Relativistic Nuclear Models: Reason or Treason?

"The last temptation is the greatest treason:
To do the right deed for the wrong reason"

T. S. Eliot, "Murder in the Cathedral"

As evidenced in the recent LAMPF workshop on Dirac approaches to nuclear physics, the impressive experimental studies of spin observables in high-energy proton scattering have stimulated renewed interest in the role of relativistic effects in nuclear physics. To complement the current enthusiasm for extremely simple relativistic models arising from their phenomenological success, the workshop organizers asked me to assume the role of the Devil's advocate and to provide a critique of these models. In that same spirit, in this Comment I would like to critically assess the strengths and limitations of alternative contemporary approaches to nuclear structure and high-energy nuclear scattering, to examine the degree to which phenomenology actually discriminates between alternative physical mechanisms, and to raise some of the conceptual questions inherent in relativistic nuclear physics. In order to disentangle the physical issues as clearly as possible, I will separately discuss the theory of the nuclear ground state and high-energy proton–nucleus scattering.

MANY-BODY THEORY OF THE NUCLEAR GROUND STATE

We know empirically that low-energy nuclear physics is describable in terms of nucleon coordinates. The shell model is specified by the quantum numbers of single nucleon states. The charge density difference between ^{206}Pb and ^{205}Tl has the shape of a $3s\frac{1}{2}$ proton orbital and the density of ^{209}Bi differs from that of ^{208}Pb by a $1h\,\frac{9}{2}$ proton orbital. The scaling variable for inclusive electron scattering below 1 GeV involves the nucleon mass, not that of subnuclear constituents

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and the structure function $S(q,\omega)$ measured in $(e,e'p)$ experiments clearly delineates the structure of deep-lying nucleon hole states.

In striking contrast to these clear empirical facts, there is as yet no fundamental theory in terms of quarks and QCD for defining nucleon coordinates in the nuclear medium and for deriving an effective low-energy Hamiltonian in terms of these coordinates. Thus, contemporary approaches to nuclear structure must introduce physical assumptions and models to deal with the physics of subnuclear degrees of freedom.

Until we have a theory of the nucleon–nucleon interaction, there is no viable alternative to using the immense body of experimental nucleon–nucleon data we have as fully as possible. It is this information which has provided the foundation of the traditional understanding of nuclear structure. If a theorist insists on discarding all this physics, he or she had better replace it with something equally substantial.

Nonrelativistic Potential Theory

Nonrelativistic potential theory provides one possible framework for a many-body theory in which the constituents have substructure. Consider, for example, liquid helium. One may define a phenomenological two-body atom–atom potential which fits experimental scattering data and virial coefficients and then use this potential to accurately calculate the binding energy, liquid structure function, and fundamental excitations of liquid helium. Theoretically, we can understand this potential microscopically in terms of the electrons, helium nuclei, and photons (a pretentious way of referring to the Coulomb interaction to parallel later references to gluons) comprising the atoms. At large distances the Coulomb induced dipole–dipole interaction gives rise to $1/r^6$ attraction and the orbital rearrangement of the four electrons forced by the Pauli principle produces strong short-range repulsion. The potential model thus includes the physics of the finite size of the constituents in a definite, and in this case correct, way. In addition to two-body forces, the potential model incorporates the effect of suppressed degrees of freedom through the presence of three-body and higher many-body forces. In the case of helium, the long range part of the three-body force can again be understood from induced dipole interactions and produces observable effects. When applied to nuclei, potential theory offers the same possibility of including the physics of substructure, in this case, quarks and gluons. In practice, one of the principal uncertainties is the choice of a specific phenomenological potential which implies off-shell behavior unconstrained either by present theory or experiment.

A primary consideration for purposes of comparison with relativistic theories is the accuracy of nonrelativistic kinematics. The characteristic momentum scale for the nuclear ground state is given by the mean momentum in the Fermi gas $\langle p^2 \rangle_{FG}^{1/2} = 200$ MeV/c. For this momentum, $v/c = 0.21$ and the kinematical error in the kinetic energy is $\beta^2/4 = 0.01$. Thus, a naive estimate of the error in propagators is of the order of 1%. Even this error will be partially compensated if the same nonrelativistic propagators are used in defining the potential from the T-matrix and in the many-body theory of the ground state. Thus, one only expects trouble with the nonrelativistic theory if some extreme cancellations amplify relativistic effects. Otherwise, the structure calculated nonrelativistically should be essentially correct, and when necessary, can be corrected by treating relativistic effects perturbatively.

One of the salient features of nonrelativistic potential theory is the crucial role of strong short-range correlations, induced both by the strong repulsive core and by tensor forces. The effective interaction between nucleons in a nucleus thus acquires a strong medium dependence, with both the Pauli exclusion operator and binding corrections making the G-matrix differ significantly from the bare interaction v.

In recent years, substantial progress has been made in many-body theory for potentials having the general feature of nuclear forces.[1] By utilizing complementary techniques such as perturbation theory,[2] variational methods,[3,4] the coupled-cluster approximation,[5] and Monte Carlo techniques,[6] there is now strong evidence that the many-body theory is under control and that we can accurately calculate the properties of nuclear matter and finite nuclei for realistic potentials. The result of nuclear matter calculations is that whereas a realistic two-body potential will yield the correct binding energy per particle, it produces saturation at too high a density. Since we know that suppressed degrees of freedom manifest themselves in the form of many-body potentials, the most physical remedy for the saturation problem is to include a small three-body potential of the form describing the excitation of an isobar by one nucleon and deexcitation by another nucleon.

Relativistic potential theory is an interesting theoretical alternative to the nonrelativistic potential theory.[7,8] Although not widely recognized or applied in realistic calculations, it combines the ability of a potential to incorporate the effects of substructure with the correct relativistic invariance properties for cases in which relativistic effects are important. In this sense, it is more general than a local meson–nucleon field theory. The price of this generality is the emergence of many functions in the formalism which are constrained neither by experiment nor by present theory.

Relativistic Meson–Nucleon Field Theory

The fundamental assumption of a local meson–nucleon field theory[9,10] is that in addition to point nucleons, the relevant degrees of freedom in matter at nuclear density are local meson fields. There is thus no possibility for quark substructure of either the mesons or nucleons. The free nucleon in this theory acquires structure only via its meson cloud.

If one takes seriously comtemporary quark models of nucleons and mesons, this local field theory is subject to a serious crowding problem. Since the radius of a sphere containing one baryon at nuclear matter density is 1.1 fm, the separation between a nucleon and its nearest neighbor is less than 2.2 fm. If, as in bag and constituent quark models, the radius of the nucleon is of the order of 1 fm and the pion of the order of 1/2 fm, there is simply no way to avoid very substantial overlaps of quark wave functions. Whereas this kind of structure can be accommodated in a potential, local fields and point particles do not include such physics.

It is important to note that although there is a common prejudice in the nuclear physics community that the nucleon cannot be described by a bag with a radius of the order of 1 fm, it has no foundation in fact. There are two experimental bases for our understanding of hadron sizes: electromagnetic form factors and hadron–hadron scattering. Since a uniformly charged sphere of radius 1.09 fm has the observed rms radius of a proton, experimental electromagnetic form factors are certainly consistent with a 1 fm bag. Our knowledge of the qualitative features and spatial scale of the nucleon–nucleon interaction ultimately comes from scattering phase shifts.

Since a P-matrix analysis[11,12] for the ^3S–^3D phase shifts demonstrates that it is possible to fit the observed data using the pole position predicted in the bag model for a bag radius of 1.2 fm, a bag of this size is thus completely consistent with everything we really know.

The implications for meson–nucleon field theory are at present unclear. One posibility is that quark models of large composite hadrons are simply wrong and that for some reason yet to be understood, either physical or effective meson fields are the correct degrees of freedom in nuclear matter. A second possibility is that nucleons and mesons are in fact large, but the effect of substantial overlap can be adequately incorporated by the introduction of form factors. The last possibility is that although meson–nucleon field theory is a well-posed model, it simply does not describe physical nuclei.

In addition to these unresolved conceptual questions, this meson–nucleon field theory suffers from the problem that relativistic many-body theory is presently not well controlled. Prescriptions for partial summations of diagrams are subject to presently unquantifiable arbitrary choices, leading to substantial uncertainties in the nuclear matter saturation curve. In contrast to nonrelativistic many-body theory, there are no model problems for which the same result is obtained with several complementary theoretical approaches. Hence, alternative methods, such as the Monte Carlo technique, should be fully exploited to test the approximations presently utilized in relativistic many-body theory. In addition to numerical studies, it is important to develop a physical understanding of the lowest-order Hartree–Fock–Dirac approximation such as that obtained in atomic physics. In that case, one recognizes that close to the nucleus, one is essentially solving a one-electron problem in a strong central field, for which the small components describe the correct physics, and at large distances one has an essentially nonrelativistic many-body problem for which Hartree–Fock is correct.[13] The final problem with this field theory model is that it makes no contact with our only real source of information about nuclear interactions, namely nucleon–nucleon scattering and bound state data. When, at each level of approximation, one redefines the fundamental constants of the theory to fit selected nuclear properties with no constraints from two-body data, it is exceedingly difficult to pose crisp, definitive tests of the theory.

Fundamental approaches to nuclear structure have thus far proven elusive. Direct treatment of the nucleus in terms of quarks and gluons is clearly hopeless until we can first understand the isolated nucleon and two-nucleon systems. If one thinks about it for a moment, some generalization of Landau Fermi liquid theory appears to be an appealing alternative to a direct treatment of the full microscopic theory. Unfortunately, if you think about it for more than a moment, there are presently insurmountable conceptual problems. Recall that an essential part of the argument for the Landau theory of liquid ^{3}He in nonrelativistic quantum mechanics is the one-to-one correspondence of the states of the noninteracting system and those of the strongly interacting system.[14,15] But what we want in QCD is to go from the states of the quark system to a strongly interacting many-body system described by nucleon degrees of freedom. Thus, we cannot simply mumble the old words, but rather some completely new idea is required to establish an appropriate theory of the Landau form.

In the absence of a fundamental approach, we must be content with taking what guidance we can from accessible studies of quark and gluon substructure. From the viewpoint of many-body theory, nonrelativistic quark models are the most tractable. In these models, one replaces nearly massless relativistic quarks by constituent quarks having masses roughly one-third of a nucleon mass and makes an ansatz for a confining interaction. One then has a tool for studying the nucleon–nucleon potential, clustering and the emergence of nucleon coordinates in nuclear matter, and for comparing quark and hadron descriptions. Since the problems can be well posed and powerful many-body techniques are available, substantial progress is already being made.[16,17] At the other extreme, one may also envision using lattice QCD to study problems of direct interest to nuclear physicists, including the structure of the nucleon, nucleon–nucleon interactions, and nuclear matter. Since we are particularly interested in wave functions, the Hamiltonian form is especially appealing. In addition to Monte Carlo methods, variational techniques which have been extensively developed in nuclear applications may also prove fruitful.

Comparison with Experiment

In addition to explicit adjustable parameters, it is important to recognize that these descriptions of nuclear structure involve adjustable assumptions. One should count the zeros in front of all the terms one omits in the Hamiltonian, the freedom in summing selected sets of diagrams, and assumptions concerning off-shell behavior, to name a few obvious examples.

For perspective, it useful to recall the phenomenological Skyrme force which when used in the Hartree–Fock approximation provides an extremely economical description of the gross features of low-energy nuclear physics with four parameters.[18] These four parameters are determined by the binding energy per particle, symmetry energy, surface energy, and saturation density of nuclear matter and a fifth parameter in the theory, m/m^*, is essentially unconstrained. Since, in addition to its relativistic features, relativistic Hartree–Fock with adjustable coupling constants and ranges includes the freedom of a phenomenological nonrelativistic theory, it should be able to do as well as the Skyrme force with four adjustable parameters. Not surprisingly, the QHD meson–nucleon field theory model produces the same quality of description as the Skyrme force and has precisely four parameters adjusted in essentially the same way.[10] For comparison, nonrelativistic potential theory, which begins with a potential specified by nucleon–nucleon properties, requires two parameters in the three-body force to obtain comparable results.

Looking beyond the phenomenological description of gross features, it is desirable to find specific observables capable of distinguishing between relativistic and nonrelativistic theories. The basic idea exploited thus far in seeking such observables is quite simple. In the presence of a scalar potential S and the fourth component of a vector potential V, the Dirac equation is

$$[(E - V)\gamma_0 + \gamma_i p^i - (M + S)]\psi = 0.$$

To reproduce the gross features of nuclear structure, the scalar potential is strongly attractive, $S \sim -450$ MeV, and the vector potential is strongly repulsive, $V \sim +350$ MeV. In the nuclear medium, the combination $M + S$ enters the single-particle Dirac equation in the same way as M enters in free space. It is therefore useful to define an effective mass in the medium $M^* = M + S \sim 490$ MeV which is roughly half that of a free particle and to define an effective mass enhancement ratio

$$R_M \equiv \frac{M}{M + S} = 1.92.$$

Similarly, when one relates the lower components of the Dirac equation, χ_L to the upper components, χ_U, in the medium, the result is:

$$\chi_L = \frac{1}{(E - V) + (M + S)} \left[\frac{d}{dr} - \frac{\kappa}{r} \right] \chi_U.$$

Thus, relative to free space, the lower components are enhanced by the factor

$$R_L = \frac{E + M}{E - V + M + S} \xrightarrow[E \to M]{} 1.74.$$

The problem, then, is to find an observable which can unambiguously distinguish the presence or absence of these large enhancement factors R_M and R_L.

One obvious candidate is the electromagnetic probe, for which one would naively expect the electromagnetic convention current to be enhanced by the factor R_M because of the small effective mass. Indeed, calculations of magnetic moments and magnetic form factors show that this enhancement yields results which are too large[10,19] and degrades the agreement with experiment generally attained in non-relativistic treatments. However, these results are not definitive, due to the ambiguities in the electromagnetic current operator. Transverse isoscalar inelastic transitions are particularly sensitive to possible enhancement because the anomalous magnetic moments of the proton, 1.79, and neutron, -1.91, nearly cancel.[20] The biggest problem in interpreting enhancements of the order of 2 calculated in transitions such as $^{12}C(e,e')\,^{12}C^*$ to the 1^+ and 2^+ $T = 0$ states is understanding the nuclear structure of the ground and excited states to sufficient quantitative precision.

If one wishes to measure the magnitude of lower components in the nucleus, it is natural to think of using the γ^5 operator occurring in the weak interaction to obtain off-diagonal matrix elements involving the product of upper and lower components which are thus proportional to R_L. Unfortunately, by PCAC, the matrix element of the axial current has the form[21]

$$J_A^0 \; \bar{\psi}\left[\frac{M + S}{M}\gamma^5\right]\psi \propto \frac{R_L}{R_M} \sim 0.91$$

so in essence, the enhancement of the lower component is compensated by the effective mass enhancement.

Other possibilities still remain to be explored. Relativistic QHD makes very definite and striking predictions for the interaction between nucleons and antinucleons. The sign of the contribution of each meson to the N–N potential is simply multiplied by its g-parity in the N–$\bar{N}$ potential, so, for example, the strong short-range repulsion is transformed into strong short-range attraction. This unusual feature, which does not arise in quark models of N–$\bar{N}$ potentials, is masked to some extent by the strong absorption, but may provide a signature if one thinks about it carefully in the right way. Other useful possibilities to consider include neutrino scattering and the study of specific nuclear states, such as stretched configurations, for which nuclear structure ambiguities are strongly reduced by the absence of other low-lying shell model states of the same quantum numbers.

HIGH-ENERGY SCATTERING

The role of relativistic effects in the scattering of an 800 MeV proton is clearly qualitatively different from their role in the structure of the ground state for which the characteristic kinetic energy is ~21 MeV. Obviously, some relativistic effects will be quantitatively important at this energy. The question is which approach or model captures the essence of the physics. Is it enough to include relativistic kinematics, or is there also essential relativistic dynamics? What is the correct scattering equation and how is the potential to be included in it? How does the quark substructure of the nucleon enter into processes involving antinucleon states? And how is our knowledge of the significant corrections to the impulse approximation for the nonrelativistic optical potential to be carried over to the relativistic case? To provide a background for addressing some of these questions, it is useful to review some salient aspects of nucleon–nucleus scattering theory.

Nucleon–Nucleus Scattering Theory

The self-energy for the one-particle Green's function, which has been extensively studied in many-body theory and field theory, provides the most useful framework for thinking about and calculating the nuclear optical potential both relativistically and nonrelativistically.[22] Typical low-order contributions to the self-energy for a nonrelativistic potential theory are given by the following time-ordered diagrams (Fig. 1) and in a meson–nucleon field theory the static interactions, denoted by dashed lines, would be replaced by meson propagators with finite time extent. Consider now what physics is included and omitted in various approximations to the nonrelativistic optical potential.

The impulse approximation simply sums the nucleon–nucleon T-matrix in free space over the distribution of nucleons in the ground state. It therefore sums all ladder diagrams in which the incoming nucleon interacts with one nucleon in the nucleus disregarding the Pauli principle and any possible interactions with other particles in the medium. Thus, diagrams (a) and (b) are included, binding corrections such as (c) and correlation corrections such as (d)–(f) are omitted, and spurious Pauli-violating terms of the form of (b) with occupied instead of unoccupied intermediate states are incorrectly included.

The G-matrix corrects some of the defects of the impulse approximation by summing ladder diagrams which include both the Pauli principle and binding corrections. It therefore includes diagrams (a)–(c) without spurious terms of the form of (b) having occupied intermediate states. The differences between the impulse and G-matrix approximations are often called medium corrections. For future reference, it is useful to note that the leading medium dependence has strong density dependence, arising from the fact that the Pauli operator excludes more and more phase space as the density increases, and it decreases like $1/e$ for large incident energy.

The so-called second-order corrections to impulse approximation subtract out the spurious Pauli-violating terms and include correlation corrections. Because so much attention is presently focused on the successful description of spin observables, it is essential to understand both the limitations on the spin physics which can actually

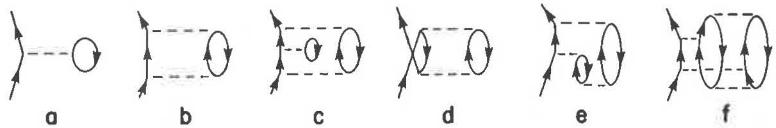

FIGURE 1

be included in the impulse approximation and the crucial role of higher-order corrections. If one writes the T-matrix in the form

$$T = A + B\sigma \cdot \sigma + C(\sigma + \sigma) \cdot q \times Q + D(\sigma \cdot Q)(\sigma \cdot q) + E(\sigma \cdot q)(\sigma \cdot q)$$

where $q \equiv p_i - p_f$ and $Q \equiv p_i + p_f$, then only the A and C terms contribute in impulse approximation for a spin-saturated nucleus. The essential point is that spin sums over closed fermion loops vanish unless each loop contains an even number of spin operators. Thus, it follows that both $\sigma \cdot \sigma$ and tensor forces will contribute to the second-order Pauli correction and since the Fourier components of the tensor force peak in the region of several k_F, these corrections will be quantitatively important. The spin-dependent amplitudes contribute strongly to correlation corrections for the same reason. Since the nucleon–nucleon interaction within the nucleus has the same spin-dependent components, there are always nonvanishing contributions to correlation diagrams such as (e) and (f) above.

Finally, let us compare the structure of the optical potential arising from nonrelativistic many-body theory with the nonrelativistic reduction of the Dirac equation in the presence of vector and scalar potentials. When the four-component Dirac equation is reduced to a two-component local Schrödinger equation, the central and spin-orbit potentials for a spherical nucleus have the following form[23]

$$U_{\text{central}} \sim \frac{E}{M} V + S + \frac{1}{2M}(S^2 - V^2),$$

$$U_{\text{spin-orbit}} \sim \frac{1}{2M} \frac{1}{E - V + M + S} \frac{1}{r} \frac{d}{dr}(S - V).$$

Note that in addition to the linear terms which have the form one would expect in nonrelativistic impulse approximation, the S^2, V^2 and $1/(E - V + M + S)$ terms yield an apparent medium dependence. Thus, even when the relativistic self-energy is calculated in impulse approximation, phenomenologically, these terms will look like the density-dependent correction in a G-matrix or other contributions of higher-order terms in the self-energy.

Comparison with Experiment

With this background, it is instructive to look at comparisons between experiment and the nonrelativistic impulse approximation as well as various corrections to it. In Fig. 2, the cross section and analyzing power (which is equivalent to the polarization) are shown for proton scattering from ^{208}Pb at 400 and 500 MeV. As is the custom in discussions of relativistic theories, the result of the nonrrelativistic impulse approximation is shown by dashed lines. Note that the total cross section is tolerable, with the principal error being diffraction minima which are too deep, but that the analyzing power is systematically grossly overestimated. The principal phenomenological success of relativistic theories is the description of spin observables, and

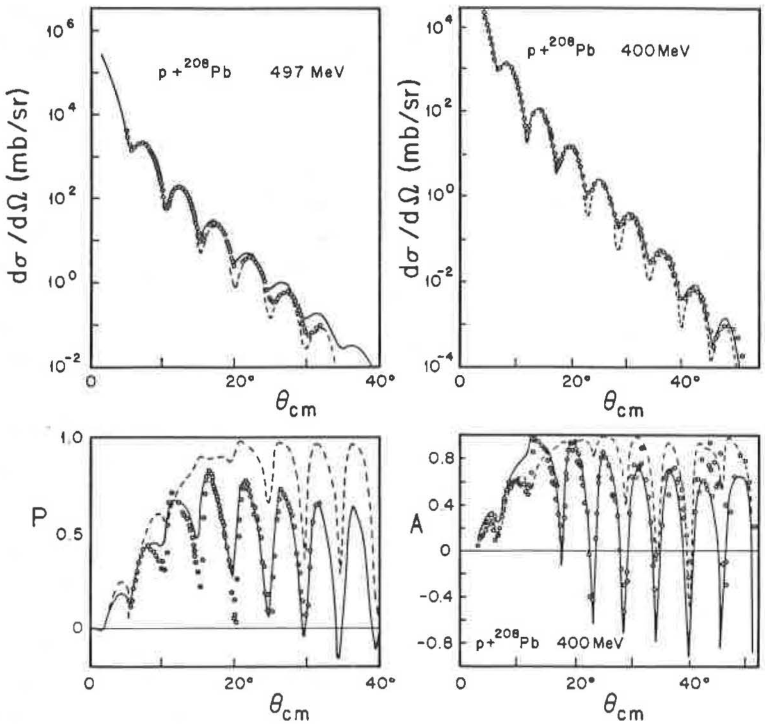

FIGURE 2 Comparison of the alternative theories of proton scattering from ^{208}Pb with experimental results. Whereas the dashed curves denote nonrelativistic impulse approximation at both energies, the qualitatively similar solid curves denote totally different physical approximations as described in the text.

one is used to seeing on the same graph solid curves for the relativistic impulse approximation which not only improve the total cross sections, but also bring the analyzing power into good agreement with experiment. Although that is just what is shown by the solid lines on the left portion of Fig. 2 for 497 MeV proton scattering,[24] the solid line on the right is completely different; it actually corresponds to a nonrelativistic optical potential incorporating medium corrections through use of a G-matrix.[25,26] Phenomenologically, these two approximations embodying dramatically different physical effects are roughly equally successful and they each differ from the nonrelativistic impulse approximation by comparable amounts.

One should not be surprised that the medium effects in the G-matrix are large at 400 MeV and that they are phenomenologically similar to those of the relativistic theory. The simplest estimate of the order of magnitude of the Pauli correction is given by the blocking factor for a nucleon of energy E outside a Fermi sea with Fermi energy E_F, $P \sim 1 - (7/5)\,(E_F/E)$, which yields corrections of 17%, 10%, and 6% at energies of 300 MeV, 500 MeV, and 800 MeV, respectively.[27] The actual effect may be significantly enhanced relative to these estimates by the fact that long-range attractive central forces and tensor components sample the excluded phase space more strongly than the short-range repulsive components, and the final result involves sensitive cancellations. Note also that both the second-order G-matrix contribution $v(Q/e)v$, and the factor $1/(E - V + M + S)$ arising in the nonrelativistic reduction of relativistic impulse approximation have the same characteristic $1/E$ dependence at high energy.

The quantitative significance of correlation corrections in the optical potential for proton scattering from ^{208}Pb at 800 MeV is equally dramatic.[28] As expected from the previous discussion of how spin-dependent amplitudes enter into the optical potential, calculations clearly show that corrections to the impulse approximation for spin observables are of the same magnitude as the discrepancy with experiment.

These results render it impossible to use the phenomenological success of any of the presently implemented theories to judge their actual validity: any one of them may indeed do the right deed for the wrong reason. What is absolutely clear, however, is that corrections to impulse approximation are so large that no theory can hope to be credible until it includes them in a controlled way.

Conceptual Questions

Beyond the phenomenological issues of the previous section, there are several important conceptual questions which need to be addressed.

One crucial question is the validity of the Dirac equation for composite particles. For point-like electrons in an external field, the fundamental length scale in the Dirac theory is the Compton wavelength $1/M$ and the external field induces transitions between point electron and point positron states with no form factors. In contrast, the proton with an rms charge radius of 0.8 fm is four times bigger than its Compton wavelength $1/M = 0.2$ fm, so it is far from being a point Dirac particle. Somewhere, the theory must reflect the fact that it is harder for an external field acting on the distributed quarks in the nucleus to simultaneously convert them all to antiquarks in the ground state of an antinucleon than to connect a point particle to its antiparticle. Thus, the overlap between the internal quark wave functions for a proton and antiproton ought to give rise to some form factor which appears in the Dirac equation and suppresses Z-graphs.

It is possible that this suppression is effectively built into phenomenological theories by counterterms. For example, recall the famous problem of pair terms in pseudoscalar meson theory. Because of the γ^5 pseudoscalar coupling, two nucleons could connect with no suppression to a state of two antinucleons by exchanging a pion and then connect back to a two-nucleon state by exchanging a second pion, yielding a contribution to nucleon–nucleon scattering many times larger than the total physical scattering amplitude. Yet in a chiral model, these pair terms are cancelled by contributions from σ mesons to yield the same result as obtained with pseudovector coupling where pair terms are suppressed by the momentum factor at each vertex. In the same way, fitting experimental amplitudes with a QHD Lagrangian containing both physical and fictitious meson fields could in principle effect the same cancellation of unphysical pair terms.

To understand this question more fundamentally, it would be instructive to study a simple model. In this case, one needs to write down a relativistic model for a composite nucleon comprised of three quarks and to study its equation of motion as the ratio of the size to the Compton wavelength is varied.

A second fundamental question is the off-shell dependence. It is clear that both potential *Ansätze* and Lorentz decompositions constrained only by two-body data are not unique. Ultimately, therefore, one must look beyond nucleon and meson degrees of freedom and understand the off-shell dependence in terms of quark physics. Treatment of nonrelativistic quark models using the generator coordinate or resonating group method has already yielded some insight into the nonlocality of the nucleon–nucleon potential, but any fundamental understanding will require both relativistic quarks and QCD.

SUMMARY AND CONCLUSION

High-energy proton scattering experiments have provided a great impetus for thinking about relativistic effects in nuclei. Thus far, however, despite the phenomenological success of simple relativistic models, there is no clear evidence yet as to whether or not these models do the right deed for the wrong reason.

There are three crucial tasks facing nuclear theorists in this field. One task is to obtain the same quantitative control over relativistic many-body theory as has already been obtained in the nonrelativistic case. Then, instead of readjusting the constants of QHD every time a new set of diagrams is included, the parameters of the theory can be fixed by the two-nucleon system and used to predict properties of finite nuclei and nuclear matter. Similarly, when calculating the optical potential, it will be possible to include medium modifications and correlation corrections which are known to produce effects comparable to the discrepancy between the relativistic and nonrelativistic impulse approximations. A second task is to complement phenomenological studies with renewed emphasis on conceptual questions. There is a point of diminishing returns in the study of any model based on potentials or local meson fields beyond which one ought to examine the microscopic foundations in terms of quarks and QCD. The final task is to think seriously about the next generation of experiments. We need to use what limited understanding we presently possess to formulate the most crisp, definitive experimental tests we can. Experiment has not only drawn our attention to the fundamental questions discussed here; it will also serve as the ultimate arbiter between reason and treason.

Acknowledgments

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