, the present information on the $\pi^- p$ polarization is much worse than that for all other $d\sigma/d\Omega$ and P data. The mass splitting in πN-resonance families is at present only indirectly derived. It would be of great use to have polarization data at closely-spaced energies.

The experimental situation in charge-exchange scattering above 600 MeV/c has much improved with the new Rutherford data. Unfortunately, both the KH and the CMU-LBL groups have difficulty fitting it together with all other information and the dispersion relation constraints. This suggests that either $d\sigma/d\Omega$ charge-exchange data have an unknown systematic error, or some high partial waves are much larger than expected.

There exists much information on $d\sigma/d\Omega$ at many energies for $|\cos\theta| \leq 0.95$, but in only a few data sets for $\cos\theta > 0.95$. There are also some differences between different near-backward data. New data at $|\cos\theta| \geq 0.90$ would be of interest for several reasons. First, since $d\sigma/d\Omega$ at 0° is well determined from σ_T (which unfortunately shows systematic discrepancies) and dispersion relations, the new data would be well normalized and would improve the normalization of the (overlapping) $|\cos\theta| \leq 0.95$ data. Second, $d\sigma/d\Omega$ usually varies rapidly for $|\cos\theta| \geq 0.90$. This structure, not well resolved at present, contains important information on the higher partial waves. Finally, the reliable information on the absolute phase of the forward amplitude can be extended to larger angles only if there is no gap in the data.

The comparison of the KH and CMU-LBL analyses mentioned above will soon provide a list of discrepancies between predictions and measurable quantities. This will indicate where new data are desirable. At present, spin-rotation data (A and R) are nonexistent below 6 GeV/c. It would not be surprising to us that some such experiments will be the most sensitive ways to improve our knowledge of the πN phase parameters. At the least, a measurement of suitable spin-rotation parameters would fix the relative angle between the two isospin triangles and their orientation with respect to reflections (the "discrete ambiguity").

B. Inelastic Channels

Single pion production in πN collisions, $\pi N \to \pi\pi N$, is of interest for several reasons:

- The strong unitary coupling to the elastic channel (most πN resonances are highly inelastic) means $\pi N \to \pi\pi N$ information may be helpful in establishing πN phase shifts.
- The process, describable by phenomenological isobar models, can be used to find resonance (isobar) coupling constants.
- Aside from K_{e4}-decay, it is the only way we have at present of studying $\pi\pi$ scattering and its relation to chiral symmetry (see below).

Application of $\pi N \to \pi\pi N$ data for each of these purposes requires the use of more or less sophisticated dynamical models. Thus, if the above programs are successfully carried through, this means an enhanced understanding of the dynamics of the $\pi N \to \pi\pi N$ process as well.

Experimentally, in the "high" energy region above 800 MeV, there is a world collection of about 300 000 bubble-chamber events in the final charge states $\pi^+\pi^-n$, $\pi^-\pi^0p$, $\pi^+\pi^0p$, and $\pi^+\pi^+n$. Below 600 MeV only the $\pi^-p \to \pi^+\pi^-n$ reaction has been studied with any thoroughness, and additional data on inelastic channels are highly desirable. Most of this information comes in fact from one experiment, using counters, by Wyoming and LASL, recently completed at LAMPF. This is a one-armed spectrometer experiment in which the outgoing π^+ is identified and momentum analyzed. Apart from the integrated production cross-section data obtained here, which were used to extract $\pi\pi$ scattering lengths, the differential cross sections themselves exist and should be compared with either unitary three-body dynamical models, such as that of Aaron, Amado, and Young, or with more phenomenological isobar model partial-wave analyses.

Other one-armed $\pi N \to \pi\pi N$ measurements are now technically feasible with the intense pion beams at LAMPF. One of these, for example, is $\pi^-p \to \pi^-\pi^0p$, where the π^0 is detected with, say, the Los Alamos π^0 spectrometer set at low resolution. Also, the $\pi^+p \to \pi^+\pi^+n$ reaction could be studied by detecting a neutron with time-of-flight techniques. These examples are more difficult than the $\pi^-p \to \pi^+\pi^-n$ experiment above because of a background from single charge exchange in the target walls, which is more frequent than double charge exchange. We urge a serious consideration of such experiments.

In the future, measurements of completely determined kinematics for $\pi N \to \pi\pi N$ reactions should be considered. These would probably require larger solid-angle detectors, such as streamer chambers or time-projection chambers. Completely differential production cross sections are, of course, much more constraining on theoretical models than the integrated, one-armed data. In the farther future, the spin dependence of the $\pi N \to \pi\pi N$ reaction should be measured. This will probably require frozen spin-polarized targets and far more sophisticated instrumentation than has yet been proposed.

To conclude this section, we comment that very little is known about $\pi N \to \pi\pi\pi N$ reactions near that threshold, around 400 MeV. This is within the capability of LAMPF, and the reaction could provide a whole new test of chiral symmetry.

C. ππ Scattering and Chiral Symmetry

The amplitude for $\pi N \to \pi\pi N$ at threshold has as an important contribution the "$\pi\pi$ scattering graph" shown in Fig. II-4. Consequently, the amplitude, say, for $\pi^-p \to \pi^+\pi^-n$ is proportional to $2a_0 + a_2 + b$, where a_I is the $\pi\pi$ scattering length in isospin state I, and b represents the background from all the other Feynman graph contributions that enter. Extracting $\pi\pi$ scattering lengths necessarily depends to some degree on a model to estimate b. To the extent that b becomes small as energy decreases toward threshold, however, we can hope to extract the quantity $2a_0 + a_2$ with only a minimal dependence on the model.

To get the a_I separately, not just the one linear combination, will require measuring other charge states, such as $\pi^+p \to \pi^+\pi^0p$ or $\pi^-p \to \pi^0\pi^0n$. Preferably more than one such reaction should be measured, so as to overconstrain the $\pi\pi$ scattering parameters. We mention that, in the past, attempts to determine the $\pi\pi$ scattering lengths from higher energy data have led to serious difficulties.

The $\pi\pi$ scattering lengths are predicted by one or another of the chiral SU(2) × SU(2) symmetry models. Unfortunately, such models are not constrained by other soft-pion and current algebra considerations, and hence a_0 and a_2 are determined by chiral symmetry up to a parameter called ξ by Olsson and Turner. One of the goals of experiment to measure $\pi\pi$ scattering is to fix the value of ξ.

The recent LAMPF experiment on $\pi^-p \to \pi^+\pi^-n$ has found $\xi \approx 0$, consistent with the Weinberg chiral symmetry model. (This is consistent with the type of

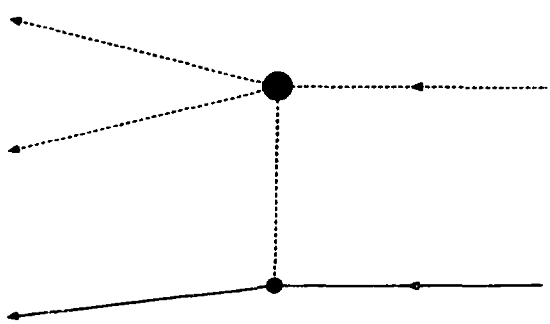

Fig. II-4.
The pion-exchange contribution to $\pi N \to \pi\pi N$, as a means of studying the $\pi\pi \to \pi\pi$ amplitude.

PCAC, chiral invariance, and chiral symmetry breaking that has been derived from the quark model.) This satisfying situation ought to be checked in other $\pi N \rightarrow \pi\pi N$ reactions, however.

The same models when extended to chiral SU(3) × SU(3) also make specific predictions for $\pi K \rightarrow \pi K$ or $\pi\pi \rightarrow K\bar{K}$ scattering lengths, measurable in the same way in $KN \rightarrow K\pi N$ or $\pi N \rightarrow K\bar{K}N$ reactions. Such experiments will require high-intensity K or π beams and may have to await the advent of a kaon factory before being feasible.

V. KAON-NUCLEON INTERACTIONS

Despite the growing interest in a kaon factory, the P-1 panel did not have enough time to more than touch upon the KN and $\bar{K}N$ systems. Clearly these interactions would be an important part of any kaon factory experimental program. In this regard we note that the πN interaction was relatively better understood at the time that pion factories were first discussed seriously than the KN and $\bar{K}N$ interactions are understood today.

The relatively weak KN interaction is something that might be well exploited in probing the atomic nucleus. However, the basic interaction itself needs clarification. Do Y = 2 exotic Z^* resonances exist? There are theoretical grounds for believing that they should, either as a result of attraction due to the inelastic K^*N channel or as $(q^4\bar{q})$ states in bag models. The experimental phase-shift information, especially in I = 0, is not clear on this point. If Z^*s exist in these analyses, they are generally p-wave rather than the expected s- or d-wave resonances.

Apart from the question of Z^* resonances, it is clear that the low-energy KN amplitudes are not yet well enough known to use in K^+-nucleus scattering analyses for purposes of extracting, say, information on the neutron matter distribution in the nucleus.

The $\bar{K}N$ interaction with its abundance of Y = 0 Y^* resonances seems to be better understood (i.e., more often studied). Nonetheless, most quark models predict more Y^* resonant states than are presently known. (That is even more true for Ξ^* resonances.) Further, the kaon-nucleon coupling constants $g_{KN\Lambda}$, $g_{KN\Sigma}$ are rather poorly known at this time, and progress on this is very slow. Finally, here too, different low-energy parameterizations of the $\bar{K}N$ amplitudes predict vastly different K^--nucleus scattering cross sections.

VI. QUARK MODELS, QCD, AND BAGS

The "new slant" referred to in the Introduction is the implication that quark models and quantum chromodynamics have for strong interactions at intermediate energies. There is strong overlap with the other subtopics discussed in this report, and we have often mentioned some of these ideas already above. Most of the ideas we are about to discuss, however, have not yet been carefully developed. Thus, what we present here must be considered as *highly speculative*.

There are two popular bag models for discussing the structure of hadrons. The older, more-established MIT bag has a large size (radius about 1 fm), is spherical, and predicts a rich-level density of dibaryon states. The "Little Bag" model from Stony Brook is newer, involves a quark bag of smaller radius (about 0.5 fm), deformed and surrounded by a cloud of pions. The pion in this model is a Goldstone boson and not itself a bag of quark-antiquark, as in the MIT model. It is conjectured that the Little Bag model also gives a rich dibaryon level density, but no calculation exists so far.

We have already mentioned, in Sec. III, the ideas of quark "molecules" and "color chemistry" as a way to predict many states in the $N\bar{N}$ system ("baryonia"). We also noted there that annihilation branching ratios might be able to distinguish between the two different bag models.

Regarding the interactions of hadrons in this context, there are several interesting conceptual questions:

- What is the limit of validity of the meson exchange picture?
- Is there a *duality* between the quark-bag theories and the meson-exchange theories? If so, which theory is simpler?
- If the answer to the duality question is "no," what modifications of conventional meson theory would be required to give such a duality? Or, in what limit does such a duality exist?

There is quite a bit of work here for the theorist in sorting out answers to these questions.

We turn now to the question of whether NN scattering can give us information on the bag size. We first note that, in low-energy scattering, the meson-exchange theories (involving *point-like* nucleons) work well when the nucleons are ≥0.7 fm apart. This suggests that the bag radius satisfies $2R_{bag} \leq 0.7$ fm, which would be rather small bags indeed. On the other hand, bag theories themselves appear to be qualitatively successful when the nucleons are ≤1 fm apart. On the basis of these two (mildly contradictory) pieces of evidence, it is difficult to come to any conclusion. However, there is an implication that at least some limited duality is effective.

For medium-energy NN scattering, up to 1 GeV or so, we need to extend the meson theory calculations and confront them with relevant data. It is here that some members of the P-1 panel felt there is the best chance of learning about bag structure.

At energies above 20 GeV, where the de Broglie wavelength is short and the pp differential cross section becomes diffraction-like, it appears the elastic scattering is consistent with a core of 0.2 to 0.4 fm. The break in the cross section is a dramatic effect.

If not NN, then can πN scattering say anything about QCD and bags? A fairly large number of papers deal with quark models for the nucleon and its excited states. Aside from that, there has been less work done, but the Little Bag model does lead to a successful Chew-Low type of theory for low-energy scattering. This model predicts the (3,3) resonance width correctly. What happens for higher energy πN scattering is largely uninvestigated. It may be that the Little Bag and the MIT Bag give different predictions for the electromagnetic form factors, which are related via unitarity and dispersion theory to πN scattering amplitudes.

The quark model itself, with or without the bag model, can give rise to a nonelectromagnetic source of isospin symmetry breaking if the mass of the "u" and "d" quarks differ. This can provide an explanation of why the neutron is heavier than the proton, a $\Delta I = 1$ mass difference that has always been hard to understand electromagnetically. Such isospin violation might also show up in πN and NN scattering. (One example is that the S_{31} and P_{33} phase shifts deduced from π^-p-scattering data may not agree with those found from π^+p.)

The Big Bag quark model appears to require or enhance multibody forces between nucleons. There may be some indication of such forces in recent elastic electron-scattering measurements at large-momentum transfers. These forces may also be the reason why nuclear matter theories cannot reproduce the binding energy and density of nuclear matter. We suggest that experiments studying the energy sharing in the final state following (true) pion absorption in nuclei might show the large three- and four-body correlations expected if this idea holds up.

Another difficult experiment that has been suggested to determine whether the bag for the (3,3) resonance state is spherical or strongly deformed is to measure the Δ-quadrupole moment in the reaction $\pi N \rightarrow \pi N \gamma$ near resonance. (The reason this is difficult is that we have not yet been able to unravel the easier Δ-magnetic moment, despite much effort.)

The implications of QCD for nuclear structure are even more speculative. There are conjectures of a "crystal structure" of the nucleus in the Big Bag model. Electromagnetic form factors at large-momentum transfers may reflect quark-counting rules. And the suggested stable dihyperon (an $S = -2$ $\Lambda\Lambda$-bound state) may be found in doubly strange hypernuclei.

To conclude, we suggest the following experiments as most likely to bear fruit in this speculative new enterprise of QCD and nuclear physics:

1. careful, systematic study of NN scattering in the medium-energy domain to determine the level density and elastic and inelastic widths of dibaryon resonances,
2. pp and πp elastic-scattering studies up to a few GeV with an eye to obtaining information on bag size and excited states of the bag,
3. study of level densities of NN states, a potentially rich area of new physics,
4. study of $N\bar{N}$ annihilation products,
5. experiments to measure isospin violation in πN and NN interactions,
6. searches for multinucleon correlations, as in π-absorption experiments, and
7. search for $S = -2$ hypernuclei.

VII. PCAC AND CHIRAL SYMMETRY

In general, the SU(2) × SU(2) chiral symmetry and PCAC are in good shape when compared with experiment. There is one *caveat*: there are certain processes in which the "background terms," presumably zero in the true soft-pion limit, can be quite large for physical pions. For example, the cross section for $NN \rightarrow NN\pi$ at 740 MeV predicted using the PCAC soft-pion theorem is about a factor of 8 too small. It was conjectured (and more recently checked in a model calculation) that the discrepancy is due to "background" contributions from (3,3)-resonance poles.

The outstanding areas in which there are PCAC difficulties, or for which it would simply be nice to have more data, are these:

1. $\pi N \to \pi N$ data near threshold, to improve the present amplitude analysis,
2. $\gamma N \rightleftarrows \pi N$ and $eN \to e\pi N$ data, also at low energies, to enable a richer amplitude analysis to be carried out,
3. threshold $\pi N \to \pi\pi N$ in one or two other reaction channels, as mentioned in Sec. V.C, to tie down the nature of SU(2) × SU(2) chiral symmetry breaking and the $\pi\pi$ scattering lengths,
4. high-statistics study of the $K_{\ell 3}$ decays (e.g., $K^+ \to \pi^0\mu^+\nu$) to verify the Callen-Treiman relations in detail, and
5. more information regarding the mysterious $\eta \to \pi^+\pi^-\pi^0$ decay. Note that the latter two experiments are not now things that can be done at "medium-energy facilities."

The more general SU(3) × SU(3) chiral symmetry and the associated kaon-PCAC are on rather less-solid experimental grounds. Here, further experimental information or input that is needed includes:

1. determination of the $g_{KN\Lambda}$ and $gg_{KN\Sigma}$ coupling constants, to allow an evaluation and test of the SU(3) × SU(3) Goldberger-Treiman relations,
2. determination of axial-vector coupling constants in hyperon β decays (e.g., $\Sigma^- \to ne\nu$) to check the extensions of the Adler-Weisberger sum rule, and
3. measurement of low-energy $KN \to KN$ scattering to a sufficient accuracy to allow an evaluation of the SU(3) × SU(3) σ term.

In this case all experiments mentioned will have to be done at energies higher than available at intermediate-energy machines. Perhaps some of these would only be feasible with a kaon factory.

To close this section, we remark that all the above statements deal with PCAC at the phenomenological hadronic level. At the quark level the nature of PCAC is still controversial and is in the process of being sorted out and understood.

VIII. APPLICATIONS TO OTHER AREAS OF PHYSICS

As nucleons are the basic building blocks of nuclei, a detailed understanding of NN forces is necessary in order to have a microscopic theory of nuclei. This applies not only to nuclear structure and nucleon-nucleus reactions, but also to nuclear reactions involving other probes (e.g., pions or photons). These always depend, to a greater or lesser extent, on multinucleon effects such as meson-exchange currents, intermediate isobar states, many-body forces, etc.

Nucleon-nucleon amplitudes are used as input for calculations of proton-nucleus scattering cross sections. It appears that lack of knowledge of the spin-dependent NN amplitudes at 800 MeV is standing in the way of using proton-nucleus scattering data to learn about neutron density distributions. For this reason the N-1 panel has recommended a crash program to measure the NN amplitudes they feel they need (from 0 to 30°), using both the HRS at LAMPF and the polarized deuteron beam at Saturne (for quasi-free $\vec{n} + \vec{p}$ information from $\vec{d} + \vec{p}$ reactions). A number of persons on the P-1 panel view such a crash program with caution, since the information that is really necessary may not come from (or be well established by) such a limited set of measurements.

The inelastic $NN \to NN\pi$ amplitudes are likewise needed as input if we are ever to understand the processes of pion production or absorption on nuclei. We concur with the recommendation of the N-7 panel that an increased effort be made to develop our understanding of inelastic NN reactions.

Calculations concerning the properties of pion condensates depend, in their turn, on properties of the πN interaction at low energies. The πN-scattering amplitudes are also input to multiple-scattering or optical model treatments of π-nucleus scattering. We remind the reader of a remark by Gibson that, within a given multiple-scattering treatment of π-helium elastic scattering, equally good parameterizations of the present-day low-energy πN amplitudes give enormous qualitative differences in the predicted π-helium scattering angular distributions.

Another "engineering application" of strong interactions to medium-energy physics will be proton-nucleus production cross sections for kaons and antiprotons. At present these are not well enough known (there is a disputed "knee" in the production curve at the ZGS energy for both K^+, K^- and $\bar{p}$ production) to make a rational choice as to what energy a kaon factory should strive for. We recommend an experiment to measure these cross sections at enough energies, angles, and for enough nuclei to help in the planning and decision-making concerning a future kaon factory and its secondary beams.

There are astrophysical implications of the NN interactions, particularly with respect to neutron stars. The equation of state for neutron matter is needed in order to estimate the mass, radius, and moment of inertia of the neutron star, as well as the sequence of events in the supernova leading to its formation. This equation of state is very much determined by the properties of the short-range repulsive NN interaction. Data at medium energies, as already indicated in Sec. VI, are going to be very important in establishing details of this short-range behavior.

In a more speculative vein, it might be the case that better knowledge of the NN interaction at small distances can be used, together with hadronic scattering experiments, to study the electromagnetic form factors of nuclei. The example we have in mind is the *ad hoc* adjustment made in the deuteron form factor by Gurvitz and Rinat some time ago to fit the back-angle pd elastic scattering, assuming then-known NN amplitudes. Later electron-scattering experiments at SLAC confirmed the postulated 30-times-larger form factor.

IX. NEW FACILITIES — NEEDED AND DESIRED

In the following we do not count as "new" those facilities and improvements that are already under way, such as variable-energy operation, EPB area improvement, and spin-precession equipment at LAMPF, polarized target development at LAMPF, TRIUMF, and Saturne, and polarimeter development at LAMPF and Saturne. Obviously our awareness of these programs had an impact on the suggestions made in this section. We consider the needs at the various intermediate-energy facilities separately.

A. LAMPF

There are three items:

- Dilution refrigerator and frozen spin targets are needed for both the NN and πN programs. This would entail an initial cost of (roughly) \$0.5M and would require a continuing manpower effort (about \$200k/year) for maintenance.
- For use of superconducting magnets in spin-precession solenoids and polarized-target dipoles, a system for recovery, purification, and reliquification of liquid helium is needed for existing targets and superconducting magnets, as well as new acquisitions. We roughly estimate this to cost about \$400k. Perhaps some arrangements can be made with other divisions of LASL to share the cost and work involved.
- For LAMPF to be competitive with Saturne in the production of polarized-neutron beams, an intense polarized H^- source that gives 200-300 nA of polarized protons in Line X is required. (Actually, with such a source LAMPF would be about equal with Saturne in intensity, but some five times better off in energy definition of the neutron beam.) Design and construction of such a source should be under way in one or two years, with operations beginning in three or four years. The cost of such a source is estimated by the LAMPF Long-Range Planning Committee to be about \$1M/-year over the next six years, including the cost of three or four years of operation and maintenance. P-1 panel felt this estimate was too high and suggested that a collaborative effort with the ANL polarized source group might result in a better engineering match of source and the present injector configuration, as well as a more trouble-free performance with deuterium as the charge-exchange medium instead of cesium. We urge LAMPF management to look into this possibility.

B. Saturne

In the near future the polarized proton and deuteron beam in the accelerator will only be transverse. A solenoid and other spin-precession equipment are needed to provide the other spin orientations. We roughly estimate this equipment to cost about $200k.

C. LEAR

We urge the machine designers to look into the question of whether the antiprotons in the storage ring will (or, with easy modifications, could) develop transverse polarization. An estimate by D. Underwood suggests that this useful polarization might evolve in as little as 10 minutes.

D. A Future Kaon Factory

We urge the designers of such a machine to bear in mind the possibility of accelerating polarized protons and providing variable-energy beams (a front or back "porch"?). Polarized deuteron beams would also be desirable, but probably more difficult if a present-day meson factory is used as the injector.

Chairman: Bruce H. J. McKellar
Co-Chairman: Peter Herczeg

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I. INTRODUCTION

The study of the weak interactions has been an extraordinarily fruitful way to obtain information about the fundamental particles. Theoretical and experimental work during the last decade has pointed strongly to the likelihood that the weak and electromagnetic interactions are described by a renormalizable unified gauge theory. Indeed, at the present time all experimental data seem to be consistent with the so-called "standard (Weinberg-Salam) model."[1] In Sec. II we outline the open questions that arise when one wishes to determine some important fine details of the standard model, and when one starts to inquire in the spirit of some theoretical speculations about the possible existence of new interactions which are not contained in the standard model.

The physics involved manifests itself at low and intermediate energies in small corrections to the observables of known processes, and in nonvanishing, albeit very small, branching ratios for reactions that would otherwise be forbidden. It is because of this circumstance that intermediate-energy physics has a unique opportunity to contribute to the advancement of the physics of the fundamental interactions.

Modern meson factories provide beams of π- and μ-mesons nearly three orders of magnitude more intense than those previously available. With these and other high-quality beams one can observe decays with smaller branching ratios, detect small symmetry-violating effects, and measure parameters to higher precision than was possible before. These experiments will be able to determine or place limits on coupling constants or the masses of bosons associated with possible new interactions, in many cases before the new particles are accessible to direct observation.

For this reason the panel believes that a vigorous experimental program at intermediate energies is of the greatest importance.

In this program it will be important that full use be made of high-flux beams available at meson factories. This will require improved beam quality and improved detection systems to reduce backgrounds and it will require substantial commitments of time, manpower, and resources towards single experiments. The rewards, measured in terms of the contribution these experiments will make to our understanding of the properties of the fundamental particles, amply justify the investment required.

In this report we first of all summarize the important open questions in the light of our present theoretical ideas (Sec. II). Then we discuss possible intermediate-energy experiments which bear on these questions (Secs. III-X), concluding the report with our recommendations.

It should be noted that other aspects of weak interactions in intermediate-energy physics are discussed in the reports of panels P-3, P-4, and N-5, to which we refer the reader.

II. THE OPEN QUESTIONS

When considering the physics of weak-interaction processes there seem to be two major areas of inquiry. The first one relates to the identification of the gauge group $\mathcal{G}_{EW}$ of the weak and electromagnetic interactions [i.e., those with coupling constants of the order of $G_F \simeq (1.17 \times 10^{-5})$ GeV^{-2} and $e \simeq (4\pi/137)^{1/2}$], and elucidating the detailed properties of the interactions and particles involved. The second is concerned with the possible existence of other, presumably weaker, nonstrong interactions and with their symmetry group, the flavor group $\mathcal{G}_F$, which will in general contain $\mathcal{G}_{EW}$ as a subgroup.

A new and different class of interactions is predicted by theories which unify the flavor and the strong interactions. However, if the associated bosons are as heavy as expected, the possibility of the proton being unstable would be the only manifestation at present energies.

Turning to the first class of questions we note that, of the many possible renormalizable gauge theories of the weak and electromagnetic interactions,[2] the sequential $SU(2)_L \times U(1)$ (Refs. 1 and 3) model has been especially successful in accounting for the presently available data.[4,5]

In this model the left-handed leptons and quarks are grouped into SU(2) doublets, viz.,

$$\begin{pmatrix} \nu_e' \\ e \end{pmatrix}_L , \begin{pmatrix} \nu_\mu' \\ \mu \end{pmatrix}_L , \begin{pmatrix} \nu_\tau' \\ \tau \end{pmatrix}_L , \ldots$$

and (1)

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L , \begin{pmatrix} c \\ s' \end{pmatrix}_L , \begin{pmatrix} t \\ b' \end{pmatrix}_L , \ldots ,$$

while the right-handed particles are in SU(2) singlets.

By stopping with three doublets, we have already included more particles than are known to exist, as the t quark has not been seen below 15 GeV.[6] However, there are no limits in $SU(2)_L \times U(1)$ itself to the number of generations,[*,7] so *it is important to try to identify the possible existence of particles beyond the third generation.*

In general, the states ν_e', ν_μ', ν_t' and d', s', b' (the gauge group eigenstates), which appear in the SU(2) doublets, do not correspond to the physical particles ν_e, ν_μ, ν_τ and d,s,b, which are eigenstates of the mass matrix. In the six-quark case, using the Kobayashi-Maskawa[8] parameterization, one can express d',s',b' in terms of d,s,b as follows:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} c_1 & s_1c_3, & s_1s_3 \\ -s_1c_2 & c_1c_2c_3 - s_2s_3e^{i\delta} & c_1c_2s_3 + s_2c_3e^{i\delta} \\ s_1s_2 & -c_1s_2c_3 - c_2c_3e^{i\delta} & -c_1s_2s_3 + c_2c_3e^{i\delta} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} , \quad (2)$$

where $c_i = \cos\theta_i$, $s_i = \sin\theta_i$, θ_1, θ_2, and θ_3 are real mixing angles, and δ is a CP-violating phase parameter. The Kobayashi-Maskawa angles are not well determined by existing experiments, and *an effort should be devoted to measuring them.*

Another set of quantities, which at present also have to be introduced as parameters, are the masses of the fermions. It is of great importance to search for processes that would enable one to determine the experimental values of the quark masses, which can then be compared with theoretical predictions. Here it is important to note the more general need for reliable methods to calculate the effects of the strong interactions on weak reactions. Single processes, such as $\pi \to \mu\nu\gamma$, can be helpful as testing grounds of our attempts at dynamical calculations.

For the masses of the neutral leptons there are stringent upper limits, but the question *"Do the neutrinos have precisely zero mass?"* is an open one. Should the answer be no, the neutrinos will mix as do the quarks, through a matrix analogous to Eq. (2)

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*However, some hint of a limit may be found in QCD, which is not asymptotically free if there are more than 17 quark flavors. There is also a result from cosmology that there can be no more than four massless neutrinos as long as all couple to the neutral current (see the review by D. N. Schramm, AIP Conf. Proc., Particles and Fields, 1978).

(Ref. 9), introducing four more parameters into the model to be determined experimentally. In the presence of neutrino mixing, separate conservation of electron, muon, and tau-number will be violated.

In the standard model the weak interactions are carried by the charged vector bosons $W^{\pm}$, which couple only to the $SU(2)_L$ doublets, and the neutral vector boson Z°, which couples to the left-handed doublets and the right-handed singlets. The electromagnetic interactions are of course mediated by the photon. In addition, scalar bosons (the Higgs particles) are required in any renormalizable gauge theory to ensure renormalizability[10] and to give masses to the fermions and the bosons.[11] In the $SU(2)_L \times U(1)$ model, just one complex Higgs doublet suffices for this purpose, and this gives rise to one physical neutral Higgs particle, which has not yet been found experimentally. However, it is quite possible that there are more Higgs doublets (the successful relation $M_W = M_Z \cos\theta_W$ holds for any number), in which case charged physical Higgs particles must also exist. The important question that emerges is *whether we can find evidence for neutral or charged Higgs particles and determine their couplings to the leptons and quarks.*

In the second class of questions outlined at the beginning of this section we ask *whether* $\mathcal{G}_{EW}$ = *$SU(2)_L \times U(1)$ is embedded in a larger flavor group* $\mathcal{G}_F$. For example, $SU(2)_L \times SU(2)_R \times U(1)$ has been suggested as such a group.[12] By judiciously selecting the masses of the right-handed vector bosons, it is possible to ensure that the successes of the standard model are not disturbed. An observation of right-handed charged-current effects would be evidence for a nontrivial right-handed component of $\mathcal{G}_F$ so that $\mathcal{G}_F \neq SU(2)_L \times U(1)$, and some extension is necessary.

Another type of extension of $\mathcal{G}_{EW}$ is to introduce a symmetry group relating the various generations.[13] Such a symmetry may be either discrete[14] or continuous,[15] and has been considered as a means of providing constraints on the mass matrix and the mixing matrix, as well as a means of controlling the number of generations. *If the continuous symmetry is realized as a gauge symmetry, it can give rise to flavor-changing interactions.*

Finally, it is appropriate to conclude our catalog of open questions by emphasizing that the possibility always exists that new phenomena may be discovered which are totally unexpected on the basis of our present ideas.

The answers to the questions outlined in this section are of fundamental importance for the development of physics.

As we shall discuss in this report, the experiments in intermediate-energy physics offer some unique opportunities for probing them because of the high-flux beams available.

III. THE NEUTRINO MASSES

A nonvanishing mass for one or more of the neutrinos has many indirect consequences because it leads to the possibility of a Cabibbo-like mixing for the neutrinos and to the possibility of neutrino decays. These consequences are examined below and in the discussion of neutrino oscillations in the P-3 report.

The present limits on the neutrino masses from direct experiments are $m(\nu_e) < 60$ eV, $m(\nu_\mu) < 570$ keV, and $m(\nu_\tau) < 250$ MeV. There are also some indirect limits or constraints on the neutrino masses. However, the constraint from neutrino oscillation experiments[16] depends on the value of the mixing angle, and the astrophysical limit[17] depends on assumptions about the neutrino decay mechanism and mass.[18]

Studies of the ν_μ mass are well suited to meson factories. Indeed, an experiment at SIN[19(a)] on $\pi \to \mu\nu_\mu$ at rest has produced the quoted limit, and another SIN experiment using $\pi \to \mu\nu_\mu$ in flight is expected to give a similar precision.[19(b)] In attempting to reduce the limit significantly, reactions and decays which produce the ν_μ and two other detectable particles should be investigated. In the kinematic region where ν_μ carries little momentum, this class of experiments is sensitive to $m(\nu_\mu)$, while two-body decays are sensitive to $m^2(\nu_\mu)$.

Of such processes, $\pi \to \mu\nu_\mu\gamma$ (Ref. 20) and $\mu + {}^6Li \to t + t + \nu_\mu$ (Ref. 21) have been the subject of feasibility studies. The first is very difficult because of the low branching ratio to the relevant part of the Dalitz plot, but the second seems to be a feasible experiment.

The panel recommends that other processes with three particles (including the neutrino) in the final state should also be studied.

IV. MUON-NUMBER NONCONSERVATION

In discussing the possible open questions in Sec. 2, we saw that in a gauge theory, conservation

TABLE III-I

EXPERIMENTAL LIMITS ON MUON-NUMBER VIOLATING PROCESSES

Process	Limit (at 90% Confidence Level)	References
$\mu \to e\gamma$	$\Gamma(\mu \to e\gamma)/\Gamma(\mu \to e\nu\bar{\nu}) < 1.9 \times 10^{-10}$	23
$\mu \to eee$	$\Gamma(\mu \to eee)/\Gamma(\mu \to e\nu\bar{\nu}) < 1.9 \times 10^{-9}$	24
$\mu + Z \to e + Z$	$\Gamma(\mu + Z \to e + Z)/\Gamma[\mu + Z \to \nu + (Z-1)] < 7 \times 10^{-11}$	25
$\mu \to e\gamma\gamma$	$\Gamma(\mu \to e\gamma\gamma)/\Gamma(\mu \to e\nu\bar{\nu}) < 1.25 \times 10^{-8}$	26
$K_L \to \mu e$	$\Gamma(K_L \to \mu e)/\Gamma(K_L \to \text{all}) < 2 \times 10^{-9}$	27
$K^+ \to \pi^+\mu e$	$\Gamma(K^+ \to \pi^+\mu e)/\Gamma(K^+ \to \text{all}) < 7 \times 10^{-9}$	27

of muon number does not follow from general principles and would not be expected to hold except in very special circumstances. Nevertheless there are very stringent experimental limits on μ-number violating processes, summarized in Table III-I (Ref. 22).

In the sequential standard model, with just three families and just one physical Higgs particle, the μ-number violating processes can only occur at a rate several orders of magnitude below the present limits. However, as will be discussed in more detail in Sec. IV.A-E, with additional generations or additional Higgs particles or new neutral gauge bosons coupled directly both to (μe) and the quarks, much larger rates are possible, and the present experiments provide the limits on the parameters of these new particles and interactions. Improving the accuracies of the experiments may lead to the discovery of their existence.

A. Lepton Mixing in the Sequential Standard Model

With three lepton families the neutrino-mixing matrix can be written, taking ν_e and ν_μ to be degenerate, as[28]

$$\begin{pmatrix} \nu_e' \\ \nu_\mu' \\ \nu_\tau' \end{pmatrix} \simeq \begin{pmatrix} 1 - \frac{1}{2}\beta^2 & -\beta\gamma & \beta \\ 0 & 1 - \frac{1}{2}\gamma^2 & \gamma \\ -\beta & -\gamma & 1 - \frac{1}{2}\beta^2 - \frac{1}{2}\gamma^2 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} . \qquad (3)$$

It follows that all muon number-violating processes will be proportional to the quantity $(\beta\gamma)^2$. The experimental limit on the rate of the reaction $\nu_\mu + A \to e^- + X$ (Ref. 28) gives $(\beta\gamma)^2 \leq 2 \times 10^{-3}$. The rates for the various processes are[29]

$$B(\mu \to e\gamma) \equiv \Gamma(\mu \to e\gamma)/\Gamma(\mu \to e\nu\bar{\nu}) \simeq \frac{3\alpha}{32\pi} (\beta\gamma)^2 (m_\nu/m_W)^4 , \qquad (4)$$

$$B(\mu \to 3e) \equiv \Gamma(\mu \to 3e)/\Gamma(\mu \to e\nu\bar{\nu}) \simeq \frac{3\alpha^2}{16\pi^2} (\beta\gamma)^2 (m_\nu/m_W)^4 \times \ln^2(m_\nu/m_W)^2 , \qquad (5)$$

$$B(\mu^- Z \to e^- Z) \equiv \frac{\Gamma(\mu^- Z \to e^- Z)}{\Gamma[\mu^- Z \to \nu(Z-1)]} \tag{6}$$

$$\simeq C_V(A,Z) \left[\beta\gamma \frac{3\alpha}{8\pi} (m_\nu/m_W \sin\theta_W)^2 \times \ln(m_W/m_\nu)^2 \right]^2 .$$

In Eqs. (4)-(6), m_ν is the τ-neutrino mass, and $C_V(A,Z)$ is a function of N and Z, given by Shankar.[30] For Z less than about 75, C_V increases with A [for the light elements approximately as A^2 or $(Z-N)^2$, depending on the isospin] because of the coherent nature of the conversion process for the interaction considered). For ^{32}S (on which the experiment listed in Table III-I was performed), $C_V \simeq 153$. Inserting the experimental limit on m_ν, we find that the branching ratios are $B(\mu \to e\gamma) < 4.2 \times 10^{-17}$, $B(\mu \to 3e) < 2.6 \times 10^{-17}$, and $B(\mu^- Z \to e^- Z) < 5.6 \times 10^{-14}$, which would be too small to be detectable. However, if a fourth generation exists, and if the neutrino associated with that generation is sufficiently massive, then this situation changes dramatically. For $m_L \leq 1.9$ GeV and $(\beta\gamma)^2 = 2 \times 10^{-3}$, one obtains

$$B(\mu^- Z \to e^- Z) \lesssim 7 \times 10^{-11} , \tag{7}$$

which is the present experimental limit, and

$$B(\mu \to e\gamma) \leq 1.4 \times 10^{-13} \tag{8}$$

and

$$B(\mu \to 3e) \leq 3.6 \times 10^{-14} . \tag{9}$$

For neutrino masses m_L less than 100 GeV, the inequalities

$$B(\mu^- Z \to e^- Z) > B(\mu \to e\gamma) > B(\mu \to 3e) \tag{10}$$

hold.[28] Thus if lepton mixing in the sequential standard model is the source of μ-number violation, $\mu^- \to e^-$ conversion will have the largest branching ratio.

B. Muon-Number Violation through the Exchange of Higgs Bosons

As emphasized in Sec. II, in the presence of more than one Higgs doublet, muon number is in general not conserved by the interaction of leptons with the Higgs bosons.[31] To be explicit, consider a Higgs field ϕ_H with the interaction Lagrangian

$$\begin{aligned} \mathcal{L} = {} & 2^{1/4}\, m_\mu \sqrt{G_F}\, K_{e\mu}\, (\bar{e}\mu\phi_H + \text{H.c.}) \\ & + 2^{1/4}\, m_e \sqrt{G_F}\, K_{ee}\, \phi_H \\ & + 2^{1/4} \sqrt{G_F}\, K_{qq}\, (m_u \bar{u}u + m_d \bar{d}d)\phi_H , \end{aligned} \tag{11}$$

where $K_{e\mu}$, K_{ee}, and K_{qq} are dimensionless constants into which we have incorporated the Higgs mixing angles. For order-of-magnitude estimates it is usual to adopt the "natural" values $K_{ee} = K_{\mu e} = K_{qq} = 1$, but these constants are not restricted in any way by *a priori* considerations.

Assuming the Lagrangian [Eq. (11)] and using the calculations of Shankar,[30] one finds that the experimental limit on the $\mu^- \to e^-$ conversion process imposes the bound

$$m_H / \sqrt{K_{\mu e} K_{qq}} \gtrsim 50 \text{ GeV} . \tag{12}$$

For $\mu \to 3e$, one obtains then

$$B(\mu \to 3e) \leq (2 \times 10^{-16})(K_{ee}/K_{qq})^2 , \tag{13}$$

which can attain accessible values if the Higgs couples more strongly to electrons than to quarks. Furthermore, in general there may be several Higgs mesons coupled to (μe), but some of them may not be coupled to quarks. For such Higgs H', the bound [Eq. (13)] is not applicable, and all one can say is that the experimental limit on the $\mu \to 3e$ branching ratio requires

$$m_{H'}/\sqrt{K'_{e\mu}K'_{ee}} \gtrsim 1.6 \text{ GeV} \quad . \tag{14}$$

The decay $\mu \to e\gamma$ can also be induced by Higgs exchange, with the two-loop diagrams dominating in general.[31] Many diagrams can contribute, the final result depending on assumptions regarding Higgs-Higgs and Higgs-W boson couplings. A detailed analysis has not been made, but with the assumption that all couplings have their "natural" values, the estimated branching ratio is[31]

$$B(\mu \to e\gamma) \simeq \left(\frac{m_W}{m_{H''}}\right)^4 \left(\frac{\alpha}{\pi}\right)^3 \quad . \tag{15}$$

In the absence of small mixing angles, small coupling constants, or cancellations between the various diagrams which may reduce this estimate, this would require

$$m_{H''} \gtrsim 230 \text{ GeV} \tag{16}$$

for the mass of the Higgs boson H'' involved. Consequently, if H'' couples to electrons and the quarks, one would have (assuming $K_{e\mu} = K_{ee} = K_{qq} = 1$) $B(\mu \to 3e) \lesssim 4 \times 10^{-18}$ and $B(\mu^- Z \to e^- Z) \lesssim 1.6 \times 10^{-13}$.

C. Muon-Number Violation through the Exchange of Neutral Gauge Bosons

A further possible source of muon-number violation could be a neutral gauge boson X_λ (associated with horizontal interactions or belonging to a larger flavor group), coupled to (μe) and possibly also to (ee) and the quarks. Writing the coupling constants of X_λ as $K^{X'}_{\mu e}$e/sin θ_W, etc. (i.e., as a factor $K^{X'}$ times the $SU(2)_L$ coupling constant e/sin θ_W), we can adapt our previous discussion to give limits on the masses and couplings of X_λ.

For the $\mu^- \to e^-$ conversion process, we find

$$m_X/\sqrt{K^X_{\mu e}\, K^X_{qq}} \gtrsim (3 \times 10^3) m_W \quad . \tag{17}$$

and from $\mu \to 3e$

$$m'_X/\sqrt{K^{X'}_{\mu e}\, K_{e'e}} \geq 430\, m_W \quad . \tag{18}$$

Again, the constants $K^{X'}$ are unknown. and X_λ may be different from X'_λ. Consequently either of the processes could have the largest signal. With this mechanism one expects $B(\mu \to e\gamma) \sim \alpha B(\mu \to 3e)$.

D. μ → eγγ

We have not discussed the decay $\mu \to e\gamma\gamma$ *above.* In general one expects

$$B(\mu \to e\gamma\gamma) \sim \alpha B(\mu \to e\gamma) \quad .$$

However, in more complicated gauge models, e.g., where muon-number violation is due to the mixings of new charged leptons, it may not be impossible for $B(\mu \to e\gamma\gamma)$ to exceed $B(\mu \to e\gamma)$.[26]

E. K → μe, K → πμe

Additional information on the possible mechanisms of muon-number violation could be obtained from studies of the strangeness-changing processes $K \to \mu e$ and $K \to \pi\mu e$.

In the standard model with three generations the branching ratios are negligibly small, but the existence of a fourth generation could lead to $B(K_L \to \mu e)$ as large as the present experimental limit, the precise value depending on the quark masses involved, in addition to the mass of the neutral lepton. At the same time, $B(K^+ \to \pi^+\mu e) < B(K_L \to \mu e)$. In the case of a neutral Higgs boson or a neutral gauge boson, coupled to both (μe) and (sd), the K_L-K_S

mass difference imposes severe constraints on the branching ratios of $K \to \mu e$ and $K \to \pi\mu e$ (Ref. 32).

F. Proposed and Future Experiments

In any practical μ-decay experiment, the number N_μ of stopped muons which could produce the decay is limited by stopping rate × run time × detector solid angle/4π. Reasonable values of these parameters give

$$N_\mu \approx (10^7\ s^{-1}) \times (2 \times 10^6\ s) \times 0.1$$

$$\approx 2 \times 10^{12} \quad .$$

The practical statistical limit on the branching ratio is thus 5×10^{-13}. Good resolution in the detection of the decay products is required to reduce the backgrounds to this level.

For the $\mu \to e\gamma$ case, LAMPF Exp. 444 (Ref. 33) is designed to detect a branching ratio of less than 10^{-12}, approaching the limit set by the beam flux.

Using the LAMPF crystal-box detector[34] it will be possible to measure branching ratios of $\mu \to e\gamma$, $\mu \to e\gamma\gamma$, and $\mu \to eee$ with a sensitivity of 7×10^{-12}. This sensitivity is imposed by the μ stopping rate ($5 \times 10^5\ s^{-1}$), and could be improved by running the experiment with a higher duty factor beam. The proposed Dubna-SIN experiment to search for $\mu \to eee$ should reach a sensitivity of the order 10^{-12}.

At present the sensitivity of the μ-e conversion experiment is limited by the background, particularly that arising from π contamination of the beam, and the decay of the muon in orbit. Better beam quality and better detectors will enable us to search for $B(\mu \to e)$ values less than 10^{-12}. We would like to emphasize that the experiment should be performed in nuclei, both with N = Z and with N ≠ Z, to investigate the isotopic dependence of the effective interaction.[30]

The panel strongly recommends that great experimental effort be expended to push all of the μ-number violating rates to the limits set by the beam fluxes available.

V. MUON CONVERSION INTO POSITRONS IN NUCLEI

Another process which could occur in nuclei with muon-number violation, but where at the same time lepton number is not conserved, is the reaction $\mu^- Z \to e^+(Z-2)$ [alternatively, $\mu^- Z \to e^+(Z-2)$ is lepton number conserving with the Konopinski-Mahmoud lepton number assignment].

The $\mu^- Z \to e^+(Z-2)$ could take place in second order via appropriate intermediate neutral leptons.[35] It could arise also via the exchange of a doubly charged boson coupled directly to $(\mu^- e^+)$ (Ref. 36). However, even in this latter case the amplitude is second order in the weak coupling constant, in view of flavor conservation by the strong interactions, and the branching ratio of $\mu^- \to e^+$ to $\mu^- \to \nu$ capture is therefore expected to be less than $10^{-13} - 10^{-14}$ (Ref. 37), to be compared with the present experimental limit 9×10^{-10} (Ref. 38). To improve the existing experimental limit is nevertheless important in order to test the underlying theoretical assumptions and the possible presence of unusual interactions.

VI. THE DECAY $\mu \to e\nu\nu$

The main decay mode of the muon is still the most important potential source of information on the nature of purely leptonic interactions.

The energy-angle distribution of positrons emitted from fully longitudinally polarized muons decaying at rest is given by[39]

$$dN(x,\theta) = \frac{d^3p}{(2\pi)^4} \frac{m_\mu E_0}{12} A \Bigg\{ 6(1-x) + 4\rho \left[\frac{4}{3}x - 1 - \frac{1}{3}\frac{m_e^2}{E_0^2 x}\right] + 6\eta \frac{m_e}{E_0}\frac{1-x}{x} \mp \beta\xi \cos\theta \left[2(1-x) + 4\delta \left(\frac{4}{3}x - 1 - \frac{1}{3}\frac{m_e^2}{m_\mu E_0}\right)\right]\Bigg\} , \qquad (19)$$

where the upper and lower signs refer to μ^- and μ^+, respectively. E_0 is the maximum $e^{\mp}$ energy, $x = E/E_0$, $\beta = p/E$, p and E are the momentum and the energy of $e^{\mp}$, and θ is the angle between the $e^{\mp}$ momentum and the spin direction of the $\mu^{\mp}$. The constant A is related to the muon lifetime.

The present experimental situation regarding the Michel parameters ρ, η, ξ, and δ are summarized in Table III-II. Further information on the couplings involved is obtained from measuring the components of the $e^{\mp}$ polarization.[39] The present experimental limit on the electron longitudinal polarization P_ℓ is $P_\ell = 1.00 \pm 0.13$, to be compared with 1, which is the value for a pure V-A coupling. As seen, the dominant interaction responsible for the decay is a V-A type weak interaction. Analysis of the data shows, however,[39] that the strength of possible contributions from some other type of couplings could still be as large as $(1/3)\ G_F$.

In the context of unified gauge theories, the need to gain precise knowledge about the parameters describing muon decay acquires new significance, since, as discussed in the Introduction, certain deviations from a pure V-A structure are quite conceivable. In particular, a V + A type coupling may appear at some level, which could be mediated by gauge bosons belonging to a flavor group larger than $SU(2)_L \times U(1)$, such as, for example, $SU(2)_L \times SU(2)_R \times U(1)$. In addition, S- and P-type couplings may be introduced by charged Higgs mesons. Further new contributions could come from neutral Higgs bosons with flavor-changing couplings. Some of the new interactions may also violate time-reversal invariance. A test for T-violating couplings is possible through a measurement of the component P_2 of the electron polarization, parallel to $\langle\vec{\sigma}_\mu\rangle \times \hat{p}_e$. (Note that if only a V-A coupling is present, time-reversal invariance is satisfied, and therefore $P_2 = 0$).

TABLE III-II

THE MICHEL PARAMETERS FOR μ DECAY[a]

Parameter	V-A Value	Experimental Value
ρ	0.75	0.752 ± 0.003
ξ	1.0	0.972 ± 0.013
δ	0.75	0.755 ± 0.009
η	0	−0.12 ± 0.21

[a]Ref. 39.

In view of these circumstances, the panel believes that the properties of the decay $\mu \to e\nu\bar{\nu}$ should be explored as accurately as possible.

To see which of the parameters is sensitive to particular types of couplings, we shall consider two simple but important examples.

1. Consider the semiweak interaction in an $SU(2)_L \times SU(2)_R \times U(1)$ model[12]

$$\mathcal{L}_I = \frac{g}{\sqrt{8}}[(V - A)_\rho W_L^\rho + (V + A)_\rho W_R^\rho] + \text{H.c.} \quad , \tag{20}$$

where the mass eigenstates $W_{1,2}$ are related to $W_{L,R}$ as

$$W_1 = W_L \cos\xi - W_R \sin\xi$$

and (21)

$$W_2 = W_L \sin\xi + W_R \cos\xi$$

(ξ is a real angle). Equation (20) leads to a low-energy effective Lagrangian of the form

$$\mathcal{L}_{eff} = -\frac{G}{\sqrt{2}}[V_\rho^+ V^\rho + \eta_{AA} A_\rho^+ A^\rho + \eta_{AV}(V_\rho^+ A^\rho + A_\rho^+ V^\rho) \quad , \tag{22}$$

where

$$\eta_{AA} = (\epsilon^2 m_2^2 + m_1^2)/(\epsilon^2 m_1^2 + m_2^2) \quad ,$$
$$\eta_{AV} = -\epsilon(m_2^2 - m_1^2)/(\epsilon^2 m_1^2 + m_2^2) \quad , \tag{23}$$
$$\epsilon = (1 + \tan\xi)/(1 - \tan\xi) \quad ,$$

and

$$\frac{G}{\sqrt{2}} = \frac{g^2}{8m_1^2}(\cos\xi - \sin\xi)^2 + \frac{g^2}{8m_2^2}(\cos\xi + \sin\xi)^2 \quad .$$

One finds[12]

$$\rho = \frac{3}{8}\frac{[(1+\eta_{AA})^2 + 4\eta_{VA}^2]}{[1+\eta_{AA}^2 + 2\eta_{VA}^2]} \quad ,$$

$$\delta = 3/4$$

$$\xi = -\frac{2\eta_{VA}(1+\eta_{AA})}{[1+\eta_{AA}^2 + 2\eta_{VA}^2]} \quad , \qquad (24)$$

$$\eta = 0 \quad .$$

and

$$P_{e^\pm} = \pm\xi \quad .$$

2. As a second example, we shall consider an admixture of a scalar coupling to a pure V-A interaction:[40]

$$\mathcal{L}_{eff} = \frac{G}{\sqrt{2}}[\bar{\nu}_\mu\gamma_\lambda(1-\gamma_5)\mu][\bar{e}\gamma^\lambda(1-\gamma_5)\nu_e]$$

$$+ \frac{G}{\sqrt{2}}\epsilon_S[\nu_\mu(1-\gamma_5)\mu][\bar{e}(1+\gamma_5)\nu_e] \quad , \qquad (25)$$

where ϵ_S is a parameter. The Michel parameters are

$$\rho = 3/4 \quad ,$$

$$\eta = -\frac{1}{2}\left(\frac{C_V^2 - C_A^2}{C_V^2 + C_A^2}\right) \quad , \qquad (26)$$

$$\xi = -2C_VC_A/(C_V^2 + C_A^2) \quad ,$$

and

$$\delta = 3/4 \quad ,$$

where $C_V = 1 - \epsilon_S/\sqrt{2}$, $C_A = -1 - \epsilon_S/\sqrt{2}$.

The result $\rho = \delta = 3/4$ in Eq. (26) turns out to hold also for the most general linear combination of SS, SP, PS, and PP couplings (in the charge-exchange order) added to a V-A interaction.[41] The relation $P_{e^\pm} = \pm\xi$ holds only in special cases.

As follows from the above discussion, the parameters sensitive to a V + A and a scalar interaction are ρ, ξ, $P_{e^\pm}$ and η, ξ, $P_{e^\pm}$, respectively. In particular, a nonvanishing η signals the presence of a non-V,A coupling (in the charge-exchange order). At present the parameter η is the least known one ($\eta = -0.12 \pm 0.21$). The reason is that being proportional to m_e/E_0, its determination requires an accurate measurement of the low-energy end of the spectrum. The parameters ρ, η, ξ, and δ will be determined with an appreciably higher accuracy by a spectrum experiment at LAMPF[42] and an electron polarization experiment at SIN,[43] improving the limits on the coupling constants by an order of magnitude. Further reduction of these limits from the spectrum experiment would be possible if pions could be stopped in a time projection chamber and the resulting μ tracked in the chamber until its decay. Systematic effects at present limit the possible improvement in the SIN experiment to a factor of 5 to 8. It would be useful to be able to further reduce the systematic effects to take full advantage of the high flux available. If this is possible the feasibility of using integral counting techniques to reduce the statistical limit even more should be investigated.

An elegant experiment at SIN[43] is attempting to measure the transverse electron polarization $P_2 \sim \langle\vec{\sigma}_e \cdot \vec{\sigma}_\mu \times \hat{p}_e\rangle$. Preliminary results put a 10% limit on the T-violating amplitudes. Since this experiment is statistics limited, consideration should be given to developing an experiment suited to integral counting techniques.

VII. PION DECAYS

A. $\pi_{\ell 2}$ Decays and μ-e Universality

The traditional test of μ-e universality has been the ratio

$$R = \frac{\Gamma(\pi \to e\bar{\nu})}{\Gamma(\pi \to \mu\bar{\nu})} \tag{27}$$

$$= (1.26 \pm 0.02) \times 10^{-4} \text{ experimentally.}^{27}$$

With the assumption of μ-e universality and V − A charged currents, R is determined solely by masses

$$R = R_0 = \frac{m_e^2}{m_\mu^2} \frac{(m_\pi^2 - m_e^2)^2}{(m_\pi^2 - m_\mu^2)^2} \tag{28}$$

$$= 1.283 \times 10^{-4} \quad .$$

To be able to compare with experiment at the 1% level, radiative corrections are necessary. These depend on assumptions about the π form factor, but the ratio

$$R_\gamma = \frac{\Gamma(\pi \to e\nu + \pi \to e\nu\gamma)}{\Gamma(\pi \to \mu\nu + \pi \to \mu\nu\gamma)} \tag{29}$$

can be calculated to within 0.2%, to give the calculated value[44]

$$R_\gamma = (1.237 \pm 0.002) \times 10^{-4} \quad . \tag{30}$$

The most recent published experimental result[45] is

$$R_\gamma = (1.274 \pm 0.024) \times 10^{-4} \quad . \tag{31}$$

The experiments which measure R_γ are limited by systematic effects. An experiment in progress at TRIUMF[46] hopes to reduce the errors to the 1% level.

If R_γ is not in agreement with the value calculated from e-μ universality, the difference in the e and μ couplings can be ascribed to charged Higgs effects[47] or to mixing in the lepton sector.[48]

If we define the charged Higgs-Fermion Lagrangian by

$$\mathcal{L}_H = \frac{G_F^{1/2}}{2^{1/4}} H^\dagger [K_q(m_\mu + m_d)\bar{u}\gamma_5 d + K_e m_e \bar{e}(1 + \gamma_5)\nu_e + K_\mu m_\mu \bar{\mu}(1 + \gamma_5)\nu_\mu] + \text{H.c.} \quad . \tag{32}$$

so that $K_q = K_e = K_\mu = 1$ gives the canonical coupling and the neutrino mixing as in Sec. IV.A, we find

$$\frac{\delta R_\gamma}{R_\gamma} \approx \frac{2m_\pi^2}{m_H^2} K_q(K_e - K_\mu) + \gamma^2 - \beta^2 \quad . \tag{33}$$

To obtain this result, it is assumed that the massive neutrino cannot be emitted in π decay. These corrections can easily reach the 1% level if, for example, the lepton mixing angles and their differences are of the order 0.1 (a typical quark-mixing angle magnitude), or $K_e = m_\tau/m_e$, $K_\mu = m_\tau/m_\mu$, $K_q = 1$, and $m_H = 100$ GeV. It is important that the experimental errors in R_γ be reduced below the 0.2% level of the errors in the radiative correction calculations in order to test the equality of μ and e couplings.

B. $\pi \to e\nu\gamma$

The radiative π decay $\pi^+ \to e^+\nu\gamma$ can proceed via inner bremsstrahlung from the π^+ and e^+ and via radiation from intermediate states generated through the strong interactions. This latter process, called the structure-dependent term, is dominant for those decays in which the e^+ and γ are nearly back to back in the pion rest frame and share almost all of the available energy. In practice one looks for the structure-dependent term by restricting E_e and E_γ to both exceed 50 MeV.

The interest in this decay arises from the fact that the structure-dependent process tests our ability to do dynamical calculations. The matrix element can be expressed in terms of a vector form factor F_V and an axial vector form factor F_A. The F_V can be calculated from CVC and the rate for $\pi^0 \to \gamma\gamma$

(Ref. 49); $\gamma = F_A/F_V$ has been calculated using soft-pion techniques,[50] which gives $|\gamma| = 0.6$, and using hard-pion techniques,[51] which gives $\gamma \approx -0.5$. It has recently been pointed out that γ depends strongly on the up-down quark mass ratio m_u/m_d (Ref. 52) because of isospin symmetry breaking when $m_u \neq m_d$.

Two existing measurements of the decay rate[53] were severely statistics limited, observing a total of 313 events because the branching ratio is of the order 10^{-8}. They are consistent with $\gamma = 0.2$ or $\gamma = -2$, with errors of ± 0.1 in each case. Two new experiments, one in progress at TRIUMF and the other planned at SIN, will significantly improve the statistics, and discriminate between the two values of γ consistent with the total rate by measuring the electron spectrum over a wider range. The experiment is also being redone at 25 GeV at Serpukov.

It has recently been suggested[52] that a comparison of results for π^+ and π^- would help in separating the two form factors. This would require measurements of the decay in flight.

C. Pion β Decay

At present the branching ratio for $\pi^+ \to \pi^0 e\nu$ is $(1.02 \pm 0.07) \times 10^{-8}$ (Ref. 54). The experiment, done in the mid-1960's, was statistics limited. It should be possible to measure the branching ratio to better than 1% at a meson factory. This is the level of the radiative corrections to the process.

The interest in an accurate measurement of the branching ratio is two-fold:

1. It provides a test of CVC (which is fundamental to all gauge theories of the weak interactions).
2. It provides a limit on the coupling and masses of the charged Higgs particles.

These particles give rise to an S and P effective interaction, and an analysis of the branching ratio gives the limit[55]

$$\frac{K_q K_e\, m_e\, (m_u + m_d)}{m_H^2} \leq 0.14 \quad ,$$

where the couplings are defined in Sec. VII.A. This is the best available limit on the charged Higgs coupling.

As it comes from a 7% experiment, it is clear that it can be reduced significantly by a modern measurement of the branching ratio.

D. The Decay $\pi^0 \to e^+e^-$

The decay $\pi^0 \to e^+e^-$ is of interest as a probe of the $\pi^0\gamma\gamma$ vertex, and also as a potential source of information on possible nonelectromagnetic interactions between electrons and hadrons.[56]

The most general form of the decay amplitude can be written as

$$M(\pi^0 \to e^+e^-) = a\bar{u}(p_-)\gamma_5 v(p_+) + ib\bar{u}(p_-)v(p_+) \quad , \tag{35}$$

implying a rate

$$\Gamma(\pi^0 \to e^+e^-) \simeq \frac{m_\pi}{8\pi}\left(|a|^2 + |b|^2\right) \quad . \tag{36}$$

The present experimental limit is

$$B(\pi^0 \to e^+e^-) \equiv \Gamma(\pi^0 \to e^+e^-)/\Gamma(\pi^0 \to \text{all})$$
$$= (22^{+24}_{-11}) \times 10^{-8} \text{ (Ref. 57)} \quad .$$

Thus

$$B(\pi^0 \to e^+e^-) < 7 \times 10^{-7} \text{ (95\% C.L.)} \quad . \tag{37}$$

Since the effect of the CP-violating amplitude b on the rate is presumably negligible,[56] one obtains from Eq. (37) the constraint

$$|a| \lesssim 10^{-6} \quad . \tag{38}$$

In the presence of only the electromagnetic interactions

$$a = \mathrm{Re}a^{(e)} + i\,\mathrm{Im}a^{(e)} \quad . \tag{39}$$

$\mathrm{Im}a^{(e)}$ can be calculated in a model-independent way using the unitarity relation, giving

$$\mathrm{Im}a^{(e)} = 2.6 \times 10^{-7} \quad . \tag{40}$$

Hence

$$B(\pi^0 \to e^+e^-) \geq 4.7 \times 10^{-8} \quad . \tag{41}$$

$\mathrm{Re}a^{e}$ is, on the other hand, model dependent. The available calculations give values in the range

$$|\mathrm{Re}a^{(e)}| \simeq (0.2 - 2)\,|\mathrm{Im}a^{e}| \quad . \tag{42}$$

The experimental limit [Eq. (37)] would still allow an $\mathrm{Re}a^{(e)}$ of the order of $4\mathrm{Im}a^{e}$.

A nonelectromagnetic contribution comes from the neutral current interaction in the Weinberg-Salam model. However, being proportional to the electron mass, its effect on the rate is completely negligible. Another nonelectromagnetic contribution could arise from Higgs meson exchange.[40,58] Let us consider a Higgs-fermion interaction of the form

$$\mathcal{L} = f'\bar{e}e\,\phi_H + f''\,\frac{1}{2}\,(\bar{u}i\gamma_5 u - \bar{d}i\gamma_5 d)\phi_H \quad . \tag{43}$$

The contribution a_H of Eq. (43) to a is given by[58]

$$a_H = \frac{G_F m_\pi^2 f_\pi}{2(m_u + m_d)}\,g_H^{PP} \quad , \tag{44}$$

where $f_\pi \simeq 0.97\, m_\pi$ is the charged-pion decay constant and

$$g_H^{PP} = \frac{f'f''}{m_\pi^2 - m_H^2}\,\frac{\sqrt{2}}{G_F} \quad . \tag{45}$$

Assuming $|\mathrm{Re}a^{(e)}| < 6 \times 10^{-7}$, the experimental limit [Eq. (37)] implies

$$|g_H^{PP}| < 1.4 \quad . \tag{46}$$

For "canonical" Higgs couplings $f' = 2^{1/4}\sqrt{G_F}\, m_e$, $f'' = 2^{1/4}\sqrt{G_F}\,(m_u - m_d)$ one would obtain the value $g_H^{PP} = 1.4$ for $|m_\pi^2 - m_H^2| = 2.4\ \mathrm{MeV}^2$.

From the present experimental value [Eq. (37)], it is clear that an improved experiment is needed. A LAMPF experiment with much better statistics is being analyzed, but this experiment suffers from background problems and may not give definitive results. However, an improved experiment should be able to determine the $\pi^0 \to e^+e^-$ branching ratio to 10% or better.

E. $\pi^0 \to 3\gamma$

The decay $\pi^0 \to 3\gamma$ is C-violating, so its observation would be indicative of a C-violating term in the effective interaction. The predicted branching ratio depends on phase space and angular momentum barrier effects, and has been calculated to be $3 \times 10^{-6}|C_-|^2$ (Ref. 59) and $2 \times 10^{-5}|C_-|^2$ (Ref. 60), where C_- is the ratio of C-violating to C-conserving amplitudes. A LAMPF experiment using a lead-glass detector has limited the branching ratio to less than 5×10^{-7} at the 90% confidence level (C.L.) (Ref. 61), which limits $|C_-|$ to be less than 0.2 or so.

It is suggested that use of the crystal-box detector at LAMPF could measure a branching ratio of 10^{-8} to 10^{-9}, or $|C_-| \sim 10^{-2}$.

The measurement of C_- in $\pi^0 \to 3\gamma$ is a clean test of C-violation, but because of strong interaction effects it is difficult to relate C_- to other tests of C violation, such as η-decay asymmetry and the neutron electric dipole moment.

VIII. THE QUARK-MIXING ANGLES

The Kobayashi-Maskawa quark-mixing matrix was introduced in Sec. II.

In principle, one can determine θ_1 from nuclear β decay, θ_3 by combining this information with strange particle decay data, and θ_2 by combining this information with charmed-particle decay data. In practice, nuclear structure and Coulomb corrections with radiative corrections limit the accuracy of the determination of $\cos\theta_1$ to 2.5 parts per thousand. This provides most of the uncertainty in the determination of $\sin\theta_3 = 0.28^{+0.21}_{-0.20}$ (Ref. 62).

Improved tests of the quark mixing in strange particle decays will be an important part of a kaon factory program when experiments with 10^6 hyperon β decays will become possible. These experiments may resolve discrepancies in the measured and predicted values of g_A/g_V for Λ and Σ^- β decay (in the latter case the world average g_A/g_V does not even have the predicted sign).[27]

However, they will need to be combined with improved measurements of the neutron decay parameters. The neutron lifetime, for example, is known only to 2%. And it will be necessary to improve our calculational reliability for radiative corrections to β decay of composite particles — both nuclei and hyperons.

IX. NONLEPTONIC WEAK INTERACTIONS

A. The Strangeness-Conserving Nonleptonic Weak Interaction

Since a detailed understanding of the nonleptonic weak interactions still eludes us, further information on the structure of these interactions is a valuable stimulus to theoretical advancement. For example, an improved knowledge of the $\Delta S = 0$ interaction, in the weak interaction between nucleons, can help us to understand the nature of octet enhancement.

At our present stage of knowledge it is best to try to use experiments to define the structure of the parity-violating nucleon-nucleon interaction. The step to such an interaction from the underlying weak-interaction Lagrangian is still a very large and difficult one.

B. Low Energies

Here there exists a significant amount of data,[63] but much of it has rather large errors. These errors, with the uncertainties in the nuclear physics analysis of the data, make it very difficult to obtain information about the structure of the parity-violating nucleon-nucleon potential.[63,64] There is a prime need for more experimental information on few-nucleon systems — especially the two-nucleon systems.

We encourage the proton-proton longitudinal analyzing power experiments at 15 MeV (Ref. 65) and 50 MeV (Ref. 66) currently in progress. These experiments have at present reached a sensitivity level of the order of 10^{-7}, which is the order of the expected effects.[67] Since these experiments will obtain significant results, we strongly urge that they be pushed to their ultimate sensitivity level, which would be expected to be about 3×10^{-8}.

In addition, longitudinal analyzing power in p-p and n-p scattering should be measured up to 400 MeV in steps of about 50 MeV This would allow a "phase-shift" type of fit to the parity-violating mixing angles and would give some chance of fitting the shape of the parity-violating potential to the data. It appears to be feasible to reach a sensitivity of 10^{-7} for p-p scattering with the present flux. However, the $\vec{n}$-p experiments require polarized proton beams of 100 times the present intensity.

Parity violation in $n + p \leftrightarrow d + \gamma$ should be further examined since it offers a clean separation of $\Delta I = 0,2$ and $\Delta I = 1$ parts of the potential. In particular we note that the existing measurement of the photon circular polarization is difficult to accommodate in the usual theoretical framework.[63,64] Therefore we welcome and encourage proposals to remeasure the γ circular polarization, to pursue the γ asymmetry in polarized neutron capture, and to determine the analyzing power of the breakup reaction for circularly polarized photons.

We also encourage proposals to perform (e,e') reactions to low-lying excited states in light nuclei using circularly polarized electrons. These reactions, which are almost the inverse of the γ-decay investigations of parity mixing in light nuclei, are discussed in more detail in the N-5 report.

C. Intermediate Energies (Above π Production Threshold)

Above the π production threshold, there are two p-p experiments at 800 MeV and 6 GeV currently being performed and analyzed. The interpretation of these experiments will require further theoretical work. The only existing calculation of parity-violating effects at these energies[68] is incomplete in that parity violation in the inelastic channels and in the hadronic states themselves were omitted. Such an analysis will introduce parameters additional to those used at low energies. Further theoretical work is required to identify the most convenient parameterization at intermediate energies.

It seems reasonable to expect a sensitivity of 10^{-7} in these experiments also. We encourage experiments over a range of intermediate energies, as a knowledge of the energy dependence of the analyzing power may identify the important inelastic channels and thus assist in developing the theoretical interpretation.

D. ΔS = 1 Nonleptonic Decays

Nonleptonic decays of kaons and hyperons are perhaps beyond the realm of intermediate-energy physics, at least until the kaon factory era. However, the decays are observed to obey the $\Delta I = 1/2$ rule to a good approximation, and the interpretation of this rule as octet dominance links the $\Delta S = 1$ nonleptonic weak interactions to the $\Delta S = 0$ nonleptonic weak interactions of the previous section. It is therefore appropriate to briefly consider kaon and hyperon decays here. The $\Delta I = 1/2$ rule is well established experimentally, but theoretical interpretation of the rule is still somewhat tentative. Penguin diagrams (see the paper of M. K. Gaillard in Ref. 5) appear to provide a possible explanation of the $\Delta I = 1/2$ rule for decays with at least one pion in the final state. Penguin diagrams, and indeed any other model of the $\Delta I = 1/2$ rule, predict a small parity-violating amplitude for $\Sigma^+ \to p\gamma$ decay. The present experimental value of the asymmetry parameter, α, is $\alpha = -1.03^{+0.52}_{-0.42}$ (Ref. 69). This is consistent with maximal parity violation ($\alpha = -1$), but it is only two standard deviations from exact parity conservation ($\alpha = 0$).

A more precise measurement of α for this decay, and the corresponding information for other radiative hyperon decays, would either resolve or sharpen this difficulty, and is to be encouraged.

X. CP AND T VIOLATION

Fifteen years after the discovery of CP violation in the $K^0 - \bar{K}^0$ system, this remains the only one in which CP violation has been observed. However, it is possible to incorporate CP violation into the gauge theory of flavor dynamics in a natural way. In the standard model this is done either through the phase factor in the Kobayashi-Maskawa six-quark mixing matrix of Sec. II, or by introducing a least two Higgs doublets.[70]

A. The Neutron Electric Dipole Moment

Perhaps the best place to look for CP violation outside the $K^0 - \bar{K}^0$ system is to try to detect the electric dipole moment of the neutron, which will vanish unless P and T are both violated. Here the two different gauge theory mechanisms give quite different predictions: (1) the Kobayashi-Maskawa six-quark model predicts

$$d \sim 10^{-28} - 10^{-31} \text{ e cm (Ref. 71)} \quad , \qquad (47)$$

and (2) the Higgs mechanism predicts

$$d \sim 2.8 \times 10^{-25} \text{ e cm (Ref. 72).} \qquad (48)$$

An experiment in which a neutron beam was passed through a resonant cavity gave the 90% confidence limit[73]

$$|d| \leq 3 \times 10^{-24} \text{ e cm} \quad , \qquad (49)$$

while an experiment with ultracold neutrons trapped in a cavity gave the limit[74]

$$|d| \leq 1.5 \times 10^{-24} \text{ e cm} \quad (50)$$

Future experimental progress will be made with trapped neutrons. If one could keep the neutrons in the cavity for 10^3 s, it may be possible to reach 10^{-28}, but at present there are practical limitations due to

- leakage of neutrons (the present storage time is about 1 s),
- magnetic resonance conditions, which cannot be maintained at present for more than 50 s, and
- leakage currents in the presence of the strong electric fields.

With an intense pulsed source of ultracold neutrons it will be possible to increase the storage time and break the 10^{-26} barrier. The 10^{-28} level would seem to be a reasonable goal with present techniques, but it may be possible to do even better.

Notwithstanding the development of an ultracold neutron source at the Rutherford Laboratory, and the proposed development at Argonne, the panel recommends the development of such a neutron source at LAMPF and/or Troitsk.

The neutron electric dipole moment is an elusive but important parameter in particle physics. Its measurement would play a crucial role in improving our understanding of CP violation. Even if the pulsed ultracold neutron facility had no other use, it would still be worthwhile to build it for the sole purpose of measuring the neutron electric dipole moment.

B. The K^0-$\bar{K}^0$ System

This is the classic, and to date the only, system in which CP violation has been observed. Since further studies of CP-violating effects in the K^0 system may help to distinguish the possible models, it is appropriate to consider it here.

In the K^0-$\bar{K}^0$ system, CP violation is characterized by two complex parameters, ϵ and ϵ' (Ref. 75); ϵ measures the CP-violating terms in the K^0-$\bar{K}^0$ mass matrix, while ϵ' measures CP odd terms in the decay amplitudes. The experimental observables are

$$\eta_{+-} = \frac{A(K_L^0 \to \pi^+\pi^-)}{A(K_S^0 \to \pi^+\pi^-)} = \epsilon + \epsilon' \quad , \quad (51)$$

$$\eta_{00} = \frac{A(K_L^0 \to \pi^0\pi^0)}{A(K_S^0 \to \pi^0\pi^0)} = \epsilon - 2\epsilon' \quad , \quad (52)$$

$$\delta = \frac{\Gamma(K_L^0 \to \pi^- e^+ \nu_e) - \Gamma(K_L^0 \to \pi^+ e^- \bar{\nu}_e)}{\Gamma(K_L^0 \to \pi^- e^+ \nu_e) + \Gamma(K_L^0 \to \pi^+ e^- \bar{\nu}_e)} = 2\,\mathrm{Re}\,\epsilon \quad . \quad (53)$$

At present the data[27] are consistent with the superweak theory, in which $\epsilon' = 0$. The experimental data give

$$\left|\frac{\epsilon'}{\epsilon}\right| < 0.022 \text{ at } 90\% \text{ C.L.} \quad . \quad (54)$$

It is important to refine the measurements of the CP-violating parameters to attempt to detect values of $|\epsilon'/\epsilon|$ of about 2% because such values are predicted in the two attempts to put the CP-violating interaction into the gauge theoretic context.

In the six-quark model it was originally thought that ϵ' would be negligible.[71] It was subsequently pointed out that penguin diagrams can induce a nonnegligible contribution to ϵ' (Ref. 76). The six-quark prediction for $|\epsilon'/\epsilon|$ is model dependent,[77] but $|\epsilon'/\epsilon|$ can be as large as 2%.

In the Higgs model one obtains $|\epsilon'/\epsilon| \approx 0.3\, m_\pi^2/m_K^2 \approx 0.02$ (Ref. 78).

Because these two gauge theories of CP violation predict that $|\epsilon'/\epsilon|$ is near its present limit we strongly encourage attempts to measure this ratio. Perhaps a factor of 6 improvement can be achieved with present accelerators[79]; after that we may have to wait for the kaon factories.

C. $K \to \pi\mu\nu$

The Higgs model of CP violation predicts CP violation in the decay amplitudes for this process, leading to a μ polarization transverse to the decay plane. We define

$$P_\mu^{(T)} = \langle\vec{\sigma}_\mu \cdot (\hat{p}_\mu \times \hat{p}_\pi)\rangle \propto \mathrm{Im}\xi \quad ,$$

where Imξ measures the proportion of CP violation in the amplitude. The present experimental value is Imξ = 0.012 ± 0.026 (Ref. 80), while the Higgs model of CP violation predicts Im$\xi \sim 3 \times 10^{-3}$ (Ref. 81). A new experiment has been proposed[82] which should be able to reach 2×10^{-3} in K_L^0 decay. The electromagnetic final-state interactions enter at this level, suggesting that $K_{\mu 3}^+$ decays should be investigated to push for still smaller values.

XI. DIRECT SEARCHES FOR HIGGS PARTICLES

Throughout this report there have been many references to the effects of Higgs particles, which at present have only theoretical support for their existence. A universal property of such particles is that they have Yukawa couplings to hadrons of strength $\geq \sqrt{G_F}\, m_\pi$ (Ref. 83), whereas they couple to leptons with strength $\sim \sqrt{G_F}\, m_\ell$ ($m_\ell \equiv$ lepton mass). Using this property, atomic and nuclear physics experiments have established the limit $m_H \geq$ 20 MeV on the Higgs particle mass. Higher theoretical limits[84] need not apply if there is more than one such Higgs particle (this prospect receives support from the study of unified theories). It is therefore important to search every mass range for the existence of these particles.

Because of the stronger coupling to hadrons, it is efficient to search for these particles in hadronic experiments. In view of the mass limit above, one must look at K-decay experiments or in hadronic scattering above a few hundred MeV in order to be well above thresholds. At very high energies, one needs to remove multiparticle debris, and therefore one tends to beam dump experiments. However, the increasing decay rate as m_H increases makes this impractical for m_H > 100 MeV; the Higgs particles never make it to the detectors behind the dump.

This leaves direct production experiments, where Higgs production and decay are observed in the apparatus. Here experiments at modest energies available at meson factories may have the advantage of simple final states. For $m_H < 2\, m_\mu$, the main decay mode would be $H \rightarrow e^+e^-$. For m_H not too much greater than $2\, m_\pi$, there is a significant branching ratio to $\mu^+\mu^-$ (J. Ellis, Ref. 5), and the lifetimes are short (less than or of the order of 10^{-10} s). Thus an analog of the $\pi^0 \rightarrow e^+e^-$ experiment carried out at LAMPF might be able to put stringent limits on the existence of Higgs particles. The feasibility of such experiments at meson factories should be further investigated.

The entire discussion above also applies to the axion, a special Higgs particle associated with conserving CP in QCD. This particle was originally thought to be light (<1 MeV),[85] but more recently it has been realized that if there are many Higgs particles, mixing phenomena allow an axion mass as large as 1 GeV (Ref. 86). Thus its properties and searches for it in the meson factory mass range are very similar to those for ordinary Higgs particles.

XII. RECOMMENDATIONS

A. A General Recommendation

In searching for the weak-interaction effects described above, it is important that the limits of our ability to detect small effects are the intrinsic limits set by the high flux of the intermediate-energy accelerators. *To reach these limits will require improvements in beam quality and improvements in detectors, which the panel recommends be made.*

To realize this objective will require resources that are substantial on the scale of intermediate-energy physics. It should be pleasing, however, that at least some questions of interest to particle physics can be pursued at a cost which is relatively low.

B. Muon-Number Nonconserving Processes

Our first priority recommendation is that searches for the muon number nonconserving processes $\mu \rightarrow e\gamma$, $\mu \rightarrow e\gamma\gamma$, $\mu \rightarrow eee$, and $\mu + A \rightarrow e + A$ should be pushed to reach the sensitivity of about 10^{-13} set by the particle fluxes and the beam time.

We have seen that many different mechanisms can give rise to μ-number violation, and there is sufficient freedom in the theory to make it impossible to predict which process will have the largest rate. It is therefore important to search for all of them.

In support of our recommendation, we note Veltman's remarks at the Photon-Lepton Conference held at the same time as our workshop.[87] He urged the continued search for μ-number violation because of the light it can shed on the large mass structure of the theory.

C. Precision Studies of Allowed Decays

The panel recommends higher precision measurements of allowed π and μ decay parameters, in particular for

- μ beta decay,
- $\pi_{\ell 2}$ and radiative $\pi_{\ell 2}$ decay,
- $\pi^{\pm}$ beta decay, and
- $\pi^0 \to e^+e^-$.

These can all provide information about possible breakdown of the standard model, through the appearance of V + A or S, P, and T couplings induced by right-handed vector bosons or Higgs particles, and through possible breakdown of μ-e universality. It is also recommended that T-violation searches be undertaken in the case of μ decay.

D. The Neutrino Masses

Because of the possibility that there are ways out of indirect limits on the neutrino masses, *the panel recommends that experiments be designed to attempt to place limits better than 100 keV on the ν_μ mass.*

E. Neutron Dipole Moment

The panel recommends the measurement of the neutron electric dipole moment to the 10^{-26}-cm level or better. A pulsed ultracold neutron facility will be necessary to break the 10^{-25} barrier, and the panel recommends the construction of such a facility at LAMPF and/or Troitsk, at cost of the order of $50 000.

This measurement is fundamental if we are to understand the origin of CP violation.

F. $\Delta S = 0$ Nonleptonic Weak Interactions

The panel recommends that the study of parity-violating effects in the nucleon-nucleon system at low and intermediate energies be continued. This is essential if we are to determine the isospin structure of the $\Delta S = 0$ nonleptonic weak interactions and shed more light on the mechanism responsible for octet enhancement.

G. Higgs Particles

The panel recommends the study of the feasibility of direct searches for low-mass Higgs particles.

H. The K-Factory Era

The panel did not systematically study possible experiments at a kaon factory. However, a number of such experiments did arise in the course of our discussions, and we list them here:

- searches for μ-number violating K decays,
- improved determination of the CP-violation parameters in K^0 decays,
- a search for T-violating triple correlations in $K_{\mu 3}$ decay,
- high-precision studies of hyperon beta decay to verify the Cabibbo theory and to help determine the Kobayashi-Maskawa angle θ_3, and
- studies of radiative hyperon decays which will provide a crucial test of our understanding of octet enhancement.

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IV. PANEL P-3

NEUTRINO-INDUCED INTERACTIONS

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Co-Chairman: Richard Slansky

Participants: G. Brooks, D. A. Buchholz, H. H. Chen, R. Davis, Jr., T. W. Donnelly, O. D. Fackler, H. W. Fearing, M. Goldhaber, M. Jacob, K. Lande, V. Lobashev, S. P. Rosen, L. R. Sulak, A. L. Turkevich, and S. Willis.
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I. INTRODUCTION

Neutrino research, which started with the detection by a Los Alamos group of low-energy reactor neutrinos, has recently been principally the domain of high-energy physics. What is the role of neutrino physics at medium energies? It is the purpose of this report to delineate this role and to explore those experiments that appear uniquely suited to answer fundamental questions at medium energies.

It is useful to briefly identify the principal areas of neutrino research. Keeping in mind our present concept of weak interactions, the following classification may be a useful basis for discussion.

- ***Fundamental properties of neutrinos:*** rest-mass; quantum mechanical structure and capability to oscillate; numbers and types.
- ***Coupling to leptons:*** exploration of vector and axial-vector coupling constants and comparison to models of charged and especially neutral currents; universality.
- ***Coupling to hadrons:*** studies of form factors and coupling constants to nucleons or to their constituents in the framework of models with charged and neutral currents. (At medium energies, a new regime of relatively low-momentum transfer can be explored.)
- ***Interaction of neutrinos with nuclei:*** exploration of charged and neutral current couplings and form factors, as well as studies of nuclear structure.

What are the respective roles played by low-, medium-, and high-energy neutrino physics in this endeavor? Table IV-I may help to convey this overview. The entries in the column headed "Medium Energies" summarize the experimental program proposed in the following sections of this report.

II. MEDIUM-ENERGY FACILITIES AND THEIR CURRENT ROLE IN NEUTRINO PHYSICS

A. Brookhaven Alternating Gradient Synchrotron (AGS) at 800 MeV

The downgraded pulsed proton beam of the AGS ($\sim$1 μA, $\sim$1 pulse per second) is being used for a search for $\nu_\mu \leftrightarrow \nu_e$ oscillations.[1] The ν_e-induced events are sought at d = 150 m from the target. The anticipated limit for the neutrino mass difference Δ^2 is about 0.3 (eV)^2, assuming maximum mixing. Other neutrino proposals at the full AGS energy include ν_μe, $\bar{\nu}_\mu$e scattering,[2] as well as a study of the reaction ν_μd (Ref. 3). Previous work, notably ν_μp and $\bar{\nu}_\mu$p scattering, is documented in Neutrinos-78.

B. CERN Synchrocyclotron (SC) and TRIUMF

These machines have a high duty factor and thus are less suited for neutrino work. At present there are no neutrino proposals.

C. LAMPF

Neutrinos emerging from the beam dump (300- to 500-μA protons at 800 MeV) have been actively exploited during the past five years. Two experiments (LAMPF Proposal 31)[4] have been completed, and a third experiment (LAMPF Proposal 225)[5] is in progress. Below is a brief resumé of this work.

- The reaction $\nu_e + d \rightarrow p + p + e^-$ has been observed and its cross section measured to 35% accuracy.[4]

TABLE IV-I

OVERVIEW OF NEUTRINO PHYSICS

	Low Energy	Medium Energy	High Energy
Neutrino properties	$m_{\bar\nu_e} < 35$ eV	$m_{\nu_\mu} < 570$ keV	
$(\Delta^2 = m_1^2 - m_2^2)$	$\Delta^2_{\bar\nu_\mu} < 0.1\ (\text{eV})^2$ [a]	$\Delta^2_{\nu_\mu} < 0.3\ (\text{eV})^2$ [b]	$\Delta^2_{\nu_\mu} < 1\ (\text{eV})^2$ [c]
		$\Delta^2_{\nu_\mu,\bar\nu_\mu} < 0.1\ (\text{eV})^2$	
Coupling to leptons	$\bar\nu_e e$ [d,e]	$\mu^+ \to \nu_\mu / \mu^- \to \bar\nu_\mu < 6\%$ [f]	$\nu_\mu e$, $\bar\nu_\mu e$
		$\nu_\mu e, \bar\nu_\mu e$ [g]	Neutral current coupling constants g_V, g_A to ±15% [h]
		$\nu_e e \to \nu_e e$ [i]	
Coupling to hadrons and nuclei	$\nu_e Z \to e^-(Z+1)$ [j]	$\nu_e d \to ppe$ [f]	Inclusive and exclusive (e.g., $\nu_\mu p$) processes establish neutral current coupling constant to quarks g_{uL}, g_{dL}, g_{uR}, g_{dR} to ±10% [h]
	$\nu_e d \to e^+ nn$ [k] $\nu_e d \to \nu_e pn$	$\nu_\mu d \to \nu_\mu pn$ [l]	
	$\bar\nu_e {}^7Li$	$\nu_\mu {}^4He \to \nu_\mu {}^4He$ coherent [m]	
		$\nu_\mu {}^7Li$ $\nu_\mu {}^6Li$ $\nu_\mu {}^{12}C$ etc. [n]	

Note:

Boxed entries: experiments proposed in this report.
Underlined entries: proposed elsewhere.
Not underlined entries: experiments completed.

[a] Refs. 14 and 15.
[b] Ref. 1.
[c] Refs. 1, 4, and 12.
[d] Ref. 24.
[e] Inconclusive regarding neutral current couplings (see Ref. 18).
[f] Ref. 4.
[g] Ref. 2.
[h] Refs. 25 and 26. For charged current reactions, see Neutrinos-78, Purdue University.
[i] Ref. 5.
[j] Ref. 27.
[k] Ref. 22.
[l] Ref. 23.
[m] Ref. 21.
[n] Ref. 20.

- Lepton number conservation has been tested by searching for the reaction $\mu^+ \to e^+ + \bar{\nu}_e + \nu_\mu$, which is forbidden by the usual lepton conservation laws. An upper limit of 5% of the rate expected by the multiplicative law was obtained.[4]
- From a study of the process $\nu_e + e \to \nu_e + e$, information on the contribution of charged and neutral current couplings is sought (in progress).[5]

D. SIN

Despite the unfavorable duty cycle of this machine, a study at the beam dump is being conducted to establish the feasibility of neutrino experiments utilizing the microstructure of the SIN 100-μA, 600-MeV beam. A search for $\nu_\mu \to \nu_e + \gamma$ is being contemplated.[6]

E. MOSCOW

A 600-MeV, 0.5- to 1-mA linac is under construction. This facility will have a proton storage ring capable of 100 pulses per second at an average current of 500 μA. A neutrino research program is being planned.

III. THE FUTURE OF MEDIUM-ENERGY NEUTRINO PHYSICS

In this section we discuss a neutrino facility and present a detailed discussion of several significant prospective experiments in particle and nuclear physics.

A. The Facility

Among the facilities mentioned, LAMPF appears best suited to contribute to the basic understanding of neutrinos and their interactions. Some experiments that are not possible at high-energy machines can be done at LAMPF.

1. Advantages of LAMPF as a Neutrino Source

1. *High fluxes* of all neutrinos (ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$) with energies E_ν up to 200 MeV.

2. Availability of a *strong ν_e source* (not available in present high-energy facilities). This allows, for example, the study of interference effects in ν_ee scattering.

3. *Suitable energy range* for studying inelastic nuclear excitations, coherent scattering from nucleons and nuclei, as well as for the pursuit of neutrino oscillation experiments. It allows exploration of the low range of momentum transfer in scattering experiments not easily accessible with high-energy beams. In inelastic nuclear scattering, it makes it possible to exploit a strong sensitivity to pseudoscalar coupling at 100 to 200 MeV, which disappears at high energies.

4. *Short duty cycle* time structure as discussed below.

The items 1, 2, and 3 above can be realized only if the present time structure from the accelerator (7% duty factor) can be modified to give a short duty cycle neutrino beam. This can be achieved in an attractive way by taking advantage of the Proton Storage Ring (PSR), where the duty factor will be 3 $\times 10^{-6}$. The PSR is now under design.

2. The PSR Neutrino Beam

The PSR facility has been funded and is scheduled for completion in 1983. It will store up to 6 $\times 10^{13}$ protons for 0.1 s and then dump them on a production target in a spill time of 300 ns. The repetition rate is about 10 per second, giving an average current of 100 μA at a duty factor of 3 $\times$ 10^{-6}.

To use this facility as a neutrino source, it will be necessary to build a large-aperture (1 to 2 sr) pion channel and decay section in the forward direction. According to estimates by Burman,[7] the neutrino flux at a distance of 18 m from the target (12-m decay section, 6-m shielding) is $N(\nu_\mu) = 3 \times 10^6/cm^2$ s, and $N(\bar{\nu}_\mu) = 0.5 \times 10^6/cm^2$ s. Estimated neutrino spectra for two different pion momenta are presented in Fig. IV-1. Alternatively, a beam-dump neutrino source can be considered.[8]

Owing to the short duty factor, cosmic-ray background can be suppressed significantly and an acceptable signal-to-noise ratio can be obtained. Also, the time structure of the proton pulse allows temporal separation of "prompt" pion-decay neutrinos and "delayed" muon-decay neutrinos, the latter being produced by the decay of muons stopped in the region of the production target, as illustrated in the table below.

Tune	Prompt Neutrinos (<300 ns)	Delayed Neutrinos (1-4 μs)
π^+	ν_μ	$\bar{\nu}_\mu, \nu_e$
π^-	ν_μ	ν_μ, ν_e

The pion channel could be a large gap magnet, a horn, or a magnetic bottle. The first possibility appears to be a practical and efficient device, only slightly inferior in flux to the rather elaborate "Lobashov bottle."[9]

All experiments described below require the short duty factor time structure of the PSR. They also require large detectors with 100-300 tons of target material.

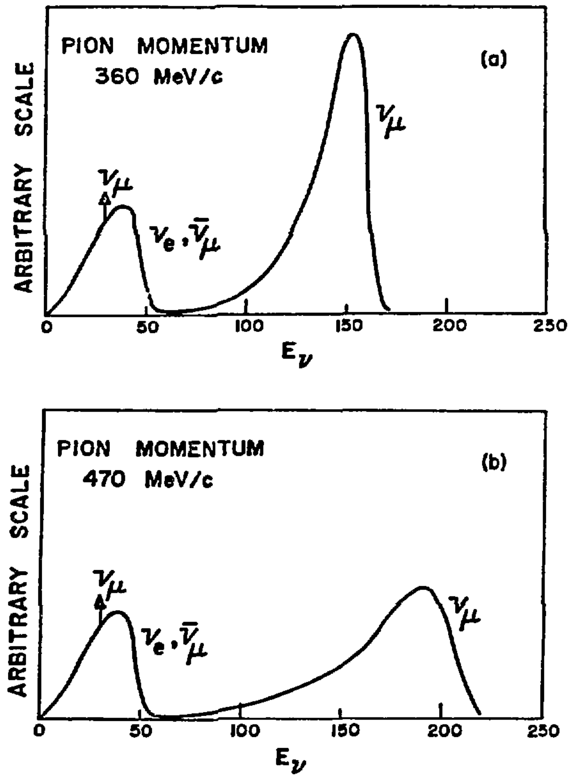

Fig. IV-1.
Estimated neutrino spectra at LAMPF PSR/Neutrino Facility (Ref. 7).

B. Possible Neutrino Experiments

1. Neutrino Properties: Neutrino Oscillations

The possibility that the physical neutrinos ν_e, ν_μ are not pure states in a quantum dynamical sense, but rather superpositions of mass eigenstates ν_1, ν_2 has been discussed in the last few years.[10] As a consequence, the physical neutrino may oscillate between its initial and other states. Oscillations of the type $\nu_e \rightarrow \nu_\mu$ ("flavor oscillations") or $\nu_L \rightarrow \bar{\nu}_L$ ("particle-antiparticle oscillations") are anticipated in many recent theories.[11]

Oscillations may occur only if the mass difference of the pure states $\Delta^2 = m_1^2 - m_2^2$ and the oscillation amplitude is nonvanishing.

Present limits on Δ^2 for oscillations associated with ν_μ have been obtained from a search for ν_e-induced reactions from a ν_μ beam. From work at CERN (Gargamelle),[12] Brookhaven,[1] and Los Alamos,[4] this limit on Δ^2 is about 1 $(eV)^2$, assuming maximum mixing. Oscillations involving $\bar{\nu}_e$ states at reactor energies have been studied by Reines' group.[13] Forthcoming results at low energies (Grenoble[14] and Savannah River[15]) will provide a sensitivity of 0.1 $(eV)^2$. These latter experiments, in which the disappearance of the $\bar{\nu}_e$ state is sought, are also sensitive to particle-antiparticle oscillations.

There are no stringent experimental limits for particle-antiparticle oscillations out of the ν_μ and $\bar{\nu}_\mu$ states, and the following estimates[16] can be made providing a basis for a possible experiment at the LAMPF neutrino facility.

a. Disappearance of the $\bar{\nu}_\mu$ State. Assume that we have a $\bar{\nu}_\mu$ beam of 150 MeV from π^- decaying in flight in a pion channel, with a flux of $0.5 \times 10^6/\text{cm}^2$ s. The detection reaction $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ has a cross section of about 1.5×10^{-39} cm^2. Then the rate of neutrino-induced events in a 300-ton, proton-rich, liquid-scintillation detector will be about 2000/day at about 12 m from the midpoint of the decay section and 10/day at 170 m, assuming no oscillations and assuming a $1/r^2$ dependence of the neutrino flux. If the ratio, R = events 170 m/events at 12 m, can be measured to 3% (3 months running time), then the limit for the oscillation length (Λ) of 3800 m can be established, which corresponds to $\Delta^2 \leq 0.1$ (eV)^2.

In this experiment, the μ^+ events are counted. The signature is a 40-MeV pulse in the liquid scintillator measured during the 300-ns interval of the beam spill followed by a delayed pulse from the μ^+ decay. There will be background signals from the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ associated with the $\bar{\nu}_e$ produced in the decay of μ^- stopped in the region of the channel. The cross section for this process at 40 MeV can be estimated to be about 1.8×10^{-40} cm^2.

The cosmic-ray background for a 300-ton detector may be 3×10^4 s^{-1} times duty cycle (3×10^{-6}) and can be further suppressed by an active veto.

b. Disappearance of the ν_μ State. Another way to study these neutrino oscillations is by the reaction $\nu_\mu + {}^{12}C \rightarrow \mu^- + {}^{12}N({}^{12}N^*)$. Carbon-12 is chosen since it is a constituent of a liquid-scintillation counter. While the ν_μ flux is larger than the $\bar{\nu}_\mu$ flux by a factor of 6, the cross section of this reaction is estimated to be an order of magnitude smaller than that of $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$. The event rate is therefore lower, and a several-month running time should be contemplated to furnish 3% accuracy on the ratio R of the event rate at 170 m to that at 12 m. Various detection schemes can be considered. The signature in the liquid scintillator is a prompt μ^- followed by a signal from the μ^- decay (2 μs), or ^{12}N decay (11 ms), or both. Clearly, the cosmic-ray background problem will be more difficult, since a larger time window will have to be chosen.

2. Neutrino Interactions with Leptons: Neutrino-Electron Scattering

An experiment to measure the reaction $\nu_e + e \rightarrow \nu_e + e$ is presently in progress at LAMPF.[5] This experiment, and a contemplated second-generation experiment[17] at the PSR will provide information on the interference of weak charged and neutral current amplitudes and help establish the identity of the ν_e's that couple to the charged and neutral currents.[18] Such information helps to identify further the properties of neutral weak bosons (one or several Z^0's).

A further experiment that can be considered is the reaction $\nu_\mu + e \rightarrow \nu_\mu + e$, which occurs only via neutral currents. It is a fundamental process and its study provides a stringent test of weak-interaction models. The reaction is presently under study at high-energy beams. Studies at medium energies will shed light on the energy dependence of the cross section. The feasibility and scale of such an experiment at the PSR beam has been considered.[19] Rates of about *2 events/day* per 100-ton detector are estimated. Cosmic-ray background appears manageable provided that an active anticoincidence is used along with the low duty factor timing. Accelerator neutron backgrounds can be reduced with adequate shielding. The experiment appears feasible.

3. Neutrino Coupling to Hadrons: Elastic Neutrino-Proton Scattering

The neutral current reactions, $\nu_\mu + p \rightarrow \nu_\mu + p$ and $\bar{\nu}_\mu + p \rightarrow \bar{\nu}_\mu + p$, have played a significant role in determining the space-time properties of the weak neutral current (see Neutrinos-78). The BNL experiment is not sensitive to q^2 below 0.4 (GeV/c)^2; improving on this may require new detector technology. However, at the lower energies at LAMPF it might be possible to measure mass-dependent effects in the cross section. This is of interest in resolving the "confusion theorem,"[18] stating that V and A can be confused with a combination of S, T, and P in high-energy cross sections. At present no detailed analysis of detection and background problems is available at LAMPF energies.

4. Neutrino Coupling to Nuclei

Elastic scattering takes place via the neutral weak interaction, and in general involves vector and axial-vector contributions of both isoscalar and isovector nature. However, one part is dominant in scattering from nuclei, the coherent contribution,*[20] which involves only the vector isoscalar part of the weak neutral current. In fact, for $J = T = 0$ nuclei this is all that contributes. This part of the current causes the cross sections to increase with increasing mass number as A^2. Thus for heavy nuclei one obtains very sizable cross sections. In contrast, the only signal for an elastic event is the recoil of the nucleus whose energy varies as 1/A. Since there is a practical lower limit to measure recoil energies, the A^2 gain is limited and there will be an optimum value of A. For the present purpose, the following discussion of ^4He will serve as an illustration.

a. Coherent Scattering on ⁴He. The coherent scattering reaction $\nu_\mu + {}^4He \rightarrow \nu_\mu + {}^4He$ is due to the isoscalar part of the neutral vector current that has amplitude a_0. In the Weinberg-Salam model $a_0 = \sin^2\theta_W$; a_0 varies widely for different models, thus providing a test of the model description.

To obtain an estimate,[21] we assume $E_{\nu_\mu} = 200$ MeV and $\sin^2\theta_W = 0.2$. The resulting cross section is 0.5×10^{-40} cm², and the nuclear recoil kinetic energy is in the range of 4 to 12 MeV. With a flux of 3×10^6/cm² s this leads to a rate of 2 events/day per ton of ^4He.

Background estimates, based upon data taken at LAMPF from a 0.4-ton plastic scintillator surrounded by appropriate shielding and and active anticoincidence, indicate that cosmic-ray and natural radioactive backgrounds are under control if the PSR duty factor is 3.6×10^{-6}. Accelerator-associated neutron backgrounds are assumed to be controllable since these neutrons can be attenuated by a factor of 10^2 per meter of iron.

This estimate suggests that it is possible to study coherent effects of the weak neutral current at the LAMPF PSR-neutrino facility. A demonstration of the feasibility depends primarily on the development of a large ^4He counter.

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*For coherent scattering, see Ref. 20(b).

b. Excitation of Specific Nuclear States by Neutrinos. The transitions discussed here are dominated by single-particle excitations; collective excitations (giant resonances) have not yet been considered. By selecting a specific initial and final nuclear state (with well-defined spin and isospin), it is possible to focus on different pieces of the weak neutral current. For example, $\nu_\mu + {}^{12}C(0^+0) \rightarrow \nu_\mu + {}^{12}C(1^+1,\ 15.1\ \mathrm{MeV})$ isolates the axial-vector-isovector contribution to the neutral current. The cross section for this reaction is strongly model-dependent, as illustrated in Fig. IV-2. (The models 1-5 are identified in Ref. 20.)

Since these reactions correspond (approximately) to single-nucleon excitations, the counting rates are relatively low. For the ^{12}C reaction mentioned above, the event rate at the PSR ($E_\nu \sim 200$ MeV) is expected to be around 0.5 events/day per ton. Another example of an interesting reaction is

$$\nu_\mu + {}^7Li\left(\frac{3^-}{2}\ \frac{1}{2}\right) \rightarrow$$

$$\nu_\mu + {}^7Li\left(\frac{1^-}{2}\ \frac{1}{2},\ 0.48\ \mathrm{MeV}\right) \quad .$$

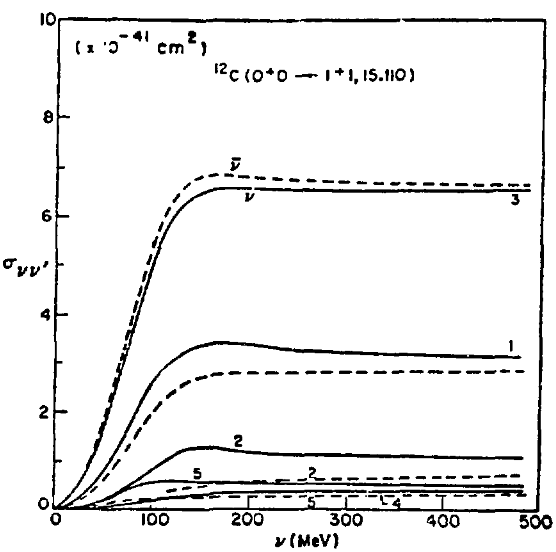

Fig. IV-2.
Illustrates the great sensitivity of the cross section to the models 1 to 5 (see Ref. 20).

which focuses on the axial-vector isoscalar and isovector contributions of the neutral current. Event rates of 2/day per ton are expected. Similarly, the event rate for $\nu_\mu + {}^6Li(1^+0) \rightarrow \nu_\mu + {}^6Li(0^+1,$ 3.56 MeV) is about 1.5/day per ton.

A reaction that is forbidden in the Weinberg-Salam model is the isoscalar-axial-vector transition, $\nu_\mu + {}^{14}N(1^+0) \rightarrow \nu_\mu + {}^{14}N(2^+0,$ 7.03 MeV). Testing for this reaction is clearly of interest.[20]

c. Neutral Current Disintegration of the Deuteron. The reaction $\nu_\mu + d \rightarrow \nu_\mu + p + n$ is of interest since it can proceed only via the axial-vector-isovector component of the weak neutral current. Studies with low-energy neutrinos[22] have demonstrated that the reaction $\bar{\nu}_e + d \rightarrow \bar{\nu}_e + p + n$ proceeds as predicted by the Weinberg-Salam model for the axial neutral vector current.

The $\nu_\mu + d$ experiment can be realized with a D_2O target interspersed with ^3He neutron counters. Estimates of the event rate at the PSR based on the results of Ref. 22, and taking into account the relatively long neutron capture time of 300 μs, predict about 2 events/day per ton.[23] In spite of the longer effective duty factor (3×10^{-3}), the signal-to-noise ratio is estimated to be 1:1, provided that adequate shielding is available.

d. Neutrino-Nucleus Interactions Involving Charged Currents. Charged current interactions can be used to study weak-interaction nuclear form factors, in analogy to electromagnetic form factors in electron scattering. Although these experiments appear interesting, their feasibility probably lies some time in the future.

Similarly, another interesting prospect is the study of the induced pseudoscalar coupling constant C_p in a reaction such as $\nu_\mu + {}^{12}C \rightarrow \mu^- + {}^{12}N$, not too far above threshold. Of course this sensitivity to C_p vanishes at higher energies, making this another example of the unique nature of the PSR neutrino facility.

In a more practical vein, we note that by virtue of their large cross sections, charged current reactions clearly play a role as neutrino detectors. For example, the reaction $\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$, which has an estimated event rate of 13/day per ton, may be of interest in oscillation experiments.

IV. SUMMARY AND RECOMMENDATIONS

1. LAMPF is a unique facility for studying neutrino interactions. For example, the LAMPF ν_e source has no counterpart at other facilities.

2. As a way of decreasing backgrounds and separating neutrino types, we strongly endorse a LAMPF neutrino facility at the PSR, where a duty factor of 3×10^{-6} should be available. To obtain sufficient count rates, the neutrino flux should be $\geq 3 \times 10^6$ ν_μ/cm² s.

3. Several currently significant experiments have been discussed and appear feasible. Among them are measurements of neutrino oscillations, ν_e scattering, and coherent and inelastic scattering on nuclei. In the medium-energy range, these experiments possess a unique sensitivity to weak-interaction parameters.

4. Attention should be given to timely and adequately supported development of detector systems. We note that a detector dedicated to one experiment might serve a purpose in another experiment.

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V. PANEL P-4

ELECTRO-WEAK INTERACTIONS AND THE EXOTIC ATOMS

Chairperson: **C. S. Wu**
Co-Chairperson: **P. O. Egan**

Participants: G. K. Backenstoss, J. Bailey, H. C. Bryant, L. Delker, G. Dugan, T.E.O. Ericson, C. Gardner, M. V Hoehn, H. Hofer, V. W. Hughes, J. R. Kane, T. Kinoshita, D. Lu, P. J. Mohr, A. Olin, H. Orth, R. Powers, G. zu Putlitz, E. B. Shera, W. W. Smith, H. D. Wohlfahrt, and T. Yamazaki.

I. INTRODUCTION

Exotic atoms are formed when any slowed-down, negatively charged particles, other than ordinary electrons, are captured into hydrogen-like orbits in the Coulomb field of the nucleus. The exotic atoms which have been observed and are under vigorous study are μ^-, π^-, K^-, $\bar{P}$, and Σ^- atoms. Still waiting to be observed are Ξ^-, Ω^-, and $\bar{D}^-$ atoms. When a positive muon or positron and an electron form a hydrogen-like atom, it is called muonium or positronium, respectively. *Muonium* is an ideal system to study the electromagnetic interaction of two different leptons and thereby test muon electrodynamics, and to search for weak, strong, or unknown interactions in the electron-muon bound state.

Exotic atoms provide an excellent tool for investigating a great variety of problems. They can be used *to determine the fundamental properties of the particles,*[1] such as masses and magnetic moments. They are ideal probes *to test fundamental theories*[2] such as the quantum electrodynamics, to observe the effect of *weak interactions* in the muon (g-2),[3] and also possibly *parity-violating effects*[4] due to the existence of the neutral weak currents.

The *muonic atom* is particularly very sensitive to *the charge distribution* of the nucleus and *nuclear structure*. Because its interaction energies are comparable to the nuclear excitation energies in certain nuclei, the muon is capable of *inducing nuclear excitations, resonances, and fissions* in deformed and transitional nuclei. The accuracy of *strong interaction shifts* measured in pionic x rays has been improved to better than 1 part in 10^{-2}. There is no fundamental reason why pion-nucleus scattering and pionic x-ray data cannot be used to obtain complementary information concerning matter distribution much as *muonic atoms and elastic electron scattering* provided detailed information concerning the charge distribution.

Hadronic atoms (K^-, $\bar{P}$, and Σ^-) have always been looked upon as sensitive probes for the nuclear matter distribution[5] in the nuclear periphery. But the presence of the Y_0^* resonance at 1405 MeV, quite close to the K^--N threshold, complicated the interpretation.[6] More accurate measurements in the low-Z region, where ρ_p and ρ_n are quite well known, are needed to clarify the situation. This is of special interest in the case of $\bar{P}$-atoms, where it is unclear whether or not resonances near threshold exist. In the last few years, a few narrow bound $\bar{p}p$ (Ref. 7) states have been reported. They are called baryonium states $\bar{N}N$. However, the experimental situation is not sufficiently clear at present, and great additional efforts are needed. Should these narrow, bound $\bar{N}N$ states exist, it will open up an important field for study of the fundamental nucleon-antinucleon interactions.

The two-electron H^- ion and its parent atom are being studied using the relativistic H^- beam[8] from LAMPF to open up a unique and novel field of atomic physics (see Appendix). These investigations are very productive and educational. The panel felt such studies require only a few μA beam, and their modest needs should be considered and their efforts encouraged.

The field of application of the *muon spin resonance (μSR)* to the study of chemical and solid-state effects was also raised and discussed* briefly. It was decided that due to its broadness and

*We wish to express our deep appreciation to Dr. zu Putlitz and Dr. R. Heffner for their efforts on behalf of the μSR research interests.

maturity, its limited coverage in our panel would not do it justice. The μSR deserves a separate workshop together with chemistry and solid-state physics to chart its new directions.

The purposes of the workshop were to critically review the present status of each subfield and to chart new directions for future research in intermediate-energy physics for the next 5-10 years. Questions posed were: What are the new advances in our theoretical understanding and new developments in experiments? What are the important theories to be tested, open questions to be answered, new directions and new frontiers to be explored, controversial experimental evidences to be clarified, and precision measurements to be carried out, etc.? The world's leading meson factories (LAMPF, SIN, and TRIUMF) have succeeded in providing us with intense μ and π beams, but to carry out the demanding second-generation μ and π experiments, beam quality and versatility, as well as intensity, should be equally stressed. We proposed a number of modest recommendations on improving the μ and π beams; although they were specifically directed towards LAMPF, this was only because of our familiarity with it. The continued improvement of the secondary beams (μ and π beams) should be kept in mind for all meson factories in general.

II. FUNDAMENTAL PROPERTIES OF PARTICLES

Exotic atoms have played an important role in precision determinations of fundamental elementary particle properties such as M_{μ} , M_{π} , M_{K} , $M_{\bar{p}}$, M_{Σ} , μ_{μ}, $\mu_{\bar{p}}$, and μ_{Σ} (see Table V-I). The principle and methods involved in these determinations appear deceptively simple. The high resolution of the curved crystal spectrometer, together with the Marushenko[9] target arrangement, have recently been utilized to determine the mass of pion to 5 ppm.[10] This arrangement has been optimistically estimated to be applicable to the determination of M_{K^-} on AGS at Brookhaven National Laboratory (BNL). Another improved method[11] of immersing thin lead plates in a liquid-hydrogen target has also been proposed and approved to redetermine the value of μ_{Σ^-}, hopefully to improve over the old results by a factor of 10 (see Sec. XI).

III. TEST OF FUNDAMENTAL THEORIES

A. QED Vacuum Polarization

The dominance of the vacuum polarization contribution in muonic atoms makes these atoms ideally suited for tests of QED in complement to other QED tests, such as the Lamb shift, electron and muon anomalous magnetic moments, and the hyperfine structure (hfs) of the ground state of muonium. The excellent agreement between theory and experiment for vacuum polarization over a wide range of Z (see Table V-II) constitutes one of the major successes of modern atomic theory and QED. Cases I to III in Table V-II are experiments which have already been carried out. Cases IV and V are still in the planning stage. In Case I, Ge(Li) detectors were used to measure the high Z, muonic-atom x rays[12] (e.g., lead, barium, etc.). Experiment II was the well-known $(\mu^4He)^+$ measurement,[13] using the tunable laser method on the 2S − 2P transition. Because of large uncertainties introduced by the rms charge radius of helium, the relative accuracy of the vacuum-polarization test in the 2S-2P experiments was limited to 2.5×10^{-3}. Case III was the V.P. test that used a curved-crystal spectrometer on light and medium nuclei at SIN, done by Leisi's group.[14] The accuracy is comparable to that of Case II. The proposed improved test in the 3D-3P transitions in muonic helium (Case IV)[15] is to avoid the uncertainties in the rms charge radius of helium. The level separations of the two 3D-3P transitions in $(\mu^-{}^4He)^+$ are given almost entirely by the vacuum polarization terms. By locating the center of a 3D-3P line to one-tenth of its 360-Å width, one would be able to check QED to at least 4 parts in 10^4. The last case, planned at SIN, employs the laser resonance method to induce the 2S-2P transition in an extremely low-pressure μ^-p gas target in a magnetic bottle.

B. Weak Interaction and the Muon g-2

The lowest order predictions of the Weinberg-Salam theory are in good agreement with nearly all experiments. However, these experiments do not test effects involving loop diagrams which are crucial in establishing the gauge theoretical aspect of theory. The most accessible and cleanest test of

TABLE V-I

FUNDAMENTAL PROPERTIES OF PARTICLES[a]

	Mass (MeV)	Magnetic Moment	Remarks
μ^+	105.659 46 ± 0.000 24	μ_μ/μ_p = 3.183 3403 ± 0.000 0044	Yale-Heidelberg
π^-	139.5686 ± 0.002		SREL, Ge(Li)
	139.5667 ± 0.0024		Gatchina, crystal spectrometer
	139.5656 ± 0.0008		Yale-Columbia, crystal spectrometer
K	493.688 ± 0.030		CERN, Ge(Li)
	493.657 ± 0.020		Columbia-Yale, Ge(Li)
$\bar{p}$	938.179 ± 0.058	−2.791 ± 0.021 (N.M.)	Columbia-Yale, Ge(Li)
		−2.819 ± 0.046 (N.M.)	BNL, Ge(Li)
Σ	1197.24 ± 0.15	$-1.40^{+0.41}_{-0.28}$ (N.M.)	Columbia-Yale, Ge(Li)
		$0.65^{+0.28}_{-0.41}$ (N.M.)	
		−1.48 ± 0.37 (N.M.)	BNL, Ge(Li)

[a] See Refs. 1 and 60

such effects, until practical calculational techniques of QCD are developed, is provided by the weak-interaction contribution to the muon g-2, which is

$$a_\mu^{weak} \simeq 2 \times 10^{-9} \quad ,$$

according to the Weinberg-Salam model (assuming $\sin^2 \theta_w = 0.2$). The best experimental value is a_μ^{exp} = 1 165 922 (9) × 10^{-9}. Thus, measurement of a_μ must be improved by at least an order of magnitude in order to detect the presence of the weak interaction in a_μ^{exp}. The intense muon beam available at

TABLE V-II

TESTS OF VACUUM POLARIZATION

	Atoms	Precision Relative to Vacuum Polarization	Method of Determination
I.	High Z, Pb, Ba, etc.	4 × 10^{-3}	Ge(Li) (Ref. 2)
II.	$(\mu^- {}^4He)^+$ 2S → 2P	2.5 × 10^{-3}	Tunable laser (Ref. 13)
III.	μ^- ^{24}Mg, ^{28}Si, ^{31}P $3D_{3/2} \rightarrow 2P_{1/2}$	2.5 × 10^{-3}	Curved crystal spectrometer (Ref. 14)
IV.	$(\mu^- {}^4He)^+$ 3P-3D	4 × 10^{-4}	Tunable laser (Ref. 15)
V.	$(\mu^- P)$ 2S-2P	5 × 10^{-4}	Tunable laser (Ref. 65)

LAMPF encourages examination of feasibility of such a measurement in the near future.

The latest theoretical prediction for a_μ is

$$a_\mu^{th} = 1\,165\,921\,(10) \times 10^{-9} \quad .$$

which includes the contribution of QED up to the order of α^4 (with a theoretical uncertainty of $\pm 2 \times 10^{-9}$), the τ-meson contribution, the hadronic contribution (uncertainty of $\pm 9.4 \times 10^{-9}$), and the weak-interaction effect.

It is clear that a_μ^{th} must also be improved to detect the weak-interaction effect. The largest source of theoretical error is in the hadronic contribution which reflects error in the measurement of $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$. The latest values of R reported since a_μ^{th} was evaluated will enable us to reduce the hadronic contribution error by a factor of 2. Some further work is needed to bring this error down to the level of 1×10^{-9}. Another source of theoretical error is the α^3 and α^4 terms of the QED contribution. However, these errors are not difficult to eliminate. Such a calculation is in progress by T. Kinoshita and co-workers.

The latest experiment[16] is still (provided one works hard enough!) statistics limited; the total number of events recorded was only 1×10^9. Work is presently in progress at CERN and at LAMPF to consider ways to extend this measurement in the future, and it seems obvious that the new generation of meson factories will play a crucial role in the next generation of g-2 experiments. It is also clear that such experiments will demand the utmost in beam quality from the new machines.

C. Parity-Violating Effects in Muonic Atoms

In the unified gauge theories of Weinberg and Salam[17] there is a neutral current interaction between the nucleons and leptons via the Z° intermediate boson. Muonic atoms may thus yield important information, complementary to the neutrino-induced reactions at high energies, from the interference between the weak neutral Hamiltonian and the electromagnetic interaction that leads to observable parity-violating effects. The parity-violating effects[18] may be observable in three possible measurements: (1) the γ angular asymmetry with respect to muon polarization, (2) the photon circular polarization from unpolarized muons, and (3) the angular asymmetry of Auger electrons.

Several exploration experiments[*,19] for neutral current effects in muonic atoms have been carried out; however, the effects are small ($\sim 10^{-5}$) and hence the experiments rather difficult. Experiments should be further improved and closely followed. It should be recalled here that although parity nonconservation was observed in the high-energy scattering of longitudinally polarized electrons by nucleons[20] in 1978, the evidence of parity violation in atomic physics is still not clear.[21]

IV. MUONIUM, MUON MAGNETIC MOMENT, MUON MASS

Recently completed muonium experiments[22] at LAMPF using the "surface" muon beam will improve the accuracy of the muonium hfs interval $\Delta\nu$ to the level of $\simeq 30$ ppb, and simultaneously determine the muon magnetic moment, μ_μ, to about 0.4 ppm. Meanwhile, a measurement at SIN[23] of the μ^+ precession frequency in Br_2 by the "stroboscopic" technique has determined μ_μ to 0.9 ppm. Both quantities, μ_μ and $\Delta\nu$, are of fundamental physical interest. The measurement of μ_μ determines the muon-electron mass ratio to the same accuracy — and this is certainly one of the most interesting, and puzzling, pure numbers in modern physics. Also, the theoretical value for the muonium hyperfine interval is now presently limited by theoretical uncertainties of about 1 ppm in the QED corrections. Muonium provides a challenge to theorists to improve our understanding of the physics of the simple leptonic system.[13]

Future Plans

The "stroboscopic" muon moment is at present limited by systematic effects in the line shape and by chemical shielding effects; future progress along this line would require intensive studies of these effects. The muonium method has so far been free of

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*Experiments on parity violation induced by weak neutral currents in muonic atoms look for the moment outside experimental feasibility (see Ref. 19).

systematic line-shape effects. Since future improvement would require a determination of the line center to 10^{-4} of the natural line width, it is clear that techniques to narrow the observed line shape are essential. Line-narrowing techniques, however, require ***a pulsed beam structure*** so that long-lived muonium atoms can be selected.

V. MUONIUM-EXCITED STATES (MUONIUM-ANTIMUONIUM CONVERSION, MUONIUM LAMB SHIFT)

In the past year, experiments at LAMPF[24] and at SIN[25] have searched for production of muonium in the vacuum regions between thin metal foils in which μ^+ are stopped. Both experiments have concluded that the fraction of stopping μ^+-forming muonium is well below 5% — in contrast with earlier results from SREL[26] which claimed 30% formation. Meanwhile, experiments at TRIUMF[27] have concentrated on understanding muonium-formation processes in fine metal-oxide powders.

Future Plans

Muonium in a vacuum would open the door to a whole generation of interesting new experiments. The method of obtaining thermal muonium by foils doesn't appear feasible, so future experiments along these lines will concentrate on the "fast" muonium emerging from thin targets in a μ^+ beam — analogous to beam-foil spectroscopy. Experiments with powders will probably concentrate on extremely thin powder densities.

In both cases, extremely good beam quality (small-range widths, small spots) is essential. For the beam-foil experiments, ***extremely narrow (≃100-ns) pulsed muon beams*** would be advantageous.

VI. NEUTRAL MUONIC HELIUM ($\alpha\mu^-e^-$)

Recent experiments[28] at SIN and LAMPF have observed the hfs transitions due to the μ^-e spin interaction in the ground state of the neutral muonic-helium atom ($\alpha\mu^-e^-$). The present experiments will determine the hfs interval $\Delta\nu$ and the negative-muon magnetic moment to the level of about 10 ppm. The theoretical problem of accurately calculating the three-body interaction involved in this system is currently the limiting factor in testing QED theory of μ^-e interaction physics in this system. Work is now in progress on the theory,[29] and a continuation of the experiment should reduce the errors to a few ppm within the next year.

VII. μ^--ATOMS

A. Determination of Nuclear Charge Distribution -- Combined Analysis of Muonic X-Ray Data and Electron-Scattering Results

Since the negative muon spends a large fraction of its time inside of the nucleus, it has always been looked upon as a sensitive probe for the charge distribution of the nucleus. However, only in the last few years has a very successful model-independent analysis,[30] which combines the information from both the muonic x-ray data and the elastic electron-scattering results, been developed to yield the information on the charge distribution of the ground state of the nucleus. In a highly deformed nucleus, the electronic quadrupole interaction energy between the muon and the nucleus is comparable to the energies of the low-lying rotational splittings and the fine structure splitting of the muonic 2P doublets. Therefore the E2 interaction mixes the nuclear ground state I_0 with various excited-state $I_1, I_2, \cdots$ and also mixes the various muon states. This dynamic E2 hfs spectrum has been observed and closely studied in most of the deformed nuclei.

Many of the hyperfine components in a dynamic E2 hfs come directly from energy levels which represent mixed muonic and nuclear states. These lines contain information about certain excited states of the nucleus as well. Recently, an effort to develop a combined analysis[31] of inelastic electron scattering data and muonic x-ray data from deformed nuclei for the transition charge densities and from the properties of the excited states has been seriously under way at LAMPF. There are plans to investigate selected deformed nuclei both by making muonic x-ray measurements at LAMPF and by inelastic electron-scattering experiments at a high-energy electron facility such as Bates.

B. Isomer Shifts (Ref. 32)

In the dynamic excitations of muonic atoms, if the subsequent deexcitation of the nuclear state has a lifetime of about 10^{-9} s, then it takes place in the presence of the 1S muon, as the muon-capture lifetime from the 1S state is about 10^{-7} s in the rare-earth region. If the charge distribution of the excited state is different from that of the ground state, then an energy shift of the nuclear γ ray, known as the isomer effect, is expected; this is the effect of charge distribution on the transition energy. The isomer effects observed by muonic atoms and by the Mössbauer technique are in rather good agreement.[33] However, the agreement between the experimental and theoretical values in the transitional region[34] is not in good accord, and needs to be further studied.

C. The Resonance Processes (Ref. 35)

The intensity anomaly[36] in ^{209}Bi that occurred between the muonic $2P_{3/2}$-$1S_{1/2}$ and $2P_{1/2}$-$1S_{1/2}$ x rays was eventually interpreted as an effect due to a resonance process. The energy of an excited state of the nucleus is (accidentally) very close to the energy difference of two muonic levels; consequently, a significant amount of the nuclear excited-state wave function is mixed into the eigenstates of the muon-nucleus system. The intensity ratios are thus strongly affected. This picture of a resonance is actually verified by the observation of the nuclear deexcitation γ rays for such nuclei as ^{209}Bi, ^{205}Tl, and ^{127}I. Recently a simple statistical analysis[37] of the density of nuclear levels at about 2 MeV (by the LAMPF μ-group) indicates that a muonic-nuclear resonance with observable intensity might occur in 1 nucleus in 10. If the resonances would occur with sufficient intensity, both the quadrupole moments and the nuclear transition matrix elements could be derived from the observed spectra. Coincidence techniques may prove to be useful in these studies.

D. Muon-Induced Fission

The nuclear fission process involves a delicate balance between nuclear binding and Coulomb forces. The presence of a 1S muon is expected to have a large effect on the fission process, so we are dealing with a potentially very sensitive electromagnetic probe.

The prompt fission yield measurements investigate the effect of a 1S muon on the fission process. There is a factor of 2 disagreement between the TRIUMF[38] and DUBNA[39] measurements in ^{238}U, with the TRIUMF values in better agreement with previous work.

A discrepancy in the capture lifetimes measured by the fission and electron decay branches was suggested as evidence for shape isomer excitation in ^{238}U (Ref. 40). There is now excellent agreement among the various fission lifetime measurements, and also among the μ-capture γ measurements, but large discrepancies remain in the electron measurements. The best fission and μ-capture γ lifetimes still disagree by about two standard deviations in ^{238}U.

In both the TRIUMF and CERN[41] measurements a decay component of $\simeq$15-ns lifetime was observed in the ^{238}U fission data. This component was not seen in the TRIUMF ^{238}U data. A similar half-life was observed in the Dubna[42] ^{238}U measurements. Taken together, these results suggest that the evidence for shape isomer excitation with high yield is growing.

The possible observation of back-decay γ's from the ^{238}U shape isomer with a lifetime of 12 ns would constitute the clearest signature for isomer production. This measurement, which suffered from limited statistics and high backgrounds, is scheduled to be repeated soon at TRIUMF under better beam conditions. It is quite clear that pure- and high-intensity muon-beams are required in these muon-induced fission studies. Our understanding of these phenomena will shed light on the *theory of fission* and the *shape isomers*.

E. Muon-Nucleus Polarization Phenomena

The subject of muon-spin rotation (μSR) was left out because of time limitations. An interesting discussion on the possible exploration into a new and exciting field dealing with the muon-nucleus polarization phenomenon was held during our panel meeting. Since this subject had just been presented as an invited talk at the Eighth International Conference on High-Energy Physics and Nuclear Structure (ICOHEPANS),[43] we will refer to only a few highlights of the discussion:

1. precise determination of bound μ^--g factors,
2. the connections between the circular polarization of μ x rays, the longitudinal polarization of μ^-, and thus the $\bar{\nu}_\mu$ helicity,
3. use of a polarized target to provide non-statistical distribution of F substates, for precise determination of magnetic hfs,

4. a polarized nuclear target to repolarize the captured μ^- to a substantial value. This repolarization of the μ^- will help in the study of neutron and γ asymmetries in μ^- capture, and
5. the μ^- spin-rotation method, which is also unique in probing internal fields *just outside the nuclear sphere*.

VIII. MUON-CAPTURE IN HYDROGEN AND HELIUM

Muon capture has long been regarded as a probe of the induced pseudoscalar term in the weak hadronic current; however, a precise determination of this term has not been made, up to the present. The determination of this quantity is made difficult by experimental problems in the simplest system (μ^-p), and by uncertainties related to nuclear structure in complex nuclei.

Nevertheless, in view of the fundamental importance of the measurements, new approaches are currently being developed. The Saclay-CERN collaboration[44] has measured the capture rate from the orthomolecular (pμp) system in liquid hydrogen, by a unique method which is free from the systematic error associated with the determination of the absolute neutron detection efficiency. This technique utilizes the pulsed-beam time structure of the Saclay Linac to full advantage. There are plans at TRIUMF[45] to measure the lifetime of the (μp) triplet state in 0.5 atm by a spin-precession experiment, as a preliminary to a possible measurement of the neutron asymmetry in muon capture in gaseous hydrogen.

Additionally, experiments[46] are being planned at LAMPF to study muon capture in ^{3}He, again as a probe of the induced pseudoscalar form factor. In ^{3}He, many of the experimental problems present in the hydrogen case are simplified; moreover, the nuclear structure of ^{3}He is well understood, so that uncertainties in the interpretation due to nuclear structure are minimal. A spin-precession experiment to measure the angular correlation between the muon polarization and the nuclear recoil, as well as a *coincidence experiment* to study radiative muon capture, are both under consideration.

In general, these experiments in hydrogen and helium gases at low pressures require μ^- beams with very high stopping densities (implying the use of low-momentum "cloud" beams), narrow momentum spread, and relatively good beam quality. At present, the LAMPF low-momentum cloud μ^- beams have sufficient intensity for these kinds of experiments, but the quality (in terms of e$^-$ contamination and momentum bite control) could be substantially improved. Additionally, the spin-precession experiments require high polarization, and could benefit from pulsed beams and improved duty cycle.

IX. π^--ATOMS

A. A Joint Program of the Low-Energy π-Nuclear Scattering and the Pionic Atomic X Rays

In the past, pionic atoms have played an important role as the primary source of information on the low-energy π-nuclear interaction. The analysis of the experiments can be made nearly model independent in terms of generalized scattering lengths. Theoretically, the interaction is linked by a velocity-dependent optical potential to elementary interactions in the microscopic theory.

It has long been recognized that pionic atoms are in principle closely related to low-energy π-nuclear scattering. It is therefore natural to analyze low-energy scattering data jointly with those of pionic atoms. Such a program has not yet been carried out, although recently the empirical interactions have been successfully applied to low-energy scattering data, resolving earlier difficulties. *A joint program is highly desirable in the next few years.*

Such a study takes on a particular importance for the following reason. While the microscopic theories may differ, they agree phenomenologically in the statement that the pion-effective kinetic energy in nuclei is very close to changing sign from repulsive to attractive. This phenomenon would lead to (broad) pion nuclear bound states as well as to π-nuclear size resonances.[47,48] The attraction associated with this phenomenon may be one of the precursory effects signaling that *nuclei are close to pion condensation.*

It is therefore of great interest to quantitatively establish throughout the periodic system how close nuclei are to the critical region. Present analysis[47,48] suggests that various nuclei are extremely close to critical effects. This indicates that in pionic atoms *priority should be given to a better determination of* *strong-interaction effects by using the curved-crystal spectrometer method.*

B. Neutron Distributions in Nuclei from Pionic Atoms

Considerable progress has been made recently toward the goal of probing neutron distributions in nuclei through pionic atom and pion elastic-scattering measurements. Pionic-atom strong-interaction shifts are presently determined with a typical precision of 1%. To extract nuclear structure information, one must introduce a model for the pion-nucleus interaction. The model uncertainties, rather than the experimental errors, limit our ability to probe the nuclear structure. However, these model differences cancel to a large extent when one considers neutron-proton distribution differences in isotopic pairs.

Powers *et al.*[49] have recently analyzed their pionic-atom data in calcium and titanium isotopes using a phenomenological optical model potential. Neutron-proton distribution differences deduced from this analysis are in reasonable agreement with high-energy proton and alpha scattering measurements, as well as with HF BCS calculations. In their phenomenological analysis they found that the fitted p-wave parameters were strongly correlated with the Lorentz-Lorenz parameter. The quality of their fit is much improved by the inclusion of the new $\pi^{18}O$ data.[50] Batty *et al.*[51] have performed a similar analysis of their $3D$-$2P$ measurements. Their optical model parameters differ from Powers' mainly in the isovector terms; Batty's s-wave isovector term is larger than the microscopic predictions, while Power's p-wave isovector is smaller than expected. This disagreement reflects the small data base of $T \neq 0$ nuclei for which the nuclear structure is well enough known.

Olin *et al.*[52] have extracted neutron-proton radius differences from $^{10,11}B$ and $^{12,13}C$ measurements using pion-nucleon scattering lengths corrected for nuclear medium effects. The results are in reasonable agreement with projected Hartree-Fock calculations and low-energy pion-scattering results. In this case, the results depend mainly on the s-wave parameters.

The present accuracy of the neutron radius distribution is comparable to that obtained from other hadronic probes,[53] and is better for light nuclei. However, the neutron radius differences are at most a factor of 3 larger than the errors, so we are not yet talking about a precision test of the nuclear structure calculation. Further progress will come from better understanding of the isovector and absorption terms, combined analysis together with low-energy scattering and absorption data, and precision measurements of the strong-interaction effects in pionic atoms of the hydrogen isotopes by high-resolution curved-crystal spectrometers.

C. E2 Dynamic Mixing in Exotic Atoms Due to Nuclear Resonance Effect

It was theoretically proposed by M. Leon[54] and observed in pionic ^{112}Cd (Ref. 55) at LASL and in kaonic ^{98}Mo (Ref. 56) at Lawrence Berkeley Laboratory (LBL) that when the energy of a nuclear excited state nearly equals a hadronic-atom deexcitation energy, then the hadronic atom deexcites by exciting the nucleus. The strong absorption of the hadrons from the atomic states due to this dynamic E2 resonance mixing should be easy to observe as it weakens one or two hadronic x-ray line intensities relative to the intensities from other isotopes of the same element. The significance of the observation of this resonance effect in pionic ^{110}Pd atom was that it verified the prediction by Ericson *et al.*[57] that the p-wave pion-nucleus interaction changes from attractive to repulsive as Z increases beyond about 36.

D. Hyperfine Structure of Pionic X-Ray Lines (Ref. 58)

Although the overlap of the hadrons with the nucleus is negligible in the outer region, the effect of the electromagnetic properties of the nucleus may be detectable in the hyperfine structure of the x-ray spectrum. For example, the spectroscopic quadrupole moment of deformed nuclei such as ^{165}Ho, ^{175}Lu, ^{176}Lu, ^{179}Hf, and ^{181}Ta have been directly determined in this manner at Nevis, CERN, and SIN. These values of the spectroscopic quadrupole moments are more precise than those determined from any other methods if the strong interaction effects are taken into account. More such studies should be carried out in LAMPF intense π-beams.

X. KAONIC ATOMS

Due to the lack of K^- beams comparable in intensity to that of the π^- beams from meson factories, the experimental situation is much inferior to that in π-atoms. The level of accuracy is in the 100-eV region; no crystal spectrometer data could be taken so far. On the other hand, the K^--nucleus interaction is simpler than the π-nucleus interaction in pionic atoms (s-wave dominance, dominant one-nucleon absorption). The fit to the strong-interaction data necessitated taking into account the Y_0^* (1405) resonance,[6] some 25 MeV below the K^-p threshold. One motivation for requiring considerably improved data on strong-interaction effects in kaonic atoms is the study of the $Y_0^*(1405)$ resonance in nuclei. At present, only one effective complex parameter of the optical potential can be derived, and the separation in K^-p and K^-n effective interaction parameters contains considerable ambiguities. Here precise measurements on selected isotope pairs may help to improve the situation. Measurements on the most basic systems such as K-H and K-D should be envisaged. However, they are particularly difficult to perform due to the suppression of the 2P → 1S transition by Stark mixing.* Preferably, the formation of the atoms should proceed in a gas target, but here a considerable effort in improving the K^- facilities is required.

XI. Σ^--ATOMS

The data on Σ^- atoms must be taken from kaonic spectra where they appear on an intensity level of ≃5% with respect to kaonic spectra. Everything said on the inferiority of the results of K^- atoms is, therefore, even worse for Σ^- atoms. However, at the present moment an ingenious way to prepare a Σ^--Pb target was proposed by exposing a system of thin multiple and closely spaced lead plates in a container of liquid hydrogen in the K^- beam. By carefully adjusting the thickness and spacing of the plates, it is expected to obtain a maximum gain in the Σ^--stops by a factor of 5 to 10. Such an arrangement[12] has been prepared to repeat the measurements of the magnetic moment of Σ^- on the K^- beam of AGS (at BNL). If the result is as good as estimated, it will be very useful for future Σ^- heavy-atom studies. However, real progress in Σ^- atoms can be made only by a rather substantial improvement of the stopping K^- beams.

*Recent first indications of pH K-lines have been reported[59,60] which are, however, in disagreement with current theoretical predictions.

XII. $\bar{p}$-ATOMIC AND $\bar{p}$-HYDROGEN RESULTS

The data obtained so far on $\bar{p}$ atoms are limited to relatively few elements[61] and to intensity determinations only. The recent measurements of the CERN group have determined two absorption widths and one shift for each of four nuclei. For the first time, an isotope effect in $\bar{p}$ ^{16,18}O atoms was measured by the CERN group. It shows that the two additional neutrons in ^{18}O enhance the absorption, and consequently the line is weaker and broader in the case of ^{18}O than in ^{16}O.

The measurement of the K-series x rays of the $\bar{p}p$ atom would provide a direct determination of the real and imaginary part of the s-wave $\bar{p}p$ scattering lengths. However, if liquid hydrogen were used as the target, then the difficulties induced by Stark mixing mentioned for K^--p atoms would also be present here. Recently the CERN group has reported indications for K-lines of the $\bar{p}$H atom[62] in a liquid-H_2 target. J. Bailey *et al.*,[63] using proportional counters and gaseous hydrogen, reported the observation of the L-series transitions in $\bar{p}$-hydrogen. All these measurements must, however, be improved a great deal.

XIII. BARYONIUM STATES

Although this subject may not belong to the $\bar{p}$ atom proper, a few remarks on the $\bar{p}p$ states will be made here since such bound states below the $p\bar{p}$ threshold have been theoretically predicted for the $p\bar{p}$ system. Experimental indications for narrow baryonium states above and below the $p\bar{p}$ threshold exist from various experiments, but the experimental situation is not sufficiently clear at present and needs great additional efforts. The interest in baryonium states stems from the fact that they are interpreted either in the quark picture as connected to $qq\overline{qq}$ states or in a potential model as $p\bar{p}$ states bound in a strongly attractive potential related by the G-parity transformation to the pp potential. In both approaches it is difficult to account for the narrow widths of the states, which implies a strong suppression of the decay into meson channels and the incomplete knowledge of the $p\bar{p}$ annihilation channels. Experimental progress will be strongly connected to substantially improved $\bar{p}$ beams of energies between 2 GeV and stopping $\bar{p}$'s, as provided by $\bar{p}$ cooling techniques.

XIV. EXPERIMENTAL INSTRUMENTS AND METHODS

With the successful completion of the meson factories, existing instruments and techniques need substantial improvements in order to take on the problems involved with the high counting rates and precision measurements. The following programs should be given special consideration and priorities.

1. *A curved-crystal spectrometer*[64] *together with a 'Gatchina'-type target.*[10] Such a combination installed near the LAMPF beam stop would make it the most effective of its kind. It can be used for (a) measuring energy shifts and line broadening of π x rays, (b) more precise tests of Klein-Gordon equation to $(\alpha Z)^6$, (c) accurate studies of electron screening in π and μ x rays, (d) pionic polarizability, (e) test of vacuum polarization in μ atoms, and (f) accurate particle mass determination, etc.
2. *Magnetic bottle.*[65] A facility that provides opportunities for the use of very thin targets ($\simeq$ a few $\mu g/cm^2$), allowing experiments in low-pressure ($\simeq$1 torr) gases, will open possibilities for a whole range of novel experiments. Such a "muon trap" device could be a superconducting magnetic bottle, utilizing μ^- muons from the decay of 40-MeV/c π^- or surface μ^+ muons from stopped pions. The generality of such a device, in terms of providing an environment in which many different kinds of experiments could be performed in a relatively background-free situation, suggests that substantial instrumentation effort be made to develop it.
3. *Coincidence measurements of x rays with (a) other x rays of the cascade, (b) nuclear γ rays following the μ^- or π^- absorption, and (c) and/or particles from the final state.*
4. *Using pulse-shaping circuitries to determine γ rays from neutrons at all energies and at all counting rates.*
5. *Studying the residual circular polarization of x rays under different conditions for detection of the parity violation in μ atoms.*
6. *Developing techniques to observe Auger electrons from μ atoms, since no Auger electrons have ever been studied.*
7. *Investigating the angular distribution of x rays relative to muon spin*
8. *Developing the multiwire proportional chamber, the drift chamber, or the time-projection chamber in order to measure simultaneously the energy of the particle and the location and direction of its motion.*

XV. PANEL P-4 RECOMMENDATIONS

The meson factories at LAMPF, SIN, and TRIUMF have recently all attained their original goals of high intensity with reliable operation. It is of primary importance now to capitalize fully on the presently available potential of these laboratories for pion and muon physics. This means improving the quality, intensity, versatility, and availability of secondary beams.

Our immediate recommendation for *all* meson facilities is:

1. Beam Quality, Septums, and Separators. Strong efforts should be made to improve the *quality* of the present secondary beams. Phase-space tailoring, improved computer modeling, and diagnostics for development of flexible beam tunes are essential for the next generation of experiments. More experimental stations on the present beam lines (e.g., a *septum* for SMC) would increase beam availability at a very modest investment. Incorporation of electrostatic particle *separators* in the present muon channels would reduce the electron contamination of the surface and cloud muon beams without the losses in rate and beam quality associated with the current method of inserting degraders in the beam.

Our recommendations for the near future, primarily directed towards LAMPF, are:

2. Crystal Spectrometers. For high-precision muonic and pionic x-ray studies, a crystal spectrometer with a "Gatchina"-type target installed near *the LAMPF beam stop* would be highly desirable. Such an installation would involve a very modest effort and cost and not interfere with existing beam lines; it would also provide a uniquely powerful facility for these basic physical measurements. It deserves high priority.

3. New Channels. Development of new low-energy muon/pion channels should be emphasized. Present plans to run the P^3 channel as a surface/cloud muon beam and to develop a short pion/muon channel at the A-5 target appear quite fruitful and would do much to improve the versatility of the LAMPF secondary beams.

4. Proton Pulsing. Pulsing the primary proton beam at LAMPF, with a pulse width of $\simeq 1\ \mu s$, would be useful for certain muon physics experiments including searches for rare-decay modes and precision muonium experiments. It appears technically feasible to pulse the proton beam at a peak current of 1 mA, compared to the present level of 7 mA. Of course this mode of operation would not be suitable for many other LAMPF experiments, but it would be valuable to examine the usefulness of such a pulsed beam with a small fraction of the macropulses. For a sufficiently important experiment, this should be considered as a mode of LAMPF operation.

5. Secondary Beam Pulsing. An alternative mode of pulsed beam operation is to include an rf pulser in the present muon channel. This method is not as clean as pulsing the main beam but it should be sufficient for most experiments that require pulsed beam. Present studies of beam-pulsing techniques in the SMC should be encouraged.

6. H^- Atomic Physics Facility. The present facility for laser-atomic physics experiments provides a unique opportunity for atomic physicists and should be maintained and possibly enlarged.

Our long-term recommendations are:

7. Proton Storage Ring. The planned Proton Storage Ring at LAMPF will provide a unique low-duty-factor, high-current proton beam. It is essential that design studies be started to include a low-energy π-μ channel as an integral part of this facility. It is important that LASL ensure a role for pion, muon, and neutrino physics at this exciting new machine. This may not be simple since three different LASL divisions, MP, AT, and P, are involved in this facility, and since the major funding is through materials science and weapons segments of the DOE.

8. High-Duty-Factor Storage Ring. Many experiments are presently limited by the low (7%) duty factor at LAMPF. The possibility of building a storage ring to lengthen the duty factor to 100% should be investigated.

9. Kaon Facility. We feel that the kaon facility plans should concentrate more on the problems associated with secondary beam lines. In particular, the limitations and plans for future improvements of current K beams (e.g., AGS), particularly in terms of beam purity, should be studied in depth. A workshop on the study of the K^- beams on the AGS should be called at BNL as soon as possible.

10. $\bar{p}$ Facility. The development of the LEAR[66] facility at CERN promises an improvement in low-energy antiprotons by a factor of 10^3-10^4 or a stopping rate $\simeq 10^6$/s, so that we are on the threshold of a new era in $\bar{p}$ physics, in particular the investigation of baryonium and $\bar{p}$ atoms. Our understanding is that a low-energy $\bar{p}$ facility is also feasible for Fermilab and that the choice of electron cooling will provide extremely good beams at energies as low as 200 MeV. Initiative (and manpower *and* money) for such a facility, however, will have to come from the medium-energy physics community since Fermilab is concerned exclusively with the high-energy applications. We recommend immediate study of the desirability of such a facility.

APPENDIX

THE ONE- AND TWO-ELECTRON ATOM AT INTERMEDIATE ENERGIES*

Since 1976 the 800-MeV H^- beam at LAMPF has been used to study, by a unique colliding-beams method, a fundamental quantum system, the H^- ion. Despite exact knowledge of the Hamiltonian, the ion's properties are a challenge to calculate, particularly in the presence of external perturbation. H^- is known to possess a single bound state (-0.742 eV); calculations predict an extensive array of autodetaching resonances, a few of which have been observed. The electron-volt range atomic scattering and vacuum uv experiments ordinarily used to study this system are notoriously difficult.

In the LAMPF experiments, H^- structure is studied via the photodetachment process $\gamma + H^- \rightarrow H^0 + e^-$. Light from a near uv laser is directed by a precision rotating mirror mechanism to collide with the H^- beam at a precisely determined angle. Variation of the angle tunes the Doppler-shifted photon energy seen by the moving ion ($\beta = 0.842$) over a wide range with millielectron-volt (meV) resolution. For example, 4.659-eV photons can be tuned from 1.36 to 15.9 eV. The detached electrons all continue forward with the same energy (435 keV) and are detected downstream with a small spectrometer.

Using this method, previously unseen "Feshbach" resonances have been found just below the n = 2, 3, and 4 states of the residual H^0 atom, and the width (23 meV) of the known n = 2 shape resonance was measured for the first time. The ion's relativistic velocity also transforms a modest laboratory magnetic field (2.5 kG) into a strong electric field (1.2 MV/cm). This enables one to study the Stark quenching of these resonances. Some of them, those with "+" symmetry of the composite wave function, are remarkably resistant to perturbation. In contrast, the n = 2 Feshbach resonance splits into three lines whose separation varies linearly with field. The m-values of the degenerate components were determined by controlling the polarization of the incident photons.

The scheduled measurement of the ejection of both electrons by a single photon attacks "one of the most important unsolved problems in atomic physics." Plans to measure lifetimes (which translate into convenient distances), multiple photon processes, and the perturbation of certain H^0 states are under way.

This work has aroused a satisfying flurry of theoretical activity; relevant Stark-effect calculations had not been attempted before. The unexpected introduction of atomic physics into the medium-energy world should continue to be fascinating.

*H. C. Bryant *et al.*, Phys. Lett. 38, 228 (1977) and P.A.M. Gram *et al.*, **40**, 107 (1978).

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Chairman: G. J. Igo
Co-Chairman: L. Ray

Participants: A. M. Bernstein, J. Friar, R. J. Glauber, J. H. Koch, D. A. Lind, J. M. Moss, J. R. Shepard, S. J. Wallace, C. Wilkin, and B. Zeidman.

I. INTRODUCTION

The objective of accurately mapping out nuclear matter densities and currents is best met with a selection of electromagnetic and hadronic probes. For charge densities, the primary probes are electromagnetic (electron scattering and muonic-atom x-ray measurements), and in principle their precision is limited only by meson exchange currents, relativistic effects, and dispersion corrections. An example of recent high-quality measurements of electron scattering by ^{208}Pb is shown in Fig. VI-1 along with an empirical fit to the data. The charge distribution extracted from this experiment is compared with Hartree-Fock predictions in Fig. VI-2.

Hadronic probes such as protons and pions complement the electromagnetic probes in three important ways: (1) larger cross sections permit rapid, systematic surveys; (2) neutron densities and currents can be probed more directly and completely; and (3) spin-dependent NN interactions strongly excite spin-flip states at small angles.

Very beautiful and precise proton- and pion-scattering data have been obtained in the past two years; however, the theoretical interpretations of the measurements are alarmingly inconclusive compared to the precision of the data. The chief difficulties are that (1) the proton remains uncalibrated as a nuclear probe, and (2) the pion reaction mechanism remains ambiguous. Nevertheless, many analyses of proton elastic-scattering data have established that it is, in principle, possible to extract very precise neutron density distribution *if* the NN amplitude uncertainties are small and if the multiple-scattering interpretations in terms of free NN amplitudes are accurate.

The focus of this report is on short-term (1-4 years) and long-term (5-10 years) programs aimed at eliminating the present shortcomings of hadronic probes for nuclear structure research. Section II discusses programs of experiments that address (1) the

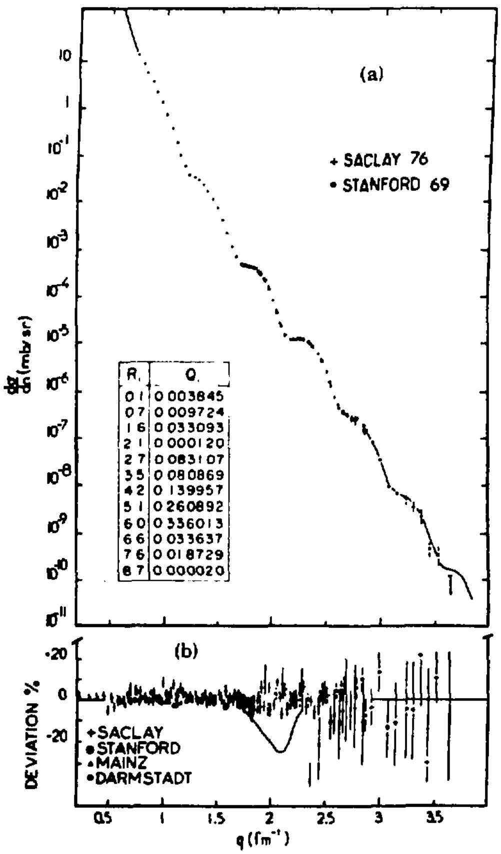


Fig. VI-1.
(a) Cross sections for elastic scattering on ^{208}Pb as a function of momentum transfer. The solid line is a fit to the data. (b) Deviation between the data and the fit.

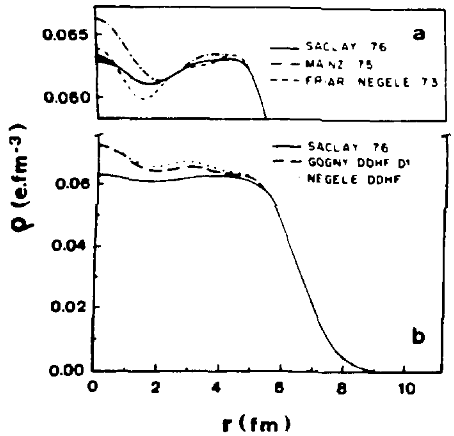


Fig. VI-2.
Empirical and theoretical charge distributions in ^{208}Pb.

NN amplitude uncertainty problem, (2) systematic tests of the multiple-scattering interpretation for proton-light nucleus interactions, (3) systematic tests of the extraction of neutron density information from hadron-nucleus elastic-scattering experiments, (4) tests of the reactive content of hadron-nucleus interaction, and (5) the use of closure to infer density and correlation information from inclusive experiments. Section III focuses on two nuclear structure aspects: (1) the need for high-precision density information and the relative benefits of 1-2-GeV pion beams for this purpose, and (2) high-resolution nuclear spectroscopy prospects using hadronic probes at intermediate energies. Section IV summarizes the recommendations.

II. TESTS OF THE REACTION MECHANISMS FOR HADRON PROBES AND INPUT INFORMATION

A. Nucleon-Nucleon Measurements

A major uncertainty in analyses of proton-nucleus elastic- and inelastic-scattering data is due to our present lack of knowledge of the nucleon-nucleon elastic amplitudes. The imprecise input data have become the principal obstructions to the analysis of the new LAMPF and Saclay data. In our opinion, the continued absence of reliable p-p and p-n amplitudes even brings into question the advisability at the present time of accumulating much more data on elastic proton-nucleus scattering. A more reasonable alternative is to begin a systematic program for measuring the necessary NN data.

Figure VI-3 illustrates the present situation for p-^{16}O scattering. Calculations of $d\sigma/d\Omega$ and $P(\theta)$, based on NN amplitudes that fit the available NN data and selected p-nucleus elastic data, do not fit the oxygen data. Very large differences, especially in the case of $P(\theta)$, arise due to the ambiguity associated with both pp and pn amplitudes. Some progress in NN scattering has of course been made in the last 10 years, but we now know from the Argonne ZGS experiments that even the p-p double spin-flip effects at small angles are large and vary significantly with energy in the range in which we are working. The situation is therefore complicated, and it is not likely that we could deduce the relevant nucleon-nucleon amplitudes self-consistently from the proton-nucleus data.

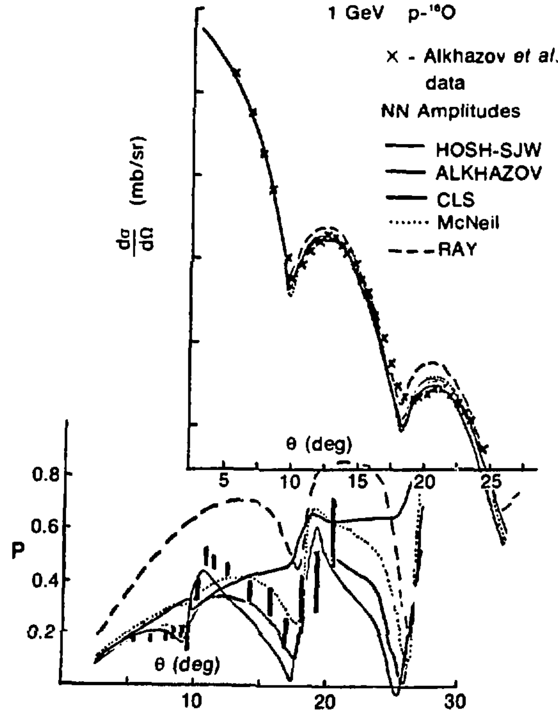


Fig. VI-3.
Cross section and polarization predictions and data for p + ^{16}O at 1.0 GeV using a variety of NN amplitudes.

In a crude *first* approximation, our requirements for the analysis of *heavy* nuclei are simply the isoscalar and isovector spin-independent and spin-orbit amplitudes in the forward-angle cone (say $\theta_{lab} < 35°$) at the same energies as the experiments on elastic p-A. In order to determine the scalar and spin-orbit amplitudes, however, it is in fact necessary to determine all the Wolfenstein amplitudes because those amplitudes cannot be isolated and measured directly. Elastic scattering by the *light nuclei* in any case demands the *whole set* of amplitudes. Everything needed for elastic scattering is also needed for inelastic scattering, which always takes place against a background of elastic scattering. In addition, inelastic scattering will itself often require the whole set of spin-flip amplitudes.

We have no doubt that someday, after the completion of a full set of NN experiments, there will be a complete set of phase shifts available in the energy range from 500 to 1000 MeV. It is worth pointing out, however, that no such elaborate analysis is required for the nuclear-scattering program. In fact, since the amplitude data are only needed over the rather limited angular range in which the nuclear angular distributions are measured, our requirement is a much more modest one than that which is imposed by the global nucleon-nucleon program.

The urgency of our needs has led this panel to give top priority to the following experiments for $\theta_{lab} <$ 35° at 800 MeV for the analysis of the LAMPF-HRS data. The panel recommends that the experiments listed in Table VI-I should be pursued by the experimentalists who are currently studying p-nucleus scattering.

Forward-angle elastic p-p scattering with a polarized beam and target should be studied at LAMPF HRS, as the conventional NN program would not normally investigate the small scattering angles necessary here. Background problems can be overcome by using the high-resolution capability of the HRS.

The same technique can be used to measure elastic proton-deuteron scattering with a polarized deuterium target. This is theoretically very valuable in that near the forward direction it provides directly a measure of the T = 0 combination of the pp and

TABLE VI-I

EXPERIMENTS TO DETERMINE THE NN AMPLITUDES FOR INTERPRETATION OF p-NUCLEUS SCATTERING OUT TO 35° [a]

Type of collision	Unpolarized	Beam: Polarized protons Target: unpolarized	Beam: Polarized protons Target: Vector polarized protons (deuterons)	Beam: Vector, tensor polarized deuterons Target: Unpolarized protons	Beam: Vector, tensor polarized deuterons Target: Polarized protons
p-p (elastic)	I_0	$<\sigma_y>$ triple-scattering parameter	Correlation Parameter		
p-d (elastic)	I_0	$<\sigma_y>$, triple-scattering parameter	Vector correlation parameters	$<p_y>$, components of the tensor (Saturne II only)	Vector and tensor-correlation parameters (Saturne II only)
p-d (quasi-elastic)	I_0			$<\sigma_y>$, triple-scattering parameters (Saturne II only)	Correlation parameters (Saturne II only)

[a] These experiments are to be done at 0.8 and 1.0 GeV with highest priority, but also at 0.6 and 1.1 GeV with lower priority; p-d elastic and quasi-elastic are to be done at 0.4 GeV. Some of these experiments (with polarized deuteron beams) can be done at Saturne II only. These are noted.

The coordinate system used throughout this report: y-axis normal to the scattering plane; z-axis along the beam direction. The unpolarized differential cross section is I_0, the individual polarization is $<\sigma_y>$ (protons) and $<p_y>$ (deuterons).

np amplitudes that is most directly encountered in p-A scattering. Although there would be some model dependence in the analysis, it is also possible to extract some of the important neutron parameters from such measurements. Uncertainties in such an extraction may not be too important for the proton-nucleus application for which the results are desired.

These measurements should be regarded as complementary to the full NN scattering program; the data they represent would provide additional input for the extraction of the NN phase shifts.

The foregoing experiments could be performed at LAMPF, and in our view the pp and pd elastic experiments should be pushed to completion before the end of 1982. On the other hand, Saclay is planning in the very near future to accelerate polarized deuterons in Saturne II. Then through the use of polarized proton targets, the p-d elastic correlation parameters can be measured. A concerted program of triple scattering and correlation measurements should be pressed to measure the 12 parts of the elastic p-d amplitudes. The individual pieces of the amplitude display considerable sensitivity to the components of the NN amplitudes. By deuteron stripping, Saclay will obtain strong beams of polarized neutrons with which to do $\vec{n} + \vec{p}$ scattering as well. Target contamination is also less of a problem in that case than for $\vec{p} + \vec{d}$. It would therefore seem that, in principle, Saclay could do a more elegant measurement of the n-p scattering, but it is essential that we have these data before long, whatever their source. Ultimately, measurements carried out on deuterium targets will be essential in any case as a check on our understanding of the underlying theory.

We are uncertain how well or how soon the small-angle region will be studied in such experiments. We noted with great interest the explanation by Dr. Thirion of the Saclay proposal to inject (polarized) gas jets of protons and deuterons into the Saturne machine and, through the detection of the recoils, to measure very small-angle elastic $\vec{p}\vec{p}$, $\vec{p}\vec{d}$ (and perhaps $\vec{d}\vec{d}$) scattering as a function of energy. It should be noted, however, that these measurements are not likely to provide accurately normalized absolute cross sections.

We turn finally to the proposal of measuring proton-deuteron quasi-elastic scattering with the motivation of obtaining information about the neutron parameters at larger angles. Such experiments are straightforward for a pure deuterium target, but there are clearly complications caused by quasi-elastic scattering from other nuclei in a polarized target. These constituents, of course, may not be polarized but they would increase the background.

The theoretical analysis of breakup reactions must be done very carefully, especially at smaller angles where the final-state interaction in the $^1S_0$ state is strong. The amplitudes extracted from the quasi-elastic p-n data may not be definitive, but they would provide a great improvement over our present knowledge.

The panel hopes that cooperation between LAMPF and Saclay can be enhanced for the purpose of providing at least the minimal nucleon-nucleon amplitudes needed to analyze both the HRS and SPES I spectrometer data.

Another source of uncertainty, which has at least some bearing on our understanding of nuclear scattering, is contributed by the effect of pion production through $N + A \to \Delta + A' \to N + A$. It would be desirable in the future to obtain production amplitude data on $NN \to N\Delta$ with corresponding polarization measurements, but this cannot be considered a first priority.

The panel discussions repeatedly emphasized that only after the NN amplitudes are known does the game begin. At that point a number of fine-structure effects should begin to show up: (1) neutron-proton density differences, (2) correlation effects, (3) intermediate deltas, (4) exchange currents, etc.

B. A = 2-4 Targets

The primary aim of proton scattering from nuclei is the extraction of nuclear parameters. Many of our theoretical techniques for handling such data can be best tested through the small- to medium-angle scattering on the very light nuclei: the deuteron and the helium isotopes. Figures VI-4 and -5 illustrate the sensitivity of $d\sigma/d\Omega$ with unpolarized deuterons, with vector and tensor polarized beams to the various sets of NN parameters which are available. The latter parameters are obtained from nucleon-nucleon measurements ($d\sigma/d\Omega$ in n-p and p-p scattering, and polarization in pp scattering). The remaining parameters (n-p spin-orbit amplitude) are obtained from fits to various sets of p-nucleus

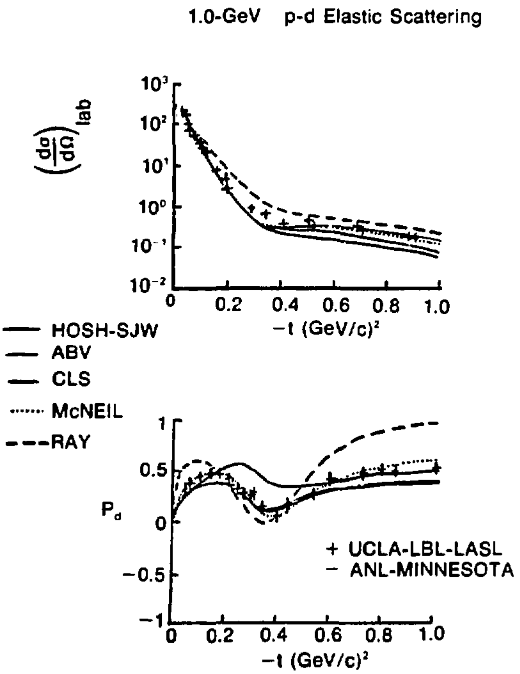


Fig. VI-4.
Dependence of 1.0-GeV p-d cross section and polarization to several NN amplitude sets.

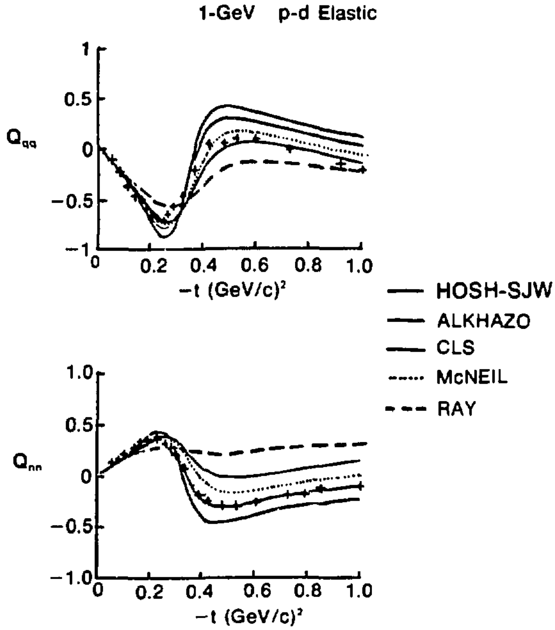


Fig. VI-5.
Dependence of 1.0-GeV p-d triple-scattering observables on several NN amplitudes.

elastic scattering obtained at Saclay, Gatchina, and HRS. A recent set of amplitudes incorporating the Argonne measurements and dispersion relation calculations is no more successful in fitting these data. Figure VI-6 illustrates the sensitivity, particularly in P and Q (see Note a in Table VI-II for a definition of Q), to the presence of intermediate isobar states. Nuclear wave functions are comparatively well known for these light nuclei, and with so few nucleons the multiple-scattering series is tractable without severe truncation. On the other hand, the results are strongly dependent upon the nucleon-nucleon amplitudes. Furthermore, because of the strong NN correlations in the light nuclei, all 10 NN amplitudes may contribute significantly, even to elastic scattering. In addition, intermediate Δ isobar states and exchange currents may be relevant. Thus it seems that if we can understand proton scattering from ^{2}H, ^{3}He, and ^{4}He, our theoretical tools should be good enough to analyze the heavier nuclei (though the converse is not necessarily true).

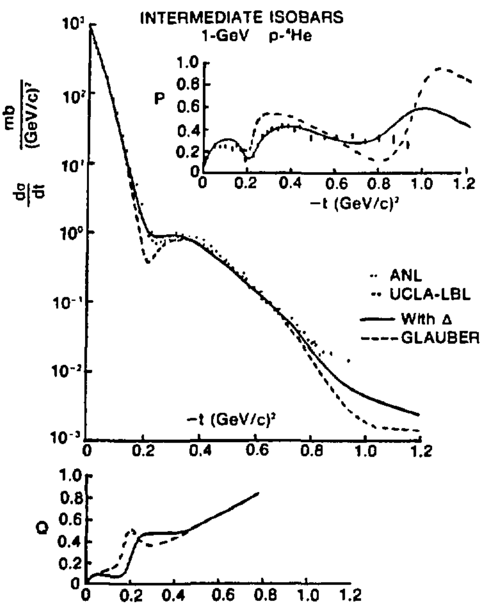


Fig. VI-6.
The 1-GeV, p-^{4}He cross section, polarization, and Q sensitivity to intermediate isobar states.

TABLE VI-II

PROTON-LIGHT ION MEASUREMENTS

		Target	Observables
1.	$\vec{p}+$	^{4}He	I_0, Q[a]
2.		^{3}He	I_0, P_y, Q
3.		$^3\vec{He}$	Spin-spin correlations
4.		^{3}H	I_0, P_y, Q
5.		$^3\vec{H}$	Spin-spin correlations
4a[b]	$\vec{n}+$	^{3}He	I_0, P_y
5a[b]		$^3\vec{He}$	Spin-spin correlations

[a]Q refers to the quantity $Q \equiv 2\text{Im}(F^*G)/(|F|^2 + |G|^2)$, where F and G are the scalar and single spin-flip amplitudes, respectively. For reference, polarization P measures the real part of the same amplitude combination.

[b]Experiments 4a and 5a are listed as alternates to the triton target Exps. 4 and 5.

We remarked previously that elastic scattering from such light systems is sensitive to exchange currents and it must be stressed that these enter in a way different for proton (or pion) scattering from that of electron scattering. A combined study with electron and hadron probes may help in isolating this important feature of intermediate-energy nuclear physics. For an isoscalar target, the pion exchange term makes no contribution for electron scattering, whereas for proton scattering it is probably the largest single contribution to the alignment dependence of the proton-deuteron total cross section. As another example, the electromagnetic form factors of ^{3}He and ^{4}He show a strong subsidiary maximum at momentum transfers of about 4 fm^{-1}, and in that region exchange currents are thought to be very important. The behavior of the form factors in this region is quite influential, through the single-scattering term, in proton-helium scattering. In principle, one should evaluate the proton-nucleus amplitude by first removing the exchange current contributions from the electron data to find the form factor, then summing the multiple-scattering series, and finally adding the hadronic-exchange current terms. Such a procedure has never been implemented in the proton-helium case because of the uncertainties in the nucleon-nucleon amplitudes. For the case of pion scattering, on the other hand, the theory of the basic scattering process in the resonance region is not sufficiently reliable to look for such small corrections.

Table VI-II lists the recommended light ion measurements, and the entries in the table are briefly discussed in the following paragraphs.

Although much effort has already been expended on p-^{4}He, further measurements are needed. The absolute differential cross section at 1 GeV remains in doubt due to conflicting data. Absolute differential cross sections have not been determined at 800 MeV. Finally, the Q-polarization measurements are absent at both energies, although P-polarization data are available.

Polarized proton-^{3}He elastic-scattering measurements provide information for a spin 1/2 target nucleus. The intermediate isobar effects are less suppressed than for ^{4}He and hence the experiment provides constraints on the role of intermediate isobars.

Systematic investigation of $\vec{p}$-$^3\vec{He}$ spin-dependent interactions can only be accomplished at LAMPF with a polarized ^{3}He target; however, Saclay could accelerate a polarized ^{3}He beam but there are no current plans for a polarized ^{3}He source. A full set of spin-spin correlation measurements is necessary in either case to investigate spin structures of the same character as those observed in free pp scattering at Argonne National Laboratory. The extent to which the double spin-flip amplitudes are modified in the nuclear environment is most clearly addressed by $\vec{p}$-^3He measurements. In this regard it is important to study the energy dependence in some detail.

A logically complete light ion program must investigate the isospin dependence by measurements of the proton-triton scattering including charge exchange (Exps. 4 and 5) to complement the p-^3He measurements. Saclay in principle could accelerate a ^3H beam which could study $\vec{p}$ + ^3H and $\vec{p}$ + $^3\vec{H}$ interactions in a very elegant fashion. Alternatively, neutron + ^3He measurements [Exps. 4(a) and 5(a)] could be used to gain isospin information at LAMPF. A polarized neutron beam would be necessary for Exp. 5(a), and again this is likely to be best done at Saclay.

A systematic proton light ion program requires careful coordination of LAMPF and Saclay programs. With regard to LAMPF, we recommend that Exps. 1, 2, 3, and 4(a) of Table VI-II be pushed forward. In addition, careful consideration of a tritium target is recommended.

When the Saclay polarized light ion beams become available, they are expected to provide an elegant means of carrying out full spin measurements for light ion-proton scattering (all experiments in Table VI-II). This program needs to be pushed forward at Saclay.

In summary, proton scattering from light-nuclei is primarily a test of our calculational methods and our input parameters, but it does contain interesting physics.

C. Heavy Nuclei

A vital part of the hadron-nucleus scattering program over the next five years should be addressed to testing the accuracy of the Glauber or optical potential approaches. Although no completely unambiguous test is possible, a number of informative energy-dependent tests are suggested. Elastic proton scattering will he emphasized initially since a proper understanding of this process is fundamental to an understanding of more complicated proton-induced reactions. Figures VI-7 and -8 show the differential cross sections and analyzing powers obtained at 800 MeV. The solid and dashed lines are first-order KMT fits and Hartree-Fock predictions, respectively. Table VI-III illustrates that the error in the rms neutron radius obtained in

TABLE VI-III

SOURCES OF ERROR IN THE rms RADII OF NEUTRON DISTRIBUTIONS FOR SEVERAL HEAVY NUCLEI AS DEDUCED FROM PROTON-NUCLEUS SCATTERED AT 800 MeV. ALL ERRORS ARE ± VALUES.

Error		Nucleus				
Source	Magnitude	^{58}Ni	^{90}Zr	^{116}Sn	^{124}Sn	^{208}Pb
Normalization	±10.%	0.019	0.017	0.017	0.017	0.018
$\Delta\theta_{c.m.}$	± 0.03°	0.019	0.021	0.025	0.024	0.028
$\Delta\rho_p(r)$	≃ ± 0.01 fm	0.010	0.018	0.005	0.005	0.007
ΔT_{lab}	± 2. MeV	0.017	0.019	0.020	0.019	0.022
$\Delta\sigma_{pp}$	± 0.5 mb	0.005	0.005	0.005	0.005	0.005
$\Delta\sigma_{pn}$	± 0.22 mb	0.002	0.002	0.002	0.002	0.003
ΔB_{pp}	± 0.005 fm^2	0.007	0.005	0.004	0.004	0.003
ΔB_{pn}	± 0.022 fm^2	0.023	0.020	0.018	0.018	0.015
$\Delta\alpha_{pp}$	±10.%	0.001	0.001	0.001	0.001	0.001
$\Delta\alpha_{pn}$	±10.%	0.002	0.002	0.002	0.002	0.002
$\Delta(\overline{\theta}_p, \overline{\alpha}_{sp}, \overline{B}_{sp})$		0.019	0.022	0.024	0.025	0.029
Statistical and model dependence		0.016	0.015	0.015	0.012	0.022
Correlation (Pauli)		0.025	0.021	0.019	0.019	0.018
TOTAL		0.074	0.072	0.069	0.068	0.075

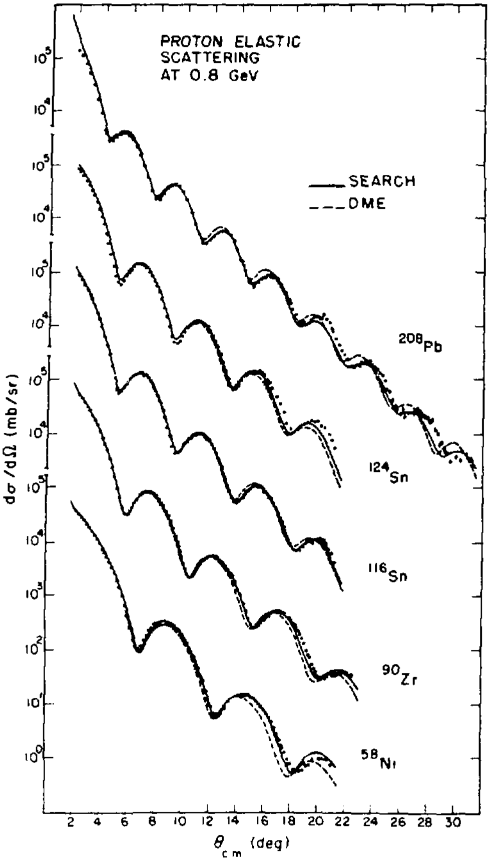


Fig. VI-7.
Proton-nucleus elastic-scattering cross sections at 800 MeV.

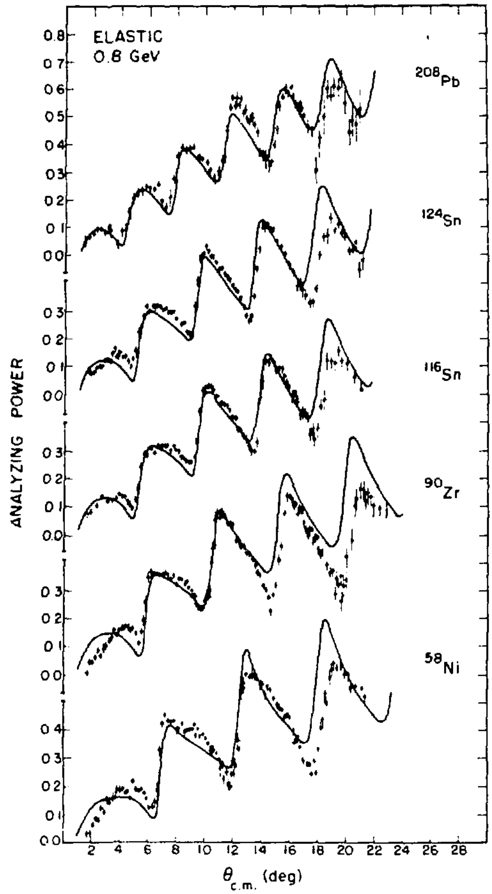


Fig. VI-8.
Proton-nucleus elastic analyzing powers at 800 MeV.

these experiments is typically about ±0.07 fm. Those tests, which of course rely on accurate knowledge of the NN amplitudes, would be most usefully applied to closed-shell nuclei, ^{16}O, $^{40,48}Ca$, ^{90}Zr, and ^{208}Pb, over an energy range from about 100 MeV to 1 GeV. Figure VI-9(a) illustrates this point. The current analyses of existing NN cross section and polarization data yield three ambiguous solutions in a two-parameter space of the NN parameters (these solutions neglect double spin-flip amplitudes and assume that the spin-independent NN amplitudes are known at $q^2 = 0$). This threefold ambiguity in the NN amplitudes results in deduced neutron rms radii which vary by 0.2 fm, or by the typical neutron-proton radius difference one is attempting to measure. The solution that gives general agreement with Hartree-Fock is selected for use in proton-nucleus analyses. Clearly this is not a satisfactory state of affairs.

Several proton-scattering tests are proposed. Neutron densities extracted from elastic-scattering data over a wide range of energies should display no energy dependence. A comparison of predicted and experimental total and reaction cross sections readily tests the gross reactive content of the theoretical model. Explicit reactive content measurements and predictions further test the sufficiency of the nonelastic channels which are summed in the imaginary part of the optical potential for elastic scattering

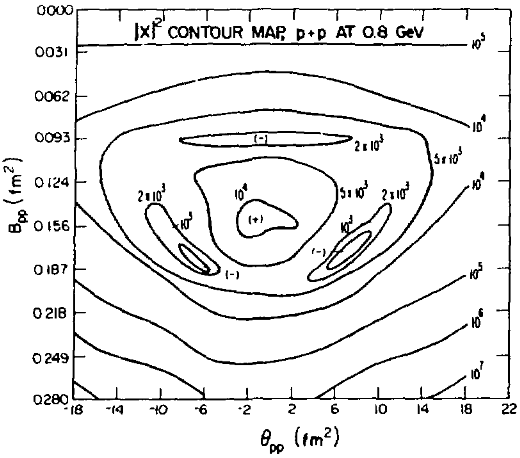


Fig. VI-9(a).
(a) Two-parameter $|\chi|^2$ contour map for p + p at 800 MeV, demonstrating a three-fold ambiguity in amplitude determinations based on present $d\sigma/d\Omega$ and $P(\theta)$ data.

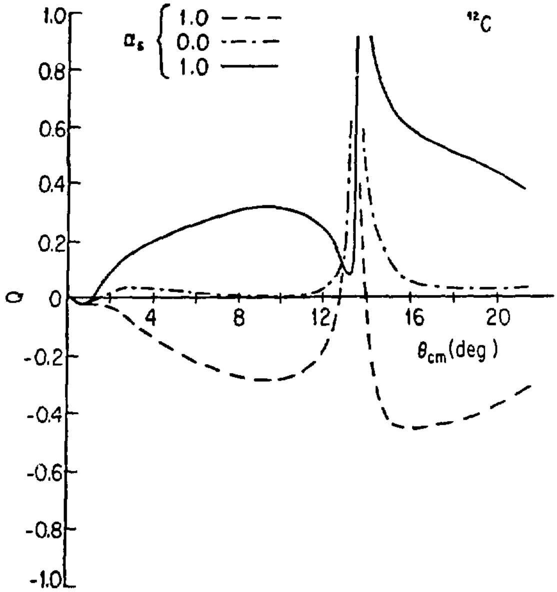
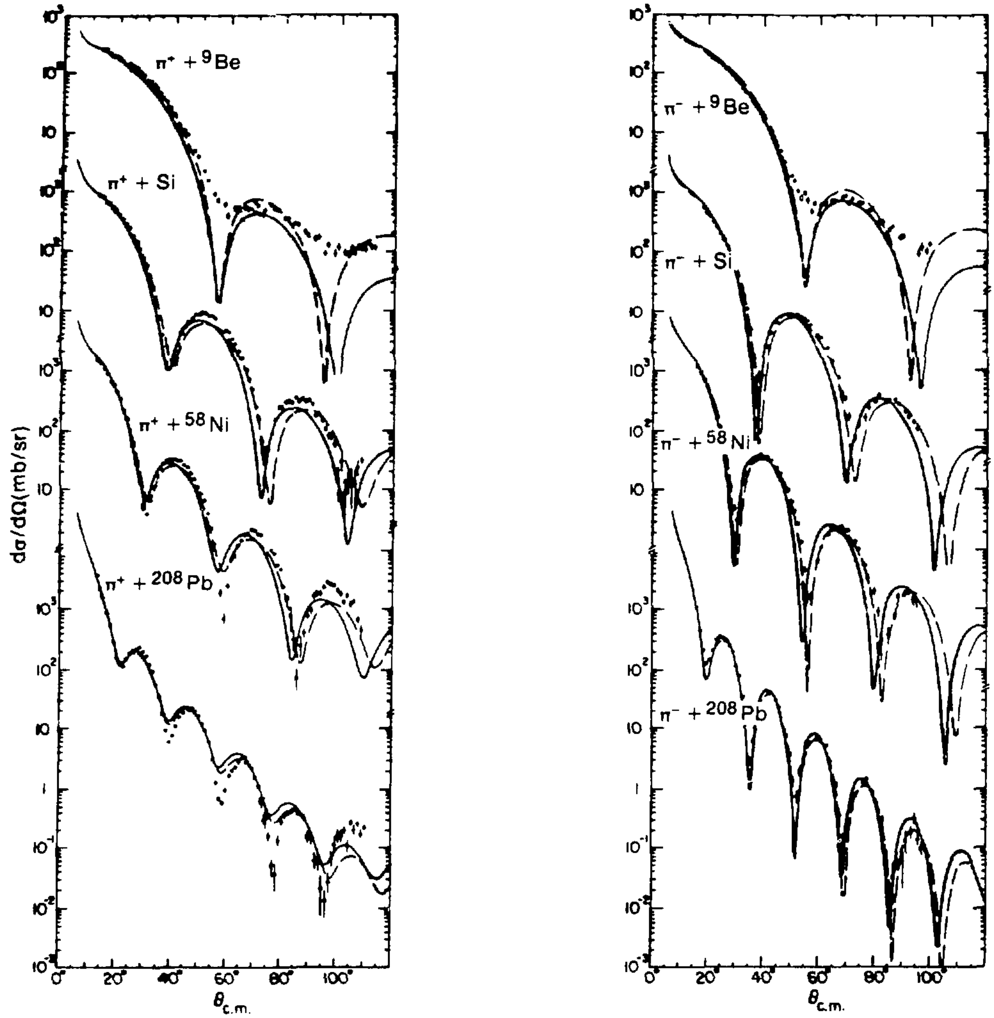


Fig. VI-9(b).
(b) Sensitivity of Q in p + ¹²C elastic scattering to the real-imaginary ratio of the NN/spin-orbit amplitude.

(see Sec. II.C). Energy-dependent predictions of the polarization and the spin-rotation parameter, Q, readily test the theoretical spin dependence. The Q parameter in elastic scattering [see Fig. VI-9(b)] has been proposed by Osland and Glauber as a very sensitive measure of the spin-orbit interaction in nuclei complementary to the polarization $P(\theta)$. Knowledge of the proton-nucleus spin-dependent amplitude is important for accurate determination of neutron densities, particularly in medium-weight nuclei ($A \sim 12$-28). Finally, tests of the predicted depths of the diffractive minima are vital in assessing the importance of several higher order corrections, in particular that of the intermediate Δ. The new experimental data needed to carry out this program are (1) differential cross section and polarization data for closed-shell nuclei, with accuracy comparable to that presently attained at the HRS, momentum transfers $\leq 3\ fm^{-1}$ and at energies between 100 and 1000 MeV in roughly 100-MeV steps; (2) measurements of the spin-rotation parameter Q for a few nuclei (^{16}O, ^{40}Ca, ^{208}Pb) at several energies; (3) some σ_{tot} and σ_{reac} data to fill in gaps in energy between 100 and 1000 MeV for existing data for light nuclei (^{16}O) and for a few heavy nuclei (^{40}Ca, ^{208}Pb); and (4) reactive content studies on a few targets (^{16}O and ^{208}Pb) at several energies. The combined efforts of the IUCF, TRIUMF, LAMPF, and Saclay are thus called for.

A similar series of tests and consistency checks are suggested for pions. This complete study, however, requires 1-2-GeV high-resolution pion beams. The specific motivation for performing experiments at energies considerably above the (3,3) resonance is the short wavelength, reduced absorption, slow variation with energy of πN amplitudes, reduced binding energy and Fermi motion corrections, and the simplicity of πN amplitudes relative to NN. Figures VI-10 and -11 illustrate the quality of the current data for $\pi^{\pm}$ elastic scattering on ^{9}Be, Si, ^{58}Ni, and ^{208}Pb. The solid lines are an optical model fit to the data.

The final and most demanding test of reaction theories of hadron-nucleus scattering is that consistent nuclear densities be obtained independent of probe or incident energy. Indeed, the combination of



Figs. VI-10 and -11.
Angular distributions for the elastic scattering of 162-MeV $\pi^{\pm}$ by ^{9}Be, Si, ^{58}Ni, and ^{208}Pb. The curves result from optical-potential calculations discussed in the text, and are displayed with no adjustment of magnitude.

these projectiles and energies are likely to reveal differences that will reflect both the theoretical limitations and correlation effects present in nuclear structure. The elucidation of these phenomena is one of the major tasks to be undertaken in the next decade.

D. Reactive Content

It is only possible to treat the hadron-nucleus interaction under simplifying assumptions in the theoretical interpretation of experiments. Thus, hadronic probes must be subjected to tests which discriminate between overly simple interpretations and well-founded ones. Some basic tests are the inclusive experiments such as (e,e'), (e,e'p), (p,p'), (π,π'), (π,πN), and (p,p'π), since they provide information about the breakdown of the total reaction cross-section mechanism. Ultimately, this inclusive information validates or corrects the assumptions that have been used to interpret elastic-scattering data in terms of neutron radii differences or free NN t-matrix parameters. However, the same experiments give much more information concerning the hadron-nucleon interaction in the nuclear medium and the hadron-nucleus reaction mechanism, topics which are addressed more directly by panel N-6. Thus the N-1 panel recommendation does not specifically address the inclusive experiments, but we stress that the experiments mentioned bear directly on the accuracy with which matter densities and currents can be determined by hadronic probes.

An example of the value that reactive content studies have on one's understanding of the reaction mechanism is the following. In 1-GeV inclusive charge exchange in deuterium, pd $\rightarrow$ nX, there is a high-energy neutron peak corresponding to quasi-elastic scattering pd $\rightarrow$ npp but a much larger one due to quasi-free pion production pd $\rightarrow$ nΔp. When the final states are looked at in kinematically complete experiments, it is found that a fraction of the quasi-free peak is not associated with pion production. It seems that about 20% of the charge-exchange reaction involving only nucleons, pd $\rightarrow$ npp, is due to virtual Δ production with the decay pion from the isobar being absorbed on the spectator nucleon. Though the pion absorption probability is low in a diffuse system such as the deuteron, the pion production cross section is about an order of magnitude greater than the nucleon charge exchange.

On a heavy nucleus, the pion absorption probability may approach one-half so that the reaction is dominated by virtual pion production.

It is characteristic of medium-energy physics that we can find large cross sections, involving only nucleons which cannot be considered as purely nucleonic processes. Reactive content measurements can do much to elucidate such reaction mechanisms.

E. Closure Cross-Section Measurements

The program of using hadronic probes to determine nuclear density distributions can be addressed by means of inelastic as well as elastic scattering. Inelastic scattering of high-energy hadrons can be exploited to determine nuclear densities by summing together the cross sections for all transitions in which no particle production occurs. This angular distribution, which we shall call the closure cross section, can easily be analyzed in terms of the nuclear ground-state densities. The calculations, which are carried out by taking careful account of the attenuation of the incident particle beam in crossing the nucleus, show that at the large momentum transfers most of the closure cross section is contributed to by particles scattered near the outer edge of the nucleus. Closure measurements, in other words, furnish a sensitive approach to the determination of the nuclear surface density parameters.

One set of survey experiments of inelastic proton scattering at 800 MeV has already been performed at the HRS by Palevsky and collaborators. Their analysis has centered, however, on verifying the distorted wave impulse approximation predictions of the spectral shape rather than integrating to find the closure cross sections. The analysis of these experiments should be extended to evaluate closure cross sections and investigate their sensitivity to the nuclear surface parameters. It seems likely that a more extensive set of closure experiments analyzed at smaller angles would also furnish data, perhaps the best that can be found from nucleon-scattering experiments, on nucleon density correlations within the nucleus.

III. NUCLEAR INFORMATION

A. $\rho_n(r)$ (Ground State)

The study of nuclear properties begins with a description of nuclear sizes and densities. Since in lowest order the nucleus consists of protons and neutrons, even the most elementary models of nuclei are required to reproduce both proton and neutron density distributions reasonably well. As a benchmark, efforts to provide density distributions have been and continue to be a significant part of the experimental intermediate-energy program.

Electron scattering has provided the most precise measurements of proton and charge density distributions. The high precision of the measurements and a precise knowledge of the interaction result in quite reliable density determinations. However, a complete description of nuclear densities requires knowledge of the neutron distributions, and electron scattering is unable to do this. We must therefore rely on hadronic probes to complete the picture.

High resolution, high-intensity proton beams are currently available at energies up to several GeV. The proton interaction with nucleons is both spin and isospin dependent as well as energy dependent. At lower energies the protons can probe farther into complex nuclei, but as the energy increases toward 1 GeV, increasing inelasticity restricts the region of sensitivity to the surface.

At low energies, <50 MeV, nuclei are relatively transparent to pions which can be used to probe the nuclear interior. However, in that case the wavelength of the pion is so long that only rms radii can be measured. Indeed, recent measurements at TRIUMF indicate that such measurements may be expected to provide precise data in the near future. Near resonance, the strong π-nucleon interaction results in such a short mean-free path for the pion that the scattering is sensitive to only the region of <25% of the central nuclear density. At much higher energies, 1-2 GeV, the nucleus is much more transparent to pions, so that use of high-energy pions might be able to provide precise information over the entire nucleus. Pion-nucleon interactions are relatively simple since the pion has spin zero, and the isospin dependence of the interaction is particularly useful in providing differential selectivity in the reaction. The major deterrent to the extraction of reliable absolute density distributions by pion scattering is the theoretical difficulty in treating the complex correlation-dependent effects which are very strong in pion scattering.

The density-dependent Hartree-Fock (DDHF) calculations are at present the best theoretical descriptions of nuclear densities. These calculations have successfully reproduced the densities determined in electron scattering and result in qualitatively good agreement with neutron density distributions deduced from proton scattering. There are, however, serious questions about the precise predictions of DDHF for neutron distributions. At present, it appears as if the rms neutron radius in ^{48}Ca is 0.1 fm smaller than predicted by DDHF. Inasmuch as DDHF is really expected to be highly reliable only near closed shells, there is a distinct need for high-precision nuclear density determinations.

Future studies of nuclear density distributions should investigate isotopic and isotonic density dependence. Nuclei such as the nickel and tin isotopes and the N = 28 and N = 82 isotones would be ideal testing grounds. Since each additional nucleon adds not only its single-particle density to the core, but also interacts with the other nucleons, the overall density distribution reflects not only the single-nucleon density distribution, but also correlation effects.

B. Spectroscopy

Nuclear dynamical properties can be obtained by measurements of transition matrix elements, or even more quantitatively by measurements of transition densities. In general, one can measure both neutron and proton (or isoscalar and isovector) quantities:

$$M_{n(p)} \equiv \langle f \| \Sigma\, r^{\lambda} Y_{\lambda} \| i \rangle \text{ neutrons (protons)} \quad ,$$

and

$$\rho_{n(p)}^{fi}(r) \equiv \langle f \| \;\Sigma\; Y_{\lambda} \| i \rangle \text{ neutrons (protons)} \quad ,$$

where λ is the multipolarity of the transition. M_p is measured by Coulomb excitation or lifetime measurements and is the electromagnetic matrix element in the long wavelength limit; (e,e') experiments can measure the Fourier transform of $\rho_p^{fi}(r)$.

It would be of considerable interest to obtain M_n and $\rho_n^{fi}(r)$ from hadron-scattering experiments, and this of course requires an accurate understanding of the reaction mechanism. To date, our ability to extract M_n and M_p has been tested only in a limited number of cases. However, several tests suggest themselves: for example, for a T = 0 (N = Z) nucleus, observing a ΔT = 0 transition which should have $M_p = M_n$. For T = 1/2 and T = 1 nuclei, one can use the data on the lifetimes of the analog state and isospin symmetry to determine M_n. In these cases our ability to either predict, or extract the correct value of M_n from, inelastic hadron scattering can be tested. Tests of this type for each hadron should be undertaken to demonstrate the feasibility of extracting information.

It would be very interesting to obtain $\rho_n^{fi}(r)$ information from hadronic probes. This can be done best in the surface region, but can be extended into the interior by more penetrating probes such as the low-energy pion or kaon. Again, this can be tested against (e,e') results for $\Delta T = 0$ transitions in $T = 0$ nuclei for which $\rho_n^{fi}(r) \cong \rho_p^{fi}(r)$.

At the present time there has been only a limited study of M_n values. Figure VI-12 shows the present status for single closed-shell nuclei. The agreement between the different probes is reasonable and a trend is indicated, but further information is needed.

It is important to single out some of the salient features of the different hadronic probes. Medium-energy proton scattering (100 MeV to 1 GeV) has the advantage that accurate calculations of the scattering can be performed once the input amplitudes are known. For 100- to 200-MeV protons the mean-free path for protons is greatest, and this energy region should, in principle, give the most information about the nuclear interior. On the other hand, calculations seem more accurate at the higher energies.

Pions have the advantage that one has both π^+ and π^- to scatter, and under certain conditions one can obtain more accurate information from the ratio of the π^+/π^- cross sections since the systematic errors can cancel out. In particular, at the Δ resonance the ratio of the π^-n/π^-p and π^+p/π^+n amplitudes is 3. This has been exploited to measure M_n/M_p for ^{18}O and the result is in agreement with the electromagnetic values so that an important check has been performed. For both pion and proton probes one can excite spin-flip states with both $\Delta T = 0$ and $\Delta T = 1$.

Alpha particles can also be useful probes. Because of the $J = 0$ and $T = 0$ nature of the α particle, only states with $\Delta T = 0$ are excited. Because of its composite nature, the α particle is strongly absorbed, which gives rise to diffractive scattering. This enables one to make accurate J^π assignments for inelastic scattering. The alpha particle and pion at the Δ region interact at 10 to 20% of central density but do not penetrate any deeper. This feature should enable us to extract relative density information from a comparison of the various hadronic probes.

There are many ways in which inelastic hadron scattering can make a valuable contribution to

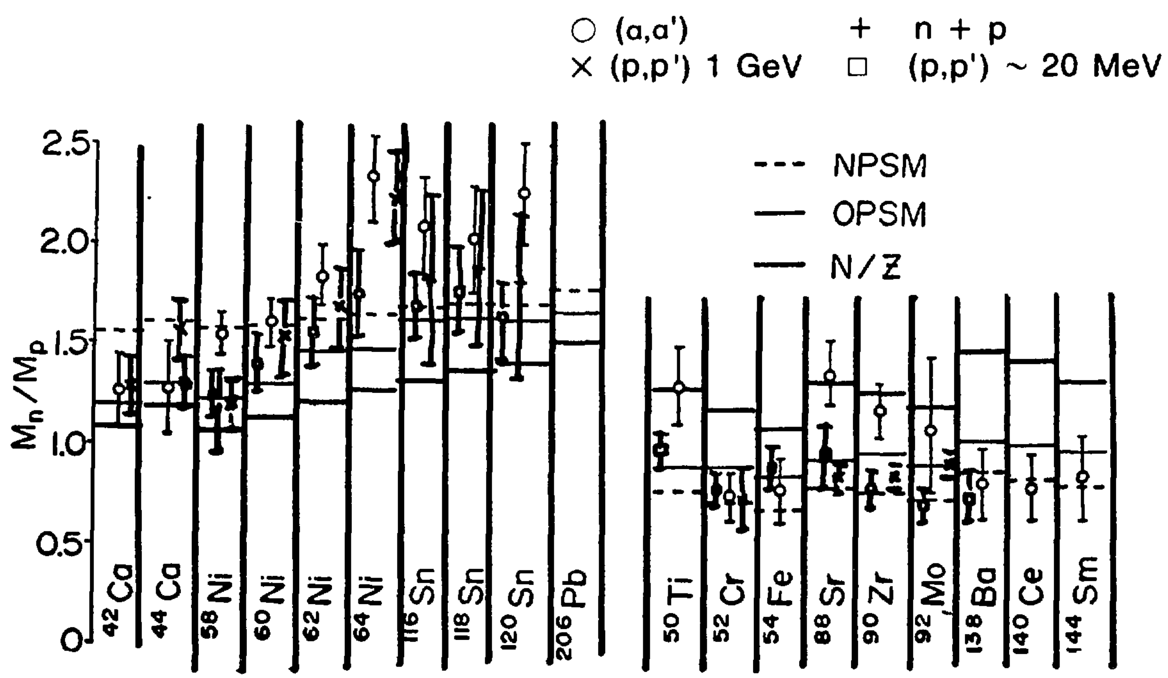


Fig. VI-12.
M_n/M_p ratios for many nuclei obtained from (α,α'), (p,p') at 1 GeV, n + p, and (p,p') at 20 MeV.

nuclear spectroscopy. It furnishes a way to locate specific states (both discrete and in the continuum) and to infer the J^{π} quantum numbers from the shape of the differential cross section. A systematic comparison of alpha particle, proton, and pion inelastic scattering should enable us to identify nonnatural parity states and the isospin of the excited level. Spin-flip measurements in (p,p') should clearly identify this type of state. These methods can provide a relatively easy way to track states over a region of nuclei (e.g., away from closed shells) and observe such features as energy shifts, fractionization of strengths, approximate sum rules, etc. More precise dynamical information about specific states can be obtained from inelastic electron scattering, but both protons and pions show promise of providing nuclear structure information that is complementary to electron scattering in the area of isovector spin-flip excitations. Additionally, both probes excite isoscalar spin-flip excitations which are not appreciably excited with electrons. Figure VI-13 is inelastic electron scattering of the T = 1,1⁺ state in ^{12}C. Figure VI-14 shows DWBA calculations for inelastic scattering of protons. At 800 MeV, the cross section at forward angles is large due to essentially zero momentum transfer at that angle. Figure VI-15 shows the excitation of known T = 1 states. Figure VI-16 shows the angular distribution for protons.

Strong and selective excitations of $0^+ \rightarrow 1^+$ transitions have been observed at forward angles in the (p,n) reaction at 120 MeV and in the (p,p') reaction at 800 MeV. Additionally, high-spin unnatural parity excitations have been observed in the (p,p')

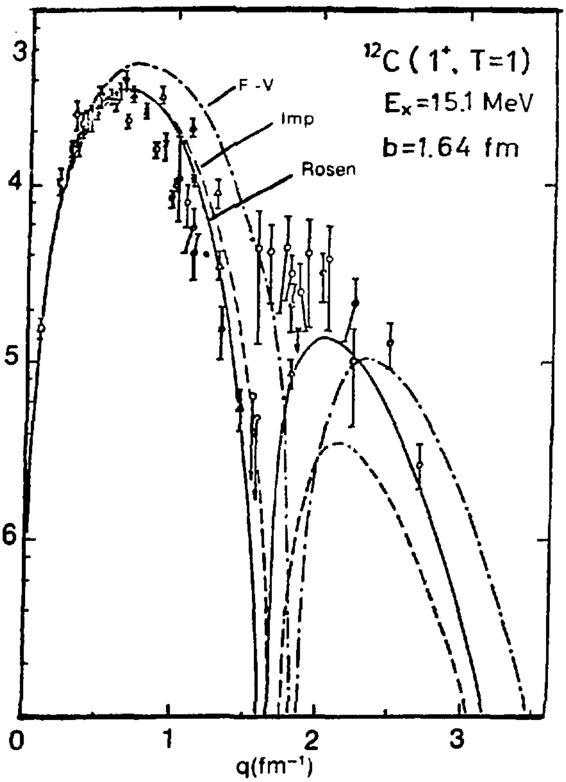


Fig. VI-13.
Inelastic transition form factors obtained from inelastic scattering to excite the $T = 1,1^+$ state in ^{12}C.

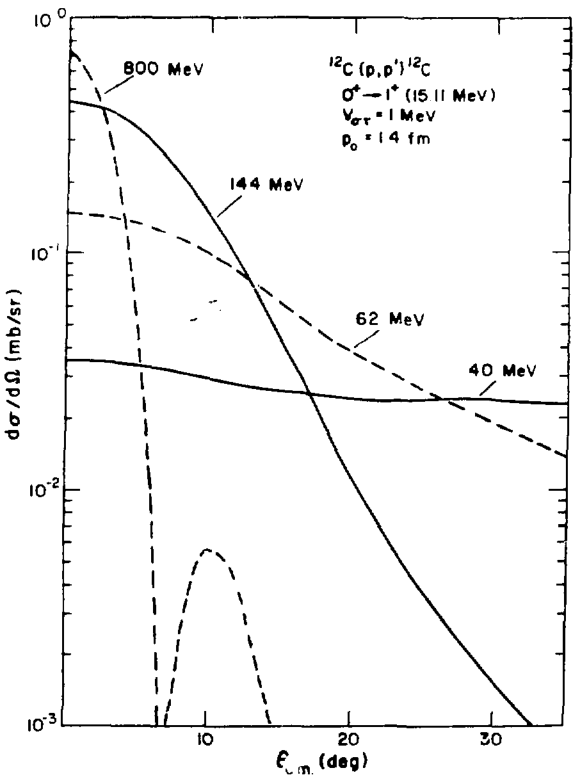


Fig. VI-14.
DWBA calculation of the differential cross section for the reaction $^{12}C(p,p')^{12}C(T = 1, 1^+$, 15.11 MeV) at 40, 62, 144, and 800 MeV.

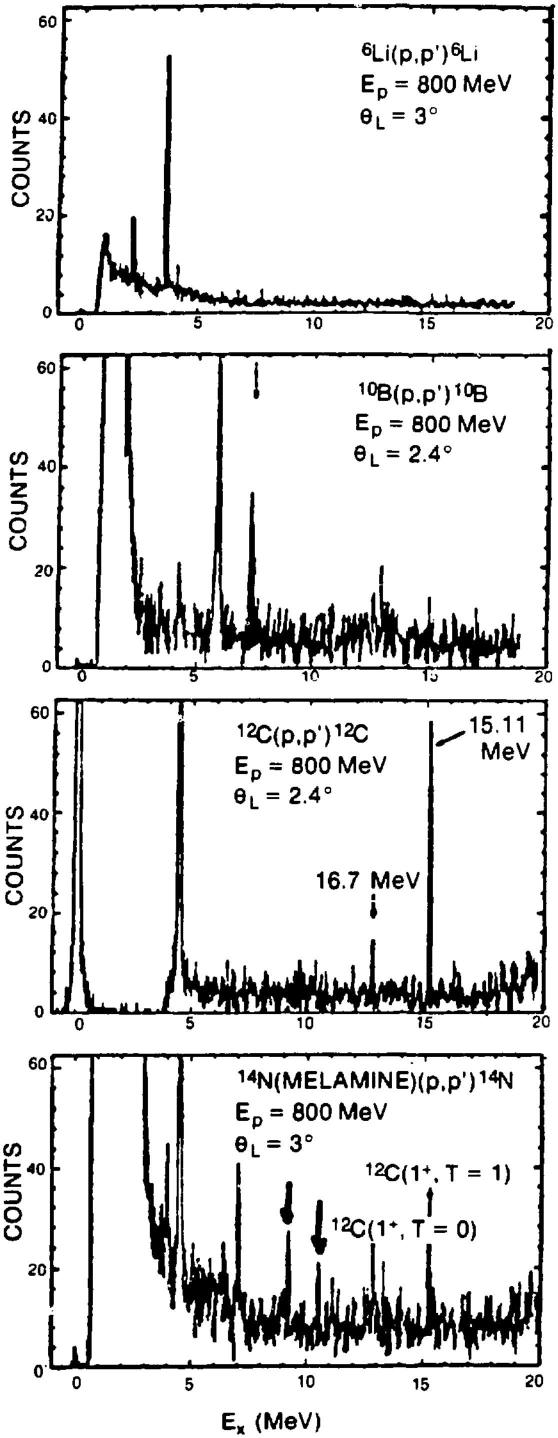


Fig. VI-15.
Excitation of known states by (p,p') at 800 MeV at small angles.

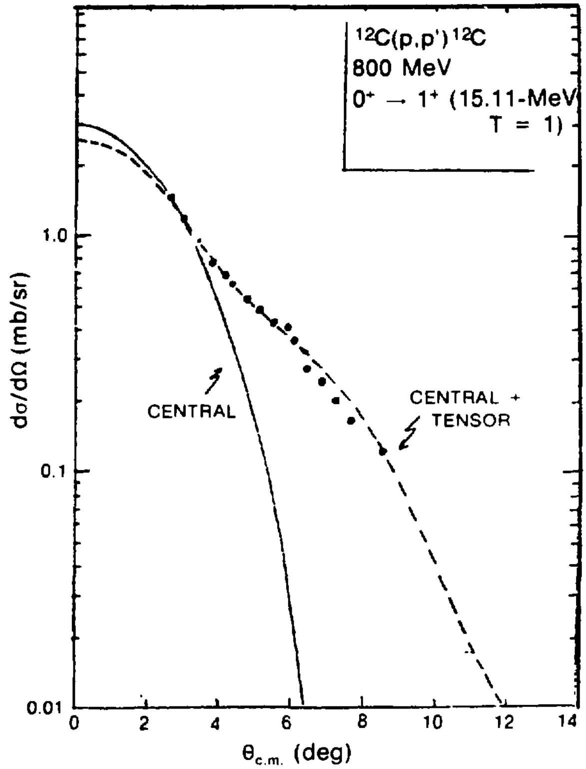


Fig. VI-16.
The observed differential cross section for $^{12}C(p,p')^{12}C$ (T = 1, 1^+, 15.11 MeV) measured at 800 MeV. Theoretical calculations are labeled.

reaction at 140 MeV. In future studies of spin-flip states, polarization transfer studies will undoubtedly play an important role. Selective excitations of high-spin "stretched" configurations in $(\pi^\pm,\pi^{\pm\prime})$ reactions in the resonance region demonstrate the large future potential of pions in this area of nuclear structure studies. Medium-energy protons ($E \geq 150$ MeV) have extremely long ranges in matter and it is therefore feasible to construct a double-scattering polarimeter with conversion efficiencies in the range of 0.1 to 10%. When combined with magnetic spectrometers, such polarimeters offer exciting new possibilities for the measurement of polarization observables in inelastic scattering. The Wolfenstein D parameter in inelastic scattering has been suggested as a sensitive indicator of the action of spin-dependent NN forces. The other Wolfenstein parameter, R,A,R', and A' should be also measured.

Stringent tests of reaction theories will be provided by measurement of the triple-scattering parameters in addition to the more conventional cross section and analyzing power. Given complete knowledge of the NN amplitudes and a successful reaction theory, the complexity of the NN interaction may be seen as an advantage in nuclear structure studies. As an example, spin-flip transitions, both isovector and isoscalar, may be excited by operators which have structures which are very different from that which enters in magnetic electron scattering.

IV. SUMMARY

The recommendations of panel N-1, which have been discussed in the previous sections, are summarized in Table VI-IV. The top priority is to obtain nucleon-nucleon amplitudes at HRS and at Saclay from studies of $\vec{p}\vec{p}$ and $\vec{p}\vec{d}$ elastic scattering and $\vec{p}\vec{d}$ quasi-elastic scattering. It should be emphasized that high-intensity polarized neutron beams obtained from stripping vector polarized deuterons will be available at Saclay early in 1980. At LAMPF, there is need for a polarized deuterium ($\vec{d}$) target. The panel recommends an accelerated effort on the part of the users and urges the support on the part of LAMPF to complete the Saclay target and to build a copy of the CERN target. Another recommendation includes a complete set of elastic measurements of 1s-shell nuclei as a test of the multiple-scattering interpretation. Measurements of Q are strongly urged for closed-shell nuclei, as well as a complete study of the energy dependence of cross sections and polarizations.

Completion of the spectrometer at TRIUMF is urged to extend new measurements to lower energies. Spin-flip excitation studies including $d\sigma/d\Omega(\theta)$ at zero degrees, $P(\theta)$, and triple-scattering parameters will add new dimensions.

TABLE VI-IV

NN Immediate Needs (1-4 years)

$\vec{p} + \vec{p}$ at 800 MeV, $\theta_{lab} \leq 35°$, complete determination of Wolfenstein amplitudes.

$\vec{p} + \vec{d}$ elastic and quasielastic at 800 MeV, $\theta_{lab} \leq 35°$, to further constrain n + p amplitudes: develop a polarized deuterium target at LAMPF, refurbish old Saclay target, build copy of the CERN target.

$\vec{n} + \vec{p}$ at Saclay, full set of amplitudes.

Eventual Needs (1-10 years)

The full n-p and p-p amplitudes between 500 and 1000 MeV, energy step size contingent upon possible NN energy-dependent structures.

Light Nuclei (1-4 years)

$\vec{p}$ + ^{3}H, ^{3}He, ^{4}He, $d\sigma/d\Omega$, P, Q, spin-spin correlations to test reaction theories, and to investigate correlation, spin effects, and intermediate isobar states.

(Continued on next page)

TABLE VI-IV *(continued from previous page)*

Heavy Nuclei

$\vec{p}$ + ^{16}O, $^{40,48}Ca$, ^{90}Zr, ^{208}Pb, $d\sigma/d\Omega$, P, Q, from 100 to 1000 MeV in steps of 100 MeV. Test of the energy dependence of the reaction theory and approximations.

Reactive Content

Proton and pion inclusive scattering from a few nuclei from 100 to 1000 MeV to test reaction theory and reactive content of optical model and multiple-scattering theory.

Closure Cross Section

Proton inclusive scattering from a few targets at 800 MeV.

Isotopic and Isotonic Density Studies in Heavy Nuclei

In particular, the nickel and tin isotopes and the N = 28,82 isotones.

Transition Densities

Test cases for T = 0 nuclei, $\Delta T = 0$ transitions.

Spin-Flip Transitions

$d\sigma/d\Omega(0^\circ)$, $P(\theta)$, triple-scattering measurements, spin-flip probabilities.

Completion of a High-Resolution Proton Spectrometer at TRIUMF

Variable Beam Energy at LAMPF

Pion Probes (1-10 years)

a. Theoretical advances needed.
b. 1-2-GeV pion beam with magnetic spectrometer;

Resolution	100 KeV
Solid angle	15 msr
Angular resolution	1 msr

c. Magnetic spectrometer for the AGS.

VII. PANEL N-2

ELEMENTARY EXCITATIONS

Chairman: G. T. Garvey
Co-Chairman: Helmut Baer

Participants: A. Arima, A. D. Bacher, V. Bunakov, A. Gal, G. Goldhaber, J. Ginnochio, S. S. Hanna, N. M. Hintz, G. M. Temmer, H. A. Thiessen, and N. Matsushita.

I. INTRODUCTION

We define an "elementary excitation" to be a simple operation on a nuclear ground state — for example, flipping the spin of one of the nucleons, removing a neutron, rotating the entire nucleus, etc. The observation of the consequences of such operations depends crucially on the *response* of the nucleus. When the operation produces a nearly quasi-stationary state of the system, the elementary excitation can be readily observed. This is often the case. For example, changing a neutron into a proton produces an isobaric analog state, and rotation of a deformed nucleus produces the well-known ground-state rotational bands. In these cases, the only problem facing the experimentalist is finding the appropriate probe to implement the desired operation. However, in other cases with high excitation energy involved, the large decay and/or spreading width of the elementary excitation renders it difficult if not impossible to observe. Theorists conceive elementary excitations — God makes nuclei!

Several elementary excitations are already known in nuclear physics and they play a significant role in our understanding of nuclear structure. Intermediate-energy physics presents an opportunity to produce new elementary excitations and provide additional critical information on ones already known. The reasons for this conclusion are:

1. Higher bombarding energy allows excitation of high-lying states.
2. Higher incident momentum allows large angular momentum transfer to nucleons, i.e., $\Delta J > 10\ \hbar$.
3. Electron beams with energy 100 MeV and greater allow details of the transition density to be determined and directly compared to theory.
4. The *impulse approximation* appears to work satisfactorily for proton scattering with $E_p >$ 100 MeV; more fundamental approaches work well at $E \gtrsim 300$ MeV.
5. The $\pi^{\pm}$ scattering allows the neutron and proton character of a transition to be determined.
6. K reactions allow the injection of strangeness into the nucleus by converting a nucleon into a Λ or Σ hyperon.

The contribution to our knowledge in each of these areas has greatly expanded over the past year. In fact, a program to be followed for the next five years can be seen rather directly in recent developments offering significant promise.

The report is divided into discussion of the following topics:

I. Low-Spin Giant Resonances
II. High-Spin Giant Excitations
III. Further Investigation of Known Low-Lying Excitations
IV. Strangeness Exchange — Hypernuclear Spectroscopy

II. LOW-SPIN GIANT RESONANCES

The experimentalist wishes to determine the position (E), width (Γ), and transition density as a function of momentum transfer (q) of the various multipole excitations of the nucleus, including the spin and isospin degrees of freedom. In referring to a giant resonance we usually refer not to a single state but rather to an observable concentration of transition strength which exhausts a significant (20%)

fraction of the appropriate sum rule. The systematic characteristics of the low q properties of the $(J^{\pi},T) = (1^-,1)$, $(2^+,0)$, and $(0^+,0)$ transitions are known and for the most part understood. The $(1^+,1)$ giant resonance is known in light nuclei, but above A = 60 little is known. Much less is known of $(1^-,0)$, $(2^-,1)$, etc.

A. Important Topics to be Investigated

1. Search for New Giant Resonances

One should identify important missing multipoles or determine the level at which they do not exist as compact resonances, and why. We consider the systematic location of M1 strength in heavy nuclei and in ^{208}Pb, in particular, to be a problem of great importance. A similar statement also applies to the systematic location of M2 strength and to the higher magnetic multipoles if they exist as concentrated resonances. Inelastic scattering with protons at very forward angles may be very important for picking out 1^+ excitations as shown in Fig. VII-1. It is becoming well established in this kinematic region that this "spin-flip," isospin-flip interaction results from single pion exchange. This might lead one to conclude that (p,p') is the ideal reaction to search for precursors to pion condensation discussed in panel N-4. Signature of the precursor phenomena is an enhancement of the yield to "pion-like" states at momentum transfers of ~3 f^{-1}, where unfortunately the (p,p') reaction is more complicated than simple one-pion exchange. We do, however, believe it is important to test if pion-like transitions $\Delta J^{\Delta\pi}$, $\Delta T = \Delta J^{(-)^{\Delta J+1}},1$ are systematically enhanced at these momentum transfers relative to the yield for other transitions.

Isoscalar spin flip would likely be enhanced if deuterons were used rather than protons. We would therefore believe that these modes could be identified using the highest available deuteron energies at forward angles.

The establishment of the isovector electric monopole and quadrupole resonances are of prime importance. The use of (n,p) or (π^-,π^0) reactions offer the best hope for seeing these $T_>$ states free from the complexity of the $T_<$ background. The 1-ħω part of the electric octupole strength appears to be well established, but it is vital to determine the 3-ħω strength. A similar statement can be made for the

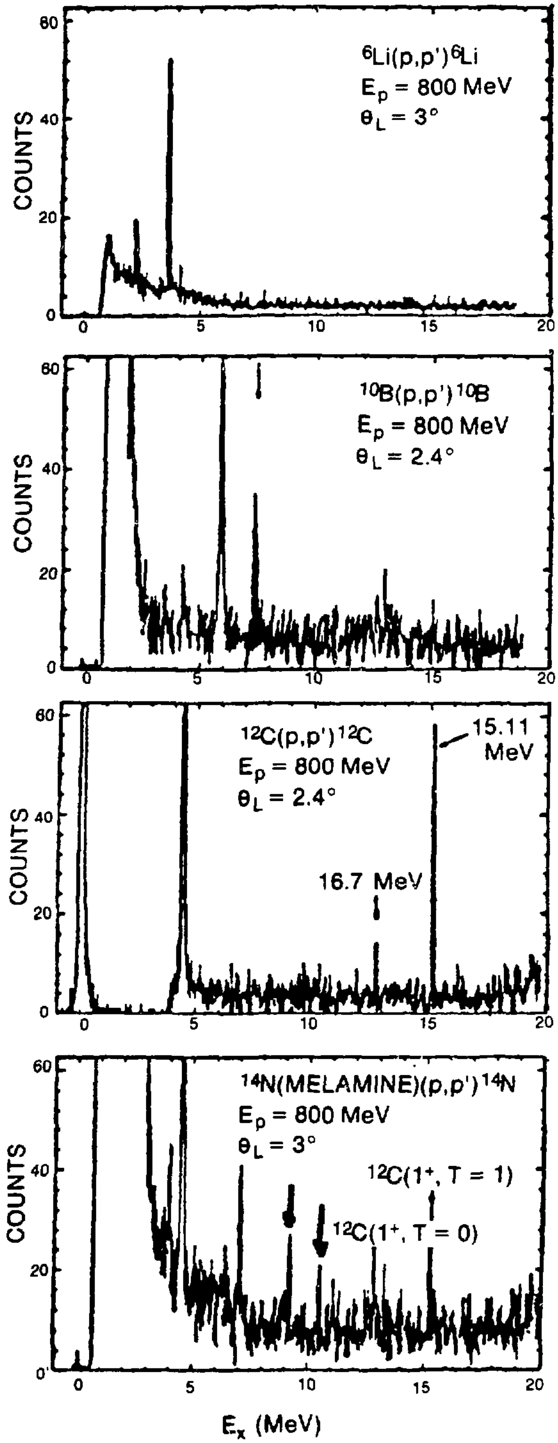


Fig. VII-1.
Spectra of very forward angle inelastically scattered 800-MeV protons.

E4 strength. We expect the important probes in locating these resonances to be those currently employed: (e,e'), (p,p'), and (α,α'), but other probes could prove important. For example, pions may prove effective because there can be no knockout contribution to the continuum background. Charge-exchange reactions will contribute to this program in providing complementary evidence. Because of the general boundary conditions of this workshop, we will not discuss excitation by heavy ions. The push to higher energies will be vital in the research on the higher multipoles.

Key to a research program on low-spin giant resonances is the determination of probes, kinematic conditions, or specific signatures that enhance the resonance yield relative to the background in which the resonance is embedded. Figure VII-2 shows a (p,p') spectrum at 800 MeV. The broad bump centered at 18-MeV excitation is the giant $2^+,T = 0$ resonance. It is important to understand the underlying background to select the optimum conditions. To this end we recommend using several probes at different energies on the same nucleus to quantify this point and to provide guidance to future research in searches for new giant resonances.

We believe (in the medium-energy range) the Indiana Cyclotron, LAMPF (perhaps running at lower energy), and TRIUMF can provide the necessary capabilities for the hadronic research and the present electron accelerators at Bates and abroad, and the new 100% duty factor electron accelerators at Stanford and Illinois will provide the appropriate facilities for the electron work.

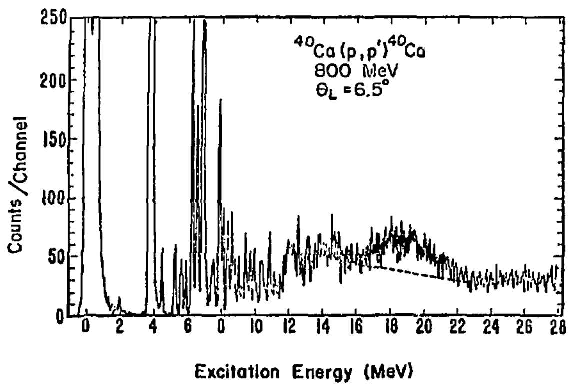


Fig. VII-2.
Spectrum of inelastically scattered 800-MeV protons from ^{40}Ca. The bump above the dashed line is the giant E2 resonance.

2. Coincidence Measurements

An important new tool in this study of giant resonances (GR) may be the measurement of the angular correlations of decay products which would provide a unique and independent signature of the multipolarity. This use of angular correlations has already been demonstrated by coincidence measurements on the E1 resonance with the high-duty-factor accelerator at Stanford.

While the claim is often made that valuable information can be obtained by studying the decay, this point should be examined carefully. In all save the lightest nuclei, the giant resonances are at energies where the level density is very high. It is therefore possible that the GR will mix almost completely with the background states and the decay will therefore be nearly statistical. Hence the observed particle decay widths would carry little or no nuclear structure information pertinent to the resonance.

In the light nuclei, the E1 resonances are known to decay largely by a semidirect process, i.e., the decay goes directly through the giant resonance doorways and the decay channels reflect the properties of the giant resonance itself. At ^{90}Zr the semidirect decay of the $T_<$, E1 resonance may have dropped to ~30%, the rest being statistical, reflecting the random nature of all the underlying 1^- states. But a significant point is that a large percentage of the p_0 and n_0 channels, and presumably transitions to other low-lying hole states, is semidirect and hence these channels reflect the properties of the giant resonance.[1] At ^{208}Pb the semidirect decay is 15-20%, but again decay through p_0 and n_0 channels is largely semidirect.[2] In both ^{90}Zr and ^{208}Pb the evidence strongly suggests that the $T_>$ analogs also follow this general pattern.[1] Thus, it is of the greatest importance that the decay properties of these giant resonances be determined by coincidence experiments, with both electrons and hadronic probes.

The evidence on the E2 resonances is incomplete and contradictory. The (α,α') measurements on ^{16}O, which detect decays of the E2 resonances in coincidence, do not agree with the capture experiments (α,γ) or (p,γ) (Ref. 3). In ^{58}Ni the (α,α') experiments[4] indicate predominantly statistical p decay while the (e,α) experiments[5] show nearly

100% α decay. Around U the (α,α') experiments[6] indicate little fission decay while the (e,f) experiments[7] show dominant fission. In the face of these experimental contradictions, we can conclude little at this time about the nature of the decay. Further coincidence experiments with electrons and hadronic probes are needed to clear up the experimental situation and provide the ground work for establishing the scope of a useful program in studying giant resonance decays.

In order to effectively carry out this program of research, a large solid-angle (30-50 msr) magnetic spectrometer of moderate resolution ($\Delta p/p = 10^{-3}$) is needed. This spectrometer must be able to rotate to different electron-scattering angles. Its cost is estimated at $1.5M.

3. Polarization

We feel that an important tool in the search for characterization of GRs will be polarization studies that are just beginning to be carried out. Asymmetry measurements are not yet understood but should, in principle, be of significant help. Spin-flip measurements will likely be more useful establishing the spin-flip character of transitions.

4. Special Topics

We give one example of a special topic not covered in the scope of the above program. Giant resonances built upon excited states have been recently suggested by means of (p,γ) measurements. Recently at the Indiana Cyclotron, strong capture strength has been observed to a level or group of levels at about 19 MeV. It is not yet known whether this process can be described in terms of a giant resonance built upon these levels or if it is a direct capture process. To carry out research in this area, large-volume NaI-detectors (25 cm × 25 cm), capable of counting at high rates (3×10^6/s), are required.

VII. HIGH-SPIN GIANT EXCITATIONS

A. Present Status

Recent (e,e'), (p,p'), and (π,π') experiments at high-momentum transfer[8] have located states whose spins correspond to the maximum angular momentum that can be made from low-lying, one-particle, one-hole excitations that are 1 $\hbar\omega$ removed from the Fermi surface. Examples include $J^\pi = 6^-$ states (T = 0 and 1) in ^{28}Si $(d_{5/2}{}^{-1}f_{7/2})$, and in ^{208}Pb, $12^+(i_{13/2}{}^{-1}i_{11/2})$, $12^-(h_{11/2}{}^{-1}i_{13/2})$ and $14^-(i_{13/2}{}^{-1}j_{15/2})$ states.

Figures VII-3-5 show the spectrum of the 4^- states in ^{12}C, the 6^- states in s-d shell nuclei, and the high-spin states observed in ^{208}Pb.

These states, at least in medium and heavy nuclei, appear near the unperturbed 1p-1h energy[9] and are found to contain an appreciable fraction (0.3-0.85) of the strength expected for the pure 1p-1h configuration.

A study of these relatively pure high-spin 1p-1h states is nearly the only way to obtain information on the high-momentum components of the p-h interaction. In the case of (p,p') or (π,π') excitation, the states can provide a relatively clean test of reaction theories and the relevant projectile-nucleon interaction. The high-spin magnetic states (unnatural parity) are expected to be sensitive to effects of meson-exchange currents.

B. Unresolved Problems

The high-spin p-h states have been observed in only a few nuclei near doubly closed shells and in the middle of the 1p and the 2s-1d shell. For example, Fig. VII-4 shows the 6^- state readily observable in ^{24}Mg and ^{28}Si but not present in ^{32}S and ^{40}Ca. The full 1p-1h strength is generally not found in a single state. The shifts in excitation energy from the unperturbed 1p-1h energy, the spectroscopic strengths, fragmentations, and A-dependence have not been explained theoretically. The natural parity states appear to contain a larger fraction of the 1p-1h transition strength than do the unnatural parity states. The mixing of the 1p-1h degree of freedom with other high angular momentum modes is at present unknown.

C. Future Experiments and Recommendations

1. High Resolution

The most serious experimental problem at present is that even with the best energy resolution currently

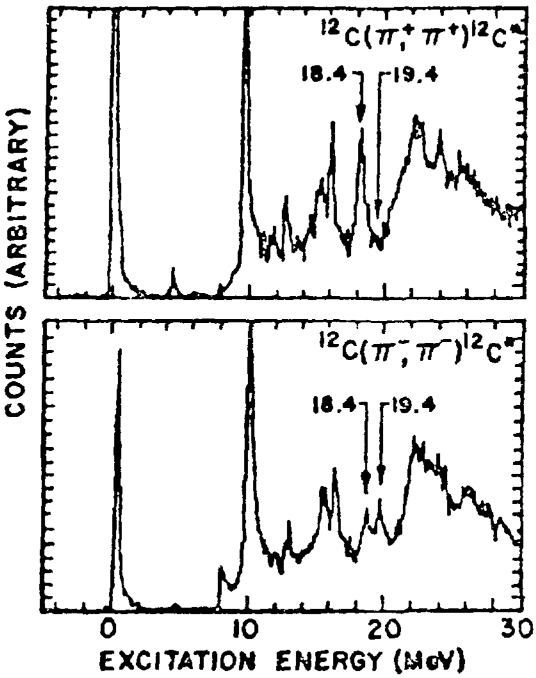


Fig. VII-3.
Spectra of inelastically scattered pions from ^{12}C.

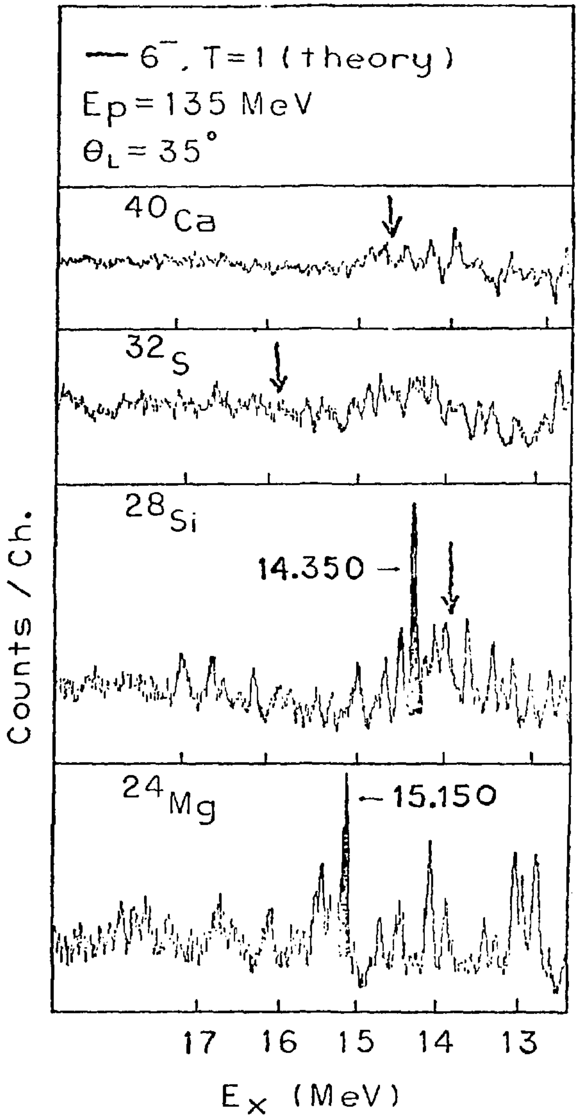


Fig. VII-4.
Spectra of inelastically scattered 135-MeV protons from s-d shell nuclei. The arrow indicates a theoretical prediction for the location of the 6⁻ state and the shaded peaks identify known 6⁻ transitions.

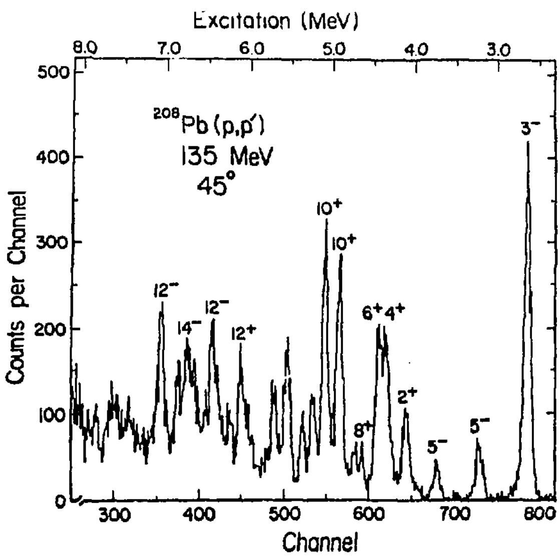


Fig. VII-5.
Spectra of protons inelastically scattered from ^{208}Pb.

available at electron and proton intermediate-energy facilities (30-50 keV), the strongest of the high-spin states are not fully resolved and the search for weaker components is nearly hopeless. What is urgently needed for the study of these states and for many of the low-spin magnetic giant resonances (mostly bound), as well as the known low-lying vibrational and rotational excitations in nuclei, is a facility (electron and/or proton) in the energy range of 300-500 MeV with better than *10-keV* overall energy resolution. For protons, it should be possible to establish the optimum energy range for exciting these transitions using the known energy dependence of the NN interaction.[10]

2. Need for Various Probes

Experiments with both electrons and protons have been shown to be necessary to make unique configuration assignments, as in the case of the 10^+ and 12^- states in ^{208}Pb, where several nearly degenerate 1p-1h excitations can mix.

Valuable information on the isospin structure of these states in light nuclei has already been obtained from (π,π') experiments of moderate (150-MeV) energy resolution. It is expected that pions will be of increasing importance in sorting out the separate neutron and proton excitations of these states in heavier nuclei as experimental resolution is improved.

3. Use of Polarized Beams

Experiments should be performed with polarized beams to obtain information on the spin structure of the high-spin p-h modes. Measurements of both the analyzing power and the spin-flip probability can be very sensitive to the configurations involved and can, in the case of protons, reveal which components of the NN force are responsible for exciting these modes.

Calculations indicate that the detection of spin flip can aid in the identification of relatively weak magnetic giant excitations in the presence of the more strongly excited electric modes.

D. Conclusions

1. The high-spin p-h states provide a new class of simple elementary excitations of fundamental importance.
2. The complementary information available from electron, proton, and pion probes will be of importance in understanding these excitations.
3. Experiments with both electrons and protons should be done away from the narrow regions of A studied so far in order to map the systematics of the energies and strengths of these modes.
4. High-resolution measurements at several proton energies between 135 and 800 MeV will be useful because of the energy variation of the spin-dependent parts of the NN interaction.
5. To effectively carry out the above program, a 500-MeV, 10-keV resolution facility is needed.

IV. FURTHER INVESTIGATION OF KNOWN LOW-LYING EXCITATIONS

There are many low-lying vibrations and rotations about which a great deal is already known. In certain select cases a detailed study of a few of these transition densities is very important. For example, the transition density of the collective octupole vibration in ^{208}Pb at 2.6 MeV has recently[11] been measured to 1% at Saclay via electron scattering. The agreement between this experiment and a new self-consistent random-phase-approximation calculation by Gogny[12] is extremely good and does not agree with simpler calculations performed earlier (see Fig. VII-6). This is an important case for two reasons. First, this 3^- transition is a prototype for octupole vibrations, and it is gratifying to see that its transition density can be calculated from a fundamental point of view. Secondly, this vibration amongst others gets mixed into the ground state in second order and plays a significant role in reducing the uncorrelated Hartree-Fock (HF) ground-state central density by slightly reducing the occupancy of the 3s proton orbit. Thus it appears, in cases when one wishes to calculate the ground-state charge density at the 1% level, it is necessary to know the energies and structure of the low-lying collective excitations. It is clear that to make progress in this particular area extensive interaction between experimentalists and dedicated theorists is required.

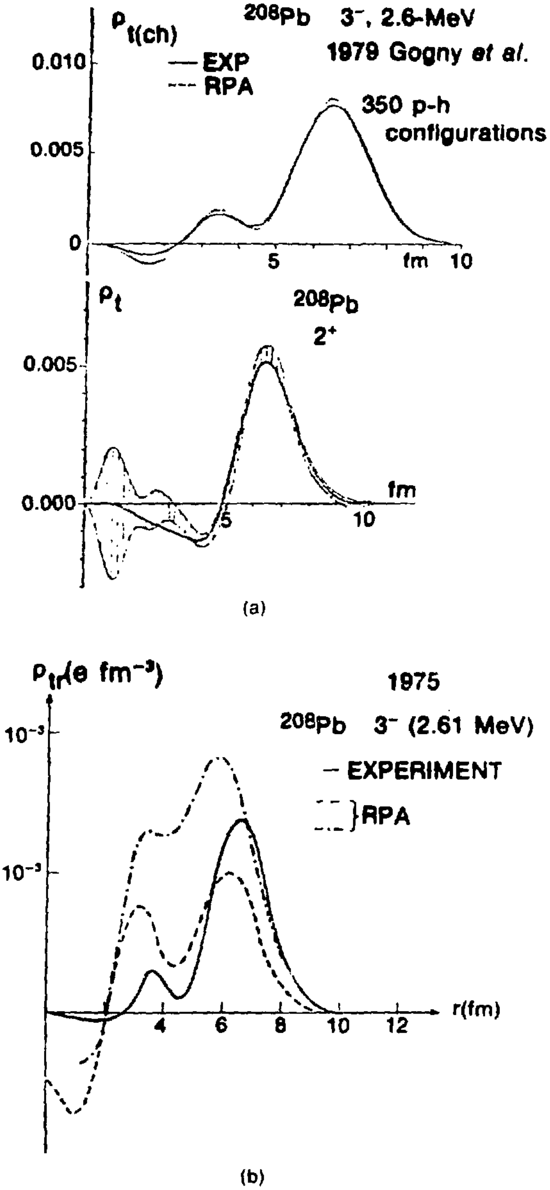


Fig. VII-6.
(a) Transition densities for collective states in ^{208}Pb; (b) results of earlier calculations of the 3^-, 2.61-MeV transition density.

The 1% measurements do not make sense unless there is a theory working to obtain that level of accuracy.

One of the striking aspects of nuclear structure at present is the fact that nuclear properties and spectra change dramatically for small changes in mass number. These dramatic changes occur both in medium-weight nuclei (see Fig. VII-7 for the germanium isotopes) and heavier nuclei (see Fig. VII-8 for the samarium isotopes). In these cases, the positions of the low-lying levels shift quite markedly. Generally the excited states will drop in energy and then rise again as neutrons are added. The exact pattern will vary from level to level. In ^{72}Ge the "two-phonon" 0^+ state drops in excitation energy below the first excited "one-phonon" 2^+ state, and becomes the first excited state of the nucleus!

There are a variety of nuclear models which attempt to explain this behavior. The models include HF,[13] the dynamic deformation model (DDM),[14] the boson expansion method (BEM),[15] the interacting boson model (IBM),[16] and the variable moment-of-inertia model (VMI).[17] Each of these models has its own success. Also, the models differ in the extent to which they are presently derived from more microscopic theories.

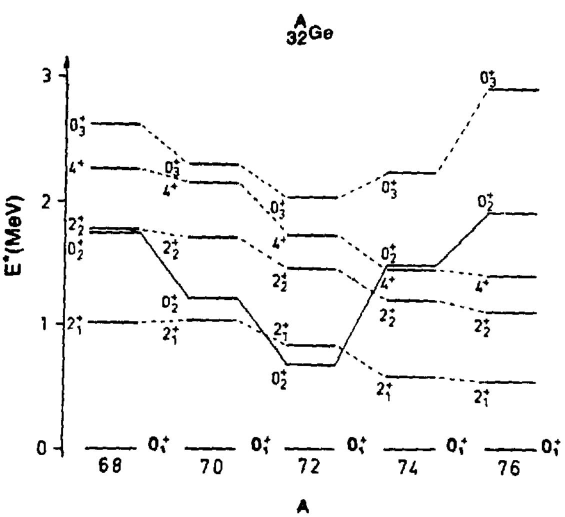


Fig. VII-7.
Spectra of lowest lying levels of germanium isotopes as a function of atomic mass A.

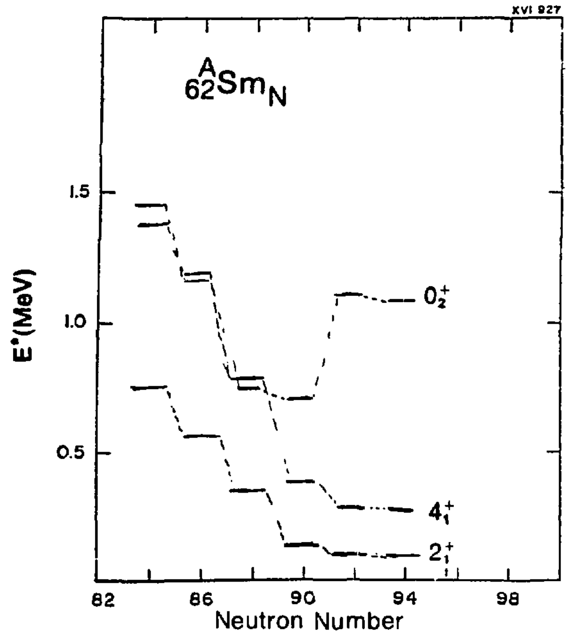


Fig. VII-8.
Spectra of first $J = 2^+, 4^+, 0^+$ excited states in samarium isotopes as a function of neutron number.

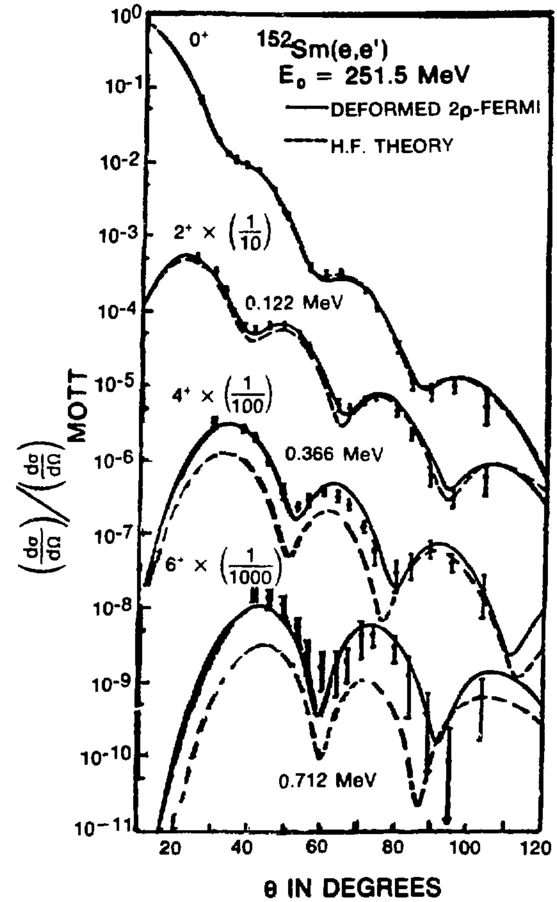


Fig. VII-9.
Comparison of HF calculations of different cross sections to measurements for ^{152}Sm.

The HF theory has the best microscopic underpinnings to date. Unfortunately it does have the limitations that it produces a deformed density which may only be applicable to a couple of the excited states in a deformed nucleus. In Fig. VII-9 a HF calculation[18] is compared to the differential cross section for electron scattering to the lowest Yrast levels in ^{152}Sm. We see that agreement with HF deteriorates rapidly for states above the first 2^+ state. The situation is expected to be worse in the lighter samarium isotopes, which are not well-developed rotational nuclei. A set of experimentally determined transition densities for ^{144}Sm-^{152}Sm is shown in Fig. VII-10 (Ref. 19). To theoretically reproduce these transition densities, large-amplitude RPA as a next correction to HF will be required. The models which have so far attempted the most microscopic approach for the transitional nuclei (DDM and BEM), however, use a series of approximations which leave their connections to a microscopic foundation obscure. Up to the present time the IBM has been to a large extent a phenomenological theory. However, recent research has begun to explore the microscopic structure of the IBM.[20,21] For nuclei as light as germanium, shell-model calculations are feasible. In fact, ^{76}Ge has been calculated in the shell model,[22] and although ^{72}Ge is more difficult it is also tractable.

Medium-energy probes elucidate this nuclear structure by measuring the transition densities to the excited states in a series of isotopes. Such measurements will push these models to buttress their microscopic foundations in an attempt to explain these transition densities.

Not only are the spin levels of the ground-state band of interest in this regard, but also members of side bands as well. In particular, the first excited 0^+ state shows very interesting behavior in many

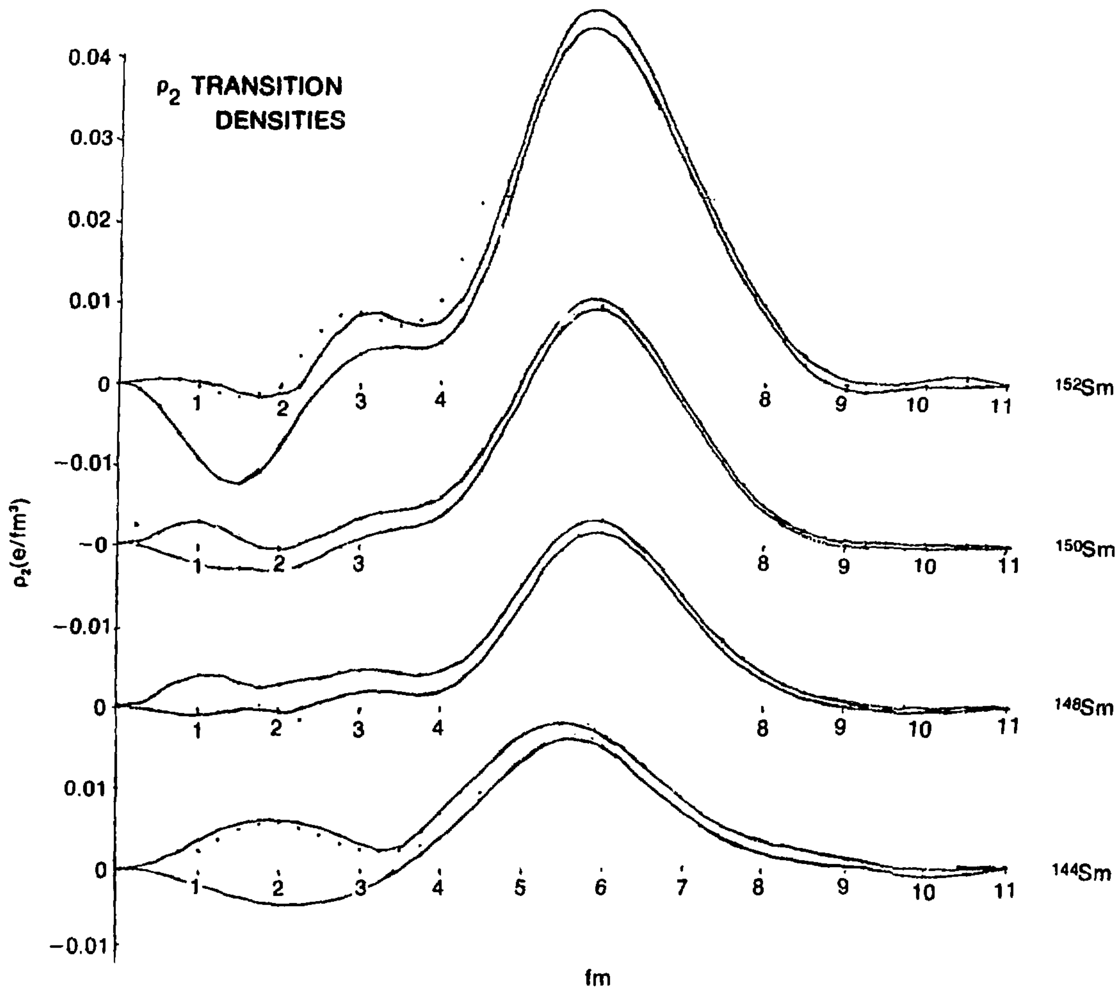


Fig. VII-10.
Transition density for $0^+ \rightarrow 2^+$ extracted from (e,e') data of Fig. VII-9.

nuclei, and its position may be a signature of "γ-soft" nuclei.

Electrons are the best probe for the task of studying these transition densities because the nuclear structure can be extracted in the most reliable fashion. However, it yields only one linear combination of neutron and proton transition densities. In this respect, the $\pi^\pm$ inelastic scattering in the (3,3) resonance region is the most selective. However, at present, medium-energy protons seem to be a better probe than pions because of the high-momentum transfer available, higher energy resolution, and a more reliable means of extracting nuclear structure. If a neutron beam of similar characteristics were available, the two probes together would provide a powerful tool.

Though the positive and negative pions in the 100- to 200-MeV range may not be most reliable for extracting transition densities, they could play a unique role in identifying isovector excitation modes as well as isoscalar modes. In large measure the models mentioned consider only isoscalar collective modes. However, the lowest-lying isovector mode has the same isospin as the ground state and may very well occur at fairly low energy. For example, in the palladium isotopes there is an excited 2^+ state just above the two-phonon energy region, which might be an isovector mode.

From the preceding three sections (Secs. II-IV) of this panel's report it is clear that pion scattering is now playing a large role in many aspects of the study of elementary excitations. We expect this role, if anything, to increase. To present this case in a *coherent fashion, as the use of pions is not as well* known as electrons or protons, we include an appendix to this report dealing with the role of pions in the 3-3 resonance region in studying elementary excitations. Included in this appendix is a recommendation for greatly improving the effectiveness of pion scattering.

V. STRANGENESS EXCHANGE — HYPERNUCLEAR SPECTROSCOPY

The main interest in using negatively charged kaons as projectiles stems from their ability to transfer strangeness to the nucleus, thus creating a new type of spectroscopy[23] and new elementary excitations.[24] The ultimate goal of studying these Λ, Σ, Ξ, or ΛΛ hypernuclei is to derive quantitatively as much as possible the YN interaction.

The "work horse" of Λ-hypernuclear spectroscopy — presently at its infancy at CERN and Brookhaven — is the (K^-,π^-) reaction, which is particularly useful because of the low-momentum transfer it imparts to the nucleus. Examples of present observations are shown in Figs. VII-11 and -12. Figure VII-11 shows the energy spectrum of π^- observed at 0° on ^{12}C, ^{32}S, and ^{209}Bi. The largest peak represents the conversion of valence nucleons into a Λ hyperon in a similar orbit. The smaller peak to the left corresponds to forming the ground state of the respective hypernucleus. Figure VII-12 shows a similar spectrum except that some 80 MeV above the large peak there is observable yield associated with the production of a Σ^0 hyperon in the nucleus. It is interesting that such sharp peaks are observed in ^{9}Be. Figure VII-13 shows the angular distributions associated with the "valence" transition and the "ground-state" peak. Each shows the expected $\Delta L = 0$ and $\Delta L = 1$ shapes expected for these transitions.

Each of the bumps seen in the spectrum likely consists of several peaks which cannot be resolved with the 2-MeV resolution available with the existing facilities at CERN and Brookhaven. To improve our understanding of the reaction mechanism and the resulting hypernucleus spectroscopy the following improvements need to be made in the coming years:

1. lower momentum of the incoming K^- beam, so that the existence of Λ^- analog states in heavy elements could be established or disproved. Similarly, in the Σ^- excitation region, the question of existence of relatively narrow ($\Gamma \lesssim$ 10 MeV) Σ-hypernuclear states should be further explored.
2. improve the resolution to a level better than 0.5 MeV in order to resolve states belonging to the

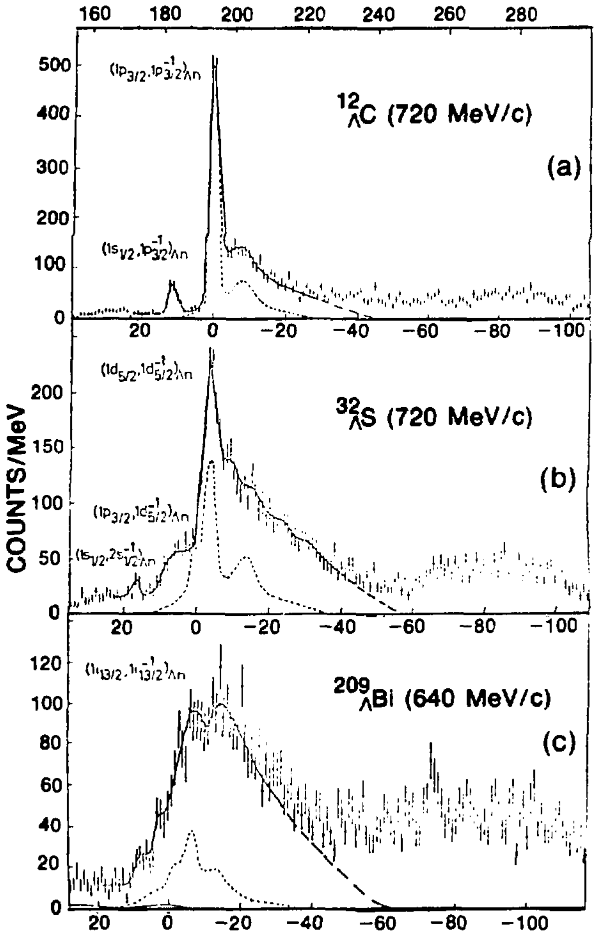


Fig. VII-11.
Spectrum of π^- at 0° from (K^-,π^-) reaction (see Ref. 25).

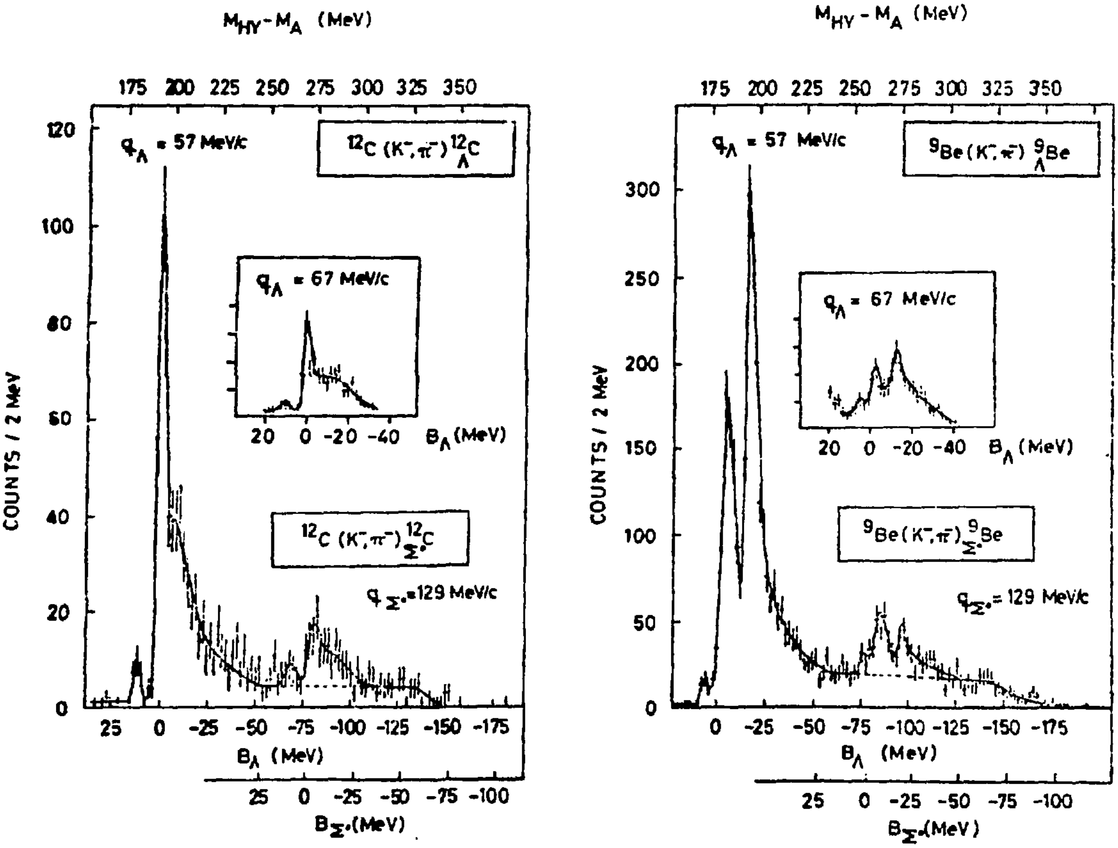


Fig. VII-12.
Spectra of π^- at 0° from (K^-,π^-) reaction (see Ref. 26).

same configuration, be it the analog configuration or the ground-state configuration. This is necessary in order to derive the YN effective interaction, in particular the spin-dependence of this interaction, more reliably than is currently done. In this respect the low-lying hypernuclear states (particle-stable) may be investigated by means of $\pi^-\gamma$ coincidence measurements following the (K^-,n^-) reaction.

3. increase the intensity to make the spectroscopic content of the (K^-,π^-) reaction comparable to that of (p,d) and (d,p) in conventional nuclear spectroscopy. Of course, one may mention the (π^+,K^+) reaction as an example where pion machines could be used with a 10^3 improvement in incident flux relative to kaons. However, this same factor will roughly be lost because of the high-momentum transfer involved in this reaction.

4. to make most effective use of this new and important scientific opportunity, increase the level of effort in this area in the United States by a factor of 2.

A reaction mentioned for the study of ΛΛ hypernuclei (or Ξ hypernuclei, in case these exhibit some narrow states) is the (K^-,K^+). Dover and Gal[27] estimate the forward nuclear cross section (for $P_{K^-} \leq$ 1 GeV/c) to be of the order of several tens of μ/sr. However, in view of the large-momentum transfer (≤400 MeV/c), excitation of particular elementary excitations (including the ground state) may be suppressed by 10^3-10^4 from the above estimate.

The panel did not discuss electromagnetic processes such as (K^-,γ), (γ,K^+), and $(e,e'K^+)$. More theoretical work is required to sort out these reactions.

Side benefits of kaon-nucleus interactions consist of (1) deriving the optical properties of K^- by

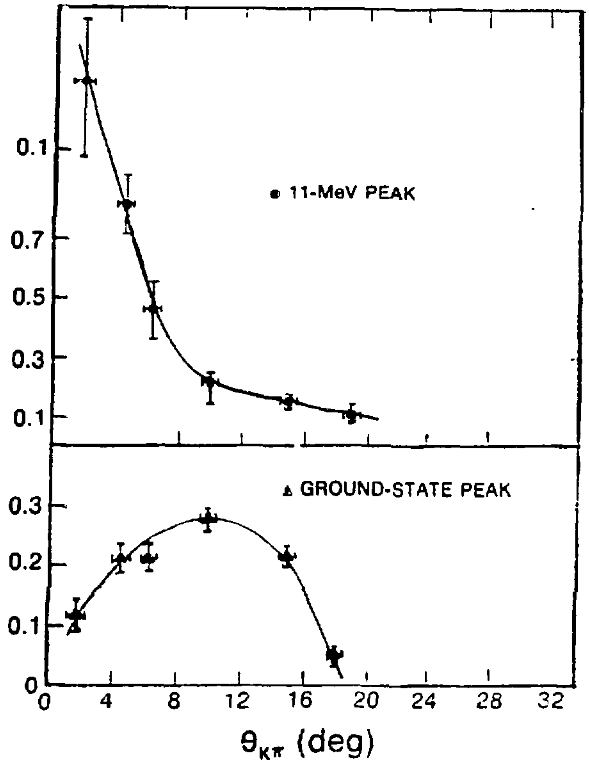


Fig. VII-13.
Differential cross sections of π from the (K ,π) reaction (see Ref. 28)

measuring elastic and inelastic angular distributions [this is essential for input into the (K ,π) reaction evaluation], and (2) using K⁺ weakly absorbed probes at $P_{K^+} \leq 800$ MeV/c, to excite $\Delta S = 0$, $\Delta T = 0$ states and to obtain complementary information on neutron distributions.

The entire committee would like to thank those experimentalists who generously contributed the new (and often as-yet-unpublished) data that have been used to illustrate the current status in this area.

VI. SUMMARY

The panel was most enthusiastic over the significant role that intermediate-energy physics has assumed in the study of simple modes of excitation in nuclei. Each of the probes employed (e, p, π, and K) has a unique role to play in revealing particular elementary transitions. Existing or planned beams of electrons and protons seem quite adequate. The biggest need is for ancillary equipment providing higher resolution or larger coincidence data-acquisition capability. The facilities providing both K's and π's need to be improved. It appears that if further progress is to be made in exploiting the (K ,π) reaction, final-state resolution of 500 keV or better will have to be obtained. This is required to resolve specific final states. In the absence of this resolution much of the detail of the Λ-nucleus interaction will simply remain undetermined. The panel believes it makes a great deal of sense to capitalize on this unique opportunity to examine a different set of baryonic interactions.

Pions are revealing a great deal about the neutron and proton components of simple excitations. Unfortunately, the existing systems have limited flux $\sim 10^8$ π/s, and moderate resolution ($\Delta E \sim 150$ keV). Improvement in both of these parameters seems possible, and further study should be devoted to producing a cost-effective upgrade of the EPICS facility aiming for at least a 10-fold increase in flux (so that a differential cross section at a single energy could be measured in two to three days) and resolution on the order of 30-50 keV. This development would allow one to employ pions in investigating the structure of the low-lying elementary excitations in the region A > 90, which includes the "transition" regions and regions of strong deformation.

To make best use of the 100% duty factor electron accelerators that are now becoming available, large solid-angle (~50-msr), moderate-resolution ($\Delta p/p \sim 10^{-3}$) magnetic spectrometers are necessary to study the decays from the "giant-resonance" region. If these studies are successful they will provide a unique and essential characteristic of giant resonances in nuclei. A few preliminary experiments should be able to show the information content of the decay in, say, A ~ 60 nuclei. If these investigations show that the decay is direct, the design and construction of such a coincidence-type magnetic spectrometer should be undertaken.

Improved resolution has continually yielded significant advancement in our ability to study the nucleus. Present-day magnetic spectrometers work at the $\Delta p/p \sim 10^{-4}$ range. It appears possible that 10^{-5} is achievable. We recommend that a workshop or study group of experts examine this problem, and if 10^{-5} can be obtained, that a proton or electron facility be selected and such a spectrometer be designed and constructed.

APPENDIX

THE PION AS A PROBE OF ELEMENTARY EXCITATIONS

Near the P-wave T = 3/2, J = 3/2 resonance at 180 MeV, the pion-nucleon interaction is well understood. The interaction may be written in the form

$$f(\vec{k},\vec{k}') = \alpha(k) \frac{(2 - \vec{t} \cdot \vec{\tau})}{3} \times (2 \cos \theta + i\vec{\sigma} \cdot \vec{n} \sin \theta) \quad . \qquad (A.1)$$

where k is the pion-nucleon relative momentum, $\vec{t}$ and $\vec{\tau}$ are the isospin of the pion and nucleon, respectively, θ is the pion-nucleon scattering angle, σ is the nucleon spin, n is the normal to the scattering plane, and $\alpha(k)$ is a function of the magnitude of the pion-nucleon momentum. To obtain this simple form, all phase shifts other than the P_{33} are ignored.

The high intensity and good resolution of EPICS at LAMPF have made possible pion inelastic-scattering experiments which demonstrate that the form of pion-nucleon interaction is evident in pion-nucleus scattering.*[,26] In particular, it has been shown that the yield of a natural parity transition at fixed q increases with pion energy while a spin-flip transition decreases with energy, and that pure isoscalar or isovector transitions are approximately equally excited by positive and negative pions.

As written in Eq. VII-(A.1), $\pi^+(\pi^-)$ has a cross section on protons (neutrons) which is nine times larger than that of neutrons (protons). One can define an asymmetry in observed yields

$$A = \frac{Y_{\pi^-} - Y_{\pi^+}}{Y_{\pi^-} + Y_{\pi^+}} \quad , \qquad (A.2)$$

in analogy with the usual spin asymmetry for polarized beams. For the case of pure neutron (proton) transitions, A = 0.8 (-0.8). A spectrum for $\pi^\pm$ inelastic scattering on ^{13}C is shown in Fig. VII-(A.1). The most striking effect is the absence of yield for the state at 9.5 MeV in the π^+ spectrum. This is an example of an essentially pure neutron transition. The isospin asymmetry for the low-lying states of ^{13}C is shown in Fig. VII-(A.2). These data show the relative neutron/proton strengths of several transitions, including a "pure" neutron transition at 9.5 MeV, which is seen with π^- only.

In T = 0 nuclei, neutron and proton states can exist if there is significant isospin mixing among two or more levels. The ^{12}C data [Fig. VII-(A.3)] show an example of such a pair of levels at 19.25 and 19.65 MeV, which show up as a structure in the $Y_{\pi^-} - Y_{\pi}$ data.

A theorem relating the various isospin channels for the scattering of pions on a nucleus with isospin T = 1 is

$$\frac{d\sigma^{IAS}}{d\Omega}(\pi^+,\pi^0) = |f^-(\theta) - f^+(\theta) - 2f^{IAS}(\theta)|^2 \qquad (A.3)$$

where $f^-(\theta)$ is the elastic π^- scattering amplitude, $f^+(\theta)$ is the elastic π^+ scattering amplitude, $f^{IAS}(\theta)$ is the (π^+,π^0) charge-exchange amplitude to the

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*An up-to-date review of pion inelastic scattering can be found in H. A. Thiessen's invited talk at the Eighth ICOHEPANS, Vancouver, Canada, August 1979.

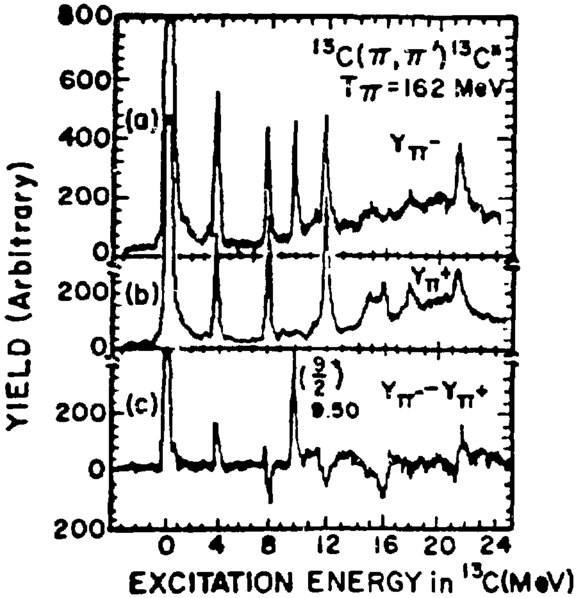

Fig. VII-A.1.
The $\pi^{\pm}$ inelastic scattering from ^{13}C summed from 62 to 82° at 162 MeV. The lower curve is the difference between π^- and π^+. Yields are normalized to the same number of incident pions.

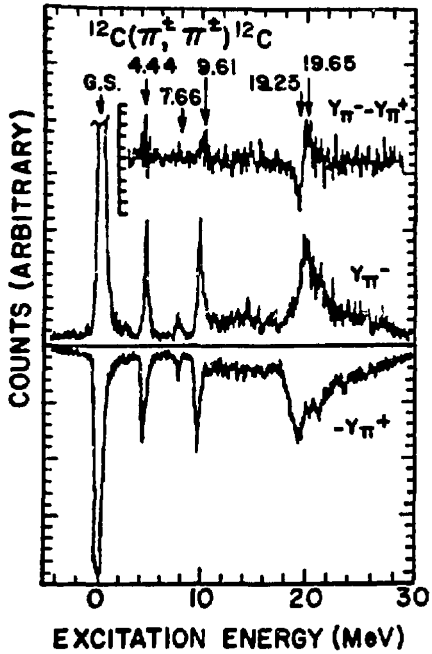

Fig. VII-A.3.
The $\pi^{\pm}$ inelastic-scattering spectra from ^{12}C near 70° at 162 MeV. The inset shows the subtracted yield, $Y_{\pi^-} - Y_{\pi^+}$.

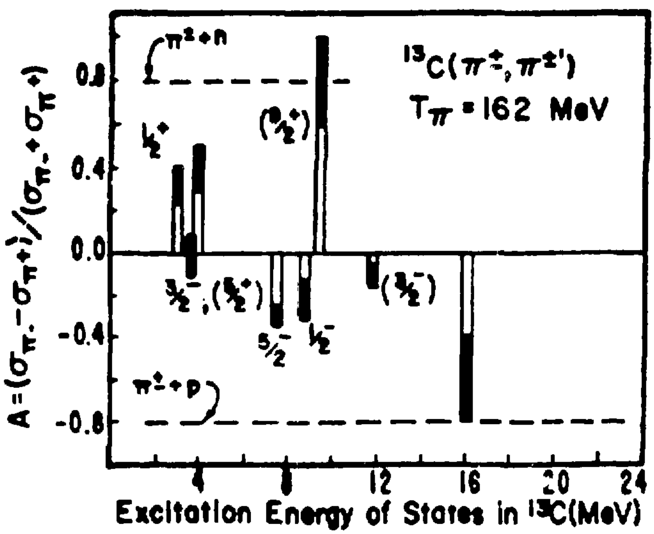

Fig. VII-A.2.
Asymmetry $A = (Y_{\pi^-} - Y_{\pi^+})/(Y_{\pi^-} + Y_{\pi^+})$ for several transitions in ^{13}C. The data were selected at an angle near the maximum of the angular distribution of each state.

isobaric analog state, and $d\sigma/d\Omega_{DIAS}$ is the cross section for the double isobaric analog state. The proof of this relation assumes that the target, IAS, and DIAS are related simply by rotations in isospin space. Tests of this relationship have not yet been made since the necessary precision data on elastic and single-charge-exchange data were not available.

Just recently the isobaric analog state has been observed in (π^+,π^0) scattering on nuclei from throughout the periodic table. Representative data taken at T_π = 100 MeV are shown in Fig. VII-(A.4). One sees that the IAS stands out above the background. Similar data were measured at 70 and 180 MeV. When these data are analyzed together with elastic data the above theorem can be put to test. For future experiments it would be desirable to coordinate the measurements of elastic, charge exchange, and double charge exchange to the same targets and energies so that such tests will be as sharp as possible.

The pion double-charge-exchange reaction $(\pi^\pm,\pi^\mp)$ has been studied at EPICS. The data obtained indicate the dominance of a two-step, double-analog transition at energies above the resonance. These data have already been used to measure the masses of several nuclei not previously measured with any other technique, and may be used to understand the weaker two-step portion of the pion-nucleus reaction mechanism.

Pion-scattering experiments are presently limited both by counting rate and resolution. The 180° electron-scattering counting rates at Bates are one order of magnitude larger. An improved version of EPICS that increases the resolving power by a factor of 2 or more and increases the counting rate by an order of magnitude would be the most useful addition to the arsenal of probes available for elementary excitation studies at intermediate energy.

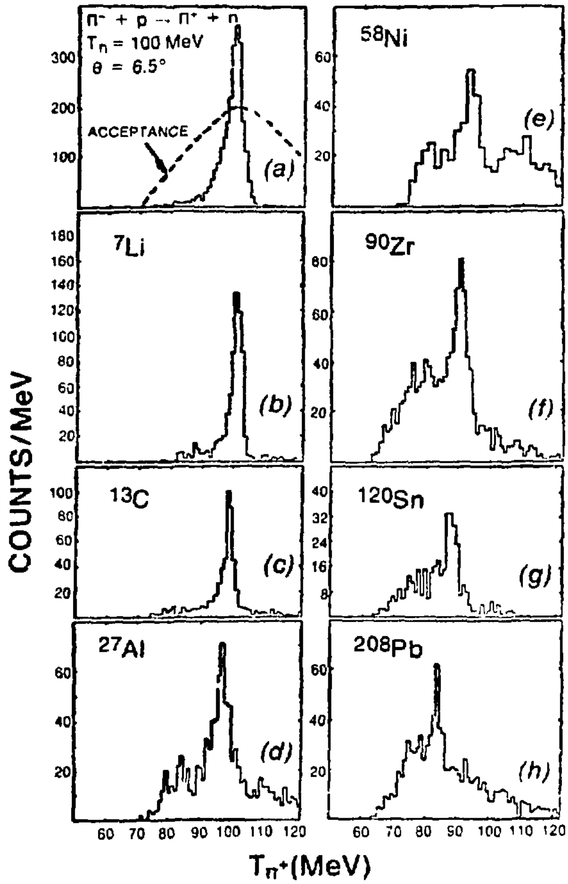

Fig. VII-A.4.
Neutral pion spectra measured for the (Π^+,Π^0) reaction at T_π = 100 MeV on targets of hydrogen (a), ^{7}Li (b), ^{13}C (c), ^{27}Al (d), ^{58}Ni (e), ^{90}Zr (f), ^{120}Sn (g), and ^{208}Pb (h). The peak in each spectrum is due to the isobaric analog state. The Π^0 spectrometer was set for a scattering angle of 0° with an acceptance of 0 to 12°. The variation of acceptance with Π^0 kinetic energy is shown in (a).

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VIII. PANEL N-3

CORRELATIONS IN NUCLEI AND HIGH MOMENTUM COMPONENTS

Chairman: **Ingo Sick**
Co-Chairmen: **Charles A. Whitten**
Jonas Alster

Participants: T. Antaya, R. Burman, K. M. Crowe, P. T. Debevec, S. Frankel, B. F. Gibson, E. J. Moniz, P. G. Roos, W. Turchinetz, and A. H. Wapstra.

I. INTRODUCTION

The long-range aspects of nuclear wave functions are reproduced quite accurately by the shell model, i.e., a model where nucleons move freely in an average potential well determined by the interaction with the remaining (A-1) nucleons. The most advanced types of such models — Hartree-Fock calculations based on density-dependent effective nucleon-nucleon interactions — are very successful. They properly reproduce masses, densities, and transition densities. Shell-model correlations are quite successful in predicting excited states, spectroscopic factors, long-range correlations, and collective excitations.

These mean-field theories "hide" in the effective interaction one important piece of physics: the strong repulsive core of the NN interaction for NN distances of $r_{NN} < 0.6$ fm. For such small NN distances the relative two-nucleon wave function has to become very small, a feature not accounted for by independent-particle models. The repulsive core of the NN interactions is expected to lead to strong short-range correlations between nucleons. The rapid vanishing of ψ_{NN} at small r_{NN} should lead to important high-momentum components in the nucleon wave function.

One of the important tasks of intermediate-energy physics is to isolate experimentally and understand theoretically these correlations and high-momentum components. Only this can lead to a microscopic understanding of nuclear wave functions. This is needed in order to decide where mean-field theories can be expected to work.

Discussing the theme of the N-3 panel in terms of simple ideas is not straightforward. High-momentum components and correlations are intricately linked to other short-range phenomena such as isobar components and off-shell effects. In addition, the independent-particle aspects dominate nuclear wave functions to a large extent: the volume for short-range correlations is a few percent of the nuclear volume, and the high-momentum components amount to perhaps a percent of the total momentum space density and are spread over a large momentum region.

In the past, attempts to isolate the effects of the short-range structure have produced disappointing results. Many apparently convincing proposals to measure them with first-order processes have been investigated. Detailed analysis in general has shown that more complicated processes dominate. Multistep processes depending on large (shell-model-related) amplitudes often overshadow the one-step process depending on small (short-range-related) amplitudes.

Consequently the approach taken in the present report is a rather cautious one. The past attempts and failures will be discussed in detail. The emphasis lies in understanding why past attempts failed, in the isolation of those processes that are most likely to be interpreted quantitatively with a finite theoretical effort, and in the identification of those areas where additional theoretical or experimental effort would be most likely to succeed. Proposals for new processes (not analyzed in detail) are given, but not strongly advocated.

II. CAVEATS

In discussing the accessibility of the short-range wave function to experimental "measurement," it is important to realize that there are strong theoretical expectations about its general characteristics (e.g., the range of the "hole" in the relative wave function, or the healing distance). These expectations are borne out indirectly by theoretical calculations of processes in which correlations play a comparatively minor role. An example of this is the increase in the *effective projectile-nucleus* cross section seen in high-energy coherent nuclear reactions [such as elastic hadron scattering or (γ,p)]. This increase is due to the larger effective area presented to the projectile by nucleons that are repulsively correlated.

We stress that the information extracted from such experiments is necessarily model dependent. This is true even for a world consisting of static nucleons interacting only through static potentials. Basically, the short-range wave function is inside the NN interaction volume. It is impossible to probe this region while escaping short-range final-state effects generated by the same force originally responsible for the wave function.[1] This does not mean that the task is impossible; however, to interpret the data a model and a sufficiently powerful calculational technique are needed. In particular one might expect the model dependence to be minimized when the energy of the detected nucleon is very large, since the final-state interaction in this circumstance is expected to be small.

Unfortunately, the real world is not so simple, since the nucleon itself has internal degrees of freedom (e.g., π). In this regard it is no accident that experiments run into these ambiguities precisely in the kinematical region where a sensitivity to the short-distance wave function is expected. The energy/momentum scale associated with the repulsive core in the NN interaction is $\sim(0.5\text{ fm})^{-1} \simeq 400$ MeV; this is comparable to the pion mass and the Δ-excitation energy. Consequently an understanding of the short-distance wave function *must* extend to a consideration of these additional degrees of freedom and, again, lead to considerable model dependence. For example, the length scale associated with a ΔN wave function component is $\sim(M_N\Delta M)^{-1/2} \simeq 0.4$ fm, where $\Delta M = M_\Delta - M_N$. This is small compared even to the $NN \to N\Delta$ transition potential range, so that again model dependence cannot be avoided.

This model dependence does not preclude success. It means that an approach must be used that is somewhat more sophisticated than the one used in the past. It implies that perhaps no single experiment will provide "the answer." In particular, oversimplified reaction models (e.g., scattering omitting the finite πN interaction range) for isolating short-range properties (e.g., NN correlation) should be avoided. A systematic program to measure the most promising large-energy/large-momentum transfer reactions and the auxiliary information needed for their interpretation (e.g., pion and nucleon distorted waves) is called for. Emphasis should be on light targets where there is some hope of constructing more detailed nuclear models.

III. TOPICS DISCUSSED

The topics discussed can be separated into several distinct classes:

1. *inclusive scattering of weakly interacting projectiles (e,e')*. The inclusive nature of the reaction makes (e,e') very insensitive to the interaction of (nondetected) final-state hadrons and their multistep reactions.
2. *exclusive reactions involving detection of hadrons*. These reactions are, in principle, able to obtain more detailed information on the short-range structure. However, they are subject to difficulties due to the strong interaction of the hadron(s) and to multistep reactions. These reactions are subdivided into
   - processes involving "normal" kinematics like (p,2p), $(\pi,\pi'p)$, (e,e'p), (π,π), and (p,p);
   - processes exploiting a large-momentum mismatch like (p,π), (d,p), (γ,p), and (X,p); and
   - processes explicitly involving two nucleons like π absorption and the (π^+,π^-) reaction.

In the following, these processes will be discussed one by one.

IV. INCLUSIVE (e,e') AND SUM RULES

The inclusive spectra of electrons scattered from nuclei offers, in principle, the cleanest known means to determine NN correlations.[2] The use of a probe with known (and weak) interaction, and using sum rules to eliminate all the detailed nuclear properties, offers the only possibility to extract the *static* correlation function. Only for this type of data are difficulties due to hadron final-state interactions absent.

In practice, for existing experiments the integration of experimental data over the electron energy loss ω has not been possible. The strength due to short-range correlations appears mainly at large ω: the effects of the tail of the N^*-excitation peak and meson-exchange current contributions are not negligible. Given the fact that the effects of correlations are $\gtrsim 10\%$ of the sum-rule value, the application of sum rules to existing data has not been fruitful.

In order to suppress Δ excitation and meson-exchange current contributions — both of which are magnetic (transverse) excitations — the (e,e') response function needs to be separated into longitudinal and transverse components. The longitudinal component then could allow a promising application of sum rules.

The N-3 panel recommends that the determination of the longitudinal response function be most actively pursued.

V. (e,e') AT LARGE q, "SMALL" ω

In the impulse approximation, (e,e') at large momentum transfer q ($q > 5\ fm^{-1}$) and an electron energy loss $\omega \ll q^2/2M$ leads to a direct measurement of large-k components.[3] The cross section $\sigma(\omega)$ at small ω can be shown to depend mainly on high-k components with $k \simeq q(A-1)/A$. If $\omega \geq 100$ MeV, the final-state interaction of the nuclear debris (mainly knocked-out nucleons) is sufficiently small to be accounted for quantitatively, or even neglected. Modifications to the impulse approximation, meson-exchange current contributions, have been calculated[4] to be small for the "low" ω regime. The main ingredient neglected in the interpretation of (e,e') data as well as all other data discussed in this report is the final-state correlation mentioned in Sec. II.

Such inclusive experiments often yield information that is hard to visualize. For the case discussed here, however, the situation is very favorable. At large q, the quasi-elastic cross section should scale; i.e., spectra at different ω, q, and incident energies should define a unique scaling function. Taking as the scaling variable $k_{//}$, the initial nucleon momentum component parallel to q, this function directly measures the probability of finding a nucleon with a given momentum component $k_{//}$. The scaling property of (e,e') could give us the information on high-k components.

Figure VIII-1 shows the (e,e')[3] data for ^3He measured recently at energies between 500 MeV and 10.8 GeV, plotted as a function of the scaling variable k (in MeV/c). Clearly, as q increases the different data sets do merge into a unique curve, which asymptotically becomes the momentum distribution (in MeV/c). This demonstrates the potential such inclusive scattering experiments at large q/low ω would have for measuring the momentum distribution at large k.

The N-3 panel recommends that such inclusive (e,e') data for more than the one nucleus (^3He) presently investigated should be measured. (This requires electron energies >1 GeV.) Also, the theoretical analysis of both initial- and final-state correlations *together* should be undertaken; all interpretations of data relevant to large k suffer from the lack of such an analysis, and (e,e') is perhaps the simplest case in which one might overcome such a difficulty.

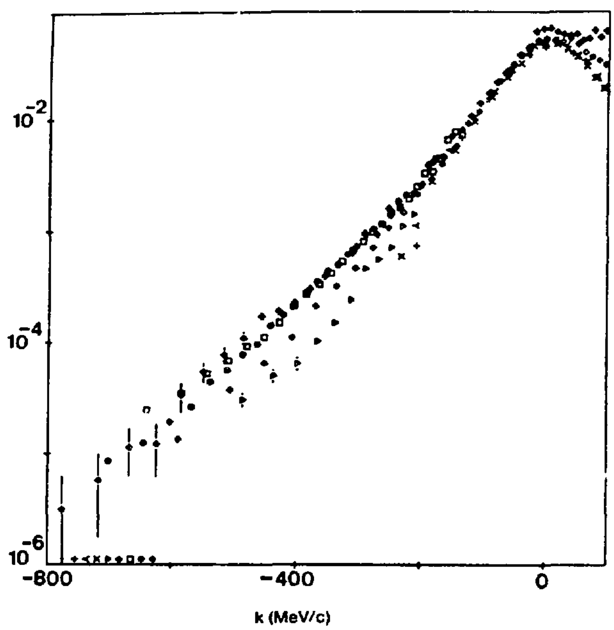

Fig. VIII-1.
The $^3He(e,e')$ data for incident energies of 500 MeV to 10.8 GeV as a function of the scaling variable k.

VI. KNOCKOUT REACTIONS (p,2p), (e,e'p), (π,πp)

Knockout reactions are the best available tool to investigate the spectral function, i.e., the separation energy and momentum distribution of nucleons. Complications in the interpretation arise mainly from the strong interaction of initial- and final-state hadrons. For small momenta and separation energies, distorted wave impulse approximation (DWIA) calculations can properly account for this distortion; in this region the shell-model aspects of nuclear wave functions are mainly tested.

At large momentum, k, and for nuclei $A \gtrsim 10$, multistep processes of the hadron(s) limit the usefulness of (p,2p) to $k < 200$ MeV/c and separation energies (SE) < 40 MeV. For (e,e'p), the limit in SE appears to be SE < 100 MeV; a limit has not yet been reached for the k range up to 300 MeV/c, which have been presently explored experimentally. As an example, Figs. VIII-2(a) and -2(b) show the deuteron momentum distribution obtained[5] from (p,2p) at E_p = 600 MeV, and from (e,e'p) at E_e = 500 MeV.[6] For $k > 240$ MeV/c, the (p,2p) result strongly deviates from expectation due to multistep reactions, while the (e,e'p) result even at 340 MeV/c shows only a manageable 10% final-state interaction effect.

The N-3 panel recommends that (e,e'p) measurements should be pushed to much larger k. This requires a cw accelerator of ~1-GeV energy.

VII. p AND π ELASTIC SCATTERING

The *main purpose of (p,p)* elastic-scattering studies at intermediate energies has been the study of nuclear neutron and mass distributions. In the analyses that extract information on these distributions, a number of researchers[7] have included correlation effects — center of mass, Pauli, short range, or dynamic. The effect of these correlations on the calculated angular distribution has been found to be fairly small — about 10 to 30% at the diffractive maxima, and increasing with angle. These effects must be included, as accurately as possible, in a serious analysis of proton-nucleus elastic scattering. However, it is difficult to see how the problem can be turned around and the elastic

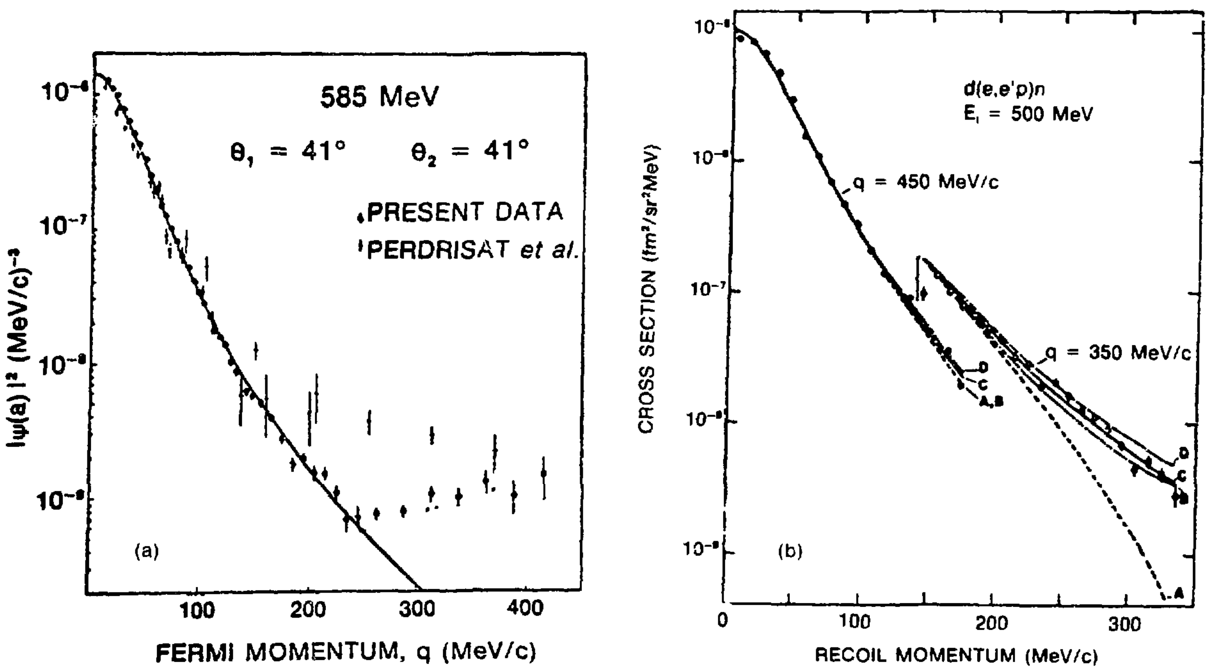

Fig. VIII-2.
(a) Spectator momentum distribution from (p,2p); data[5] obtained by using the simple impulse approximation; (b) spectator momentum distribution from the (e,e'p) reaction.

angular distributions be used to study correlation effects, particularly short-range correlations. Short-range correlations are just one of a large number of second-order effects, and their specific contribution to the elastic angular distribution will be extremely difficult to disentangle.

For pion elastic scattering there is now a large body of data in the 3-3 resonance region. Not surprisingly, first-order optical potentials give qualitative agreement with the data but fail to properly describe the related inelastic channels (σ_{tot}), implying that such a simple model is incomplete. At low pion energies, data exist between 30 and 50 MeV in several nuclei. There, even first-order potentials are qualitatively in bad agreement with the data.[8]

Several authors have introduced terms proportional to ρ^2, which account for true absorption and other two-nucleon effects at short distances.[8] These potentials improve the fits to the data considerably, indicating a sensitivity to correlations. However, there are additional features in the optical potentials, such as variation in the off-shell descriptions and finite-range effects, which strongly influence the calculated angular distributions. To learn something on short-range correlations it will be necessary to isolate the various effects including the absorption due to widely separated ("uncorrelated") nucleons. This cannot be accomplished without detailed fits to many angular distributions on many nuclei and several energies. Such a survey will also have to include the energy region between 50 MeV and the 3-3 resonance region in order to identify the energy where the higher order terms start to play a significant role.

To pinpoint the importance of any one of the higher order effects, it will be necessary to analyze together elastic scattering, single-charge-exchange (SCE), and double-charge-exchange (DCE) data (despite the difficulties with the reaction mechanism of the DCE reaction). Introducing a second-order process may lead to a minimal effect for the elastic scattering while showing an exaggerated influence on the SCE and DCE results.

The N-3 panel recommends that more angular distributions for SCE and DCE on the *same* target nuclei and with the same (low) bombarding energies as for elastic scattering be taken and coherently analyzed.

VIII. (p,π)

The (p,π) reaction (or its inverse) can involve momentum transfers greater than 500 MeV/c (momentum mismatch). The experimental situation has improved dramatically over the past few years. There are now available systematics on energy dependence, mass dependence, and asymmetries.[9]

The theoretical situation has changed little over the past years. Discussion has focused on a variety of mechanisms. The initial promise of the (p,π) reaction was linked to Fig. VIII-3(a), where the large momentum is absorbed by a single nucleon. Recent polarization data have shown that a dominant contribution comes from Fig. VIII-3(b). Thus high-k components are difficult to extract.

Once initial- and final-state interactions are included, Figs. VIII-3(a)-(c) are no longer distinct. A consistent formalism treating nucleons, deltas, and pions on an equal footing is needed.

IX. (p,d) REACTION

If the simple neutron pick-up mechanism held for the (p,d) reaction at intermediate energies, this reaction could be a source of information on high-momentum components in both the bound-state neutron wave function and the deuteron wave function, due to the high-momentum transfer involved in this reaction. However, (p,d) data taken both at Saturne and LAMPF have provided definite evidence that the momentum transfer necessary for the (p,d) mechanism is not supplied by the wave functions alone. At the very least there are significant higher order processes (inelastic scattering plus pickup) involved, since states are strongly excited which do not correspond to simple neutron pickup.

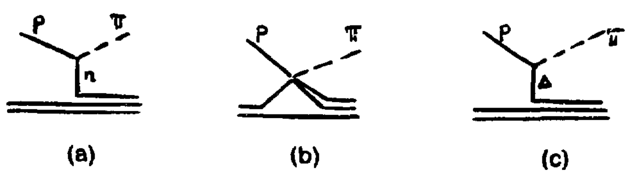

Fig. VIII-3.
Three diagrams for the A(p,π⁺)A + 1 reaction: (a) single-nucleon stripping, (b) p + p → d + π vertex, and (c) Δ stripping.

Other reaction mechanisms have been proposed for the (p,d) reaction in this energy range.[10] Although the reaction mechanism for the (p,d) reaction around 800 MeV is at present the subject of considerable controversy, the possibility to extract high-momentum components of nuclear wave functions in any definitive way is tenuous, and probably impossible.

X. (γ,N) REACTIONS

Up to about 150 MeV the total photon absorption cross section follows the pseudodeuteron model, and at higher energies it roughly tracks an incoherent sum of the elementary photopion production cross sections, although in the few cases measured (^{7}Li, ^{6}Li, and ^{9}Be) the cross section may be somewhat smaller than expected.

Very few measurements exist of the hadronic spectra for either the inclusive (quasi-free kinematics) or exclusive (large-momentum transfer kinematics) photoreactions. The type of data now available are exclusive proton spectra observed in the (γ,p) reaction on mostly light nuclei. These data exhibit features similar to those seen in (p,2p) and (e,e'p) knockout reactions, and comparisons have been made to single-particle momentum distributions[11] (Fig. VIII-4). Because of the favorable kinematics provided by the zero-mass photon, the (γ,p) measurements can probe the momentum distribution to much higher momenta than can the existing (e,e'p) measurements, which are limited by random coincidence problems.

The validity of a single-particle direct knockout mechanism for the (γ,p) reaction is, however, questionable: for low γ energies the cross sections for (γ,n_0) reactions[12] are seen to be of comparable magnitude to that for the (γ,p_0). Since a direct neutron knockout can occur only through the photon's interaction with the neutron magnetic moment, or coherently with the (Z,A-1) system, and these are both demonstrably small effects, the (γ,n_0) cross sections are an indication that two-particle processes are playing a role.

Two-step, two-particle effects, such as meson-exchange currents[13] (mainly isobar excitation), are expected to play a role for $k > 400$ MeV (Fig. VIII-5), but calculations have not yet met with quantitative success in accounting for the (γ,p_0) results.

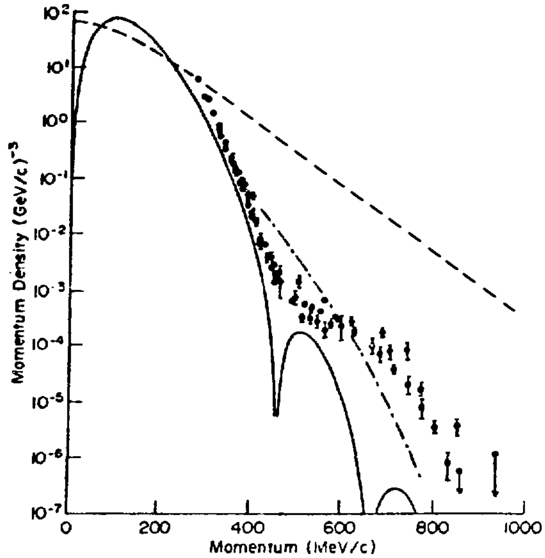

Fig. VIII-4.
Comparison of the momentum distribution derived from $^{16}O(\gamma,p_0)$ data (solid circles) with that obtained from high-energy backward proton production data [see Ref. 14(a)]. The dashed line represents the analysis of Amado and Woloshyn [see Ref. 14(b)], assuming a quasi-elastic mechanism, and the dot-dashed line that of Weber and Miller [see Ref. 14(c)], assuming an A-1 nucleon exchange mechanism. The solid curve is the Elton-Swift distribution.

The N-3 panel recommends that the theoretical analysis of large-k components and isobar configurations be tied together. A detailed experimental investigation of the (γ,n) reaction is called for to clarify the reaction mechanism.

XI. (X,p), (X,π) WITH PARTICLES OF LARGE MOMENTUM AT BACKWARD ANGLES

The production of particles in kinematic regions forbidden in the reactions between free elementary particles is sensitive to the high-momentum components of the nuclear wave functions, but there is at present no precise understanding of how to go from the experimental data to the desired wave functions. Assuming a two-body reaction mechanism, the cross

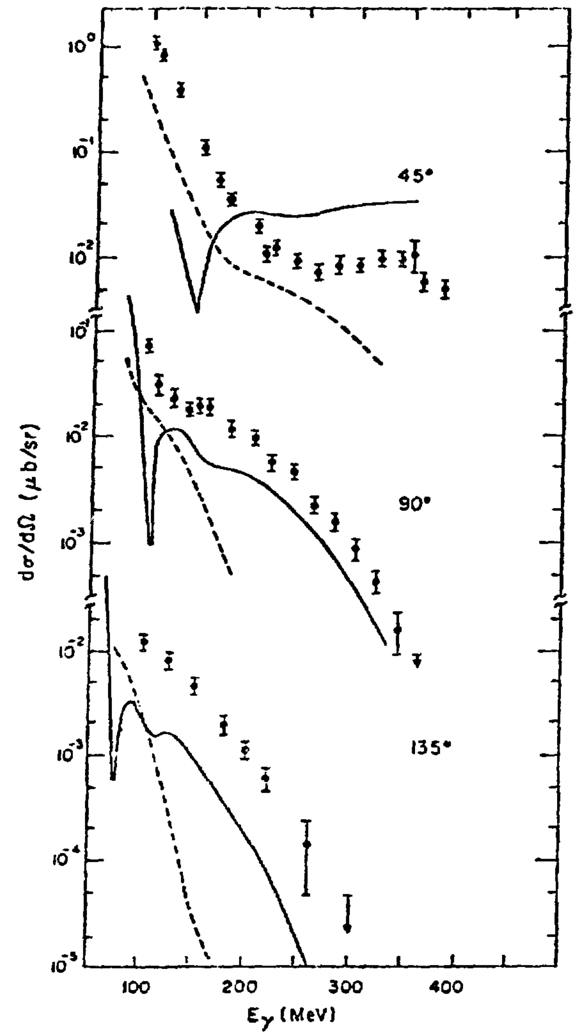

Fig. VIII-5.
Lab differential cross sections for $^{16}O(\gamma,p_0{}^{15}N)$ vs photon energy at angles of 45, 90, and 135°. Dashed curves: distorted wave impulse approximation; solid curves: impulse approximation plus $\Delta(1232)$ isobar excitation.

section can be factored into a function describing the elementary particle reaction ($X + p \to p + y$, $X + p \to \pi + y$, $X + p \to \bar{p} + y$, . . .), and a nuclear structure function $G(k_{min})$ where k_{min} is the minimal k the detected particle had before being ejected from the nucleus. This prescription has been used[15] for hadronic, weak, and electromagnetic reactions over a wide range of energies with as yet unexplained success.

1. For the production of protons and pions (and antiprotons below particle threshold) in nuclei from ^{6}Li to ^{238}U, a common G is found for all angles. These results are in the region from 0.6 to a few GeV incident protons, deuterons, and α (see Fig. VIII-6).
2. In the region of low available energies, in the capture reactions $\pi + A \to n + \gamma$ (140 MeV) + X, $\mu + A \to n + \nu$ (105 MeV) + X, and p,d,α + A $\to$ p + X (90 MeV), we have an illustration of a common structure function in electromagnetic, weak, and strong initiating interactions. The resulting G has a weak momentum transfer dependence.

Difficulties arise due to the fact that theoretical calculations point to contributions of multistep reactions[16] (distribution of energy and momentum to several nucleons).

The panel recommends that coincidence experiments involving backward-emitted p, particularly for $A \leq 4$, be carried out to establish the one/multistep nature of the (X,p) reaction. In order to make measurements of $G(k_{min})$ useful, theoretical calculations linking G(k) and the momentum space wave function clearly are needed.

XII. PION ABSORPTION

The absorption of pions proceeds mainly by the interaction with two nucleons. The two nucleons do not have to be close to one another, but short-range correlations could have a large effect on the cross sections. The reactions (π,NN) on light nuclei seem most appropriate for learning about effects at short distances. The reactions have to be done on targets such that the initial and final nuclear states are well known. Understanding the reaction mechanism will require that in addition to good energy resolution a large kinematic range should be covered: i.e., a wide angular distribution, Treiman-Yang distributions for in-flight pions, and a large range of momentum transfers.

Before being able to extract information on short-range effects, it will be necessary to obtain a good description of the reaction D(π,pp). Even this simplest absorption process is presently not understood quantitatively, since the π-rescattering mechanism involving an intermediate Δ is not unambiguously understood.

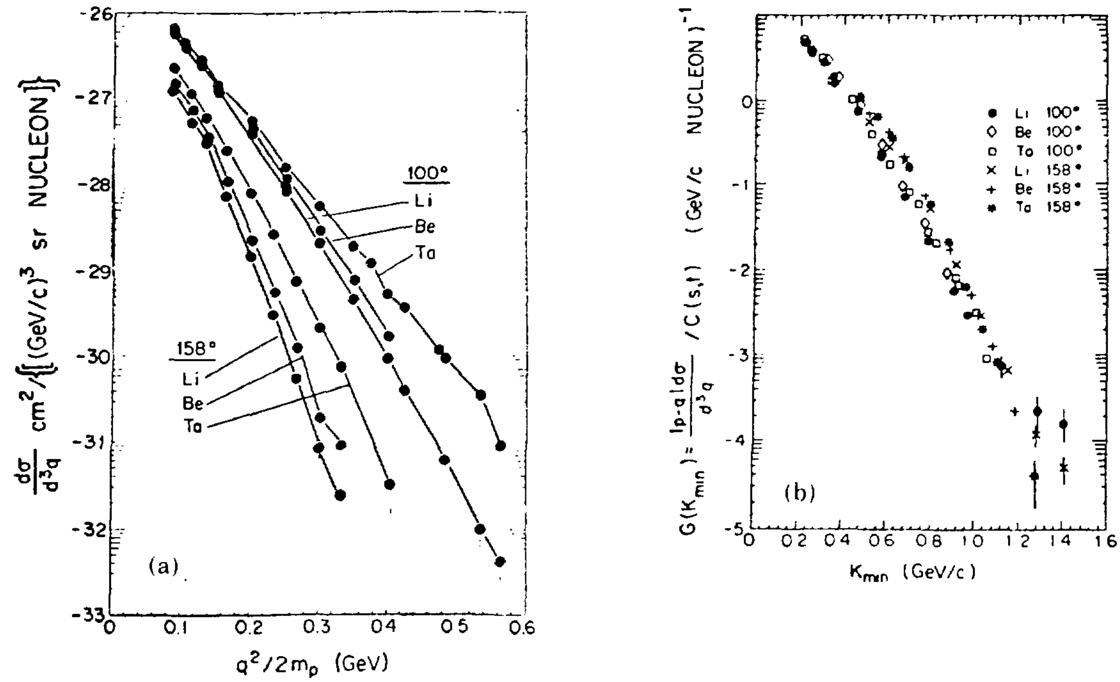

Fig. VIII-6.

(a) The $d\sigma/d^3q$ per nucleon vs $q^2/2m_p$. The different cross sections show a large A and θ dependence.

(b) Plot of $G(k_{min}) = [|\vec{p} - \vec{q}|/C(p,k_{min})](d\sigma/d^3q)$ vs k_{min} for ^6Li, ^9Be, and ^{181}Ta. Within the errors of factorization, inclusion of $C(p,k_{min})$ shows universality of $G(k_{min})$.

The N-3 panel recommends that further theoretical effort go into the understanding of πd absorption. Additional (π,2N) experiments, preferably on very light nuclei, are needed.

XIII. FUTURE EXPERIMENTS

Here we mention a number of experiments that could have an important bearing on the topic of panel N-3. These processes have only been discussed superficially; no quantitative calculations analyzing the presence or absence of complications comparable to the ones discussed in the previous sections are available. These processes should be looked into in more detail both theoretically and experimentally.

μ *Capture.* The process μ + A → N + (A-1) in light nuclei should be investigated for large N-energies.

(γ,2N), (e,e'2N). These processes are appealing as a possible means of probing the NN interaction form factor in the nuclear interior. No recent theoretical work exists, and the early estimates of deForest should be reviewed in light of our current understanding of possible complications. The (e,e'2N) should be investigated at reasonably large q and N energies of >100 MeV to minimize final-state interactions. (Both types of experiments imply a high-energy, >1 GeV, cw electron accelerator.)

A. Concluding Remarks

The discussions of the N-3 panel have dealt extensively with experiments and their interpretation aimed at the elucidation of the short-range structure of nuclei. A list of the most promising processes — those that can be interpreted with a finite theoretical effort — has been given. Special points needing further experimental and theoretical effort for those processes have been established. A coordinated effort to more extensively investigate these reactions is judged to be a promising means to isolate the short-range structure of nuclei.

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IX. PANEL N-4

MESON DEGREES OF FREEDOM AND PROPAGATION IN NUCLEI

Chairman: J. M. Eisenberg
Co-Chairman: G. J. Stephenson, Jr.

Participants: V. Bunakov, D. Campbell, J.G.P. Deutsch, D. Drechsel, J. J. Domingo, I. M. Duck, T. Ericson, D. S. Koltun, B. W. Mayes II, B. M. Preedom, M. M. Sternheim, A. W. Thomas, and G. M. Vagradov.

The subject matter of this panel deals with phenomena that, by their very nature, represent refinements or higher order effects when probed in nuclei. For this reason it is inevitable that their experimental study must go hand in hand with a great deal of theoretical analysis. We shall in the following address both the question of experimental work that is required for examining mesons in nuclei and the matter of theoretical developments that will be needed for the elucidation of this topic. The panel subdivided its considerations into three parts:

1. Pion condensation and precursor phenomena (D. Campbell,* J.G.P. Deutsch; J. J. Domingo, and G. M. Vagradov).
2. "Inner" vs "outer" pions — absorption effects in scattering (D. S. Koltun; I. M. Duck, B. M. Preedom, and A. W. Thomas).
3. Meson exchange effects in hadronic processes (G. J. Stephenson, Jr.; D. Drechsel, B. W. Mayes II, and M. M. Sternheim).

I. PION CONDENSATION

A. Introduction to Pion Condensation

The basic idea contained in the phrase "pion condensation" is that there *may* exist a new phase of nuclear matter at high density, that is, at density greater than that of the interior of ordinary nuclei. This new phase — the "pion condensate" — is characterized by an ordering of the spins of the nucleons in such a way that the source of the pion field $\psi_N^\dagger(x)\vec{\sigma}\,\underset{\sim}{\tau}\psi_N(x)$ has a nonvanishing, spatially varying expectation value. This source in turn generates a nonvanishing expectation value for the pion field, $\langle\phi_\pi(x)\rangle \neq 0$. It is this nonvanishing value of $\langle\phi_\pi\rangle$ that gives the new phase its name. A schematic comparison of ordinary nuclear matter and a pion condensate is shown[1] in Fig. IX-1. Note that in ordinary nuclear matter $\langle\phi_\pi\rangle = 0$.

The expectation value of the pion field $\langle\phi_\pi\rangle$ will thus serve as the order parameter for the discussion of phase transitions to the condensed mode. The analogy[2] between these phase transitions and those of ferromagnets* is discussed in Appendix A. As for any theoretical treatment of phase transitions, we note that the problem of predicting such a phenomenon from data at only one point — standard nuclear density here — is *not* a trivial task.

B. Calculational Techniques and Theoretical Results

If we accept the possibility of pion condensation, the obvious question is how to study this phenomenon in more detail. Clearly, one could study it through nuclear spin/isospin correlations, since the pion-condensed phase corresponds to a complete spin/isospin ordering and hence to infinite-range correlations. This approach would require *no* explicit reference to the pion field and could be phrased completely in terms of the nucleon spin/isospin current operator, $\psi_N^\dagger\vec{\sigma}\,\underset{\sim}{\tau}\psi_N$. From experience with phase transitions in magnetic

*Names in parentheses preceding semicolon refer to subpanel chairmen. Other contributors to the panel were M. Cooper, P.A.M. Gram. L. Heller, K. Seth, J. Thirion, and several student participants.

*In fact, a closer analog, in view of the spin alternation in pion condensation, might be an antiferromagnet.

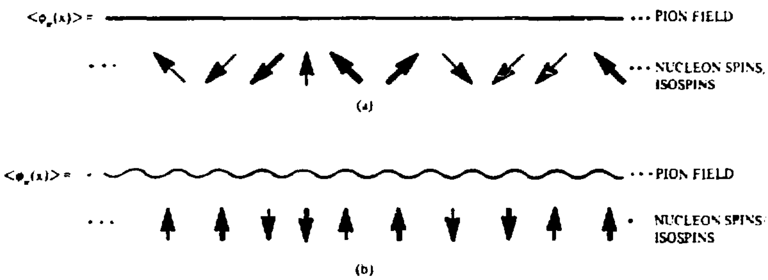


Fig. IX-1.
A schematic illustration of (a) the lack of spin/isospin ordering in ordinary nuclear matter, and (b) the long-range spin/isospin ordering in a pion condensate. The light arrows represent neutrons, the heavy ones protons, and the direction indicates the direction of the nucleon spin. Note that in case (b) the spin/isospin ordering produces a nonzero expectation value of the pion field. (For precise illustrations of the relation between the nucleon ordering and the expectation values of the pion field, see Ref. 3.)

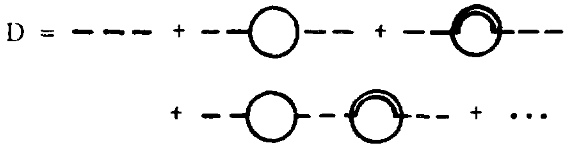
systems, however, we know that since we have identified $<\phi_\pi>$ as an order parameter for the phase transitions, it is equally natural and possibly easier to study pion condensation in terms of $<\phi_\pi>$. From our previous remark (see also Appendix A), we expect that for $\rho > \rho_c$, $<\phi_\pi> \neq 0$. Further, although $<\phi_\pi> = 0$ for $\rho \lesssim \rho_c$, the fluctuations in $<\phi_\pi>$ will reflect the intermediate-range ordering which will become long range as $\rho \to \rho_c$. These fluctuations are described by the pion "correlation function," or "propagator," which is *defined* by

$$D \equiv <\phi_\pi \phi_\pi> \quad . \tag{1}$$

Thus we shall study the behavior of D in normal matter ($\rho < \rho_c$) and expect to see anomalous behavior as $\rho \to \rho_c$.

The details of the study of the phase transition to be expected in nuclear matter at ρ_c comprise much of the literature on pion condensation, and thus the following qualitative summary is very inadequate.*,[4] The basic theoretical problem is to calculate how D is altered by the nuclear medium. In many-body language, an obvious crucial interaction affecting D is the coupling of the pion to a particle-hole pair via the attractive p-wave interaction $\nabla \boldsymbol{\Phi}_\pi \cdot \psi_N^\dagger \vec{\sigma} \boldsymbol{\tau} \psi_N$, as illustrated in Fig. IX-2(a). In addition, it has been established that a similar attractive coupling to an isobar-hole pair, as shown in Fig. IX-2(b), is also crucial.

Since these attractive interactions can occur any number of times, at the first level of approximation the pion propagator in the medium is given by the formal sum



$$= \frac{D_0}{1 - \Pi_0 D_0} \quad . \tag{2}$$

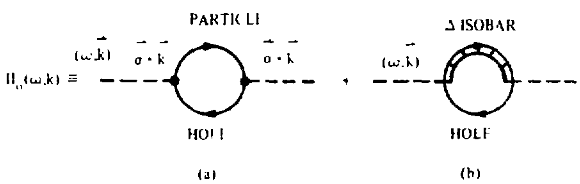


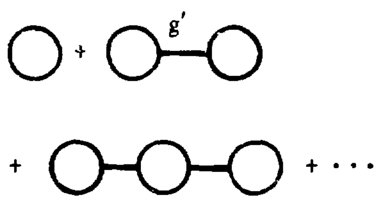
Fig. IX-2.
The p-wave particle-hole and Δ-hole interactions contributing to $\Pi_0(\omega,k)$, the lowest-order pion self-energy, which is closely related to the pion optical potential.

*For a much more extensive discussion, see the excellent review of A. B. Migdal (Ref. 7).

Assuming that the signs are indeed such that the denominator can be small for certain energy-momentum regions, we see that in these regions the interactions in Fig. IX-2 strongly enhance D. Indeed, if for a given density there exist values of $\omega \equiv \omega_0$ and $k \equiv k_0$ (generally $\omega_0 \simeq 0$ and $k_0 \simeq 2$ to $3\ m_\pi$) such that $\Pi_0(\omega_0,k_0)D_0 = 1$, then D approaches infinity, signaling a collective, many-body mode with pion quantum numbers. (An instructive, simple model of condensation behavior is given in Appendix B.)

To obtain a realistic model, only two modifications are needed. First, the repulsive short-range interactions among nucleons reduce the attraction of the diagrams in Fig. IX-2. This can be modeled by a phenomenological Ericson-Ericson Lorentz-Lorenz effect,[5] which amounts to replacing Π_0 in Eq. (2) by

$\Pi(\omega,k)$ =



$$= \frac{\Pi_0(\omega,k)}{1 - g'\Pi_0(\omega,k)/k^2} , \qquad (3)$$

where g' is the Landau-Migdal spin-isospin Fermi liquid parameter.[6] A detailed analysis establishes that the net effect of the denominator in Eq. (3) is to reduce the enhancement factor expected from Eq. (2). Second, the formal nature of Eqs. (2) and (3) obscures the imaginary parts of Π and hence D which, for $\rho < \rho_c$, damp any collective mode so that D is enhanced but not infinite. In coordinate space, the damped collective mode corresponds to the intermediate-range order that is the precursor of the pion condensate. In momentum space, the strength and location of the enhancement are functions of the density, the N/Z ratio, and the charge state of the pion.

Although most theoretical discussions of pion condensation are in terms of infinite matter — as in our example in Appendix B — the extension to finite nuclei is conceptually clear and has begun to be studied.[7] The present conclusion of these studies is that the enhancement in D *is* expected in finite nuclei, and the question then becomes how to test this theoretical prediction experimentally. Before turning to this question let us first offer a synopsis and critique of the current status of the theory of pion condensation.

First, there is a broad theoretical consensus that pion condensation should occur (although in slightly different forms) in both nuclear and neutron matter at a critical density of the order of twice nuclear density.[4] It is important to recall that the language of phase transitions is truly appropriate only in the infinite-volume limit, that is, only for infinite matter. In a finite nucleus, the signal for the presence of a true phase transition in the infinite system would be the degeneracy of the ground state with states which can be coupled to it by pion quantum numbers. Thus in a nucleus with a $J^P = 0^+$, $T = 0$ ground state, one or more of the $T = 1$, $J^P = 0^-, 1^+, 2^-, \ldots$ states would become degenerate. Theoretical estimates directly on finite nuclei suggest that if nuclei were roughly twice as dense as they in fact are, such degeneracies would occur.[7]

Second, since both finite nuclei and nuclear matter calculations suggest that $\rho_{nuc} < \rho_c$, we can hope to observe "precursors" to pion condensation, which precursors depend only on the predicted enhancement of the pion propagator generated by the damped collective mode.[2] For $N \simeq Z$ nuclear matter near nuclear density, and hence by inference for finite nuclei with $N \simeq Z$, this enhancement is expected to occur near[4,8,9] $\omega \equiv \omega_0 \simeq 0$ and $k \equiv k_0 \simeq 2$ to $3\ m_\pi$.

Third, almost all true predictions are subject to two serious criticisms:

1. The critical density for pion condensation in infinite matter, and hence the size of enhancement effects in finite nuclei, are very sensitive functions of the parameters in $\Pi(\omega,k)$ and, in particular, of the inadequately known parameter g'.
2. The basic physical mechanisms leading to pion condensation are being probed in kinematic regions where their correctness is not otherwise tested. In simple terms, the theorists are insisting that they understand the pion optical potential in the (relatively) far space-like region $(\omega_0^2 - k_0^2) = -(4 \text{ to } 9)\ m_\pi^2$ well enough to believe its predictions, at least semi-quantitatively.

Clearly there is room for substantial theoretical work on pion condensation. But despite the theoretical uncertainties and objections, the possibility of pion condensation seems sufficiently exciting to motivate serious experimental study of any process in which its effects might be observed. Thus in the next section, we catalog and analyze critically a number of possible experiments to detect precursors of pion condensation.

C. Laboratory Tests of Pion Condensation

Presently proposed experimental tests for pion condensation fall into three general categories: (1) astrophysical tests,[10] (2) tests involving heavy-ion collisions,[11] and (3) tests involving probes scattering on fixed-target nuclei.[2,4,8,9]

Although astrophysical tests have the advantage that there *do* exist objects with densities greater than the expected critical density ρ_c and with relatively low temperatures — neutron stars, for example — the signal of pion condensation in such objects is complicated and can possibly be masked by other effects.[1] Further, one cannot vary the experimental sample. Heavy-ion collisions may generate transient densities greater than ρ_c, but questions of the time scales for approach to equilibrium and the consequences of large effective temperatures make theoretical predictions in this area very difficult.[11] Thus in view of the uncertainties in these areas and of the nature of this workshop, we shall focus solely on laboratory tests involving the properties of, and scattering from, ordinary nuclei.

Since ordinary nuclei are *not* expected to be in the finite-system analog of a condensed pion phase (i.e., $\rho_{nuc} < \rho_c$), we must test for precursors to pion condensation. If such precursors are indeed observed, this gives us some confidence — although no proof — that at higher densities pion condensation will occur.

The laboratory tests for precursors to pion condensation require the observation of the enhancement of some specific quantity above a "noise"-level, and are therefore hard to predict reliably. It is thus important to realize that a single experiment will be insufficient for a definitive determination. The issue can be settled in a convincing way only through converging lines of evidence from experiments involving a variety of targets and probes in an extended range of energy and momentum transfer.

In principle, any nuclear probe which is spin-dependent may show the existence of precursors.[2] In the following we shall list some of the specific experiments considered and note their advantages and disadvantages, as well as the questions they raise. Bear in mind that the problem is still in its infancy, and more questions — both theoretical and experimental — are raised than answered!

1. Experiments

a. Polarized Targets. For completeness we mention[2,4] (e,e'), pion or nucleon scattering, and photoproduction experiments on polarized targets, which may show, for example, spin/isospin ordering in nuclei as condensation is approached. It would be interesting to extend the theoretical investigations to the light nuclei and to add targets in which the polarized nuclei can be produced without a strong contamination of unwanted species.

b. Momentum-Dependent "Precursor Phenomena."[2] It has been noted[2,8] that at some specific momentum-transfer value ($2\ m_\pi < q < 3\ m_\pi$), the driving mechanism of pion condensation implies enhancement of a great variety of different cross sections.

Experimentally it would be preferable to perform inclusive reactions leading to a sum of nuclear final states (case of "smeared-out" energy transfer ω). It is, however, not yet clear theoretically whether in such reactions we would not lose the specificity of the "blow up" of the pion propagator restricted to well-defined J, P, and T quantum numbers. This question is clearly an important challenge to theory.

For the following we shall restrict the discussion to *exclusive* reactions which lead to specific nuclear states, implying a transition having the quantum numbers of the pion ($\Delta T = 1$, natural to unnatural spin-parity); the energy transfer ω will be taken fixed and small. These transitions are expected to be specifically enhanced in the range of momentum transfer noted above.[8,9] An additional bonus of this "exclusive" approach is the possibility of also observing, as a "zero test," the nonenhancement of ($\Delta T = 0$) transitions leading to nearby final states.

An interesting approach consists in the consideration of the relevant transition form factors (such as the M1 case in ^{12}C to the 15.11-MeV 1^+,T = 1 level) measured in backward (e,e') reactions.[9] A clear enhancement over predictions of Cohen-Kurath wave functions is found in the relevant momentum-transfer range[9]; it would be useful to clarify the connection between the enhancement predicted by the "precursor" mechanism and other approaches which also fit the transition form factor,[12] and to consider nearby $\Delta T = 0$ transitions as a zero test as well. It should also be noted that the (e,e') approach to the precursor phenomenon is a "surface-restricted" probe[13] (low-density region), since the relevant γ and π couplings require the presence of a density gradient. It would be interesting to clarify the optimal A-region where the effect would be expected to be maximal.

Let us now consider the various probes in increasing strength of their (unwanted) initial/final-state interaction with the probed nucleus.

The (ν_e,e) and (ν_μ,μ) Reactions.[14] These are quoted for completeness. The feasibility of suitable "exclusive" reactions was not investigated in detail, but is believed to be beyond our present or foreseen experimental possibilities.

Electro-Pion Probes. The precritical enhancement of some (γ,π) transitions has been investigated and found sizable, neglecting, however, Δ contributions and final-state interactions[15]; it would be interesting to refine these computations to include these effects. On the experimental side, the intensity of the existing monochromatic photon beams seems insufficient; the use of the continuous photon beams (real or virtual) and existing pion spectrometers seems also impracticable. Estimates indicate, however, that some alternate pion selection schemes may prove workable, even with the existing beam intensities, provided one can find suitable final-state patterns.

The theoretical aspects of the inverse (in-flight) (π,γ) reactions are very similar to the (γ,π) ones we have noted. On the experimental side, the use of existing pair spectrometers (LAMPF, SIN) was considered, but the feasibility of the experiments was not ascertained. In particular, in order to achieve the required energy resolution with the high-energy photons to be detected, one may have to go beyond the bending power of the existing pair spectrometers, and we recommend that equipment be upgraded for this purpose (see also recommendations of panel N-5).

The low conversion efficiency and relatively small solid angle of the pair spectrometers may encourage us to consider the (π,ee) reaction. Work is presently going on to investigate the effect to be expected from this reaction[16] and to design a large solid-angle device for the selective detection of the (e,e) pair.

The $(\pi,\gamma\gamma)$ reaction has also been considered[17] and may prove useful to investigate the issue if "inclusive" reactions (the only practicable ones with this method) turn out theoretically to be sufficiently selective.

Hadronic Probes. The (p,p') reaction on ^{208}Pb to 1^+ excited states was considered by the authors of Ref. 8 and a strong enhancement predicted, though relatively little consideration was given to initial/final-state interactions, which may be small for $E_p \simeq 700$ MeV. (Otherwise, they may mask the effect!) Unfortunately, the experimental situation of the (1^+) final state considered there is still unclear.[18] One may take,[16] as an alternate target, ^{12}C; it is interesting to note that there may be an unexplained anomaly in the cross section $0^+ \to 1^+(T = 1)$ around $2m_\pi < q < 3m_\pi$ observed at E_p = 155 MeV, and absent in the corresponding transitions to $(T = 0)$ levels.[*,19] The extension of these investigations to other energies and targets seems of utmost importance in order to ascertain the presence of recurrent enhancements in the predicted q^2 region.

We wish to stress that the possible precursor probes (e,e'), (p,p'), and (π,γ) or (γ,π) mesh well with existing experimental and theoretical programs of research and therefore should receive high priority in the search for this phenomenon. This should be done by systematic survey of nuclear transitions with pionic quantum numbers ($J^P = 0^-, 1^+, 2^-, \ldots$; T = 1) in both light and heavy nuclei, and with correlated programs amongst the various probes.

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*We thank H. Toki and W. Weise for drawing our attention to this reference.

In this context, the consideration of (p,n) and (n,p) reactions to analogous levels may be also of interest, and possible experiments of this sort involving initial and final nucleon polarization were also raised. The nucleon charge-exchange reactions are believed to be one-pion-dominated in the forward direction, making them especially appealing for this purpose. Finally, reactions such as (π,N), $(\pi,2\pi)$, $(e,e'\pi)$, and $(N,N\pi)$ were also mentioned, though without thorough investigation.

II. "INNER" AND "OUTER" PIONS: ABSORPTION EFFECTS IN PION SCATTERING

The following topics are intimately related: a consistent theory of π-scattering that includes the Yukawa interaction ($\pi + N \leftrightarrow N$), and the effect of π-absorption on other π-induced reactions. The problem of consistency follows from the fact that the same elementary interaction that leads to the pionic parts of nuclear forces also contributes to the πN scattering interaction. In a nucleus, the same interaction makes the π-absorption (π-annihilation) possible. It is necessary to disentangle these two aspects properly in order to make use of the multiple-scattering theories which have been our standard tool for studying reactions on nuclear targets. This has been done by several different methods which lead to similar practical approaches.[20]

These approaches have been used to look at the effects of absorption on πd elastic scattering.[21] Hence one has fair confidence in the theoretical methods for calculating both the three-body aspects of the problem and the absorption channel $\pi d \to 2N$. For zero energy, one finds that absorption contributes about 10% of the *real* part of the πd scattering length (aside from an imaginary part $\mathrm{Im}\,a \simeq -0.1\,\mathrm{Re}\,a$). At higher energies in the Δ-resonance region, the predictions[22] are for small effects in $\sigma(\theta)$ for $\pi d \to \pi d$, but for large effects in the tensor polarization for $\pi d \to \pi \dot{d}$. (Incidentally, large asymmetry effects in $\pi \dot{d}$ would also be produced if there were NN resonances in this πd mass region.[23]) Other light nuclei are also of interest here, e.g., at low energy, where the amplitude for absorption is *comparable* to that for scattering as seen from 1S-level widths and shifts in π-atoms, particularly for ^{3}He.

For energetic π scattering on nuclei, most of the work remains to be done. There is almost no theory including absorption in scattering in a consistent way, with the exception of the Δ-hole models,[24] which may apply in the 100 MeV $< T_\pi <$ 250 MeV domain. A full theory that covers the range from zero energy to well above the resonance is desirable. There has, however, been some increase in understanding of the general way (or ways) in which absorption affects elastic πA scattering through the theory of the optical potential. The point is to show consistency between the optical potential employed and the assumptions made about the major nonelastic channels, presumably inelastic scattering and π-absorption. (The subject has been called "reactive content of the optical potential.") Recent experiments[25] show us that both of these cross sections are very large components of $\sigma_{\mathrm{reaction}}$ ($\sim \pi R^2$) for 100 MeV $< T_\pi <$ 200 MeV. The use of this information in analysis of elastic scattering may help sort out the absorptive contribution to the optical potential.

The scattering experiments which are called for are partly those which have been under way already: elastic-scattering surveys on many targets over a large energy range, and various inelastic reactions. In addition, one needs information on the *large* branches of the reaction cross section $[(\pi,\pi N)$, $(\pi,\pi 2N)$, . . .$]$, as well as of the absorption cross section $[(\pi,2N)$, $(\pi,d\lambda)$, . . .$]$.

The low-energy region (including π-atoms) seems particularly attractive, since it may be easiest to separate absorptive and scattering effects. (For example, it is here that the old assumption that absorption appears as an additive term, proportional to $\rho^2(r)$ in the optical potential, is probably most reliable.) It would be extremely interesting to see low-ℓ (s,p,d levels) data from π-atoms for large nuclei, as well as low-energy ($T_\pi \simeq$ 10 to 50 MeV) scattering data for all A. It would be interesting to see the onset of inelastic scattering as a competitor to absorption, with increasing energy, in this energy regime.[26]

The effects of absorption on scattering, at resonant energies and higher, may be harder to extract (uniquely) from elastic scattering and total cross-section data. The theories do make predictions here, which apply much more to the competition of quasi-free scattering (nucleon knockout) with absorption. These experiments would be very interesting here.

III. HADRONIC PROBES OF MESON EXCHANGE EFFECTS

A. Heavy-Meson Exchange

No one doubts that heavy mesons, specifically rhos and omegas, couple to nucleons and to isobars, can be used to parameterize the nucleon-nucleon interaction at short distances, and consequently influence strong reactions. However, in the analyses to date, particularly of elastic scattering of low-energy pions, the conclusions to be drawn about the presence of rho meson exchange are representation-dependent. This leads various authors to reach diametrically opposed conclusions from analysis of the same phenomena.[27,28] In addition, the rho-coupling constants are not certain. This could be improved by studying rho production by pions on nuclei.

This confusion arises because there is a trade-off in the description of pion scattering between the effects of the form factor assumed for the pion-nucleon scattering and the amount of cancellation required between pion and rho intermediate states. A soft form factor (long range or large size in coordinate space, short range in momentum space) suppresses the contribution of successive scatterings between two nucleons close to each other.[29] If one assumes a hard form factor, that suppression must be supplied by short-range correlation effects (i.e., the Lorentz-Lorenz effect[5]) which are supplied by rho and omega exchange in the force and by explicit cancellation due to the rho meson replacing the pion in intermediate states.

However, a quantitative measure of the equivalence of the two schemes is not available since calculations to date have been made by proponents of each approach separately. It is incumbent on theorists purporting to show the advantage of one point of view to carry out otherwise identical calculations with both schemes to properly assess their influence on elastic scattering and to push both descriptions through to a consistent calculation of pion-induced reactions.

This point can, in principle, be sorted out, and it is important to do so for making contact with current ideas in particle physics. For example, the description that uses pion-nucleon interactions with a very soft form factor (corresponding to a range of about 1 fm) may be consistent with large bags for nucleons (and for pions), while the description that requires the exchange of rhos, and hence the concept of two nucleons retaining their identities at separations of about $^1/_2$ fm, may be consistent with small bags and meson clouds.

B. Hadronic Probes for Meson Exchange Effects

Hadronic tests of exchange currents suffer from many of the same ambiguities that are discussed above and, in addition, are also confused (in a representation-dependent way) with pieces of the wave function in which some of the baryons are in excited states. Furthermore, it is already known from electron scattering that relativistic corrections to the wave functions introduce effects comparable to those from exchange currents.[30] There already exist three reviews of tests of isobar contents and exchange currents[31-33] that discuss various experimental tests. Their view may be summarized as being positive in the large, but finding all specific experiments individually inconclusive.

A promising possibility is to use the unique feature of the pion that it can undergo double charge exchange to look for particular cases where the meson field enhances the reaction over the value expected from conventional multiple-scattering theory. In particular, Germond and Wilkin[34] discuss double charge exchange on ^{4}He leading to four protons and a negative pion. Their estimate of the contribution of the diagram (Fig. IX-3) is two orders of magnitude above a fixed-scatterer calculation.[35] Unfortunately, there are other differences between the calculations, and data can be found that support both theoretical results.[36]

This example illustrates our general conclusion: to identify exchange current contributions properly,

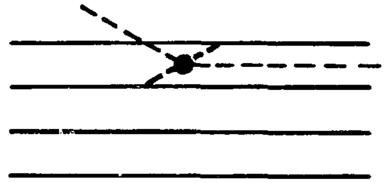

Fig. IX-3.
Pion double charge exchange on a pion being exchanged between two nucleons in ^{4}He.

it is necessary to measure the particular transition with different probes whose energy and momentum-transfer dependence can allow a separation of the nucleonic and mesonic contributions. It is also necessary to study competing effects in otherwise identical theoretical settings.

* * *

Two general points emerge from this survey of meson degrees of freedom in nuclei. First, for each of the topics raised here, no *single* experiment is definitive; rather, a *program* of studies involving many processes, probes and targets, energy and momentum-transfer ranges, and partial-wave channels will be needed. Secondly, it seems clear that the theoretical work which must accompany the program of measurements will require more manpower than is now available — especially in the form of bright and fresh theorists. This experimental and theoretical effort seems well justified, however, in view of the great intrinsic interest of this area.

We also note that the programs discussed here do not require major new facilities but rather a concerted and directed effort with existing facilities. In view of these facts and the strong theoretical interest, such programs should be pursued with high priority.

APPENDIX A

THE ANALOGY BETWEEN PION CONDENSATION AND MAGNETIC PHASE TRANSITIONS*

Since we are dealing with a phase transition and since the spin/isospin ordering is very reminiscent of the spin ordering in a ferromagnet, it is useful to recall some properties of phase transitions in magnetic systems. In a ferromagnetic material, there exists a critical temperature T_c below which the spins are aligned so that a net expectation value of the magnetic moment $<\vec{M}>$ is produced even in the absence of an external magnetic field. This nonvanishing value of $<\vec{M}>$ reflects the long-range order in the spins of the individual atoms. For T greater than but near T_c $<\vec{M}> = 0$, however, there exists a short-range ordering of spins over a correlation length

$$\xi \propto \frac{1}{(T - T_c)^{\nu}} \quad ;$$

as $T \to T_c$, $\xi \to \infty$, which is the mathematical statement that all the spins in the ferromagnet are aligned below T_c. The quantity $<\vec{M}>$ is called the "order parameter" of the magnetic phase transition, since its value indicates whether the system is in the ordered ferromagnetic phase or not.

To translate these familiar results to the less familiar context of pion condensation we assert that:

1. the analog of the ordering of atomic spins is a spin/isospin ordering of nucleons, and the order parameter is the expectation value of the pion field $<\phi_\pi>$:
2. the analog of *decreasing* the temperature T of the magnet to the critical value T_c is *increasing* the nuclear density ρ to a critical value ρ_c: that is, $<\phi_\pi> = 0$ for $\rho < \rho_c$ and $<\phi_\pi> \neq 0$ for $\rho > \rho_c$.

Both these points deserve further comment. First, if the expectation value of the pion field is nonzero then, since the pion is pseudoscalar, the state in which this expectation is taken cannot be an eigenstate of parity. Further, if the charged part of the pion field has nonvanishing expectation value, the state cannot be an eigenstate of charge. Although perhaps initially surprising, these results are in fact expected from our analogy. In a ferromagnet, $<\vec{\sigma}> \neq 0$ implies that the ordered state is not an eigenstate of rotations. Similarly, in a superconductor the Cooper pairing leading to $<\psi_e\psi_e> \neq 0$ reflects the well-known result that the BCS ground

*See Ref. 2.

state does not have a well-defined charge. Second, although a theorist may speak cavalierly about "varying the nuclear density," in fact in laboratory nuclear physics experiments — with the possible exception of heavy-ion collisions — the density is essentially *fixed* at $\rho = \rho_0 = 0.17$ nucleons/fm^3 = 2.8×10^{14} g/cm^3. Further, the present theoretical consensus is that $\rho_c > \rho_0$. Thus ordinary nuclei are *not* expected to be pion condensed. In terms of the magnetic analog, it is as if one could measure the properties of a supposedly ferromagnetic material at only *one* temperature $T_0 > T_c$ so that the system is *not* in the ferromagnetic phase. This analogy correctly suggests that the only way to observe pion condensation in laboratory nuclei is to search for precursors to the phenomenon — for example, the intermediate-range spin/isospin correlations that would become long-range as $\rho \to \rho_c$. A bit of thought about the problems of predicting a magnetic phase transition from data at only one temperature greater than T_c suggests how difficult this task is.

APPENDIX B

A SIMPLE MODEL OF PION CONDENSATION

To illustrate how many-body effects can lead to a collective nuclear state with pion quantum numbers, we study the simplest case, namely the behavior of a π^- in infinite *neutron* matter (only $T = 3/2$ interactions).[37] With no apologies and with minimal references (see the compendium edited by M. Rho and D. Wilkinson noted under the references), we assert that a satisfactory zero*th*-order approximation to the *inverse* pion propagator in momentum space is

$$D^{-1}(\omega,k) = D_0^{-1}(\omega,k) - \Pi(\omega,k) .$$

where

$$D_0^{-1}(\omega,k) = \omega^2 - k^2 - m_\pi^2$$

and

$$\Pi(\omega,k) = -\rho\left(\frac{\omega}{m_\pi^2} - \frac{g^2}{2m_N^2}\,\frac{\vec{k}\cdot\vec{k}}{\omega}\right) .$$

Here $D_0^{-1}(\omega,k)$ is obviously the free pion propagator and $\Pi(\omega,k)$ is the pion "polarization" or "self-energy," which is, in this simple approximation, given by the neutron density ρ_n times the πN scattering amplitude, here described by the s-wave plus p-wave form in brackets in the equation. For $\rho_n \neq 0$ but small and for fixed k, a plot of $D^{-1}(\omega,k)$ vs ω has the form shown in Fig. IX-4. The k-dependent zeroes labeled $\omega_+(k)$ and $\omega_-(k)$ correspond to the "true" pions (that is, the modes which exist even when $\rho_n = 0$) shifted slightly by interactions with the medium. The k-dependent mode labeled $\omega_s(k)$ is the above-mentioned collective many-body mode, which in our simple model is an actual zero of $D^{-1}(\omega,R)$ and hence an infinity (an infinite enhancement) in D (ω,k). Our simple model, however, ignores damping — that is, the imaginary part of D. In reality, for $\rho < \rho_c$, the $\omega_s(k)$ is strongly

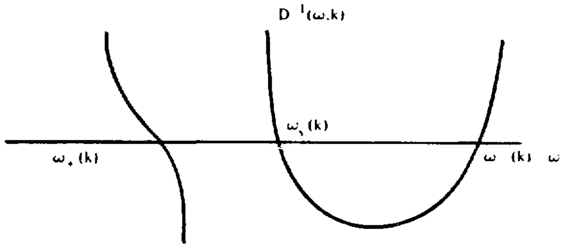

Fig. IX-4.
A plot of $D^{-1}(\omega,k)$ vs ω for fixed k and $\rho_n \neq 0$. The zeroes correspond to modes of propagation with pion quantum numbers.

Landau-damped, and D is enhanced but not infinite for ω near $\omega_+(k)$. A similar structure exists for $N \simeq Z$ matter and any charge of the pion, but the result is somewhat harder to model.

Two final points close this appendix. First, we note that the signal of the phase transition in this simple model is that as ρ_n increases, $\omega_s(k)$ and $\omega_-(k)$ in Fig. IX-4 approach each other. The density at which $\omega_s(k)$ equals $\omega_-(k)$ is the critical density ρ_c, and beyond ρ_c the neutron matter is pion condensed. Second, a quantitative model of pion condensation requires inclusion of the Δ-hole graphs shown in Fig. IX-2(b) and of the short-range nuclear repulsion effects in the channel with pion quantum numbers. The former effects are strongly procondensation, and the latter, which are usually subsumed into the Landau-Migdal Fermi-liquid parameter g', are strongly anticondensation. Uncertainties in the parameters entering these effects can produce large uncertainties, for example in the critical density for pion condensation.[37]

APPENDIX C

THE RELATION OF PION CONDENSATION TO CONVENTIONAL NUCLEAR PHYSICS

Although pion condensation might seem at first sight very exotic and unrelated to conventional nuclear physics, in fact it is conceptually linked to two very classical nuclear physics questions: the properties of the nuclear tensor force, and core polarization effects.

The relation to the tensor force is seen by recalling that static OPEP *is* the long-range part of the nucleon-nucleon tensor force, and it has long been recognized that a strongly attractive tensor force might lead, for example, to actual density oscillations in nuclear matter.[38-40] In a sense, pion condensation is a re-expression of this idea in modern parlance, with two crucial additions: first, the nonstatic nature ($\omega \neq 0$) of the pion exchange is included, and second, the important role of Δ-hole states is recognized. A more explicit discussion is best based on the diagrams in Fig. IX-5.

The attractive p-wave π-(particle-hole) interaction shown in Fig. IX-5(a) is an important part of the "driving force" that produces pion condensation (in theoretical calculations, at least!). This is clearly related to the πNN vertex in Fig. IX-5(b), and that in turn to the pion exchange between nucleons shown in Fig. IX-5(c). As indicated, the exchange in Fig. IX-5(c) is, in general, nonstatic, but since we noted that for $N \simeq Z$ nuclei the enhancement in D which is a precursor to pion condensation occurs near $\omega \simeq 0$, the driving mechanism in Fig. IX-5(a) is closely related to the $\omega = 0$ limit of Fig. IX-5(c) — namely, static OPEP — and hence to the density oscillation instabilities discussed long ago.[38-40] For pion condensation in $N \gg Z$ matter, the nonstatic behavior of Figs. IX-5(a) and -5(c) is crucial. As noted previously, for a quantitative understanding of pion condensation, one requires the π-(Δ-hole) interaction in Fig. IX-5(d). If one extends the space of nucleon states to include the isobars, then this force, too, is related, as shown by Figs. IX-5(e) and -5(f), to a generalized two-body tensor force acting between nucleons and isobars. But if one insists on considering the nucleon subspace only, then these Δ-hole effects lead, as indicated in Fig. IX-5(g), to many-body nucleon forces, and thus are not described by the two-body NN tensor force.

The relation of pion condensation and core polarization is suggested schematically by Fig. IX-6. From this perspective, core polarization calculations[41] (in channels with pion quantum numbers) amount to truncating the enhancement factor "found" in pion condensation calculations at some finite order in the RPA-like sum over particle-hole excitations which generates the collective mode.

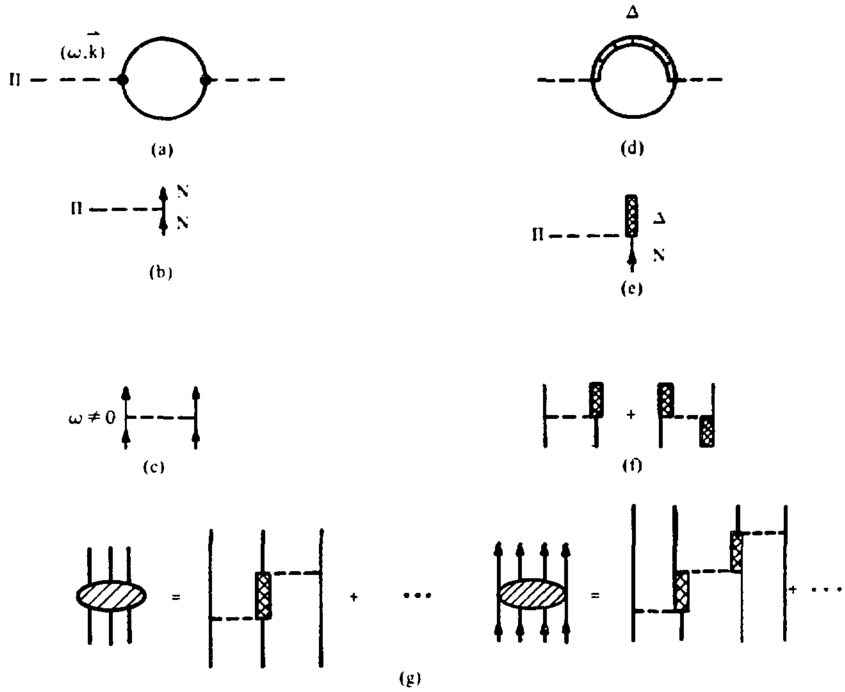

Fig. IX-5.
(a) The attractive p-wave π-(particle-hole) interaction; (b) the πNN vertex; (c) nonstatic OPEP; (d) the attractive p-wave π-(Δ-hole) interaction; (e) the πNΔ vertex; (f) generalizations of OPEP to NN → ΔN and ΔN → NΔ; and (g) three- and four-body forces among nucleons generated by processes involving Δs.

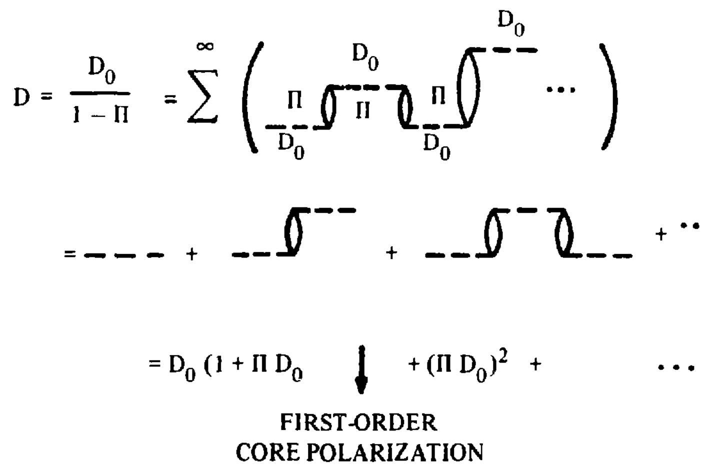

Fig. IX-6.
A schematic comparison of core polarization and "pion condensation" calculations.

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X. PANEL N-5

WEAK AND ELECTROMAGNETIC INTERACTIONS IN NUCLEI

Chairman: Kenneth M. Crowe
Co-Chairman: James Friar

Participants: H. Baer, A. M. Bernstein, C.-Y. Cheung, J.G.P. Deutsch, G. T. Garvey, P.A.M. Gram, S. S. Hanna, N. Matsushita, J. Matthews, I. Sick, and W. Turchinetz.

I. INTRODUCTION

The panel assigned to consider weak and electromagnetic interactions in nuclei found itself confronted with a large and diverse set of topics. In this report we attempt to evaluate some of the ways in which these probes, which are relatively well understood and to which nuclear matter is highly transparent, can contribute to our quantitative understanding of nuclear structure.

II. CORRECTIONS TO IMPULSE APPROXIMATION

Although commonly believed to be completely "clean," electron-scattering and muonic-atoms data do involve small corrections which muddy their interpretation in terms of charge and current densities. These corrections to elastic electron scattering are conveniently classified as recoil (finite nuclear mass) and dispersion corrections. The latter are more important and arise from virtual excitation and deexcitation of the nucleus (polarization) by the lepton. Scant experimental evidence exists for these phenomena, although the current inability to fit the diffraction minima of the cross section of ^{12}C and ^{16}O strongly hints at dispersive effects. Crude estimates of the size of dispersive effects show that they are attractive and that they change the radius deduced from data by less than $7 \cdot 10^{-3}$ fm throughout the periodic table. In view of the precision of electron scattering and muonic atom work, more experimental and theoretical work concerning dispersion corrections is needed.

Although the recoil and dispersion corrections set the limits of accuracy for transforming elastic electron scattering and muonic x-ray data into information concerning nuclear charge and current densities, it is a nontrivial extension to interpret these densities in terms of neutron and proton densities alone. In fact, this interpretation is only an approximation, the impulse approximation, and neglects a variety of mesonic and relativistic effects. In order to classify these phenomena into easily digestible parts, we separate the various contributions to the charge and current densities into nonrelativistic terms and relativistic corrections. The latter are of the order of $(v/c)^2$ compared to the former. Since v, a typical nuclear velocity, is roughly p/M (M is the nucleon mass), $(v/c)^2$ is $(p/M)^2$ and can be reckoned as $(1/M^2)$. Since typical nuclear momenta are 100-200 MeV/c, we immediately see that $(v/c)^2$ is on the order of one to a few percent and sets the scale of relativistic corrections in a nucleus. In addition, since a nucleus is weakly bound, potential and kinetic energies are roughly equal and opposite. Thus we also reckon the potential V as of the order (1/M), like the kinetic energy. Since relativity treats all forms of energy on an equal footing, it is reasonable to expect potential-dependent contributions to relativistic corrections to be of a size comparable to those kinetic contributions which depend only on momenta. Figure X-1 shows the order of these corrections — for example, the nuclear charge operator, whose lowest order part in powers of 1/M is of the order of $(1/M)^0$. This is the nonrelativistic part, and is basically potential-independent — that is, independent of meson exchange contributions other than those which determine the wave function. The relativistic corrections of the order of $(v/c)^2$ or $(1/M^2)$ are of both kinetic- and potential-dependent types. An example of the former type of contribution is the spin-orbit interaction between nuclear neutrons and protons and an external electric field. The interaction is explicitly of the order of $1/M^2$ and

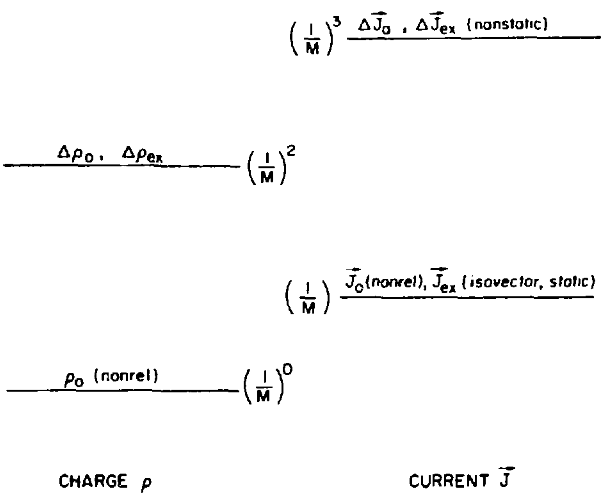

Fig. X-1.
Classification of the recoil and dispersion corrections to impulse approximation.

allows neutrons to make a small but nonnegligible ($\sim 1\%$) contribution to the charge density, which is now routinely taken into account in discussions of isotopic charge differences. The potential-dependent parts arise from meson exchange and generate operators of the order of V/M or $(1/M^2)$ in our counting scheme. Typical processes are depicted by "pair," $\rho\pi\gamma$, $\omega\pi\gamma$, and meson "recoil" and isobar graphs.

The current operator is different in an interesting way. The usual kinetic nonrelativistic contributions are the convection and spin-magnetization currents, which are explicitly of the order of (1/M). Because the isospin dependence of the nonrelativistic potential does not commute with the nonrelativistic nuclear charge operator, there must be an additional two-body or meson-exchange current in order for current continuity to be satisfied. This contribution is of the order of V or 1/M, is isovector, and in principle could be as large as the usual kinetic contribution. This is not the case because the isovector spin-magnetization current is proportional to the extremely large isovector nucleon magnetic moment (4.7 nuclear magnetons). Isovector exchange current corrections are roughly 10% in the M1 multipole. The best examples of such exchange effects are the threshold n-p radiative capture process (M1), with its 10% discrepancy with impulse approximation, and the analogous threshold electrodisintegration of the deuteron. In addition, there are serious deficiencies in the impulse approximation treatment of the isovector magnetic moment and form factor in the ^3He-^3H system, and in n-d radiative capture at threshold. The discrepancies are adequately accounted for by a one-pion-range meson-exchange current and constitute the best evidence for exchange currents.

Of a very different nature is the isoscalar channel because the usual nonrelativistic isovector exchange currents don't contribute. The meson exchange currents which do contribute are basically of relativistic order. The relativistic corrections to the current operator are of the order of $(1/M^3)$, and are of both kinetic- and potential-dependent types. The latter are of the order of (V/M^2) or $(1/M^3)$ and thus are generally much smaller. They are the exchange currents that contribute to the deuteron magnetic moment and magnetization distribution.

It has been conventional to attempt to extract the "nucleons-only" component of measured charge distributions by eliminating the effect of meson currents. This is impossible to do for fundamental reasons having to do with how relativistic effects in wave functions are calculated. It is conventional to "map" relativistic problems from a manifestly covariant formalism into a form that appears nonrelativistic, but by virtue of appropriate momentum dependence in the Hamiltonian is actually "relativistic." This procedure is not unique, however, and for every different formalism for calculating wave functions there is a corresponding formalism for calculating meson-exchange currents. In general, these give different answers, and their contribution to the charge (or isoscalar current) operator is not uniquely defined. We emphasize that this is not a problem for the nonrelativistic (isovector) exchange currents and is a purely theoretical problem in how one chooses to do a calculation. Matrix elements of charge and current operators are free of these ambiguities.

It should be pointed out that other probes suffer from the same ambiguities, in addition to the others which are peculiar to those probes. These problems are related to our methods of doing relativistic quantum mechanics, not to a specific probe. In view of these problems and in spite of recent progress, the field of relativistic and meson-exchange effects in nuclei deserves much more theoretical emphasis in order to exploit fully experiments on the few-body problems to be detailed later.

III. ELECTRON SCATTERING

As the field of electron scattering is too diverse to summarize in detail here, we will simply list a few experiments that we regard as the most important to pursue in the next few years. The bulk of the electron-scattering work that is currently being done and that will be continued in the near future concerns mapping the nuclear charge and current distributions of ground states and transition distributions for discrete excited states. The experimental effort is in response to advances in many-body techniques for calculating wave functions of complex nuclei and serves as the primary testing ground for the "goodness" of these wave functions. It is the "bread and butter" of the electromagnetic probes at present. Most of our detailed knowledge of the gross properties of nuclei comes from electromagnetic measurements at low and intermediate momentum transfers. The topics listed in Table X-I deserve special effort in the near future, since their pursuit will play an important role in the development of new techniques, equipment, and theoretical approaches.

IV. DETERMINATION OF $\rho(r)$, $\rho_{tr}(r)$

For selected cases, where it is important to test theory to the maximum extent possible, special experimental considerations must be taken into account. The existing data in most cases are insufficient, simply because it has been very hard to perform experiments reaching 1-2% accuracy in the extracted quantity. An example is shown in Fig. X-2.

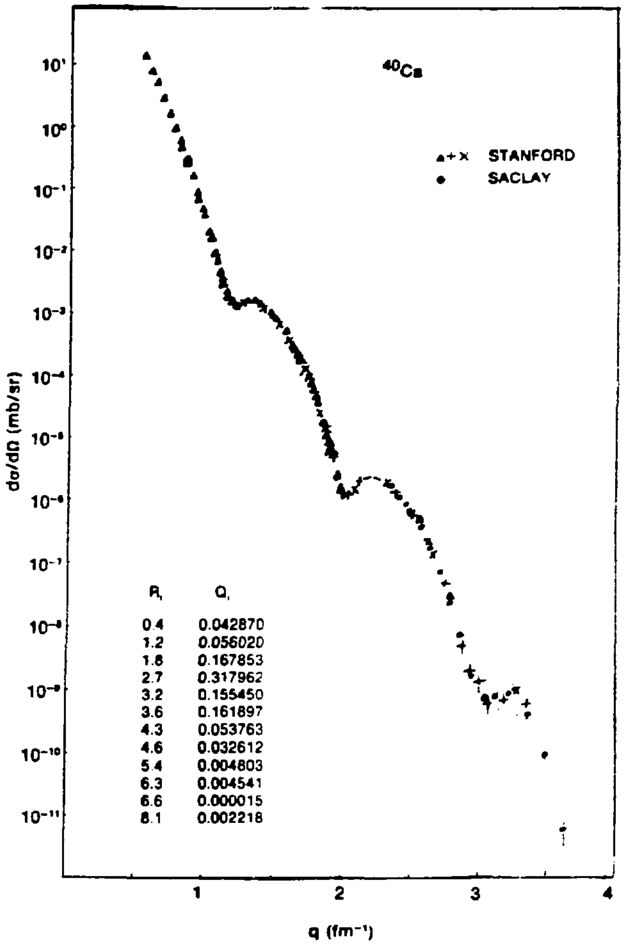

Fig. X-2.
Modern precise electron-scattering form factor measurements.

TABLE X-I

ELECTRON SCATTERING

1.	(e,e) up to $q_{max} \sim 4\ fm^{-1}$	→ $\rho(r)$, $\rho_{tr}(r)$ accurate to ±1% for nuclei where theory is adequate
2.	(e,e')	→ high-spin p-h states
3.	($\vec{e}$,e)	→ structure of weak neutral currents
4.	$\vec{d}$(e,e), d(e,e'p)	→ short-range NN interaction
5.	(e,e'p), (e,e'n)	→ S(k,E); E < 100 MeV, k > 400 MeV
6.	(e,e'$_x$), $E_x \sim 20$ MeV	→ decomposition of giant resonances
7.	(e,e') q ~ 2 fm^{-1}	→ sum rule puzzle
8.	(e,e') q > 5 fm^{-1}	→ high-k components (E < 200 MeV)
9.	(e,e') $E_e > 1$ GeV	→ excitation of *N*'s in nuclei*
10.	(e,e) large q, forbidden M1 transitions	→ meson-exchange currents

To discuss the simplest case, $\rho(r)$ is given by $\int F(q) \sin(qr)/(qr)dq$, where $F(q) = (\sigma/\sigma_{Mott})^{1/2}$. Plotting this integral as a function of its upper limit for an especially simple case, $r = 0$, shows that ρ is a damped oscillatory function of the maximum momentum transfer measured. Only when $q_{max} > 3.5$ fm^{-1} is $F(q)$ small enough so that further oscillations change $\rho(r)$ by less than 1%. Most experiments stop at 2-2.5 fm^{-1}, which for calcium, for example, would mean $\delta\rho(0) = \pm 10\%$. A q_{max} of ~4 fm^{-1} should be reached for many nuclei and for excited levels [for which the same argument applies except that $\sin qr/qr \to j_\ell(qr)$], and for nuclei with $J \neq 0$ where a separation of charge and magnetization contributions is required. Figure X-3 shows the results of the analysis made on ^3He.

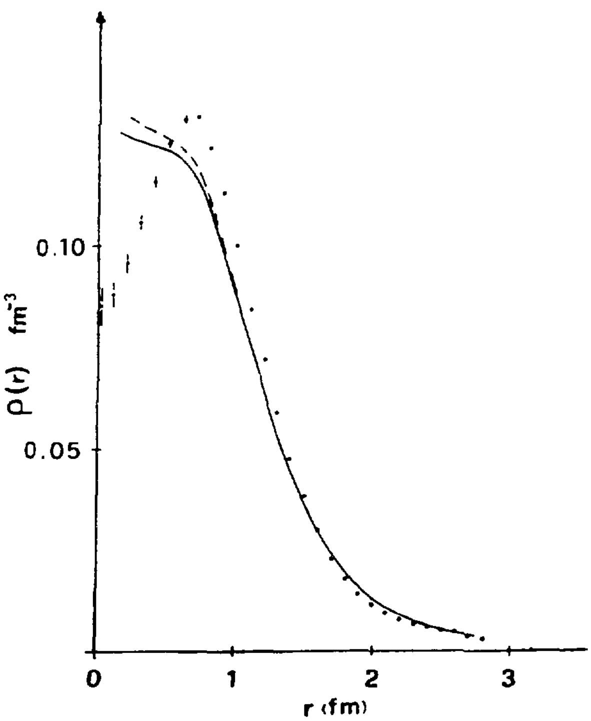

Fig. X-3.
Charge density distribution of ^3He obtained from analysis of electron-scattering data.

V. MOMENTUM SPACE DENSITIES

The best tool to investigate densities in momentum space is the (e,e'N) reaction. In the past, this has been exploited for (e,e'p) and nuclei with $A < 60$, but not in a very systematic way. The reason is simple: the 1% duty cycle of existing accelerators is an enormous hardship for coincidence experiments. With the high duty cycle accelerators available in the future, two main topics should be pursued.

1. The measurements of the $\rho(k)$ can be extended to momenta k where short-range correlations come into play, i.e., to the k where $\rho(k) < 10^{-3} \rho_{max}$. The most interesting region of the momentum distribution would then become accessible.
2. The (e,e'n) reaction should become a routine experiment. Realistically estimating the added complexity of neutron detection (mainly the small solid angle for a setup allowing time-of-flight energy determination) shows that (e,e'n) could be done with the quality achieved today for (e,e'p). This will offer us a tool for measuring wave functions of individual neutron orbits more suitable than anything available today.

VI. INCLUSIVE (e,e') AT VERY LARGE q AND SMALL ω

Such measurements at $q > 5$ fm^{-1} and $\omega < 200$ MeV are of importance for the determination of high-momentum components in nuclear wave functions (see the report of panel X-3). Such data should be obtained for a number of nuclei. (This requires electron energies >1 GeV.)

VII. SUM RULES AND INCLUSIVE (e,e')

The inclusive spectra of electrons scattered from nuclei offer a very clear tool to determine NN correlations (see the report of panel X-3). In order to exploit this potential, the contribution due to the excitation of the Δ has to be eliminated. This contribution can be reduced by separating the longitudinal and transverse response functions. The determination of the longitudinal response function should be actively pursued.

VIII. HIGH ANGULAR MOMENTUM STATES

At high q, high angular momentum states can be identified and mapped out in a unique way. For example, the spectrum obtained for ^{58}Ni is shown in Fig. X-4 and shows prominent peaks at large excitation energy which are 8^- states, i.e., high-j states we know very little about. In addition, form factors have been measured for 10^- and 12^- states in ^{208}Pb, where states up to 14^- have already been seen. The study of these high-spin states promises to be interesting. These states are rather elementary excitations of simple structure, i.e., particle-hole states with only small admixtures, and thus are more accessible to quantitative theoretical calculations than many other nuclear levels. This topic was also discussed in panel X-2.

IX. DEUTERON GROUND STATES PROPERTIES

In order to gain new information on the spherical and tensor portions of the deuteron wave function inside the range of the nuclear force, it is necessary to separate the quadrupole and monopole form factors experimentally. This can be done by measuring

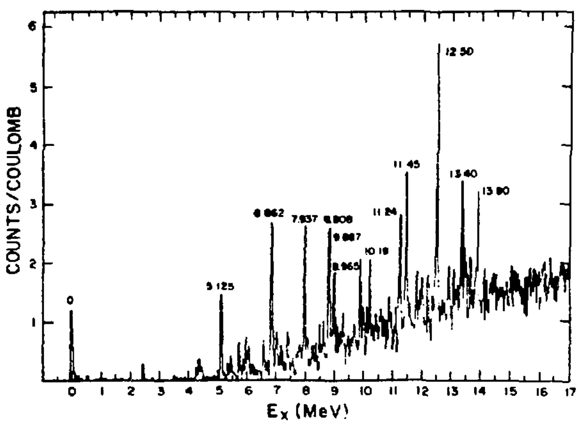

Fig. X-4.
Back-angle-scattered electron spectrum from ^{58}Ni showing $J^\pi = 8^-$ states.[1]

the alignment (T_{20}) of the recoil deuteron in an elastic-scattering experiment. Such a measurement at momentum transfers greater than 2 fm^{-1} is strongly encouraged. This work must be coupled with improved theoretical calculations in order to make any interpretation possible.

X. STUDY OF GIANT RESONANCES USING THE (e,e'p) REACTION

For a discussion of this topic, see the report of panel X-2. One aspect of this problem not discussed there is the measurement of the total multipole strength in terms of the appropriate sum rules. For the isovector modes these measurements give important information on exchange currents and mesonic effects in nuclei. For the isoscalar modes, features of the charge distribution are involved, but little theoretical work has been done because of the paucity of definitive data.

XI. NONNUCLEONIC (ISOBARIC) EFFECTS

Inclusive electron scattering at energies $E \geq 1$ GeV will be the ideal tool to study N^* propagation within the nucleus. Electrons readily excite the N^*'s, which are produced throughout the nuclear volume, and not only in the surface as is done, for example, by pions. A systematic experiment of even the simplest type, (e,e'), could yield interesting information. The creation of bound N^*'s is quite appreciable, and perhaps already indicated by the experimental data. No systematic experiments, however, are presently available. For a detailed investigation of N^*'s in nuclei, the more specific (e,e'Δ) experiments are obviously needed.

XII. PARITY VIOLATION IN ELECTRON SCATTERING

In order to map out the structure of the weak neutral current, experiments observing the interference terms between electromagnetic and weak interactions may be the most practical means. One very successful experiment at SLAC, on deep-inelastic polarized electron scattering from the nucleon, demonstrated the success of this approach. To learn more, experiments involving scattering from discrete nuclear states are needed. A few GeV is perhaps the best electron energy for these experiments: individual nuclear states can still be resolved, and the asymmetry, which is proportional to q^2, is larger than that (10^{-6}) expected at today's low energies.

The goals of this program would be to (1) determine all the coupling constants in the phenomenological theory to check the consistency of standard theory, and (2) obtain a precise determination of $\sin^2 \theta_w$, which should be rather free of theoretical ambiguities. Polarized elastic electron scattering from ^1H, ^2H, and ^{12}C would be important experiments.

An interesting feature of the electron scattering from nuclei is that it involves parity mixing in the nuclear state itself as well as the parity nonconserving term of the weak interaction. The former effect arises from the parity nonconserving part of the strong interaction and has been the object of considerable experimental and theoretical effort. In elastic electron scattering this term is generally smaller than the interference effect in the weak interaction. However, in inelastic electron scattering the "nuclear" effect can be much larger, reaching 10^{-4} at certain momentum transfers and energies. Inelastic scattering from nuclei such as ^{12}C, ^{19}F, and ^{21}Ne would be important experiments.

XIII. PHOTONUCLEAR REACTIONS

A. Technical Advances

Around 10 years ago, the field traditionally called photonuclear physics took a qualitatively new turn due to advances in accelerator and also experimental measurement technology. Experiments began to be feasible that hadn't been contemplated previously. The distinguishing feature of this "new generation" of experiments is the use, or simulation, of monoenergetic incident photons. This, together with sufficiently precise spectrometry of emitted particles, allows initial and final states of well-defined energy to be specified (as has been taken for granted in charged-particle-induced nuclear spectroscopy for years), and has helped this field to move into the intermediate-energy domain.

Four techniques for producing real or effective monoenergetic photons can be enumerated: (1) "endpoint," i.e., using just the tip of the bremsstrahlung spectrum and either throwing away kinematically or subtracting out the rest; (2) "tagging", i.e., observing a coincidence between the photonuclear reaction product and the electron that radiated the photon; (3) positron annihilation in flight; and (4) Compton back-scattering of laser light by storage-ring electrons. High-intensity linear accelerators, along with good-resolution magnetic spectrometers, have facilitated experiments using method (1), and to a lesser extent, (3). The high-duty-factor linacs of the future will make method (2) feasible. Method (4), presently being pursued at Frascati, has formidable technical problems, as well as intensity limitations.

A very important supplementary method is that of nucleon capture, which is the inverse of the photonuclear process. This method, which provides high resolution and counting rate, is now feasible with the advent of high-intensity, intermediate-energy accelerators such as the Indiana Cyclotron.

The endpoint method has been limited in resolution, so far, to ~1 MeV. Whereas better resolution is feasible in principle, in both the bremsstrahlung tip (or isochromat) method and the difference method, the small cross sections and the need for adequate statistics have necessitated the use of thick targets and thick radiators, producing a smearing of the emitted particle spectra. In addition, one's knowledge of the shape of the endpoint region of the bremsstrahlung spectrum can become a serious limitation. In Table X-II, the reactions are listed which represent the future work planned.

B. Exclusive (γ,N) Reactions

Photoproton spectra with moderate resolution have been measured for several nuclei, allowing the unambiguous determination of ground-state cross sections and some information on the excitation of low-lying excited states. The kinematic arguments relating (γ,p_0) cross sections to nuclear high-momentum components and/or short-range correlations are well known and need not be repeated here. Despite ambiguities in the reaction mechanism, it has been possible to extract effective single-particle momentum distributions from the (γ,p_0) data, thus extending the results of (e,e'p) measurements to $k \approx 800$ MeV/c. This subject is also discussed in the report of panel N-3. The most extensive (γ,p) data are for the $^{16}O(\gamma,p_0)$ reaction, and one sees that

TABLE X-II

PHOTONUCLEAR REACTIONS

1. Exclusive (γ,N) reactions	(γ,p_0), $(\gamma,\vec{p}_0)$, (γ,n)
2. Few-body problems	$d(\gamma,p)n$, $^3He(\gamma,d)p,n$; $^4He(\gamma,p)$, $^4He(\gamma,n)$
3. Inclusive reactions	(γ,N), (γ,π), (γ,NN), $(\gamma,\pi N)$
4. Clustering and correlations	$(\gamma,2N)$, (γ,np), $(\gamma,2p)$, (γ,d), (γ,t), (γ,α)

available theoretical calculations can only qualitatively account for the experimental results. The common feature of these calculations is that a second particle is involved in the (γ,p) reaction in varying guises: Δ (1232) excitation, meson-exchange currents, Jastrow correlations, and the phenomenological quasi-deuteron model. The fact that all of these descriptions can yield the correct order of magnitude indicates that two-particle (two-step) processes are important; the fact that none of them is quantitatively successful demonstrates a clear need for further theoretical activity. In addition, an extension of the experimental results in several areas should be useful in elucidating the reaction mechanism, viz., more complete angular distributions of the $^{16}O(\gamma,p_0)$ and $^{40}Ca(\gamma,p_0)$ processes, and measurements with modestly improved energy resolution and statistics so that $(\gamma,p_1,p_2, \ldots)$ cross sections could be determined for these nuclei, as well as (γ,p_0) measurements in two heavier nuclei (say in the ^{90}Zr and ^{208}Pb regions). Also, $(\gamma,\vec{p}_0)$ measurements, which will be feasible with the new large solid-angle spectrometers being constructed at Bates and at IKO, along with calculations of this process, may be of help.

These measurements could equivalently be obtained in proton capture with the polarized proton beam of the Indiana Cyclotron.

We note that studies of intermediate-energy (γ,n) reactions are only just beginning; recent measurements on the $^{16}O(\gamma,n_0)$ process at E_γ = 60 MeV yield cross sections roughly equal to that for (γ,p_0). As discussed also in the report of panel N-3, we believe that this is an important area for future experimental and theoretical work.

C. Few-Body Problems

In the context of photon interactions with few-body systems, one might first mention the "zero-body problem," viz., the bremsstrahlung spectrum. All photonuclear experiments rely on a calculation of its shape and/or intensity, and experiments on few-body systems are especially vulnerable because the kinematics allows one to use a large portion of the spectrum. Beams of uncharged particles are obviously difficult to monitor. Further thought as well as experimental work is needed. However, the bremsstrahlung spectrum probably cannot take the entire blame for the "mess" in the 1s-shell. Large discrepancies ($\sim$50%) are seen in various measurements of the $d(\gamma,p)n$ and the $^3He(\gamma,d)p$ cross sections at intermediate energies, and the theories fail to reproduce the data with any accuracy. There is apparently still a controversy over the ratio of (γ,n) and (γ,p) cross sections in ^4He for $E_\gamma \lesssim 30$ MeV. Other more subtle puzzles exist, such as the $d(\gamma,p)$ cross section at 0°. The resolution of some of these problems, theoretically and/or experimentally, should be given a high priority for the immediate future.

D. Mesonic Degrees of Freedom — Nonresonant and Resonant

In addition to the effects seen so far in exclusive (γ,p_0) reactions and in few-body problems, meson-exchange currents and nuclear dynamics may be observed (perhaps more clearly) in inclusive (γ,p) and (γ,π) processes. In particular, since the $\Delta(1232)$ isobar is seen to dominate the photon absorption probability for $E_\gamma \approx 300$ MeV, one can use the incident photon as a means of "planting" a Δ in the nuclear interior. The spectra of emitted particles, singly or in coincidence — e.g., (γ,N), (γ,π), $(\gamma,2N)$, and $(\gamma,N\pi)$ — should help elucidate the pion absorption process in nuclei, and will yield information complementary to that obtained from pion-induced reactions taking place mainly in the nuclear surface region.

E. Clustering and Correlations in Nuclei

No experiments have as yet been done to look at the dynamics of these effects directly. Coincidence measurements of (γ,np), (γ,pp), etc., cross sections for $E \gtrsim 100$ MeV, are feasible but difficult now, and will become "easy" with cw machines. Processes such as (γ,d), (γ,t), and (γ,α) populating low-lying final states are almost completely unknown theoretically and experimentally. Although the interpretation of, say, the (γ,d) reaction is bound to be complicated (i.e., the dominant effect is either clusters in the ground-state wave function or pickup in the final-state interaction), this process can provide valuable data complementary to that in, say, $(p,{}^3He)$ studies, and the electromagnetic interaction is more likely to allow the separation of nuclear structure information from problems of the reaction mechanism.

XIV. PHOTOPION REACTIONS

We note that the three reactions (π,γ), (γ,π), and $(e,e^-\pi)$ have some desirable properties for the study of nuclei:

1. The processes on the nucleon $(\gamma N \to \pi N)$ are *relatively well understood theoretically*. At threshold, the production operator is simply $A\ \vec{\sigma} \cdot \vec{\epsilon}$. It contains no gradient terms and is known to an accuracy of $\simeq 3\%$. In both respects this differs from the $NN \to NN\pi$ process, which is the other production reaction used in medium-energy physics.
2. In the study of π-nucleus interactions, it is an advantage to have a γ or e in one channel. Since the γ and e interactions are weaker and well understood, the π-nucleus interaction is most clearly exposed.
3. The types of nuclear excitations which dominate in charged pion production are those with large Gamow-Teller matrix elements. Thus in principle one can measure the distribution of spin-flip strength in the nuclear excitation spectrum.

These general features have been exploited to a considerable extent since 1970 in studies conducted at medium-energy accelerators. The ${}^6Li \to {}^6He$ and ${}^3He \to {}^3H$ transitions have provided exceptionally good comparisons between experiment and theory. A conference on photopion physics was held at Rennselaer Polytechnic Institute in the summer of 1978 in which all aspects of this work were reviewed.

Before discussing a possible program, one must consider the experimental state of the art. For (π^-,γ) reactions, pair spectrometers with 0.7-MeV resolution and efficiencies of $\sim 10^{-5}$ have been employed. Measurements of (γ,π) total cross sections have been performed either by measuring the $\pi^+ \to \mu^+ \to e^+$ decay chain after the beam burst, or by detecting the residual radioactivity, a method subject to large backgrounds. Differential cross-section measurements for $(\gamma,\pi^\pm)$ reactions have been performed from 10 to 50 MeV above threshold at Bates and Sendai with an energy resolution of ~ 0.5 MeV. New facilities are being planned at both these laboratories. The one at Sendai will have better energy resolution and a solid angle of 5 msr. The new facility at Bates will have a solid angle of 35 msr, a resolution $\Delta p/p$ of 5×10^{-4}, a flight path of 4.5 m, and a dynamic range of 15%. With these new instruments, a new era in the field will arrive. In addition, (γ,π^0) experiments are being planned at Bates with resolutions of several MeV. These experiments will be performed with photons or with electrons without observation of the scattered electron. This means that one needs to know the shape and magnitude of the real or virtual photon spectra. The Bates group has been performing measurements on these spectra and plans to upgrade these measurements with their new facility. In addition, theoretical calculations of these spectra need to be improved. Keeping in mind the present state of theory and experiment, the program envisioned at Bates includes the following experiments:

1. *Measurements of $(\gamma,\pi^\pm)$ reactions to selected discrete nuclear final states, including spin-isospin collective states, in order to check the reaction calculations.* This should include energies from the threshold through the Δ region and differential as well as total cross sections.
2. *Measurements of coherent (γ,π^0) reactions in selected nuclei in the Δ region in order to test the reaction calculations.* We note at this time a large discrepancy between theory and an old (and probably unreliable) experiment.
3. *Study of few-nucleon systems with photoproduction.* At the present time, the Saclay coincidence experiments on $D(\gamma,\pi p)p$ have selected the kinematics in order to obtain

information on the Δ-N interaction and also to search for a possible dibaryon resonance. Further work on both of these topics is required to clarify the interpretation. In addition, the same techniques should be extended to A = 3 and 4 targets.

4. *Investigation of inclusive spectra of pions and protons produced by photons in the 200-400-MeV region.* This should shed some light on Δ propagation and interactions in the nuclear interior.
5. *The $(\gamma, p\pi^-)$ coincidence experiments in the quasi-free region to obtain more detailed information about Δ propagation and interactions.* A preliminary experiment of this type has been performed on ^{12}C at Tokyo for $E_\gamma > 300$ MeV and has shown interesting results.
6. *The $(e,e'\pi)$ reactions, particularly in light nuclei, to extend the dynamical range of (γ,π) experiments.* These reactions will be difficult but should be tried, particularly if the 100% duty factor electron accelerators attain 300 MeV and above.

XV. MUON CAPTURE AS A NUCLEAR PROBE

We list briefly some of the topics which seem promising in the field of muon capture and indicate some of the improvements required to tackle the issues more efficiently. No references will be given to the original research papers; these can be found in the reviews we refer to at the end of this note. See also the conclusions of panels P-2, P-3, and N-3.

Some of the fundamental issues in muon capture are related to the nature of the interaction itself and to the symmetry properties of the hadronic weak current.

1. The helicity of the muon neutrino could be determined in a model-independent way by measuring the polarization of the recoil neutron in singlet capture by the proton. This experiment would require the development of a high-luminosity polarimeter.
2. The determination of the *basic coupling constants* through "recoil order" in hydrogen could be performed ideally by determining separately the singlet and triplet capture rates in hydrogen. This requires a high capture rate in low-density hydrogen gas. Spin-precession measurements, which also address the same issue, depend on a long relaxation time to see the triplet polarization, a possibility that remains to be ascertained. Precession measurements on the ^{3}He → ^{3}H transition (similar to p → n) were also considered. These would require both high stop-rate and nonvanishing polarization in the triplet hyperfine level.
3. One of the basic hypotheses concerning the symmetry properties of the hadronic weak currents is the conserved isovector current hypothesis (CVC); it is interesting to test it in muon capture because the process is characterized by higher momentum transfer than beta decay. The test requires precise experiments on a given transition: the determination of both the partial capture rate and of the correlation between either the muon spin, the spin of the initial (final) nuclear state or the recoil momentum. These correlation measurements fall into different classes:
   - hyperfine effects observed using polarized targets or detecting the interdoublet conversion by muon disappearance-rate measurements, and
   - final-state polarizations and/or alignments observed, e.g., through the Doppler pattern of a deexcitation gamma ray.

These experiments are also useful for some other purposes we shall discuss in item 1 below. Let us note, however, that their use to check CVC requires a precise knowledge of the axial form factor: qualitatively, a 10% precision on the weak magnetism requires the knowledge of the axial form factor to ~1%. The precise predictability of the axial form factor is still under theoretical investigation.

For the *investigation of the nucleus*, some of the basic questions are:

1. Are the couplings to be used in the impulse approximation description of *nuclear muon capture* the same ones as for *free nucleons*? (Especially the induced pseudoscalar?) The predictions are sensitive to the mesonic degrees of freedom in nuclei; they require the same type of partial capture rate and correlation experiments as mentioned under item 3 above. It should be noted also that *radiative muon capture* experiments between well-defined nuclear states test the same type of predictions for various values of the momentum transfer.

2. An interesting question is that of a predicted relation between *pion capture* and *muon capture* with the emission of high-energy nucleons from either capture, along with their directional correlations. A complete test would require the determination of the excitation energy of the residual nucleus. This would be possible in some light nuclei: one could measure the recoil energy of the charged final state. These measurements are sensitive to the *high-momentum components* of the nuclear wave functions, and/or *nucleon-nucleon correlations* in nuclei. Experimentally they require neutron and charged-particle spectroscopy in muon capture.
3. The different aspects of *muon-induced fission* allow us to investigate mostly the electromagnetic properties of heavy nuclei and some of the basic physics of fission; e.g., (a) Coulomb-perturbed barrier shapes, and (b) time of the fission process (viz., the muon transfer by the fragments). They require the detection of the fission products.

We conclude that the next few years of investigations in *muon capture* will probably require high stop rates in gaseous or very thin targets, pure, and in some cases, pulsed muon beams, the use of polarized targets, high-resolution detection of charged particles, neutrons and gamma rays, and a more thorough study of radiative muon capture.

XVI. RECOMMENDATIONS

The preparation of detailed recommendations of specific proposals was not attempted by this working group. The consensus was that continuation of electron and photon studies promises to provide data essential to the elucidation of nuclear properties as outlined above.

To implement the continuing study of the electromagnetic interaction of nuclei, present accelerators must be improved toward higher energies, currents, and duty cycles in the next five years. At the same time detection systems to exploit these enhanced capabilities must be built. For example, coincidence measurements with high duty cycle machines will require pairs of large acceptance spectrometers or sophisticated particle detector systems.

Members of the panel see the electromagnetic aspects of the hadronic reactions (e.g., bremsstrahlung, inverse photo reactions) also capable of complementing the interpretation of topics of high priority in medium-energy physics such as pion opalescence and Δ's in nuclear medium. Improved photon detectors with better resolution and higher efficiency are necessary to provide nuclear spectroscopic information. Higher efficiency and solid-angle devices are also needed for coincidence measurements. A higher energy spectrometer will be needed to follow the photo decay of the Δ and to study (π,γ) reactions through the resonance. A high resolution pair spectrometer and liquid argon counters are potentially useful here.

The panel also encourages the development of photon beams with narrow energy spread. Back scattered laser beams are an exciting possibility as the needed technology develops.

The present cw accelerators should be extended to at least 500 MeV. The long-range plans should include a high-current cw electron accelerator with energy greater than 1 GeV.

In the weak interactions, information from muon capture reactions will improve with the development of higher flux and smaller energy-spread muon beams. We urge the rapid construction of high-intensity stopped μ beams with time structure in the low-MHz range (or pulsed) to aid the suppression of background and to facilitate spin-rotation techniques. (See panel P-4.)

Intense beams of polarized electrons have a bright future for the study of weak interactions. Improvements in both the flux and polarization realized by polarized electron sources are needed for this work.

REFERENCE

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XI. PANEL N-6

PARTICLE INTERACTIONS WITHIN NUCLEI

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An important goal of intermediate-energy nuclear physics is the understanding of hadron dynamics inside the nucleus. Modification of the elementary process in the nuclear environment can teach us about the strong interactions of mesons, baryons, and isobars. This knowledge is essential, in turn, for studies of nuclear structure with medium-energy probes. Several closely related issues come to mind in this context: the off-shell projectile-nucleon transition matrix (i.e., model dependence of many-body amplitudes), isobar creation and propagation in the nucleus, and modifications of the transition matrix originating in Pauli effects and pion annihilation. These are clearly difficult problems, with interpretation of experimental results relying generally very heavily upon strong-interaction models, and very often upon assumptions about short-range nuclear structure (see the discussion in the N-3 panel report, Chapter VIII).

While these questions about particle interactions within nuclei are not directly relevant to traditional questions about nuclear structure (i.e., long-range correlations), answers to them are crucial for obtaining new, quantitative information about the structure of nuclear bound states. For example, while the role of the projectile optical potential in analyzing elastic scattering is obvious, higher order terms in the potential might be summarized in a modified transition matrix, and may have less obvious but nevertheless important implications for treating the reaction mechanism in inelastic scattering.

Certain information relevant to these questions has been inferred from analyses of pion and proton elastic scattering, reactions on which there exist already considerable data. However, "deep inelastic" reactions (i.e., those which transfer to the nucleus an energy well above particle-emission threshold) probe more directly the reaction mechanism but have received considerably less experimental attention. These will be discussed in Sec. I of this report. This section is of most immediate interest, since it involves questions to which answers are both needed and accessible in the near future. We stress now that, because of the model dependence intrinsic to such studies, *programmatic* commitments are very important.

Most of the experiments discussed in the remainder of the report will require extension of experimental capabilities beyond those now available to medium-energy physicists (e.g., higher energy primary beams). The creation and propagation of "unstable particles" or hadronic resonances through the nucleus has been alluded to already in the context of meson factory experiments. In Sec. II, this issue will be addressed for energies sufficiently above threshold that the resonances have appreciable decay lengths.

Section III focuses upon the nuclear interactions of strange particles. This discussion will involve not only experimental programs feasible with available kaon beams, but also those possible with construction of a low-energy kaon beam and/or kaon factory. The primary beams needed for the latter would, of course, make feasible much of what is discussed in Sec. II.

Section IV is described best as a brief flight of fancy. A couple of topics potentially relevant to the use of nuclei in tests of the current model of hadron structure (i.e., QCD) are discussed.

I. πN AND NN TRANSITION MATRIX IN THE NUCLEUS

The question of defining a transition matrix "in the medium" is related closely to that of constructing microscopically the elastic-channel optical potential, and to that of including multistep reaction mechanisms in calculations of inelastic reactions. This point is made most easily through a simple example. Two contributions to the pion optical potential are indicated in Fig. XI-1. The standard first-order optical potential $v_{opt} = t\rho$ is indicated in Fig. XI-1(a), while Fig. XI-1(b) represents a contribution coming from pion annihilation (note that the intermediate state is a 2p-2h state with no pion present). The connection between the optical potential and inelastic processes is clear from the latter figure: a large imaginary contribution to the optical potential from Fig. XI-1(b) should be reflected in a large annihilation cross section. The nuclear elastic amplitude is generated by iteration of the optical potential. We now consider use of this optical potential in the calculation of an inelastic process. For a simple example, we consider coherent π^0 photoproduction.* Two contributions to the $\gamma N \to \pi^0 N$ transition matrix in the medium are indicated in Fig. XI-2. The first corresponds to impulse approximation (i.e., use of the free production operator, presumably in a DWIA calculation). The second term is analogous to Fig. XI-1(b), corresponding to a two-step process going through the annihilation channel. Clearly, if this channel contributes strongly to the pion optical potential (and it does), then we can expect the corresponding two-step reaction [Fig. XI-2(b)] to be important [calculations indicate that it changes the $^{16}O(\gamma,\pi^0)^{16}O$ cross section by about a factor of 2].

In principle, the theorist could be asked to calculate everything from the fundamental interactions. In reality this is impractical. First, the interactions are generally not known fully; even though the two-body on-shell scattering amplitude is measured, the interaction itself (or off-shell amplitude) is constrained but not specified. Second, it is extremely difficult to calculate the (dominant) continuum contributions to the higher order optical potential; successful optical potentials still must rely upon some degree of theoretically motivated phenomenology in handling these terms. We cannot expect any greater sophistication in handling the multistep reaction mechanisms going through the continuum. Consequently, the use of an effective transition operator is essential. The physics input, whether completely microscopic or semiphenomenological, should be consistent with that in the relevant optical potentials. Success is to be judged in terms of the resultant ability to provide a unified description of a variety of reactions. Clearly one hopes eventually to explain quantitatively any phenomenological aspect of the optical potential or of the effective transition operator.

*Pion excitation of nuclear particle-hole states would supply an equally good example.

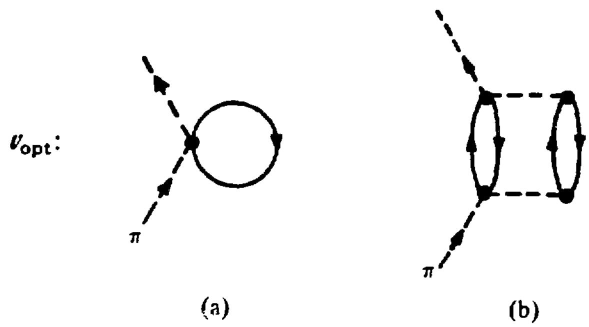

Fig. XI-1.
Two contributions to the pion optical potential: (a) standard first-order term; (b) contribution from pion annihilation.

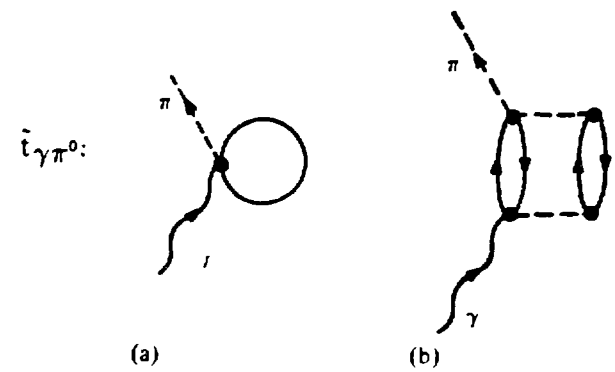

Fig. XI-2.
Two contributions to the $\gamma N \to \pi^0 N$ transition matrix in the medium: (a) impulse approximation term; (b) two-step process through pion annihilation.

While the discussion was phrased in the language of projectile optical potentials, the Δ isobar plays a central role in what follows. To a good approximation, it is the doorway for πN scattering and for inelasticity in NN collisions at intermediate energies.

In the remainder of this section, we discuss experiments relevant to the above considerations.

A. Bremsstrahlung

Nucleon-nucleon bremsstrahlung at intermediate energies (≳200 MeV) still appears to be the most direct method for studying different phase-shift equivalent NN interaction models. Such energies are needed to achieve sensitivity to "off-shell" differences among various reasonable models. However, the situation is quite confusing since no model appears capable of reproducing the sparse available ppγ data (even at 42 MeV). A high-statistics measurement in the 200-MeV region far from the elastic geometry (including an asymmetric configuration) is needed to resolve this difficulty. In addition, calculations indicate that the asymmetry in bremsstrahlung with polarized protons would be sensitive to different NN interaction models.

Results from the one experiment in the pion production region (730 MeV) indicate large effects from the NΔ intermediate state. High-precision data at several energies and under differing kinematic conditions will be required to unravel the coupled-channel effects. (Of particular interest may be the region of the dibaryon resonances.) However, *no* quantitative theoretical calculation exists for this energy range.

Pion-nucleon bremsstrahlung has been studied with the motivation of learning about Δ electromagnetic moments. Results from the one experiment do not conform to theoretical expectations. Comparison of $\pi^{\pm}p$ bremsstrahlung should help clarify the theoretical situation. (Again, calculations indicate that the asymmetry in $\pi\vec{p}\gamma$ is model sensitive.)

B. Inclusive Reactions

1. (e,e')

Deep inelastic electron scattering (or high-energy total photoabsorption) provides a fairly direct means of looking at the nucleon and Δ propagators for the relevant energy transfer to the nucleus (i.e., for electron energy loss corresponding to quasi-free nucleon knockout and quasi-free Δ excitation, respectively). We stress that this sensitivity arises because the inclusive measurement is insensitive to the details of nuclear structure. [In contrast, the (e,e'p) coincidence experiment measures primarily the hole propagator.] As an example, the nucleon effective mass is measured rather directly by the scaling characteristics of the quasi-free response function with small-momentum transfers ($q \lesssim k_F$). At moderate-momentum transfers ($q \sim 2k_F$), a long-standing disagreement between theory and experiment appears to be resolved by inclusion of a Δ-spreading interaction (determined in pion scattering) in the Δ propagator. Two experimental advances are called for. First, the data should be extended to large energy loss, so that the Δ-excitation peak is covered. Second, the longitudinal and transverse response functions should be separated. This is important because the quasi-free nucleon knockout and Δ-excitation peaks overlap (this problem becomes progressively worse as the momentum transfer is increased) and the Δ physics presumably resides primarily in the transverse response function.

2. (π,π')

We still lack extensive systematic data (with energy, angle, and target mass) on inclusive pion reactions. As noted earlier, the optical potential reflects directly the dominant direct reaction mechanisms. Consequently, the inclusive data are essential for constraining in a general way the relative importance of various dynamical inputs to the optical potential and to the in-medium transition matrix. (An example of the problem one can get into without such constraints is the reliance, until recently, upon first-order static optical potentials, which have some success in reproducing elastic scattering in the resonance region but have the wrong dynamical content.) In short, the dominant reaction channels define the framework for reasonable theoretical considerations.

The inclusive reactions remove much of the dependence on details of nuclear structure and final-state interactions. This is indicated schematically in Fig. XI-3, where the final nucleon states are

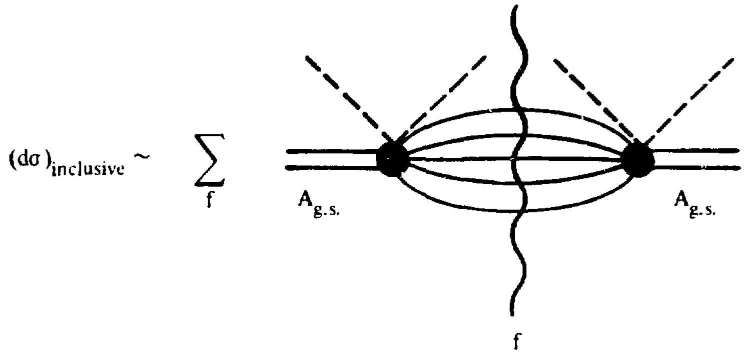

Fig. XI-3.
Schematic representation of the inclusive cross section.

summed over and can therefore be removed by closure. As such, the characteristics of the transition matrix in the medium may be seen more easily. It should be clear that neither very good resolution nor very good statistics are essential for most of these measurements. However, establishment of the systematics *is* crucial.

The total cross sections for pion elastic and inelastic scattering and for pion annihilation (as well as for pion charge exchange) are available as a function of mass number for a few energies up to the resonance. Extension of the data to higher energy is important for guiding construction of the optical potential to those energies. This is especially true for the total annihilation cross section. The rather crude data available above the resonance energy indicate generally a cross section substantially smaller than that expected. This may indicate that a Δ damping mechanism other than pion annihilation becomes very important.

The energy spectrum of scattered pions in $^{16}O(\pi^{\pm},\pi^{\pm})$ indicates dominance of the one-nucleon knockout mechanism and the importance of Pauli blocking of Δ decay (through a suppressed cross section at small scattering angles). These measurements should be extended to larger nuclei and should include small pion scattering angles. An important complementary measurement is the inclusive double charge exchange $(\pi^{\pm},\pi^{\mp})$, since this reaction essentially removes the one-step mechanism. A measurement of the energy spectrum of final pions for 240-MeV pions incident on ^{16}O indicate that ~30% of the inelastic cross section at this energy comes from two-nucleon knockout. Such data are also valuable for determining the extent to which the forward-angle $(\pi^{\pm},\pi^{\pm})$ inclusive data come from two-step processes (and thus for fixing the role of the Pauli blocking in the one-step process). It is important to extend these measurements to lower incident energies (the cross sections will get smaller) as well as to heavier nuclei.

Another interesting inclusive reaction is $(\pi^{\pm},\pi^{\pm})$ on different isotopes. Specifically, if we assume that the dominant Δ-spreading interaction (or t-matrix modification) arises from pion annihilation, the isospin dependence of the interaction can be tested. Such a measurement has been performed on $^{16,18}O$ at 150 MeV, with the perhaps surprising result that the backward π^{+}-^{18}O cross section is ~20% smaller than the π^{+}-^{16}O cross section. Such a qualitative effect must originate in the isospin dependence of the t-matrix modifications; in fact, a simple estimate based on the Δ-spreading interaction determined in π-^{16}O elastic scattering reproduces this qualitative feature. Systematic information of this type (i.e., as a function of energy and for heavier isotopic pairs) would be very instructive in constraining models of the in-medium t matrix and therefore of the optical potential.

In a similar vein, scattering from polarized targets or measurement of angular correlations should provide information on the Δ-nucleus spin-orbit potential.

3. (N,N')

The same basic issue of constraining the dynamical input to the optical potential or multiple-scattering theory through inclusive scattering information arises for nucleon-nucleus interactions. The absence of the annihilation channel makes the situation here somewhat easier. Nevertheless, the existence of a strongly coupled channel in the NN interaction (i.e., the NΔ channel) dictates that systematic measurements be made of inclusive proton scattering in the 600- to 1000-MeV energy range. The measurements must extend to nucleon-energy losses covering both the quasi-elastic scattering and the Δ-production regions. This is clear from Fig. XI-4, which represents one contribution to the *first-order* nucleon optical potential; quasi-free Δ production should represent a large part of the reaction cross section. The object of those measurements is the partitioning of the reaction cross section into its major components with an accuracy of ~10%.

The energy-loss spectra in (p,p') corresponding to quasi-elastic scattering and to Δ production will overlap to some extent. The (p,n) inclusive cross section, as a complement to the (p,p'), may help separate the contributions. The final neutron and proton spectra may be different in the Δ region; basically, this is because the protons are expected to come mostly from Δ decay, but not the neutrons. Further, the $(\vec{p},\vec{p}')$ inclusive spectrum would help in isolating these two (presumably dominant) mechanisms, since the spin structure of the NN → NN and NN → NΔ amplitudes are different.

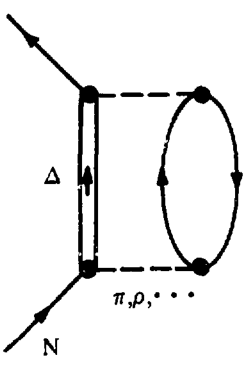

Fig. XI-4.
Contribution to the first-order optical potential from intermediate-Δ excitation.

As discussed above, the Δ propagator in the nucleus is apparently modified strongly by coupling to the pion annihilation channel. Consequently, the (p,π) and (p,pπ) inclusive measurements are also needed. In the latter case, the angular distributions of the produced Δ should be measured. We stress that strong modification of the Δ propagator generates a modified NN transition matrix, and this must be understood for quantitative nuclear structure studies with high-energy protons.

C. Exclusive Reactions

In exclusive reactions, the final state is completely determined kinematically, allowing for greater flexibility in isolating simple quasi-free reaction mechanisms or in probing short-range interactions.

1. Nucleon Knockout: (p,pN) and (π,πN)

The knockout process to a discrete final state has long been considered a means for getting at the off-shell projectile-nucleon transition matrix. The reason is clear from the impulse approximation diagram shown in Fig. XI-5; since the kinematics of all external particles is known, the off-shell kinematics of the exchanged nucleon can be specified. Obviously, multiple-scattering effects complicate the situation. There are basically three "unknowns": (1) the momentum distribution of the struck nucleon, (2) the distorted waves, and (3) the off-shell behavior and medium modifications of the projectile-nucleon transition matrix. The classical (p,2p) experiments were performed with equal angles and energies for the outgoing protons. Unfortunately, this makes extraction of any of the unknowns very complicated. A better approach is to

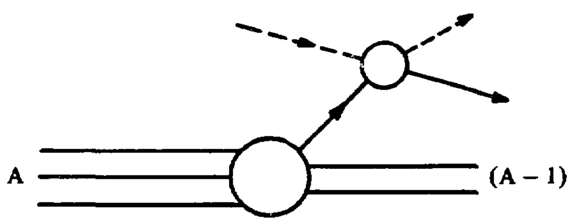

Fig. XI-5.
Impulse approximation for nucleon knockout.

use the available kinematic flexibility to change the variables relevant to only one of the unknowns. For example, a "fixed-condition geometry" appropriate to probing the transition matrix entails fixing the energies of incoming and outgoing nucleons [or pions for $(\pi,\pi p)$], the separation energy, and the magnitude of the nuclear recoil momentum. The remaining free variable is the angle of the recoil nucleus. The major variation with this angle is then the ratio of initial and final relative momenta in the transition matrix. Such experiments should be carried out below the pion production region, although theoretical calculations indicate that sensitivity to off-shell variations may not be large.

Asymmetry measurements in exclusive $(\vec{p},2p)$ would also be of considerable interest. A theoretical calculation predicts a large asymmetry, although again little sensitivity to the off-shell extrapolation of the NN amplitude.

Medium corrections to the transition operator in exclusive $(\pi,\pi p)$ are expected to be large. For example, a theoretical calculation of the Pauli modification of the πN transition matrix (basically, a quenching of the isobar decay width) has predicted an increase in the coincidence cross section of roughly 50% for certain kinematics. Significant Pauli modifications of the (p,2p) cross section might also occur for energies of about 100 MeV, since Pauli effects are known to modify significantly the optical potential at these energies.

Interpretation of the exclusive knockout reactions rests to a large degree on the one-step reaction mechanism assumption. Measurement of the distribution of recoil nuclear momenta would test this assumption. Measurement of the Treiman-Yang distribution would be difficult but would provide a strong consistency check on the reaction mechanism. One such measurement exists for $(\pi,\pi p)$ and indicates a breakdown of the assumption for nuclear recoil momenta as low as 150 MeV/c.

2. Few-Body Breakup

Kinematically complete measurements of few-body breakup are very instructive for disentangling different reaction mechanisms. A model program relevant to pion physics is the Saclay intermediate-energy photonuclear breakup and pion production program. Similar measurements with pion beams ($\pi d \rightarrow \pi pn$, $\pi ^3He \rightarrow \pi pd$, . . .) should be carried out in the resonance region. The measurements should start with kinematics for which the impulse approximation should be valid, and then go off to more "unusual" kinematic regions where more complicated reaction mechanisms enter strongly. As an example of the sensitivity possible, we note that the Saclay group has extracted ΔN s-wave interaction parameters from the $\gamma d \rightarrow pp\pi$ reaction.

3. Reaction to Nuclear Bound States

Coherent π^0 photoproduction is an especially good probe of the pion wave function (as predicted by an optical model derived from elastic scattering), since the photon interacts weakly and the nucleus stays in the ground state. As discussed in the example at the beginning of this chapter, the production operator in the medium must be treated in a fashion consistent with the pion optical potential used; theoretical estimates indicate a reduction of the cross section by as much as a factor of 2 in the resonance region because of Δ-spreading interactions. It is important that measurements be made in the resonance region with energy resolution sufficient to resolve the ground state. Experiments should be carried out at least on one fairly light nucleus and on a heavy nucleus. The differential cross section at large angles (beyond the region dominated by the nuclear size) is small but would provide valuable information on the pion-nucleus interaction. Inelastic pion scattering or pion charge exchange to nuclear bound states may also be useful for extracting information on the πN transition matrix in the medium. Systematic study of the excitation of well-understood particle-hole states would be most useful.

Phenomenological parameterizations of the low-energy pion optical potential imply that pion-nucleus size resonances may occur in the energy region 0-50 MeV. They would be highly inelastic due to absorption, with typical widths on the order of 10-20 MeV, and would most likely show up as anomalies in the elastic-scattering amplitude from doubly closed shell nuclei (e.g., ^{28}Si, $^{40,48}Ca$, and ^{208}Pb). A phase-shift analysis at several closely spaced energies may be necessary. The existence of these resonances is related to the speculation that there may be pion-nucleus "bound" states. One might find such states with high-precision, inclusive (e,e') studies below pion production threshold.

In the energy region 500 to 1000 MeV, the pp spin-dependent amplitudes are known to be large and have characteristic energy dependencies. Nuclear spin-flip excitations provide a way to isolate these spin-dependent amplitudes. Therefore, the excitation functions for such states are sensitive to the modification of these amplitudes in the medium. Use of polarized beams would allow separation of the individual spin-flip terms in the amplitude.

II. INTERACTION OF UNSTABLE "PARTICLES" WITH NUCLEI

The production of hadronic resonances inside nuclei, at energies sufficiently high so that the resonance decay length is at least comparable with the nuclear diameter, provides a means for extracting dynamical information about resonance-nucleon scattering. At the least, such information provides a simple test for quark model predictions. The classic example of this technique is the measurement of coherent ρ photoproduction for photon energies ranging from about 2 to 20 GeV; the extracted ρN cross section agreed with theoretical expectations. This general approach could be used for coherent production of multipion systems or of massive N*s with primary beams of several GeV. Measurement of the A-dependence of these cross sections is crucial.

An extension of such measurements could be the extraction of the resonance line shapes as a function of energy. These would be very sensitive to the hadron dynamics of the resonating system and to the nuclear interactions of the resonance "constituents." This could be especially interesting for energies not too far above the production threshold; however, the cross sections would then be considerably smaller because of the increased momentum transfer required.

III. KAON-NUCLEUS INTERACTIONS

The K and $\bar{K}$ differ dramatically in their interactions with the nucleus (KN and $\bar{K}$N amplitudes are not related by crossing symmetry), especially within the energy range available for studies in intermediate-energy physics. Therefore, we shall discuss these two probes separately.

A. $(K^-,\bar{K}^0)$

The $\bar{K}$ (with strangeness $S = -1$) interacts strongly with the nucleon. There are open inelastic channels at threshold: $\bar{K}N \to \pi Y$, $Y = \Lambda, \Sigma$. The $\bar{K}N$ can form a variety of Y^* resonances ($S = -1$) just as the πN form the Δ. Two of the more interesting Y^*s are (1) the Λ(1405), which lies just below threshold in the K-atom, qualitatively altering the $I = 0$ $\bar{K}N$ amplitude in the medium; and (2) the Λ(1520), which has a very narrow width (16 MeV), making it potentially useful in investigating the propagation of isobars in the nuclear medium. Like the π, the $\bar{K}$ is strongly absorbed in nuclei; its elastic channel wave function is localized primarily in the nuclear periphery.

The driving interest in $\bar{K}$ physics has been the use of the (K^-,π^-) reaction to transfer strangeness to the nucleus in investigating the properties of Λ- and Σ-hypernuclei. Studies of ground-state systematics (including low-lying core-excited states) as well as the level structure of the excited (including strangeness-exchange analog and super symmetric) states provide indirectly our primary knowledge of the YN interaction, a sector of the SU(3) baryon-baryon interaction not explored with conventional probes. The s-shell hypernuclei appear to be sensitive to such questions as the ΛN-ΣN coupling, the tensor nature of the triplet force, and charge symmetry breaking. The p-shell hypernuclei have been studied in an effort to understand the spin-orbit and spin-spin structure of the ΛN force; the spin-spin force is expected to be repulsive here, opposite to the NN case. Explicit three-body ΛNN force effects appear to be significant.

Interpreting the $(\bar{K},\pi)$ reaction requires that we study thoroughly the $\bar{K}$-nucleus scattering problem (and the π-nucleus problem). To construct a valid model to describe the $\bar{K}$ distortions, one must have experimental information on the $(\bar{K},\bar{K})$, $(\bar{K},\bar{K}')$, $(\bar{K},\pi)$, and ($\bar{K}$NN,YN) channels. The relative importance of $\bar{K}NN \to \pi YN$ and $\bar{K}NN \to YN$ must be established. Measurements of σ_{tot} and σ_{reac} as a function of incident momentum are called for. As with pions, one must treat consistently all the ingredients in the DWIA calculation.

Experimentally, the primary effort has been the (K^-,π^-) reaction in the region of 800 MeV/c. This work should be continued with emphasis upon improving the resolution (possibly to a level of better than 0.5 MeV) in order to resolve hypernuclear states belonging to the same configuration. This is necessary to determine the ΛN effective interaction, particularly the spin-dependence, more reliably.

The (K^-,π^-) angular distributions on light nuclei with non-alpha-particle structure are encouraged, including isotope and isotone comparisons such as $^{6,7}Li$, $^{12,13}C$, $^{16,18}O$, and ^{11}B-^{12}C. Comparison of (K^-,π^-) and (K^-,π^0) on targets such as ^9Be would permit separation of the I = 0,1 structure.

We would encourage exploring $(K^-,\pi^-\gamma)$ coincidence experiments on very light nuclei, including (π^-,γ) angular correlation measurements to fix the spin of the γ emitter.

A concerted effort in low-momentum (<500-MeV/c) $\bar{K}$ scattering would seem most rewarding. The recoilless production of Λ hypernuclei occurs at about 550-MeV/c incident momentum; strangeness analog state searches in heavy nuclei, where such collective states might be expected, would be possible. The recoilless production of Σ hypernuclei occurs at about 320 MeV/c; the existence of narrow states suggested by preliminary CERN work would require approaching this momentum as closely as possible. Such states would constrain the ΣN interaction and provide information on ΛN-ΣN conversion. Study of the Λ(1520) isobar propagation would require about 400 MeV/c; quasi-elastic K scattering near this momentum (as opposed to elastic scattering where Fermi motion effects are overwhelming) should elucidate some of the essential features of this process and complement our understanding of Δ propagation in the case of π-nucleus scattering. Thus a channel designed to operate in this momentum region would appear to offer much in the realm of K physics as well as permit one to study K^+ scattering where the $\ell = 0$ partial wave is dominant. Discrimination between the π from the $(\bar{K},\pi)$ reaction and the beam π contamination as one approaches the recoilless production condition does not appear to be impossible, although difficult. A serious study should be undertaken of the feasibility of constructing over the next five years such a specialized channel.

More precise $\bar{K}$-atom measurements are called for, so that second-order terms in the simple potential model description can be seen. This is necessary to learn something about Λ(1405) propagation in the medium (e.g., the effective mass).

Lifetime studies of the Λ in the nuclear medium are clearly feasible and should be undertaken to study the weak ΛN → NN decay and to test suggestions that the Λ becomes stable in the presence of strong nuclear electric and magnetic fields.

The near-threshold (γ,K^+) reaction should be explored as a "clean" method of producing low-lying hypernuclear states.

Finally, the (K^-,K^+) inclusive experiments looking for ΛΛ hypernuclei and Ξ hypernuclei should be explored. These systems are our only means of obtaining information about the S = −2 baryon-baryon interaction and completing our picture of the SU(3) structure of the baryon-baryon force. (See Sec. IV for a discussion of possible bound di-Λ six-quark states.)

B. (K^+,K^0)

Because of its strangeness (S = +1), the low-energy KN interaction is not resonant. There are no known S = +1 baryons or low-lying resonances, and no such simple structures are predicted in the quark model. (The exotic Z* would lie higher, at momentum >1 GeV/c, if it exists.) Thus, there are no compound states (as in the case of πN → Δ) and no near-threshold open inelastic channels.

The K is one of the weakest hadronic probes available. Below 800 MeV/c the cross section is $\sigma_{tot} \lesssim 10$ mb. This implies a mean free path $\lambda = (\rho\sigma_{tot})^{-1}$ of some 5-7 fm, assuming no drastic modification of the K propagation in the medium. (There does *not* exist an annihilation channel here as there does for the π or the K.) Because the KN interaction is weak, the multiple-scattering series should show rapid convergence. The connection between the optical model and the free KN interaction should be more direct than in the case of other hadronic probes. One would hope to construct V^{KN}_{opt} from first principles and to avoid the necessity of resorting to a phenomenological approach in interpreting K-nucleus scattering. The energy dependence of the KN amplitude (primarily $\ell = 0$, I = 1 below 500 MeV/c and $\ell = 1$, I = 0 above 500 MeV/c) should be useful in extracting nuclear structure. Because there are no open inelastic channels below the threshold for pion production (other than charge exchange), one should be able to insure consistency in the DWIA calculations between the model used to generate the distorted waves and the model used to describe the interaction in impulse approximation.

Experimentally, the K is also an attractive probe. Its large mass and weak interaction imply that it should be an ideal high-momentum transfer tool *below meson production threshold*, where the KN amplitudes are purely elastic. A detailed test of this idea should be undertaken: a comparison of form factor information from (K,K) and (e,e) elastic and inelastic scattering from light (N = Z) nuclei. (Of course, the required KN amplitudes must be determined first.) Precision experiments are called for.

If the K proves to be as attractive a tool as the theorists argue, then it should make an ideal companion to (e,e) since the K does see the neutrons. The (K,Kp) reaction should be used to extend the (e,ep) work to larger q, and the analogous (K,Kn) reaction should be used to explore the neutron structure of the nucleus. (Higher K fluxes than are presently available will necessarily be required.)

Testing of V^{KN}_{opt} will require that (K,K') data be taken.

The weak nature of the KN interaction may permit the extraction of Kn amplitudes from Kd scattering, a somewhat risky venture with the π and K.

Finally, the (K^+,K^0) reaction should be tested as a means of probing properties of the single-charge-exchange reaction not revealed with strongly absorbed projectiles as in the case of (p,n) and $(\pi^\pm,\pi^0)$; i.e., the K single-charge-exchange reaction is not surface localized.

IV. QUALITATIVE QCD TESTS IN NUCLEI

Much of the discussion in Sec. I involved implicitly the short-distance interaction of hadrons. Modern theories of extended hadrons, based upon the QCD quark-gluon model, would imply that these discussions should be couched in the language of interacting "bags" rather than that of mesons and baryons. In reality, it is difficult to find evidence from low- or medium-energy strong-interaction physics that clearly favors the QCD picture. Only qualitative "model-independent" results are likely to prove convincing.

A. Di-Λ

In QCD, one expects on rather general grounds that two Λ particles will be bound strongly. Basically, having more flavors available than in the NN case, the color-spin wave function can be more symmetric, thus lowering the gluon exchange energy. Estimates of the binding energy are in the 100-MeV range. With a kaon factory, a systematic search for the di-Λ would be possible through the double-charge-exchange $K^- \to K^+$ reaction on nuclei. We note that the very limited data available on ${}^{6}_{\Lambda\Lambda}He$ give no indication of the state. Nevertheless, there are ways to reconcile the existence of both ${}^{6}_{\Lambda\Lambda}He$ and the deeply bound di-Λ (if the latter is found). Therefore, an extensive attempt to knock out the di-Λ in $K^- \to K^+$ reactions would have important consequences.

B. Long-Range Van der Waals Force Between Hadrons

The long-range strong force has been thought to be governed by single pion exchange (except when forbidden by selection rules), since the pion is the lightest mass meson. However, another possibility is available in QCD: the exchange of two massless colored gluons should give rise to a long-range (i.e., falling as an inverse power of the separation) Van der Waals force between hadrons. Independent of theoretical predictions for the strength of the potential, the experimental limits on the strength for a strong r^{-n} potential should be lowered as much as possible (note that the strength must be defined relative to a length scale, generally taken to be ~1 fm). While such potentials are ruled out for small n (for example, by Eötvös and Cavendish-type experiments), the limits are not nearly so good for $n \gtrsim 7$.

Hadronic atoms offer some promise. However, all "standard" strong-interaction effects must be included or sufficiently large angular momentum selected so that only the higher order QED effects compete with the QCD effects. A detailed analysis of this possibility is beyond the scope of this report.

Nucleon-nucleon scattering may also provide useful limits. An analysis of the threshold energy dependence of existing phase shifts has led to the claim that powers $n \lesssim 10$ can be eliminated (for potentials of "hadronic strength"). However, the phase shifts used were obtained assuming one-pion exchange contributions (OPEC) dominated the long-range behavior. A measurement of 400-keV proton-proton scattering in the Coulomb interference region gave the scattering amplitude to an accuracy of ~0.005 fm. A theoretical estimate of the Van der Waals effect for these experimental conditions gives a modification of the amplitude of about the same size. Further study of these possibilities is needed.

V. SUMMARY OF RECOMMENDATIONS

We now summarize the recommendations relevant to near-term experimental work at intermediate-energy facilities.

Systematic inclusive measurements are very important for constraining the dynamical input to theories of hadron-nucleus interactions. Deep inelastic electron scattering is sensitive to the Δ propagator; the measurements should be extended to large energy transfer (for fixed, moderate-momentum transfer), and the separation of longitudinal and transverse response functions is essential.

Programs aimed at specifying the dominant reaction channels in pion and nucleon scattering should be carried out. These should cover a range of energies, angles, and target masses. For pion scattering in the resonance region, (π,π') and $(\pi^{\pm},\pi^{\mp})$ inclusive spectra give information on the nucleon knockout mechanism. The former should be mapped to small scattering angles, especially for heavy nuclei, as a function of energy. The double-charge-exchange inclusive measurements should be extended to heavy nuclei and to incident energies at or below the resonance. Isotopic differences and asymmetry measurements with polarized targets are sensitive to specific aspects of the Δ-nucleus interaction. The total annihilation cross section for pions should be measured more accurately, especially for energies above the resonance.

Inclusive nucleon-scattering programs are most important for the energy region corresponding to strong pion production (600-1000 MeV). Proton energy losses corresponding to quasi-elastic scattering and to Δ production must be covered. In addition to (p,p'), both (p,n) and $(\vec{p},\vec{p}')$ reactions should be investigated, since these help separate different reaction mechanisms. The inclusive (p,π) and $(p,p\pi)$ reactions, together with the (p,p') reaction, help specify the role of pion annihilation (or of the Δ-spreading interaction) in modifying the NN t-matrix in the medium.

The kinematic flexibility available in exclusive breakup reactions should be exploited to isolate specific reaction mechanisms. Systematic kinematically complete breakup measurements in pion scattering from few-body systems should be performed. These should probe both the quasi-free region and the kinematic regions in which multistep mechanisms must dominate.

Coincidence $(\pi,\pi p)$ and (p,pn) measurements are fairly direct ways of examining the in-medium t-matrix. The geometry must be chosen so as to isolate as few variables as possible. Qualitative tests of the reaction mechanism, such as measurement of the recoil nucleus momentum distribution or of the Treiman-Yang distribution, would be very helpful. In proton scattering, the asymmetry in $(\vec{p},2p)$ should be measured.

Coherent π^0 photoproduction appears to be a good way to examine the reaction mechanism in a nuclear "elastic" process. Accurate measurements of the angular distribution for a light nucleus and for a heavy nucleus should be performed.

The NN and πN bremsstrahlung appear to be rather direct ways of examining the dynamics of the scattering process (e.g., for measuring the off-shell amplitude). However, the situation is presently very confusing. Clarification (i.e., help for the theorists) may come from improvement of the data base, including asymmetry measurements.

Finally we turn to kaon physics, emphasizing again the near-term possibilities. The most important recommendation here is that attempts be made to improve the energy resolution and to extend the angular distribution measurements in the (K^-,π^-) experiments. This is needed for separating states belonging to the same configuration and thus for extracting information on the hyperon-nucleon interaction. Also, inclusive $\bar{K}$ measurements should be made as an aid in constructing $\bar{K}$ optical potentials.

While low-energy $\bar{K}$ scattering is not feasible now, it seems quite possible that a special low-energy channel could be constructed in a time period of about five years. Such a channel would permit study of recoilless production of Λ- and Σ-hypernuclei, and study of the Λ(1520) creation and propagation in nuclei. We urge that the possibility of constructing such a channel be looked at closely in the immediate future.

K^+ beams appear to provide an excellent nuclear structure tool. Emphasis should be placed upon those K^+ experiments that will test this possibility.

As a last note, it is clear that the programs outlined above require generally considerable theoretical analysis. In the absence of cloning, there would not appear to be a near-term solution to the present imbalance between experimental and theoretical effort. Increased support for theorists and increased opportunity for theoretical graduate students to become involved in intermediate-energy research activities would improve matters in the longer term.

XII. PANEL N-7

PION ABSORPTION AND PRODUCTION MECHANISMS

Chairman: Daniel Koltun
Co-Chairman: Barry Preedom

Participants: J. Alster, D. Drechsel, J. Eisenberg, H. Fearing, W. Gibbs, A. Hancock, W. Hesselink, B. Höistad, B. Mayes, G. Middelkoop, V. Raghunathan, C. Wilkin, P. Yergin, and B. Zeidman.

I. INTRODUCTION AND SUMMARY

A large variety of pion absorption and production experiments have been done over the years, and many more have been suggested. The N-7 panel tried to sort out what might be both of major interest and within reach in the next five years, with present or reasonably certain facilities. We first list briefly those types of experiments that we consider to be of high priority (but without ordering); fuller discussion follows in later sections.

- The pp $\rightarrow$ πd reaction is still the fundamental reaction in which both theory and experiment can be pushed, in principle, to considerable detail and to a high degree of completeness. We recommend accurate differential cross sections and less-accurate spin-polarization measurements over a large energy range.
- Closely related and less well studied are the pN $\rightarrow$ πNN reactions. Here complete experiments are much more difficult, but also not immediately required, from the point of view of nuclear absorption and production. These reactions play an important role in the program to study the NN system as well, and should be studied, e.g., for possible information on dibaryon states.
- Nuclear absorption of pions (i.e., annihilation = no pion out) is a major branch of the total cross section for $T_\pi < 200$ MeV, and perhaps at higher energies as well. It seems important for further progress in our general theoretical understanding of π-induced reactions to identify the major branches of the absorption by measuring the emitted particle multiplicities and spectra.
- The interest in the possibility of a "precursor" effect of pion condensation or, equivalently, enhancement of magnetic excitation of nuclei, suggests the value of pursuing certain special experiments, namely (π,2π), (e,e'π), and (π,e^+e^-).
- The (p,π) and (π,p) exclusive experiments have received considerable attention in recent years, partly as a possible nuclear structure tool. The reaction mechanism is not believed to be sufficiently well understood, however, and it seems worthwhile to try to pursue a set of experiments which might help clear this up.

We also discuss below the following reactions, which are of interest and accessible:

- (π,2N),
- (π,γ), (γ,π),
- (p,pπ) inclusive (and exclusive), and
- (π,d) or (d,π) exclusive.

We recognize the possible interest in high-energy inclusive π production by p, d, γ, etc., without making specific recommendations. Similarly, we have no additional comments on K-absorption and production experiments.

II. pp $\rightarrow$ πd

The pp $\rightarrow$ π^+d reaction has been studied as a function of energy from threshold over the (3,3) resonance. The strong energy dependence of the integrated cross section is given approximately by different theoretical models, all of which include π rescattering through the Δ but which make different assumptions about πN form factors and the importance of ρ-meson interference with the π. The models cannot be distinguished by the measured integrated cross sections, but they do not do very well with the angular distributions. Particularly since the experiments are somewhat ahead of theory here, one does not necessarily require simply more complete and accurate data on integrated and differential cross sections, but more information on the partial wave amplitudes for the reaction. This requires spin-polarization data. A preliminary report on measurements at 500 MeV at SIN, with both beam and target protons polarized, was delivered at Vancouver.[1]

We recommend that polarized pp → πd experiments be carried out at various energies from threshold to several GeV. This program is under way in part at SIN, LAMPF, TRIUMF, and ANL. It may be possible to do complete spin experiments by scattering the recoiling deuterons: $\vec{p} + \vec{p} \rightarrow \pi^+ + \vec{d}$.

The theoretical models will have to confront the spin-polarization data and then be improved, or eliminated accordingly.

III. NN → NNπ

The NN → NNπ reaction is basic to the understanding of π absorption and production in nuclear systems, and should be understood in all of its aspects for interpretation of the nuclear experiments. Also, this reaction is necessary for understanding of NN scattering at intermediate energies. For example, the energy variation in spin-spin correlated pp cross sections around 1 GeV has led to suggestions of dibaryon resonances. To study these in the inelastic channels requires complete pion production amplitudes, which are not measured.

This program is very large because of the three-body final states available. From the point of view of nuclear absorption and production, it would make sense to single out the low relative motion of the two final-state nucleons. Studies as a function of beam energy and π angle are needed. Polarized beam protons would also be of interest, e.g., for the interpretation of $(\vec{p},\pi)$ reactions on nuclei.

For study of the NN system, and dibaryon resonances in particular, polarized beam and target are important, as mentioned for $\vec{p}\vec{p} \rightarrow \pi^+ d$. The availability of polarized neutron beams at SATURNE will also be valuable (see also the panel P-1 report).

IV. DECOMPOSITION OF σ_T AND σ_{abs}

Any usable description of pion-nucleus interactions must describe the reactive content, i.e., the decomposition of the total cross section into its various reaction modes. The dependence of this decomposition on the pion energy and target mass is a guide to a qualitative understanding of the dominant processes, and provides a test of all reaction theories applied to pion-nucleus interactions.

Such a decomposition of σ_T into elastic, charge exchange, inelastic, and absorption parts, for a variety of targets at energies around 125 MeV and on ^{12}C for $100 < T_\pi < 250$ MeV, has been reported recently.[2] It would be of interest to extend this kind of study both downward and upward in energy. For very low energy, pion absorption should be the dominant reaction mode; above the resonance it is not clear how important it will remain. (For ^{12}C, σ_{abs} begins to drop with energy, but for large nuclei this is not known.)

Perhaps more important in the long run is a further development of the inelastic and absorption cross sections into their major branches: e.g., (π,πN), (π,πNN), etc., and (π,N), (π,2N), (π,xN + d), etc., that is, identifying the types of particles and their multiplicities with energy measurements. This means rather extensive studies that will have to use a variety of techniques for multiple-particle measurement: for example,

- large arrays of wire counters preceded by plastic 4π counters, and
- large-volume magnetic field essentially filled with wire counters, etc., as in the CERN OMICRON.

An adjunct to such a program of study for the whole mass range of nuclei might be a concentrated study of very light targets: ^3He, ^4He, ^6Li, etc., for which all particles might be seen. (Bubble or streamer chambers might be of some use here.)

Such a large program would also need theoretical attention. Statistical theories of energetic reactions (cascade, preequilibrium, and transport equations) might give guidance as to magnitudes. Current theories of elastic and inelastic pion reactions can be studied in terms of their reactive content, in which the role of absorption will have to be understood. (See also the N-4 panel report.)

V. ENHANCEMENT OF MAGNETIC TRANSITIONS — PRECURSOR PHENOMENA

Precursor phenomena of pion-condensation effects should manifest themselves by an enhancement of transitions to states with unnatural parity. A relatively recent development is the use of the (π^-,γ) reaction for studying the magnetic giant resonances.[3] This work is naturally complementary to the electroexcitation studies in these transitions.[4] The detection of the $J^\pi = 0^-$, $T = 1$ states is a special challenge. These states are reached by radiative pion capture and the reaction (γ,π), but strongly masked by 1^- and 2^- states nearby. The study of isovector magnetic monopole states is of interest not only to find possible enhancement effects but also to complete the study of the giant resonances in nuclei. In view of present predictions for precursor phenomena,[5] a range of momentum transfer of $2\ m_\pi \lesssim q \lesssim 3\ m_\pi$ is of particular interest. Three possible reactions have been proposed to achieve this goal.

1. $(\pi,2\pi)$. In a kinematical region where the pions are close to threshold, there is an appreciable S-wave component in two-pion wave functions, and the intrinsic pion parity favors the magnetic monopole transition.[6] A resolution of typically 2 MeV is required to separate the region of the 0^- states from other giant resonances nearby. Note that this process has received almost no experimental examination. It can also serve as a test of our theory of the reaction mechanism, which in this case is usually studied through current algebra techniques.

2. (π,e^+e^-). A pion with momentum in the region of 2-3 m_π and the pair with small total momentum probes the region of interest.

3. $(e,e'\pi)$. The scalar component of the virtual photon leads to similar selection rules as discussed above. However, at incident electron energies of 200-300 MeV, the 0^- is weakly excited relative to other giant resonances, and higher energies are necessary (see Ref. 4 for previous work). In addition, such coincidences absolutely require continuous-wave (cw) accelerators. Such accelerators under discussion are the proposed 1- to 2-GeV cw electron accelerator in the United States and the 800-MeV Mainz Microtron (first stage up to ~100 MeV under construction).

VI. (p,π) AND (π,p) EXCLUSIVE REACTIONS

These reactions have been of interest[7] in part because of the relatively large momentum transfers involved ($q > 450$ MeV/c) which might provide a test for high-momentum nucleons in nuclear targets. The reaction mechanism is not currently sufficiently understood to realize this aim. Extensive data exist for $E_p \sim 150$-200 MeV, including (p,π^-), and also for $E_p \sim 800$ MeV, but not between. Asymmetry data $(\vec{p},\pi)$ exist for several nuclei. Some (π^-,p) and (π^-,n) data exist for $T_\pi < 300$ MeV.

Theoretical analysis has been based on simple models which assume either a one-nucleon production or a two-nucleon mode [as in $pp \to \pi d$ or $pN \to \pi NN$ (see Secs. I and II above)]. Each has had some success for differential cross sections to some selected states, but $(\vec{p},\pi)$ asymmetries are less successful. No present calculation includes fully both one- and two-nucleon modes. It seems important that such calculations be undertaken to try to sort out the reaction mechanism here. Some similarities between (π,p) and high-energy (p,d) reactions (in terms of nuclear states excited) have been noted; this connection has not been completely understood.

In light of the lack of understanding of the basic reaction mechanism here, it seems worthwhile to perform a set of experiments specifically designed to learn more about it. The biggest lack is in the energy dependence of (p,π) between 200 and 800 MeV. Some of this could be done at TRIUMF, but a high-resolution spectrometer would be required. (Variable energy at LAMPF would also help.) Complete energy data on a few selected targets, with $(\vec{p},\pi)$ asymmetries and (p,π^-) as well, should be taken and analyzed with fully developed microscopic theories to fulfill the aims of this study. Then it may be possible to realize the usefulness of these reactions for nuclear structure. Alternatively, one should at least better understand the pion production or absorption interactions in nuclear targets.

VII. (π,2N)

This had been an active program until recent years, largely for stopped π^- or low-energy π^+ ($T_\pi < 70$ MeV) on relatively light targets. The most recent work [on (π^+,2p)] by Arthur *et al.*[8] and on stopped (π^-,2n) by Bassalleck *et al.*[9] had energy resolutions of about $\Delta E \sim 3$ MeV, sufficient for distinguishing final ground states for some of the light targets but not for most excitations, or for, e.g., ^{40}Ca(π^-,2n)^{38}K. Little data on heavy targets exist. For low energies, this reaction appears to be a direct 2N reaction, at least for valence-hole states, but the lack of energy resolution limits the usefulness for nuclear-structure studies. For identifying deep-hole states, which could be an attractive nuclear experiment, resolution is not important, but one would have to sort out energy-loss scattering by the outgoing particles, which would muddy the interpretation. Similarly, for heavy targets there are probably many-step processes. Statistical reaction theories (pre-equilibrium, cascade, transport equation) may be of some help here.

There might be some advantage in doing (π^+,2p) experiments at higher energy, with $\Delta E \sim$ few MeV, to look at deep-hole states. The resonant region (100-300 MeV) may not be very attractive since multiple scattering will be worse here, although it might be worth sweeping through this energy domain for some simple targets (^{6}Li, other p-shell nuclei). At energies well above 300-400 MeV, one might hope to handle the reaction similarly to (p,2p), as a probe of nuclear shell structure.

The (π,2N) reaction has been considered a possible method of looking for effects of NN correlations in nuclei. The complexity of the interactions involved in the reaction process, even where the 2N mode is the dominant direct mechanism for absorption, makes this a difficult piece of theoretical analysis, but perhaps not hopeless.

The comparison of the charge branches,

$$\frac{(\pi^-,nn)}{(\pi^-,np)} \quad \text{and} \quad \frac{(\pi^+,pp)}{(\pi^+,pn)} \ ,$$

sheds some light on this question but requires a more complicated experimental program. (The comparison should be made for similar kinematics.)

Theoretical studies have concentrated on low-energy or stopped pion absorption, removing valence-shell particles to bound excited nuclear states, and therefore can be compared to high-resolution data only. The degree of sophistication in handling nuclear structure, absorption reaction mechanism, and final-state interactions varies considerably.

VIII. RADIATIVE PRODUCTION AND ABSORPTION

Radiative pion production and absorption processes, (γ,π), (π,γ), and (e,e'π), are reactions in which the elementary operators are relatively well understood. The radiative capture of stopped pions has been applied (as a tool complementary to inelastic electron scattering) to the study of discrete nuclear levels and giant resonances, particularly with large spin-isospin matrix elements. This process has been recently reviewed by P. Truöl.[3] Here and for the inverse process (γ,π) or (e,e'π), the reaction mechanism is relatively well understood, at least for slow pions and excitation of low-lying nuclear levels. Current experimental activities in (γ,π) are at Bates, Saclay, Tohoku, Mainz, and Saskatoon. With the advent of cw electron accelerators, (e,e'π) coincidence experiments will make it possible to map the spatial distribution of spin-isospin transition densities by varying energy and momentum transfer, ω and q, separately.

Neutral pion photoproduction has been advocated as a probe of the nuclear matter density. Unfortunately, rescattering effects seem to mask this effect considerably.[10] The photoproduction of pions in the nucleon resonance region[11] is related to Δ propagation in nuclear matter. Of particular interest in this context are the Saclay experiments of the type (γ,Nπ), which are analyzed as a function of the invariant mass of the Nπ system and of the recoil momentum of the residual nucleus. These experiments show indications of surprisingly sharp resonances[11] as functions of Q, possibly related to dibaryon states. Unfortunately, such reactions are just at the limit of the experimental capabilities and suffer from small counting rates and a large number of accidental coincidences. Continuous-wave accelerators are required to produce a sufficient flux of monochromatic (tagged) photons and to suppress the background. Such accelerators will make it possible to study the observed anomalies in the Saclay experiments in full detail and, it is hoped, to find clear signatures of dibaryonic states.

Coincidence experiments of the type (e,e'π) will be useful for a decomposition of the nucleon resonance region into multipoles by measuring angular distributions, because coherent effects of Δ propagation in nuclei are expected to depend strongly on the multipolarity. Such experiments are of particular interest in view of many theoretical attempts to treat the Δ dynamics in the nuclear medium in a more microscopic Δ-hole model.[12]

IX. (p,pπ) INCLUSIVE REACTIONS

The (p,pπ) inclusive experiment is complementary to the (p,π) exclusive studies (see Sec. VI). The cross sections are presumably not small, but coincidence measurements are required. The reaction would be of interest for the high-energy ($T_p \gtrsim 500$ MeV) p-nucleus scattering and reaction program, since it should be a major contributor to inelasticity. The information also reflects on the pN → NNπ reaction in nuclei (see Secs. I and II), which is presumably basic to understanding (p,π). This reaction also reflects on the problem of Δ propagation in nuclei if the pπ pion is analyzed in terms of the decay of a Δ produced in the target. (The exclusive reaction is also of interest here.)

X. (π,d) AND (d,π)

The (π,d) and (d,π) exclusive reactions are not hard to do and are already under way. They are similar to (p,π) and (π,p) in that large-momentum transfers are involved — even larger for (d,π) than for (p,π) — and cross sections are very small (nb/sr). Very little is known about these reactions; the program is exploratory.

A special case worth mentioning is $d + d \to \pi^0 + \alpha$, which is forbidden by charge symmetry and is of interest in breaking of that symmetry.

XI. FACILITIES AND EQUIPMENT

Many of the recommended π- and p-induced experiments can be done at LAMPF, SIN, and TRIUMF, and some at higher energy proton machines like SATURNE. The more interesting electron or tagged photon experiments require a cw electron accelerator, and possibly higher energy. Two-arm spectrometers are required for (π,2N), pN → πNN (some), (p,pπ), and (e,e'π) experiments. A variable-energy spectrometer of high resolution is needed at TRIUMF, e.g., for (p,π). A large counter array for π-absorption multiplicities (like OMICRON) would be needed, e.g., at LAMPF.

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XIII. PANEL N-8

HIGH-MOMENTUM TRANSFER AT HIGH RESOLUTION

Chairman: **W. T. H. van Oers**
Co-Chairman: **H. A. Thiessen**

Participants: A. D. Bacher, I. M. Duck, R. Glauber, N. M. Hintz, Bo Höistad, R. Liljestrand, J. Matthews, R. L. Ray, P. G. Roos, J. R. Shepard, I. Sick, G. M. Temmer, J. Thirion, C. A. Whitten, Jr., and C. Wilkin.

After considering possible overlap with other panels, it was decided to discuss the following topics:

I. Elastic Scattering at High-Momentum Transfer
II. Inelastic Scattering at High-Momentum Transfer
III. Transfer Reactions
IV. Knockout Reactions

For all four topics emphasis was placed on the high-momentum transfer aspects. The panel noted a general lack in theoretical understanding of quite a few of the processes discussed. It recommends an increased level of theoretical support to remedy this situation.

I. ELASTIC SCATTERING AT HIGH-MOMENTUM TRANSFER

There exists at present a considerable amount of data on the p-d and p-^{4}He systems. Complete differential cross section and analyzing power angular distributions, including work with vector and tensor polarized deuteron beams, have been obtained for p-d up to 1 GeV, and up to 500 MeV and at 800 MeV for p-^{4}He. Considerable attention has been given to explaining the anomalously large backward-angle differential cross sections and rapidly changing analyzing powers in the p-d system. Most commonly used are the one-nucleon or nucleon-isobar exchange models and a model represented by a triangular graph involving the reaction pp → πd.[1] The p-^{4}He system is even more challenging with backward peaking disappearing between 200 and 500 MeV, to reappear with a backward-diffraction pattern around 800 MeV, as illustrated by the 788-MeV LAMPF data (Fig. XIII-1). The analyzing powers exhibit considerable structure with oscillations between large positive and negative values (TRIUMF data at 200, 350, and 500 MeV, Fig. XIII-2). So far, no systematic theoretical explanations have been presented of backward-angle elastic scattering of protons from the very light nuclei.

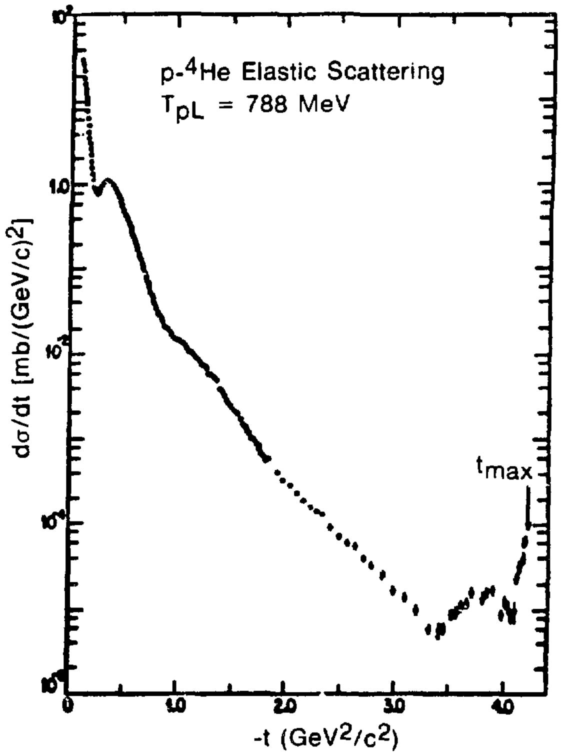

Fig. XIII-1.
Helium-4 (p,p) differential cross-section angular distribution at 788 MeV.

Recommendations

The measurement of complete differential cross section and analyzing power angular distributions for p-^{4}He above 500 MeV and for p-^{3}He above 200 MeV at 100- to 200-MeV intervals, possibly augmented with measurements of the rotation parameter Q in the case of p-^{4}He. There exist at present almost no data for p-^{3}He. One expects for p-^{3}He the importance of exchange processes to be intermediate to the p-d and p-^{4}He systems. The light nuclei in particular form an important testing ground for reaction theories. One of the prerequisites for these measurements, especially at higher energies, is an intense polarized beam (intensity on target 20-100 nA).

* * *

For the heavier nuclei there exist high-momentum transfer elastic-scattering data (up to 5-6 fm^{-1}) on ^{12}C, ^{40}Ca, and ^{208}Pb. The diffractive pattern of the angular distributions at forward angles continues smoothly to these higher momentum transfers. The value of these data is in further constraining the theoretical studies of nuclear structure properties such as the ground-state neutron densities (see also the report of panel N-1).

An example is given in Fig. XIII-3, which displays p + ^{208}Pb elastic-scattering data at 800 MeV and the

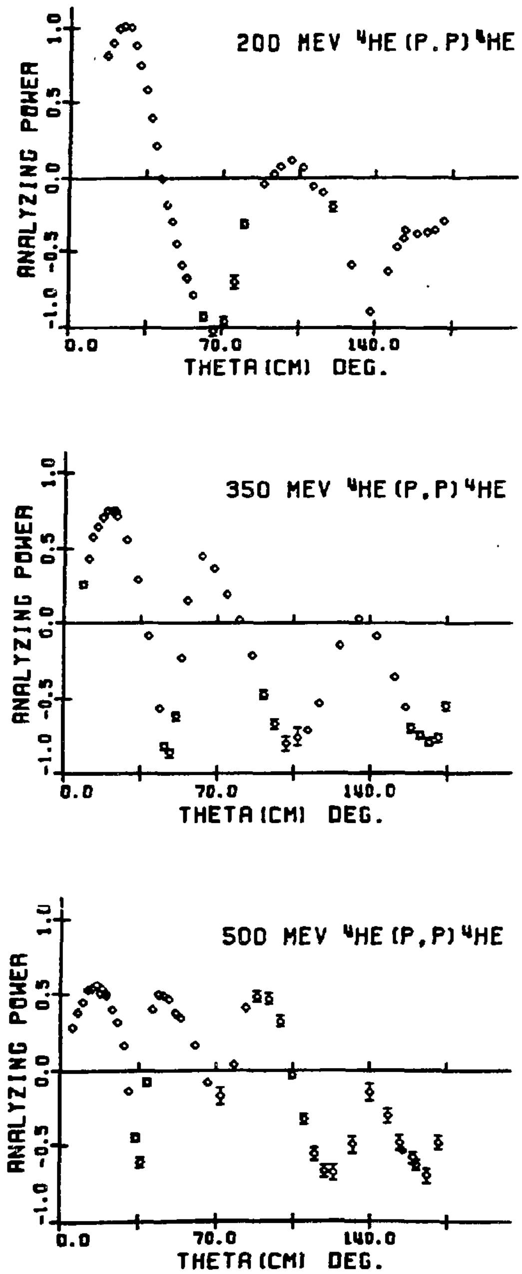

Fig. XIII-2.
Helium-4 (p,p) analyzing power angular distributions at 200, 350, and 500 MeV.

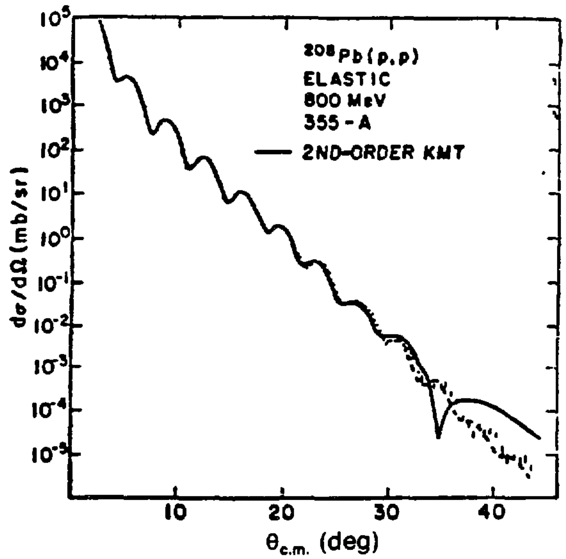

Fig. XIII-3.
Lead-208 (p,p) differential cross-section angular distribution at 800 MeV compared to a second-order KMT multiple-scattering calculation.

results of a second-order Kerman-McManus-Thaler (KMT) multiple-scattering calculation that breaks down at high-momentum transfer ($q \approx 4.5\ fm^{-1}$). The successful theoretical interpretation of selected elastic-scattering angular distributions out to very high- ($q \sim 6\ fm^{-1}$) momentum transfers would give one more confidence in the extraction of neutron distributions from data that extend out to only about $q \simeq 3\ fm^{-1}$.

Recommendations

The measurement of differential cross section and analyzing power angular distributions for a few selected targets, e.g., ^{16}O, ^{40}Ca, and ^{208}Pb, to even larger momentum transfers to constrain, test, and further develop the theoretical analyses. Differential cross-section angular distributions, extending to momentum transfers larger than the kinematically allowed momentum transfer in NN elastic scattering at the same incident energy, are interesting since off-shell NN amplitudes are required in lowest order. The inputs to these theoretical analyses are the NN scattering amplitudes. The panel urges that measurements of the *NN scattering parameters* at about 600, 800, and 1000 MeV be made with high priority. A prerequisite for the p-nucleus measurements is the availability of an intense polarized proton beam ($I \gtrsim 100$ nA).

II. INELASTIC SCATTERING AT HIGH-MOMENTUM TRANSFER

A. Introduction

In recent years the availability of high-resolution spectrometers at intermediate-energy facilities has allowed the measurement of inelastic scattering to many discrete states in nuclei to momentum transfers as large as 3-6 fm^{-1} (see Fig. XIII-4). The energy resolution currently available is ~50 keV for electrons and protons and ~150 keV for pions.

In the discovery of new states, in the assignment of spin and isospin quantum numbers, and in the determination of configurations, electrons, protons, and pions have each made significant contributions. While the interpretation of experiments at high-momentum transfer is more direct for electrons than for the hadronic probes (see the N-3 panel report), several features of the hadronic probes can be exploited to obtain additional information about nuclear structure. These include an NN spin dependence, which provides a tool for separating different spin and orbital excitation modes, and an isospin structure (protons and pions), which probes neutron and proton components in a complementary way. Furthermore, the stronger interaction of the hadronic probes results in the presence of multiple-step processes in the excitation of collective bands.

Since measurements with electrons have been the focus of panel N-3, we will deal primarily here with what can be learned additionally with hadronic probes, keeping in mind that our understanding of how to extract physics from hadronic probes is less well understood than for electrons.

B. Special Features of High-Momentum Transfer (Present Status)

1. Determination of Transition Densities

For electrons there is a direct connection between the momentum transfer observed in the laboratory and the momentum content of the elementary excitation in the nucleus. For hadronic projectiles this connection is dependent upon the validity of either a multiple-scattering description (Glauber or KMT)

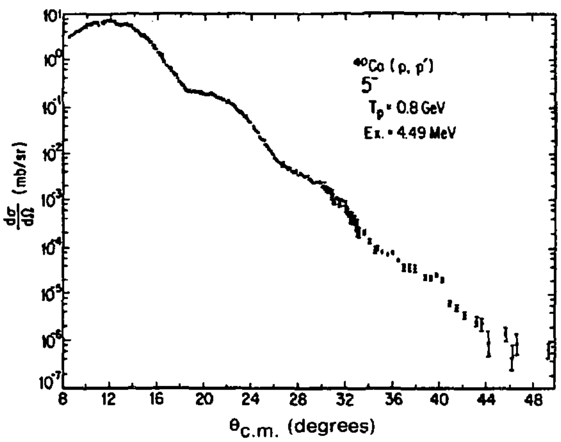

Fig. XIII-4.
Inelastic scattering of 800-MeV protons leading to the 5^- state in ^{40}Ca.

or the distorted wave impulse approximation (DWIA). Consequently it is of fundamental importance to test and further refine theories of hadronic scattering by using information obtained with greater confidence from electromagnetic probes.

In this comparison there have been some encouraging early results. The KMT formalism seems to work out to 2.5-3 fm^{-1} for elastic scattering (see Sec. I of this report). Some tests of KMT have been made for inelastic scattering using collective prescriptions for the transition densities. It is important, however, to establish the connection within a more microscopic framework.

An alternate theoretical approach, the DWIA, when applied to inelastic proton data at 135 and 800 MeV, has given angular distributions in good agreement with experiment to $q \sim 2\ fm^{-1}$ and, perhaps of more importance, has yielded *spectroscopic strengths in moderately good agreement* with those obtained from electron scattering. These calculations employed either shell-model wave functions or transition densities from electron scattering (where available). This comparison has been made both for simple configuration high-spin states and for low-lying collective transitions (e.g., ^{208}Pb, 3^-).

Thus it appears hopeful that hadronic probes can be used to extract transition densities to moderate q. In addition to the special features of the hadronic probes noted above, considerations of cross section, beam intensity, etc., favor the hadronic probes for exploratory studies and detailed mapping of systematics throughout the periodic table.

2. Selective Excitation of High-Spin States

As discussed more fully in the N-2 panel report, a new class of high-spin, one-particle, one-hole states are selectively excited at high-momentum transfer ($qR \simeq J$) and can be seen above the background of many unresolved low-spin states (see Fig. XIII-5). Data at higher momentum transfer can test our theoretical understanding of the microscopic structure of these states. This is particularly true for electron scattering. The importance of these states lies in their relatively simple structure. Thus they are useful as benchmarks for testing our understanding of hadronic probes (protons and pions) including

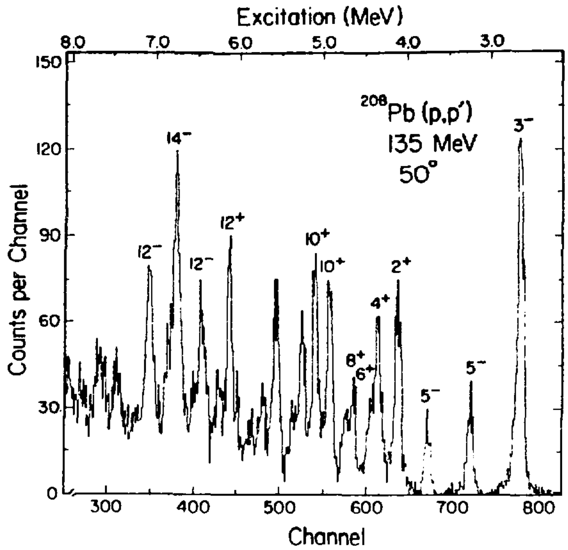

Fig. XIII-5.
Inelastic spectrum for ^{208}Pb (p,p') at 135 MeV and a laboratory angle of 50°, illustrating the selective excitation of high-spin states (e.g., 12^+, 12^-, and 14^-).

both the reaction theory and the NN force in nuclear matter.

3. Transition Densities Between Excited States

Because of the strong nature of the interactions, multiple-step excitation processes with hadrons are much more important than for electrons. Examples of situations in which multiple-step excitations have been shown to be important for protons at 800 MeV are the inelastic excitation of higher members of rotational and vibrational bands in ^{24}Mg (see Fig. XIII-6) and ^{176}Yb, and multiple phonon transitions in vibrational nuclei. In the theoretical analysis of these multistep processes, one needs the direct ground-state to final-state transition densities and the transition densities between excited states. Electron-scattering data give the most reliable direct densities (up to $\sim Y_6$), and multiple Coulomb excitation experiments can give the low multipole transition probabilities (mostly Y_2) between excited states. The best hope for obtaining the higher multipole transition densities, given the present facilities, is from high-momentum transfer experiments with hadronic probes.

Recommendations

1. Calibration of the Hadronic Probes

Tests of reaction models. In order to exploit the special features of hadronic probes, it is of crucial importance to test the reaction models and the effective NN or πN interactions in nuclei. To carry out this program we recommend experiments on selected classes of states in a few nuclei with electrons, protons, and pions (where resolution permits). Examples are

- low-lying collective states such as the 3^- and 5^- in ^{208}Pb, and
- high-spin, particle-hole states in such nuclei as ^{16}O, ^{28}Si, and ^{208}Pb.

2. New Information from Hadronic Probes

a. Spin Dependence. The spin dependence of the NN interaction can in principle allow the extraction of spin-dependent transition densities in more detail than is possible with electrons. To study this spin dependence, we recommend that inelastic scattering studies be actively pursued with polarized beams. Measurements of analyzing powers and spin-flip probabilities can be expected to provide new information on magnetic excitations in nuclei.

b. Isospin Dependence. Because (p,p') and (π,π') experiments are sensitive to neutron and proton components of nuclear wave functions in a way different from (e,e'), these measurements can provide new or complementary information. An example is the search for isoscalar magnetic excitations. High-momentum transfer is necessary to excite the high angular-momentum spin-flip modes. Recent experiments with $\pi^{\pm}$ beams indicate that these projectiles could play a major role in this effort if the experimental resolution could be improved to that at existing electron and proton facilities.

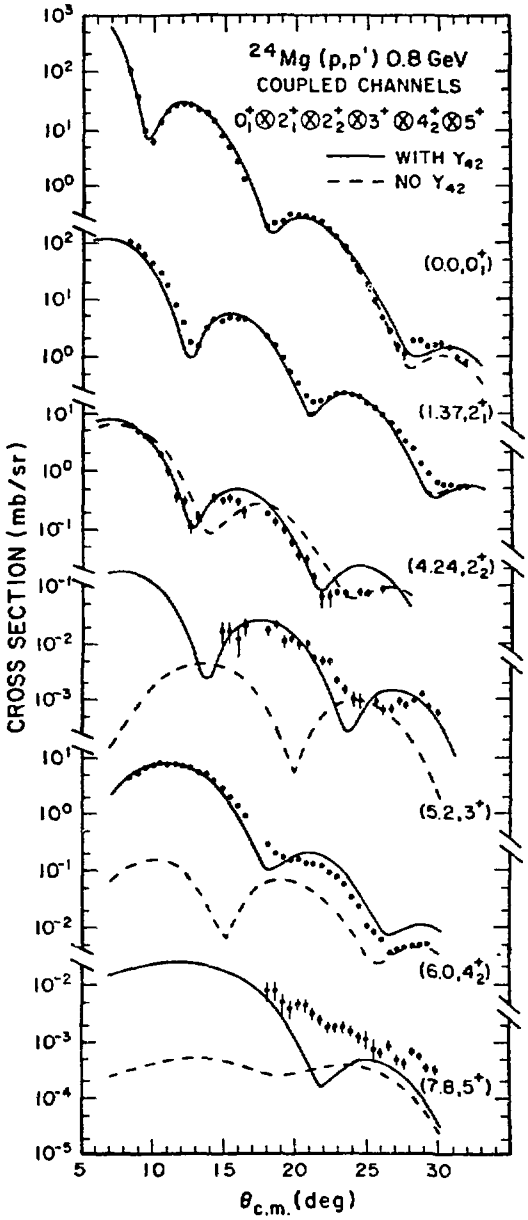

Fig. XIII-6.
Angular distributions for the ground state (K = 0) and excited (K = 2) bands in ^{24}Mg excited by 800-MeV protons. Solid and dashed curves show the results of coupled-channels calculations with and without direct nonaxial hexadecapole (Y_{42}) coupling between the bands.

c. *Multiple-Step Excitations.* The potential utility of hadronic probes for extracting information on high-multipole transitions and transition densities between excited states should be examined for rotational and multiple phonon vibrational bands in such nuclei as the rare earths (e.g., samarium isotopes) and in other well-established transition regions (e.g., germanium and palladium).

3. Emphasis on High Resolution

High-resolution facility. It has been established that new nuclear structure information can be obtained at high-momentum transfer. Unfortunately, with existing energy resolution ($\gtrsim$50 keV), a number of the states discussed above cannot be adequately resolved. In addition, the search for new states is severely limited. *It is a major recommendation of* this panel that studies be made of the feasibility of a ~10-keV resolution facility in the range of 300 to 500 MeV (electrons and/or protons).

III. TRANSFER REACTIONS AT HIGH-MOMENTUM TRANSFER

In the simplest one-nucleon model of the transfer process (Fig. XIII-7), the intermediate-energy single-nucleon pickup reactions [(p,d), (π^+,p), etc.] could be expected to give information about high-momentum components of the wave function of the picked-up nucleon. Preferential population of single-hole states is also a natural result of this model. Consequently the utility of such reactions was originally anticipated to be (1) determination of high Fourier components of nuclear wave functions, and (2) detection and analysis of "deep-hole" states. Careful examination of pickup reactions on light targets (e.g., Ref. 3) strongly suggests that other mechanisms, involving two or more target nucleons and intermediate mesons (Fig. XIII-7), may dominate the reactions at intermediate energies. Such a complexity of the reaction mechanism serves to complicate extraction of the information originally sought from these reactions.

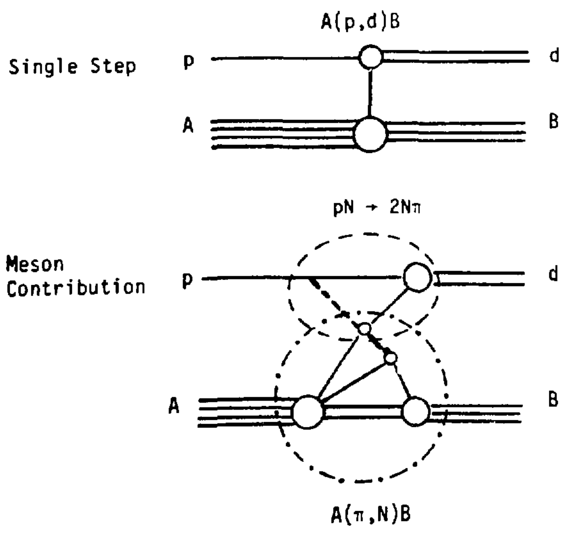

Fig. XIII-7.
Reaction diagrams for A(p,d)B.

Therefore our view of the physics to be learned must be somewhat altered. Before any nuclear structure information can be extracted from transfer reaction data, the reaction mechanism must be understood at a quantitative level. This will surely involve a great deal of theoretical effort. However, the complexity of the mechanism need not be viewed as an unwelcome impediment. The transfer mechanisms may be dominated by processes which are weak for elastic and inelastic hadron scattering and which therefore are better studied in the transfer reactions. Whether or not this is true, qualitative understanding of the transfer mechanism is a worthy goal in its own right. Furthermore, if the reaction process is different from the single-nucleon picture that describes low-energy pickup, one may expect to see new and interesting types of nuclear levels excited.

Experimental results to date show many interesting features. Angular distributions of (p,d) cross sections to discrete levels have been measured at T_p = 700 to 800 MeV for many light (A $\leq$ 40) targets. The anticipated single-particle levels are observed along with strong states believed to arise from multistep processes[2] (Fig. XIII-8). While some features of these data can be described quantitatively using the distorted wave Born approximation (DWBA) (Fig. XIII-9), others cannot. In addition, new unexplained levels are seen which do not appear in low-energy pickup reactions (Fig. XIII-8). Other recent results indicate that analyzing power measurements may be very useful, since their angular distributions (Fig. XIII-10) show considerable structure in contrast to the relatively

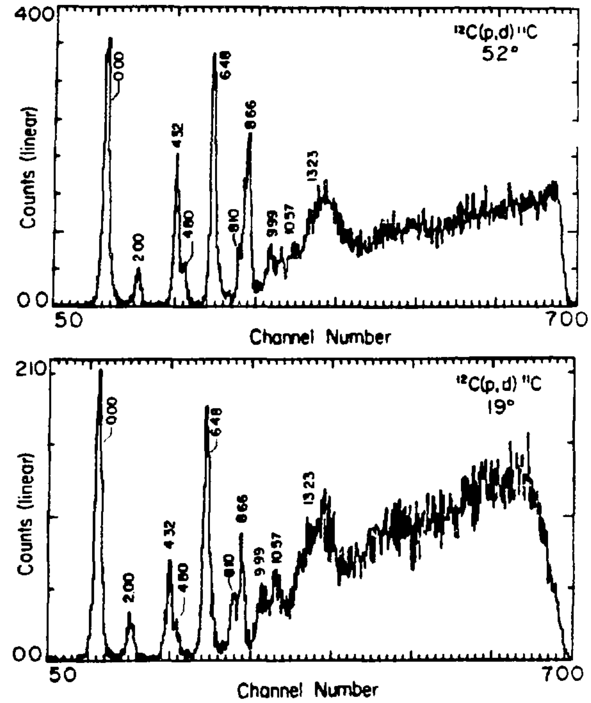

Fig. XIII-8.
Carbon-12 (p,d) spectra for T_p = 800 MeV.

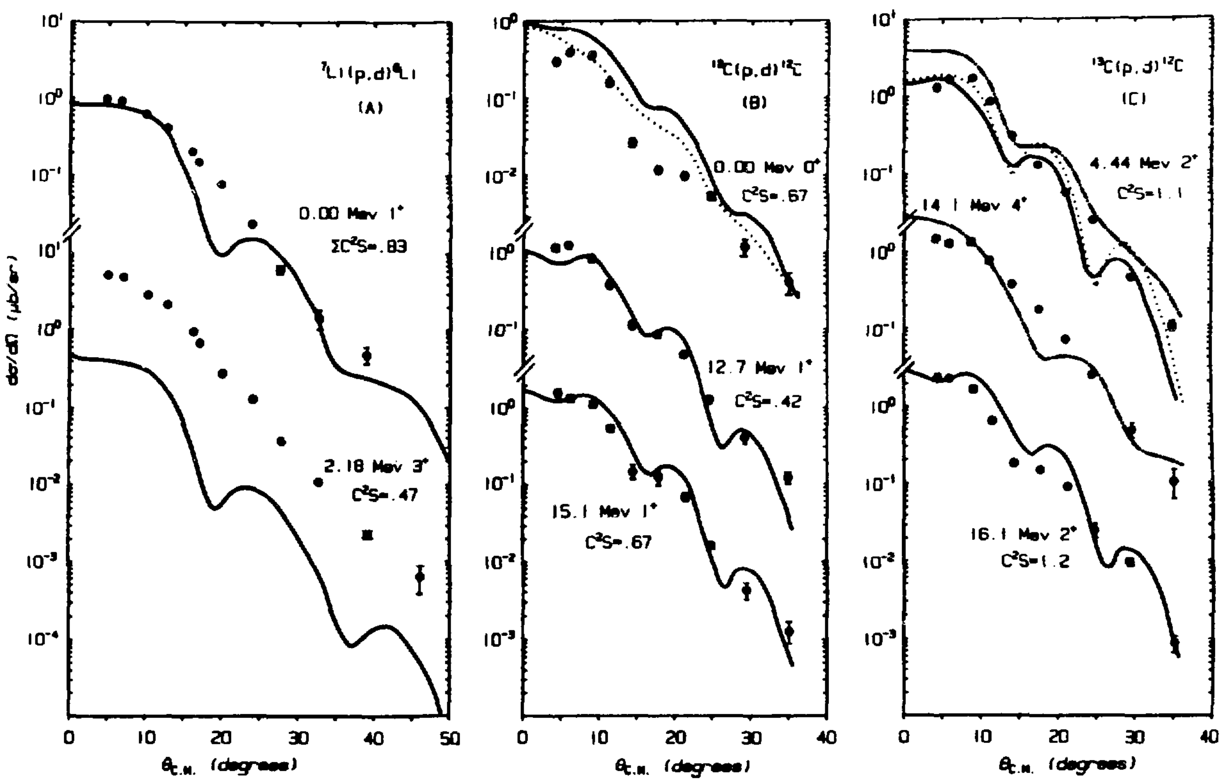

Fig. XIII-9.
Lithium-7 and Carbon-13 (p,d) angular distributions for T_p = 800 MeV. The solid curves are absolutely normalized exact-finite-range (EFR) DWBA calculations.

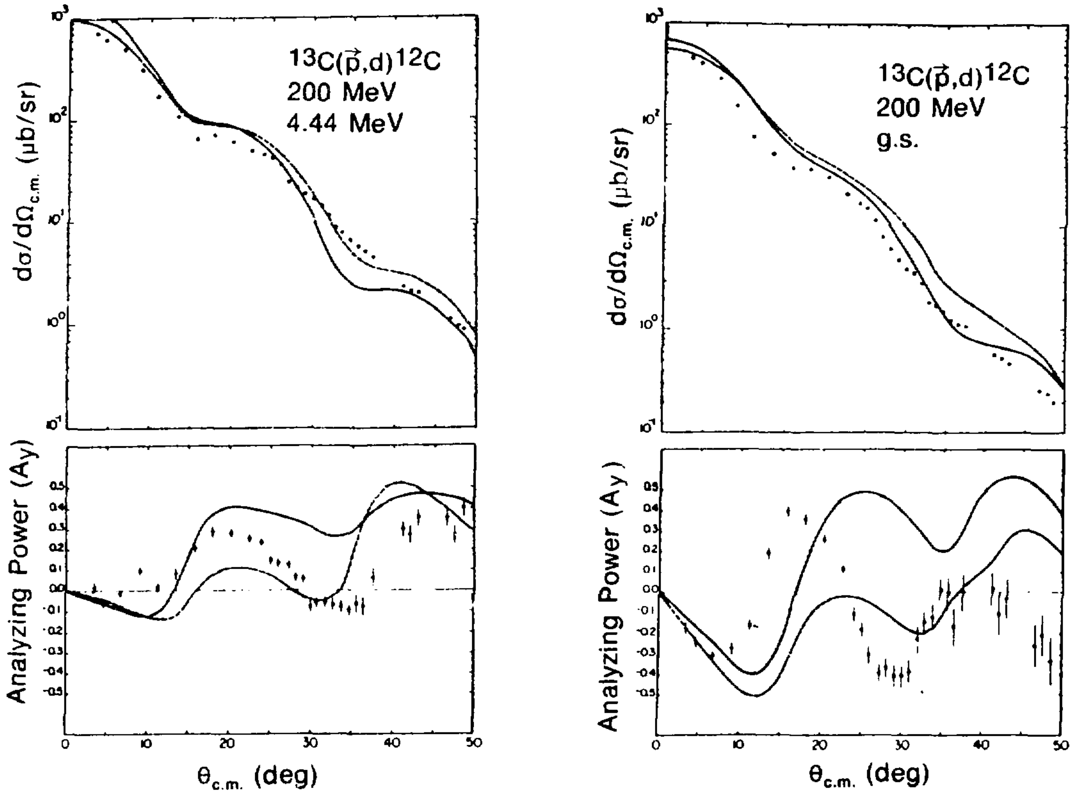

Fig. XIII-10.
The $^{13}C(\vec{p},d)^{12}C$ cross sections and analyzing powers for T_p = 200 MeV measured at TRIUMF. Curves are EFR (——) and zero-range (ZR) (----) DWBA calculations.

featureless cross sections. The apparent j-dependence of these analyzing powers suggests that the $(\vec{p},d)$ reaction at these energies (T_p = 200 MeV) may be a useful spectroscopic tool, perhaps even in making j-assignments for deep-hole states.

A large body of (π^+,p) and (p,π^+) data has also been accumulated. Perhaps the most important feature of these data is the striking resemblance to the 800-MeV (p,d) data (Fig. XIII-11). Indeed, recent theoretical work[3] has shown that this similarity can be understood by viewing the (π^+,p) as a subprocess in the (p,d) reaction which contains all of the nuclear structure effects and most of the reaction mechanism effects [see Fig. XIII-7(b)]. Direct theoretical treatment of the (π^+,p) reaction mechanism is, however, in a very confused state due to uncertainties about the reaction mechanism.

Both the (p,d) and (π^+,p) cross sections appear to display a strong A-dependence, decreasing rapidly with increasing mass. Such behavior is difficult to understand qualitatively; plane wave Born approximation (and to a somewhat lesser extent, DWBA) calculations suggest little A-dependence. A clue to the reaction mechanism surely lies hidden in this effect.

Data for the (γ,p) and (p,γ) reactions are limited due to the experimental difficulties involved. There, too, questions about the reaction mechanism make interpretation difficult. Some features of the data seem well explained using a simple single-step model. The extraction of a momentum-space wave function of the $d_{3/2}$ proton in ^{40}Ca using this model is one example. Consistency with (e,ep) measurements is perhaps another. However, the near equality of (γ,p) and (γ,n) cross sections at $E_\gamma \sim$ 60 MeV cannot be explained in such a picture. For $E_\gamma >$ 250 MeV, multiple-step processes involving Δ formation are expected to become large.

A few general features emerge from the present experimental and theoretical situations for

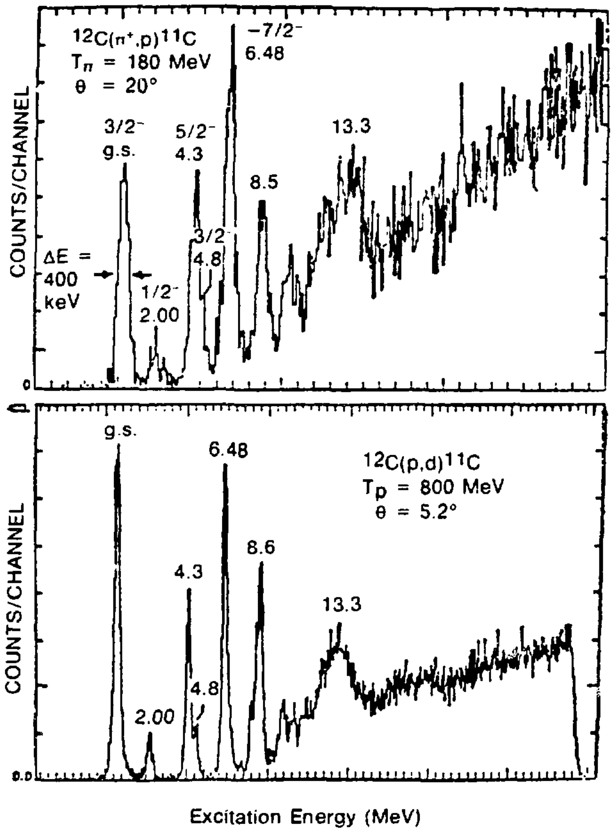

Fig. XIII-11.
The $^{12}C(p,d)$ and $^{12}C(\pi^+,p)$ spectra for T_p = 800 MeV and T_π = 180 MeV.

intermediate-energy transfer reactions. Most obvious is the pervasive uncertainty about the reaction mechanisms. The greatest investment of time and effort must be directed toward illumination of reaction processes. Theorists should be encouraged to examine carefully the large body of high-quality data already available. Experimentalists should be encouraged to perform those experiments most likely to help unravel the reaction mechanism. Also, the apparent link between the (p,d) and (π^+,p) reactions is very intriguing and must be more thoroughly established. The understanding of one of these processes is very likely to give the key to the other. Furthermore, the nature of the "new" levels observed in the (π^+,p) and the 800-MeV (p,d) measurements should be examined. The structure of these levels may be novel and interesting.

Recommendations

The measurement of ($\vec{p}$,d) cross sections and analyzing powers on ^4He and $^{12,13}C$ at 200 ≤ T_p ≤ 800 MeV in 100-MeV steps. These measurements would fill the gap between the existing low-energy (T_p ≤ 200 MeV) measurements and the 700- to 800-MeV Saclay and LAMPF data, and provide analyzing powers at all energies. These data are important because they cover the energy range where the meson-exchange processes indicated in Fig. XIII-7 are expected to "turn on," and should therefore be extremely useful in testing various reaction models. Care should be taken to choose energies which will allow comparison with (π^+,p) results. The completion of the TRIUMF spectrometer is required in order to cover the 200-400-MeV region.

The determination of the A-dependence of (π^+,p) and (p,d) cross sections. Targets should have A > 40. This program may be quite limited. Time has already been allocated at LAMPF for $^{90}Zr(p,d)$ measurements at T_p = 800 MeV. After these results become available, the need for more measurements, perhaps on ^{208}Pb, can be assessed. Such a measurement could most readily be done at LAMPF or Saclay.

An extension of (e,ep) measurements to check consistency with the (γ,p) results. This may allow a check of the (γ,p) mechanism. In conjunction with these experiments, more (γ,n) measurements should be encouraged, again because comparison with (γ,p) will likely give information about the reaction mechanism. Measurements of angular distributions for the inverse reaction (p,γ) currently under way at Indiana University Cyclotron Facility can be expected to provide a more stringent test of the theoretical models for these processes. Some further (γ,p) measurements, either on new targets or with improved resolution, should be undertaken (see report of panel N-5).

A study of the "new" levels seen in (p,d) and (π^+,p) reactions. The multiple-energy measurements contained in our first recommendation will be very useful in this regard, since the strength of these levels as a function of energy is likely to give some indication of their nature. Analyzing powers may also provide useful information. These efforts should be coordinated, if possible, with the measurement of conventional low-energy reactions which excite these states.

IV. KNOCKOUT REACTIONS (p,2p), (p,pn), (e,ep), (p,pα), etc.

A primary motivation for studying nucleon knockout is to obtain basic nuclear structure information on the single-particle structure of nuclei. At intermediate energies these reactions appear to be dominated by single-particle knockout and are reasonably well described by DWIA calculations — at least over a limited range of bound-nucleon momenta q. However, relatively little data exist with energy resolution sufficient to examine the details of individual states.

Compared to experimentally easier measurements which in first order contain the same nuclear structure information [e.g., (p,d) and (π^+,p)], the coincidence experiments have at least two advantages. First, momentum matching is possible independent of the bombarding energy. One can choose bombarding energies to minimize distortion effects and still sample the bound-nucleon momentum components to q = 0. DWIA calculations and two-body cross sections suggest that appropriate energies are $T_p \gtrsim$ 200 MeV (Ref. 4) for (p,2p), and $T_e \gtrsim$ 500 MeV for (e,ep). Second, the kinematic flexibility of the second ejectile allows one to test the reaction model in detail. For example, one can test the factorization of the two-body cross section,[5,6] measure the pole dominance with Trieman-Yang tests, and sample the same momentum components under a variety of conditions.

A comparison of electron vs proton-induced nucleon knockout shows advantages for each. The (p,2p) has a cross section roughly 10^4 times as large as (e,ep) at q = 0, providing definite experimental advantages. The availability of polarized proton beams allows one to assign j-values[7] to deeper-lying states and thereby locate the centroids of each component, $j = \ell \pm 1/2$. The primary advantage of (e,ep) lies in the fact that one has only a single strongly interacting particle. As a result, for low nucleon momenta, reduction factors due to absorption are roughly the cube root as important. Table XIII-I indicates the reduction factors for knocking out a low-momentum nucleon. Clearly for deeper-lying states and heavier nuclei, electrons have a distinct advantage and sample more of the interior of the nucleus. Nucleons in the final state corresponding to the knockout of a low-momentum nucleon can rescatter and appear to arise from a high-momentum component. This effect is almost certainly not described by the conventional DWIA. Although both reactions suffer from this effect, the presence of only one strongly interacting particle helps significantly. Comparison of d(p,2p)n (Ref. 8) and d(e,ep)n (Ref. 9) suggests that whereas (p,2p) in conventional geometries can probably be described reasonably well by DWIA to q ~ 200 MeV/c (see also Fig. XIII-12), (e,ep) may be capable of sampling to q ~ 300 MeV/c or greater.

In the case of cluster knockout such as (p,pα), the data again appear to be well described by DWIA for proton energies above 100 MeV. At lower energies one of the prime difficulties lies in the description of

TABLE XIII-I

REDUCTION FACTORS FOR KNOCKOUT OF A LOW-MOMENTUM NUCLEON DUE TO ABSORPTION

Target Nucleus	Single Particle Knocked Out	Reduction from Plane Wave $\left(\frac{\text{DWIA}}{\text{PWIA}}\right)$	
		(p,2p) 300 MeV	(e,ep) 500 MeV
^{12}C	$1p_{3/2}$	0.5	~0.8
^{12}C	$1s_{1/2}$	0.4	~0.75
^{40}Ca	$2s_{1/2}$	0.25	~0.6
^{40}Ca	Deep hole	0.05	~0.3

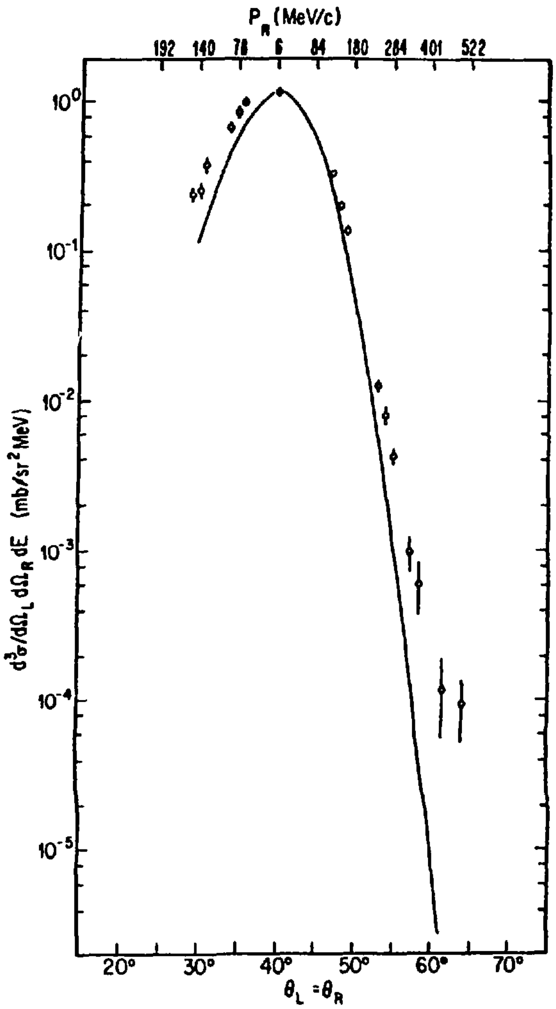

Fig. XIII-12.
Helium-4 (p,2p) coplanar symmetric angular distribution data compared with a DWIA calculation.

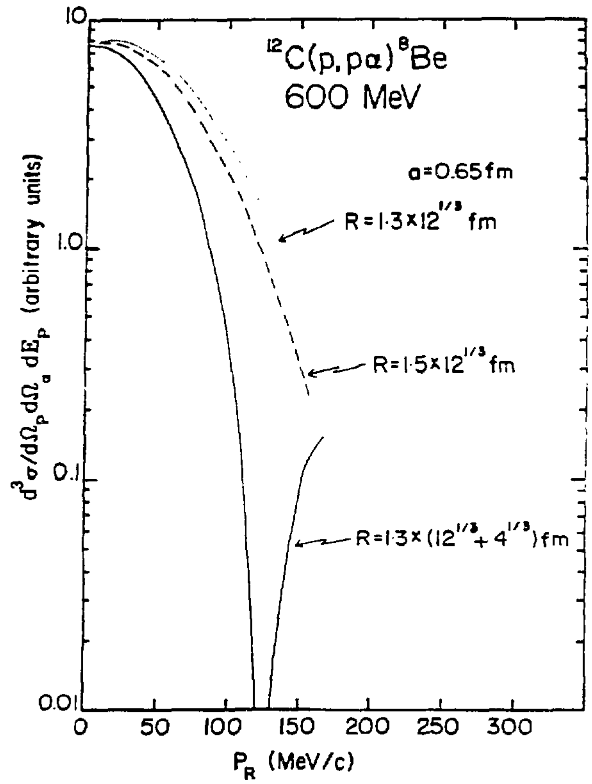

Fig. XIII-13.
Quasi-free $^{12}C(p,p\alpha)^8Be$ cross sections at 600 MeV for three different radius parameters of the bound state potential well.

the bound "cluster" wave function. This limits the accuracy with which spectroscopic information can be extracted. However, DWIA calculations[10] at higher energies indicate enhanced sensitivity to the bound wave function (see Fig. XIII-13). Data at these energies should improve the extracted spectroscopic information, and help to answer the question of whether clustering exists beyond that predicted by the shell model. In the case of electrons [e.g., (e,eα)] the cross sections are very small. The strong absorption of the α particle damps (e,eα) and (p,pα) by comparable amounts.

To reiterate, nucleon knockout provides the basic information on the single-particle structure of nuclei (centroids and widths). A combination of medium-energy, high-resolution electron and proton studies should substantially improve our knowledge for individual j-shells. Furthermore, these data should provide more detailed information on the single-particle wave functions to q $\simeq$ 200-300 MeV/c. For cluster knockout, medium-energy data should provide further information on our understanding of multiparticle correlations in nuclei.

Recommendations

The measurement with good resolution of (p,2p) and (e,ep) knockout reactions in a variety of geometries, not only to obtain spectroscopic information but also to test in detail the reaction *mechanism.* In the case of the (p,2p) reaction, the use of polarized protons has distinct advantages. This work would be greatly enhanced by the presence of a pair of large solid-angle, broad-range, and modest-resolution ($\Delta p/p \sim 5 \times 10^{-4}$) spectrometers at one of the intermediate-energy proton accelerators that has a high duty factor.

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PANELS

Workshop on Program Options in Intermediate Energy Physics

Clinton P. Anderson Meson Physics Facility of
Los Alamos Scientific Laboratory

P-1 **STRONG INTERACTIONS**
Chairman: Richard Silbar, *LASL*
Co-Chairman: Peter Carruthers, *LASL*

P-2 **WEAK INTERACTIONS**
Chairman: Bruce H. J. McKellar, *University of Melbourne*
Co-Chairman: Peter Herczeg, *LASL*

P-3 **NEUTRINO INDUCED INTERACTIONS**
Chairman: Felix H. Boehm, *Caltech*
Co-Chairman: Richard Slansky, *LASL*

P-4 **ELECTRO-WEAK INTERACTIONS AND EXOTIC ATOMS**
Chairman: C. S. Wu, *Yale University*
Co-Chairman: Patrick O. Egan, *Yale University*

N-1 **NUCLEAR DENSITIES AND DYNAMIC CHARACTERISTICS**
Chairman: George J. Igo, *UCLA*
Co-Chairman: Robert L. Ray, *LASL*

N-2 **ELEMENTARY EXCITATIONS**
Chairman: G. T. Garvey, *ANL*
Co-Chairman: Helmut Baer, *LASL*

N-3 **CORRELATIONS IN NUCLEI AND HIGH MOMENTUM COMPONENTS**
Chairman: Ingo Sick, *University of Basel*
Co-Chairmen: Charles A. Whitten, *UCLA*
Jonas Alster, *Tel Aviv University*

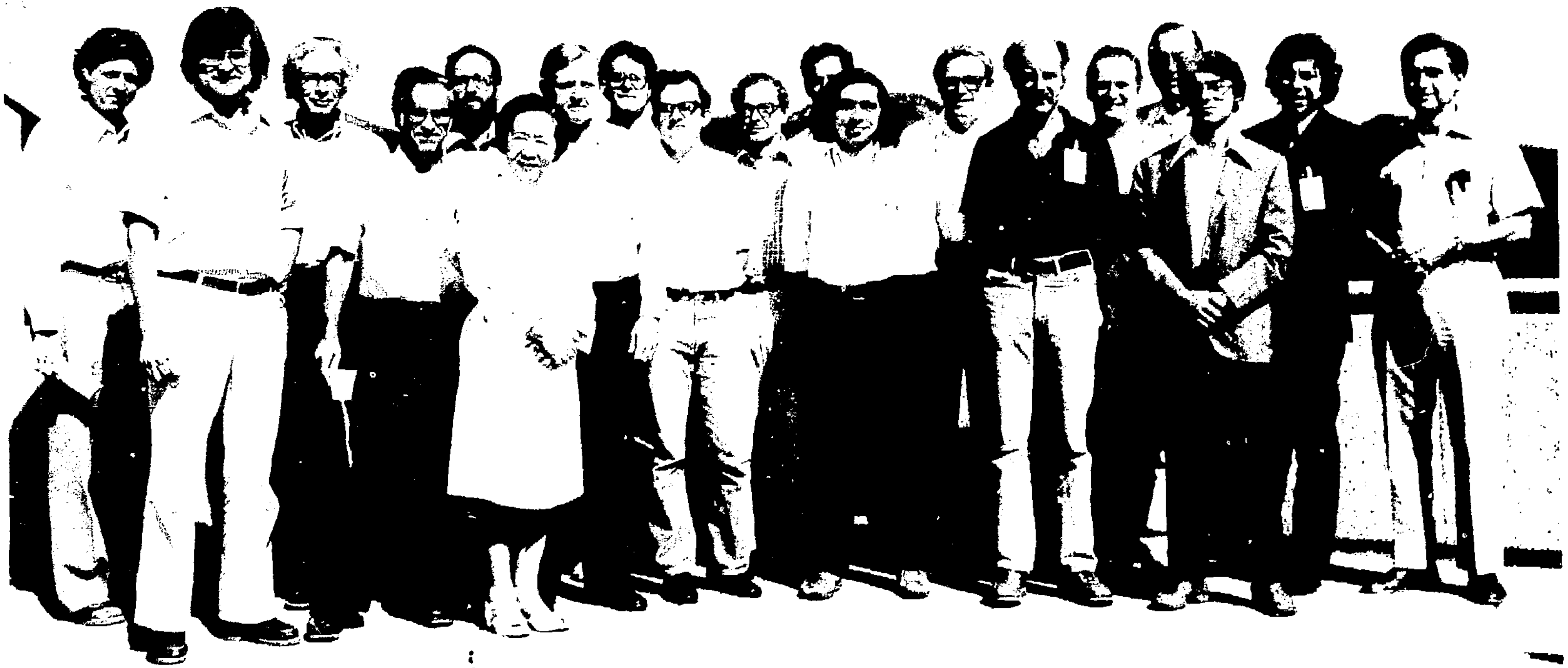
N-4 **MESON DEGREES OF FREEDOM AND PROPAGATION IN NUCLEI**
Chairman: Judah M. Eisenberg, *Tel Aviv University*
Co-Chairman: Gerard Stephenson, *LASL*

N-5 **WEAK AND ELECTROMAGNETIC INTERACTIONS IN NUCLEI**
Chairman: Kenneth M. Crowe, *LBL*
Co-Chairman: James Friar, *LASL*

N-6 **PARTICLE INTERACTIONS WITHIN NUCLEI**
Chairman: Ernest J. Moniz, *MIT*
Co-Chairman: Benjamin F. Gibson, *LASL*

N-7 **PION ABSORPTION AND PRODUCTION MECHANISMS**
Chairman: Daniel S. Koltun, *University of Rochester*
Co-Chairman: Barry M. Preedom, *University of South Carolina*

N-8 **HIGH MOMENTUM TRANSFER AT HIGH RESOLUTION**
Chairman: W. T. H. van Oers, *University of Manitoba*
Co-Chairman: H. A. Thiessen, *LASL*



Workshop Chairpersons:

(Left to right): Ingo Sick, Helmut Baer, Felix Boehm, Ernie Henley, Dan Koltun, Chien-Shiung Wu, Ben Gibson, Pat Egan, Bruce McKellar, Jonas Alster, Judah Eisenberg, Ernie Moniz, Jerry Stephenson, Gerry Garvey, Ken Crowe, John Allred, Dick Silbar, Wim van Oers, and Earle Lomon.

Dick Slansky

C. S. Wu and George Igo

Arch Thiessen and Barry Freedom

Chuck Whitten

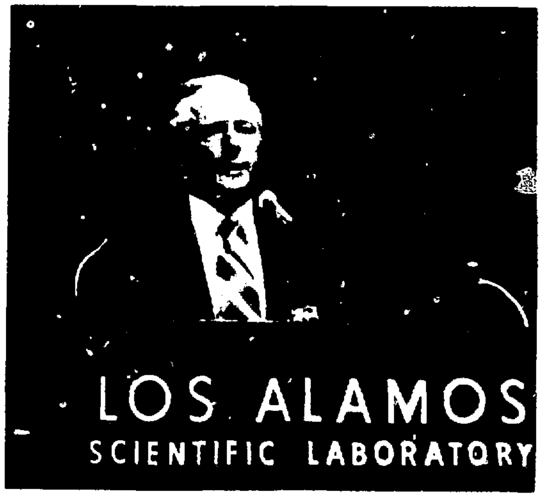
Marian Martinez,
Peter Carruthers,
Carolyn Valentine

Lanny Ray and Jim Friar

Peter Herczeg

OPENING SESSION

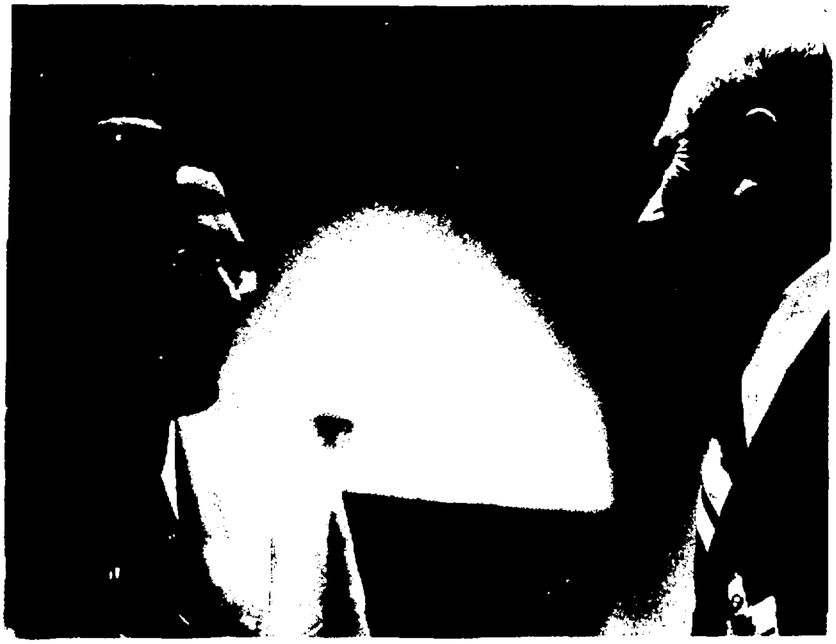
Donald M. Kerr, Director of LASL



Louis Rosen, Director of LAMPF

Ernest M. Henley, Chairman of the Workshop

Earle L. Lomon, Chairman
Steering Committee



Don Kerr and Louis Rosen

Stan Hanna and Gerry Brown

Jack Sample

Torleif Ericson

Ken and Janeane Crowe, Colin Wilkin

Gerry Garvey and Paul Debevec

Gerhard Backenstoss, Tom Romanowski

June Matthews

Peter Gram

Howel Pugh

Dick Mischke,

Nigel Lockyer,

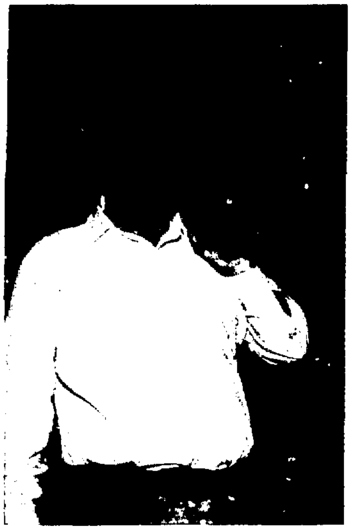
Cy Hoffman

John Allred and Vadim Bunakov

Ling-Fong Li and Tim Antaya

Dan Koltun, John Domingo

Felix Boehm and Bill Donnelly



Ed Boschitz

Claude Petitjean

Glen Rebka, Earle Lomon, Ann Rebka

Darragh Nagle

Mary Rosen and Vladimir Lobashev

Jacques Thirion, Louis Rosen, and Stan Livingston

Margaretha van Oers, Arch Thiessen

Toshimitsu Yamazaki and Tom Kinoshita

Dominique Bernard, Gerry Phillips, Dick Silbar

Charles Critchfield and Ernie Henley

Nancy Igo and Maurice Goldhaber

Jerry Stephenson and Bill Mayes

Judith and Ger van Middelkoop

Linda Tyra,

Alice Horpedahl,

Sue Willis

APPENDIX B

PROGRAM

Workshop on Program Options in Intermediate Energy Physics

Clinton P. Anderson Meson Physics Facility of
Los Alamos Scientific Laboratory

Unless otherwise shown, activities of the LAMPF Workshop are in the National Security and Resources Study Center of LASL.

Monday, August 20

8:00 - 9:00 a.m.	Registration of Panelists and Visitors
9:00 - 10:30	Opening Plenary Session
	Presiding: Ernest M. Henley (University of Washington), Chairman of the Workshop. LASL Main Auditorium
10:30 - 11:30	Keynote Address: Maurice Jacob (CERN) — "New Directions in Elementary Particle Physics, pp from Very Low to Very High Energies," LASL Main Auditorium
11:30 - 12:30	Panels Organize: N-1 through N-4; P-1 through P-4
1:30 - 5:00 p.m.	Work Sessions: N-1 through N-4; P-1 through P-4
5:15 - 6:30	*LASL Director's Reception for Members of the Workshop and Spouses*
8:00	Oppenheimer Memorial Lecture, Murray Gell-Mann (Caltech) — "Quarks and Other Fundamental Building Blocks of Matter," Civic Auditorium
	Reception following lecture, Trinity-on-the-Hill Episcopal Church

Tuesday, August 21

8:10 a.m.	LASL Colloquium and Keynote Address, G. E. Brown (SUNY, Stony Brook) — "New Directions in Intermediate Energy Nuclear Physics"
	Presiding: Louis Rosen, Director, LAMPF, LASL Main Auditorium
9:30 - 10:30	Paul Debevec (University of Illinois) — "Report on Boulder 'Future Directions' Workshop," LASL Main Auditorium
10:30 - 12:30 p.m.	Work Sessions: N-1 through N-4; P-1 through P-4
1:30 - 5:00	Work Sessions: N-1 through N-4; P-1 through P-4
9:00 a.m. - 2:30 p.m.	*Ladies' Program: Visit to Chimayo*

Wednesday, August 22

9:00 - 11:00 a.m.	Work Sessions: N-1 through N-4; P-1 through P-4
11:00 - 12:30 p.m.	Internal Reports: N-1, N-2, P-1, P-2 (N-i reports are given to assembled N Panels. P-i reports are given to assembled P Panels.)
3:00 - 5:00	Tours of LAMPF begin at LAMPF Laboratory-Office Building (LOB)
5:00 - 8:30	*Barbecue, LAMPF LOB Patio*

Thursday, August 23

9:00 - 10:30 a.m.	Internal Reports: N-3, N-4, P-3, P-4	
10:30 - 12:30 p.m.	Work Sessions: P-1 through P-4 Panels N-1 through N-4 draft reports	
1:30 - 2:30	Panels N-5 through N-8 organize Panels P-1 through P-4 reformulate goals	
2:30 - 5:00	Work Sessions: N-5 through N-8; P-1 through P-4	
9:00 a.m. - 4:00 p.m.	*Ladies' Day in Santa Fe*	

Friday, August 24

9:00 - 11:00 a.m.	Reports on Plans for Advanced Facilities: Ernest M. Henley -- "TRIUMF Kaon Factory Workshop" Darragh E. Nagle — "High-Intensity 15-GeV Synchrotron Concept" William E. Turchinetz (MIT) — "Summary of Vancouver Session on High-Energy Electron Physics" *Presiding: Earle L. Lomon (MIT), Chairman of the Steering Committee, LASL Main Auditorium*	
11:00 - 12:30 p.m.	Work Sessions: N-5 through N-8; P-1 through P-4	
1:30 - 4:15	Work Sessions: N-5 through N-8; P-1 through P-4	
4:15 - 5:00	Internal Reports: N-5 and P-1	

Monday, August 27

9:00 - 11:00 a.m.	Work Sessions: N-5 through N-8; P-1 through P-4	
11:00 - 12:30 p.m.	Internal Reports: N-5, N-6, P-1, P-2	
1:30 - 3:00	Internal Reports: N-7, N-8, P-3, P-4	
3:15 - 5:15	Plenary Session: N-1, P-3	

Tuesday, August 28

		Draft Reports
9:00 - 11:30 a.m.	Work Sessions: N-5 through N-8; P-1 through P-4	
11:30 - 12:30 p.m.	Plenary Session	N-2
12:30 - 1:30	*Lunch*	
1:30 - 2:30	Plenary Session	N-3
2:45 - 3:45	Plenary Session	P-2
4:00 - 5:00	Plenary Session	N-4

Wednesday, August 29

9:00 - 10:00 a.m.	Plenary Session	N-5
10:15 - 11:15	Plenary Session	P-1
11:30 - 12:30 p.m.	Plenary Session	N-6
12:30 - 1:30	*Lunch*	
1:30 - 2:30	Plenary Session	N-7
2:45 - 3:45	Plenary Session	P-4
4:00 - 5:00	Plenary Session	N-8
6:30 - 7:30	*Cocktails, Fuller Lodge*	
7:30 - 9:00	*Dinner*	

Thursday, August 30

9:00 - 10:00 a.m.	Final Summary, Ernest M. Henley *Presiding: Darragh E. Nagle (LASL)*	
10:10 - 11:15	Panel Discussion: Major Equipment and Facilities Maurice Goldhaber, BNL, Chairman John Domingo, SIN Vladimir Lobashev, INR, Moscow Louis Rosen, LAMPF, LASL Jack Sample, TRIUMF Jacques Thirion, Saclay	
2:00 - 5:00	Finalize Reports	

Friday, August 31

9:00 a.m. - 5:00 p.m.	Finalize Reports	

APPENDIX C

GLOSSARY OF ACRONYMS AND SYMBOLS

a	Gyromagnetic anomaly, g-2
AGS	Alternating-gradient synchrotron
ANL	Argonne National Laboratory
BATES	Electron linac, Cambridge, Massachusetts, named for the late Congressman William H. Bates
BCS	Bardeen, Cooper, Schrieffer
BNL	Brookhaven National Laboratory
CERN	Organisation Européene pour la Recherche Nucléaire, Geneva, Switzerland
CMU	Carnegie-Mellon University
CVC	Conserved vector current
CWRU	Case-Western Reserve University
DDHF	Density-dependent Hartree-Fock
DESY	Deutsches Elektronen Synchrotron, Hamburg, Federal Republic of Germany
DWBA	Distorted wave Born approximation
DWIA	Distorted wave impulse approximation
FSI	Final-state interaction
g	Gyromagnetic ratio
GR	Giant resonance
HF	Hartree-Fock
hf	Hyperfine
hfs	Hyperfine structure
ICE	Initial cooling experiment, Antiproton Storage Ring, CERN
ICOHEPANS	International Conference on High-Energy Physics and Nuclear Structure
IKO	Instituut voor Kernphysisch Onderzoek, Amsterdam, The Netherlands
INR	Institute for Nuclear Research, Moscow, USSR
ISABELLE	p-$\bar{p}$ colliding ring, under construction at BNL
ISR	Intersecting Storage Ring
IUCF	Indiana University Cyclotron Facility
JINR	Joint Institute for Nuclear Research, Dubna, USSR
K	K meson, kaon
KEK	National Laboratory for High-Energy Physics of the Ministry of Education, Tsukuba Newtown, Japan
KH	Karlsruhe-Helsinki
KMT	Kerman, McManus, and Thaler
LAMPF	Los Alamos Meson Physics Facility, renamed Clinton P. Anderson Meson Physics Facility and dedicated to the late Senator Anderson
PCAC	Partially conserved axial-vector current
LASL	Los Alamos Scientific Laboratory
LBL	Lawrence Berkeley Laboratory
LEAR	Low-Energy Antiproton Ring (CERN)
N	Nucleon
OPEC	One-pion exchange current
PC	Parity + charge conjugation operators
PEP	Positron-Electron Project, collaboration of LBL and SLAC
PETRA	Electron-positron colliding rings at DESY q.v.
PS	Proton synchrotron
PSR	Proton storage ring
PWIA	Plane wave impulse approximation
q	Momentum transfer
QCD	Quantum chromodynamics
QED	Quantum electrodynamics
RPA	Random phase approximation
RPI	Rensselaer Polytechnic Institute, Troy, New York
SC	Synchrocylotron
SIN	Schweizerisches Institute für Nuklearforschung, Villigen, Switzerland
SLAC	Stanford Linear Accelerator Center
SMC	Stopped Muon Channel
SPS	Super proton synchrotron
SRC	Short-range correlations
SREL	Space Radiation Effects Laboratory, Newport News, Virginia
TRIUMF	Meson Facility of the University of Alberta, Simon Fraser University, University of Victoria, and the University of British Columbia, Vancouver, B.C., Canada
Z	Nuclear charge, proton number
ZGS	Zero-gradient synchrotron
α	Fine structure constant, $(137)^{-1}$; ^{4}He
μ	Magnetic moment; muon
μSR	Muon spin rotation
ν	Frequency; $E = h\nu$; neutrino
π	Pi-meson; pion
ω	Angular frequency; $E = \hbar\omega$

EPILOGUE

It was a great workshop. Reading the draft reports showed that the enthusiasm of the panelists carried over into their authorship and recommendations.

As some praise was given me, I owe bouquets to staff at LAMPF and to other important contributors.

The planning of this workshop was done through the LAMPF Visitors' Center. Linda Tyra, who joined this office just a year ago, was diplomat, factotum, advisor, and friend to all the workshop participants. We could not have managed without the help of Julia Anderson, Alice Horpedahl, Janie Kelly, Kitty Maraman, Billie Miller, Lois Rayburn, Mary Riggs, Kit Ruminer, Beverly Talley, and Renate Zinn.

Many members of the PUB Department of LASL were of assistance in many ways. We thank especially Floyd Archuleta, Leeroy Herrera, and Sue Wooten for their contributions.

Biophysical Research Corporation of Houston, Texas, provided funds for hospitality for the workshop. We are grateful to BRC Trustees and to Charles L. Critchfield, President, for this grant.

Our principal chairmen, Ernie Henley and Earle Lomon, were tops — available, thoughtful, ever constructive in their suggestions.

Louis Rosen gave total support. His consistent position was that we must do what is required for the field of physics to which this workshop addresses itself.

Finally I must thank each participant in the workshop: panelists, students, visitors. Each of you came to Los Alamos Scientific Laboratory in the expectation of learning and teaching; this aim was accomplished. Our mutual interests are advanced as we hoped they would be.

John C. Allred
October 1979

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