NAL PROPOSAL No. 81

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FTS/Commercial 312 - 739-7711
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PRELIMINARY SURVEY OF 200-GeV PROTON INTERACTIONS WITH COMPLEX NUCLEI

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July 7, 1970

Change of Spokesman 10/3/72

NAL PROPOSAL No. 81

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Change of Spokesman

NAL PROPOSAL No. 81

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FTS/Commercial 516-924-6262

PRELIMINARY SURVEY OF 200 GeV PROTON INTERACTIONS WITH COMPLEX NUCLEI

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REFER:

DEPARTMENT OF
CHEMISTRY

July 6, 1970

Dr. Francis T. Cole
National Accelerator Laboratory
P. O. Box 500
Batavia, Illinois 60510

Dear Frank:

Enclosed is a joint proposal by several groups of nuclear chemists for initial use of the NAL accelerator. This is the proposal which I mentioned in my letter to you of June 3.

This proposal resulted from discussions held by a group of us on June 17 at Colby Junior College, New Hampshire, during a Gordon Research Conference on Nuclear Chemistry. It represents what, in the joint view of the experimenters listed, are the most practical as well as interesting initial nuclear chemistry survey experiments in the new energy range. Other experimenters may well wish to and will be welcome to join the effort outlined here. In this sense we are trying to speak for the community of nuclear chemists interested in high-energy interactions. On the other hand, this should in no way militate against any separate proposals that may be forthcoming.

I hope you will communicate with either Ellis Steinberg or me if you require amplification or clarification of any part of the proposal.

Sincerely,

Gerhart Friedlander

Gerhart Friedlander

GF:dp

enc.

cc: E. L. Goldwasser
Experimenters listed on Proposal

Preliminary Survey of 200 GeV Proton Interactions with Complex Nuclei

Proposal submitted July 7, 1970

Abstract: Three types of experiments are proposed by a consortium of nuclear chemists for the initial operating period (∿1 year) of the NAL accelerator: 1) Measurement of the absolute cross section for C^{11} production from C^{12} in a low-intensity (10^5-10^6 per pulse) proton beam and determination of other convenient foil activation cross sections relative to this primary standard. 2) Use of mica and lexan track detectors to study multiplicities, ranges, and angular distributions of heavy fragments from proton interaction with high-Z nuclei. 3) A survey, by radioactivity measurements, of cross sections and momentum properties of reaction products from a few selected target elements. This work could be done either in an external or in the circulating beam.

Experimenters: S. Kaufman, E. Steinberg, B. Wilkins - Argonne National Lab.
G. Friedlander, S. Katcoff, L. Remsberg - Brookhaven National Lab.
N. Sugarman - University of Chicago
A. A. Caretto, P. Karol - Carnegie Mellon University
N. T. Porile - Purdue University
L. Church - State University of N. Y., Buffalo
(Others may well join this program)

Correspondents: G. Friedlander, E. Steinberg

I. Justification and Description of Experiments

The general scope and purpose of nuclear chemistry research with high-energy accelerators are reviewed in the attached summary which was appended to a letter of January 7, 1970 from G. Friedlander to R. R. Wilson explaining the interests of nuclear chemists in the NAL accelerator.

The purpose of the present proposal is to extend some nuclear reaction studies done at lower energies into the 200-500 GeV energy range during the initial period of operation of the NAL accelerator. We propose to carry out a collaborative program of experiments to survey areas of special interest and possibly uncover new phenomena that may arise in the new energy range. In the light of the results of this initial survey some of us may, at a later date, wish to submit individual proposals in our respective fields of interest.

We propose here three basic approaches of a survey nature which should help decide the directions of future efforts. These proposals are

1) The development of foil activation techniques for monitoring the intensities of particle beams of energy $\geq$ 50 GeV.

2) The study of nuclear reactions of high-energy protons with light-, medium-, and heavy-element targets by use of particle track detectors.

3) The study of nuclear reactions of high-energy protons with light-, medium-, and heavy-element targets by activation techniques.

A more detailed description of the experiments follows.

1. Development of Absolute Beam Monitors

It is proposed to determine absolute cross sections for some nuclear reactions so that they can subsequently be used as beam-monitoring reactions.

Past experience at other high-energy accelerators has shown that monitoring of beam intensities by foil activation is essential not only for nuclear chemistry but also for many particle physics experiments [see for example, F. Turkot et al., Phys. Rev. Letters 11, 474 (1963); G. Cocconi et al., Phys. Rev. 138B, 165 (1965); C. W. Akerlof et al., Phys. Rev. Letters 17, 1105 (1966); H. L. Anderson et al., Phys. Rev. Letters 21, 853 (1968)].

The reactions that have been most frequently used for beam monitoring at lower proton energies [cf. J. B. Cumming, Ann. Rev. Nucl. Sci. 13, 261 (1963)] and are presumably also the reactions of choice at NAL energies are $C^{12} \rightarrow C^{11}$ (20 min half-life); $Al^{27} \rightarrow F^{18}$ (110 min); $Au^{197} \rightarrow Tb^{149}$ (4.1 hours);

$Al^{27} \rightarrow Na^{24}$ (15 hours); $C^{12} \rightarrow Be^{7}$ (54 days).

The only one of these reactions which lends itself conveniently to a direct absolute cross section measurement is the reaction $C^{12}(p,pn)C^{11}$. The cross sections of the other reactions can then be measured relative to it in composite foil stacks.

The proposed experiments for measurement of the $C^{12}(p,pn)$ cross section would consist of a) irradiations of plastic scintillators in a proton beam of sufficiently low intensity to permit direct determination of the number of protons by emulsion track counting or by a counter telescope, b) measurement of the C^{11} activity induced in the scintillators. The maximum track density that can be reliably measured in an emulsion is about 2×10^6 per cm^2 so that a beam of 10^4-10^5 protons per cm^2 per pulse, uniform over at least 10 cm^2, is desirable. In a 3 mm thick scintillator of 10 cm^2 area 2×10^7 protons would produce of the order of 200 C^{11} disintegrations per minute at the end of the irradiation. If the RF microstructure of the beam permits direct counting of the proton intensity in an in-beam counter telescope at rates of the order of 10^6 per pulse, this technique would be preferable because about an order of magnitude larger C^{11} activities can be produced and because the results can be obtained without waiting for tedious emulsion track scanning.

For this primary calibration of the $C^{12}(p,pn)C^{11}$ cross section it will thus be necessary to have a beam of 10^5 to 10^6 protons per pulse, uniform over an area of at least 10 cm^2 if emulsion monitoring is to be used, but preferably of small cross sectional area if the counter telescope method can be employed. At least three irradiations of 1 to 20 min duration will be needed.

The ratio measurements relating the other monitor reactions (except for $C^{12} \rightarrow Be^7$) to $C^{12}(p,pn)C^{11}$ can be performed in the scattered proton beam of $\sim 10^{10}$ protons per pulse in three to six 20-min irradiations. The $C^{12} \rightarrow Be^7$ determination will require either much longer irradiations (several hours) or the full-intensity beam.

When proton energies other than the normal maximum energy (presumably 200 GeV) become available, the calibration program outlined should be repeated at two or three lower energies to establish the energy variations of the monitor cross sections.

2. Track Detector Studies

Track detector techniques are convenient for the exploration of new phenomena in this new energy range. They require relatively simple equipment and little beam time.

We propose to irradiate thin targets of medium to heavy elements sandwiched between layers of mica and Lexan plastic. The emitted heavy nuclear fragments will then be observed in 4π geometry and the multiplicity of heavy fragments will be measured. In previous work of this type (CERN and BNL) binary and ternary fission cross sections were measured up to 29 GeV. No quaternary or higher order events were seen with mica detectors. The binary cross sections for U and Bi decrease monotonically from 1.0 to 29 GeV. Extension of the data to a few hundred GeV should help characterize the competing process which is becoming more important.

Of special interest is the mechanism of energy transfer from incident high energy protons to clusters of nucleons. Therefore the ranges and angular distributions will be measured of the very long tracks. For these experiments track detectors will be placed at some distance from the beam and target.

It would be highly desirable to carry out these experiments at at least three energies (say 50, 100, 200 GeV). However, if changing beam energy proves to be difficult or very time consuming, the work will of course initially be done at the maximum energy only.

For the experiments in which the beam passes through the detector the intensity needed is $\sim 10^8$ sec^{-1} cm^{-2} and approximately uniform over a few cm^2. The total time estimate for these runs is 14 hours: an 8 hour period for testing and preliminary exposures plus 6 hours for the final set of irradiations at three beam energies. For the experiments in which the protons pass only through the target a sharply defined high intensity beam of $\sim 10^{13}$/sec is optimum. A total of 14 hours is needed for these: about 6 hours for line-up, testing, and preliminary exposures plus about 8 hours for the final runs at three beam energies. These time estimates do not include the time necessary to change beam energy.

3. Survey of Nuclear Reactions by Activation Methods

The purpose of this set of experiments is to survey the mass and charge distribution and momentum properties of reaction products from interaction of

$\sim$200 GeV protons with some representative target nuclei and to ascertain whether they differ markedly from those observed at lower proton energies.

Wherever possible, direct γ counting of the irradiated foils with Ge(Li) detectors will be used for product analyses, but radiochemical separations followed by activity measurements on individual elementary fractions will also be employed, particularly in case of the heavy-element targets, where the γ spectra of the unseparated targets are too complex for analysis.

Foil stacks consisting of one or more target foils, recoil catcher foils, and beam monitor foils and totalling < 1 g/cm^2 will be irradiated. Targets of Al, Cu, Ag, Au (or Bi), and U may be used. Individual irradiations will require between 10 and 30 minutes of beam time, and target recovery should require no more than 20 minutes. For the experiments that involve direct γ counting (probably most of the Al, Cu, and Ag irradiations), the scattered beam with $\sim 10^{10}$ protons per pulse will be suitable. For the remainder, a beam intensity of at least 10^{12} protons per pulse will be required. Alternatively an internal target arrangement in the circulating beam would be very suitable, especially at reduced intensity ($\sim 10^{11}$ per pulse).

Nuclear chemists from several institutions will in general participate in the analyses of the targets from each bombardment. It will probably be desirable to schedule a set of irradiations (perhaps 2 or 3, totalling about two hours of beam time) approximately once a month for the first year of operation.

II. Equipment and Facilities

As outlined in a letter of January 7, 1970 from G. Friedlander to R. R. Wilson, a sustained program of nuclear chemistry research at NAL will require certain on-site facilities as well as a resident nuclear chemist. The latter need will hopefully be taken care of initially by the early appointment of a suitable person to the NAL staff on chemistry funds. Negotiations on this point are well underway with Dr. E. L. Goldwasser. This man, when appointed, will of course be in a key position with respect to preparations for implementation of the present proposal and will eventually be responsible for arranging the irradiations and for looking after the nuclear chemical facilities.

The minimum space requirements for nuclear chemistry will be office space for the resident nuclear chemist (and perhaps on an interim basis for visiting experimenters) as well as several hundred square feet each of chemical laboratory space and shielded space for radioactivity measurements. Initially, most of the needed chemical and counting equipment for the proposed research can be supplied by the using groups; also, both the ANL and University of Chicago groups have offered to make their extensive facilities available to nuclear chemists from other institutions participating in this initial survey. In the long run, a certain amount of counting equipment should be permanently available at NAL.

SUPPLEMENTAL REPORT ON NAL PROPOSAL NO. 81

PRELIMINARY SURVEY OF 200-GeV PROTON INTERACTIONS WITH COMPLEX NUCLEI

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December, 1970

Report on NAL Proposal No. 81

Preliminary Survey of 200-GeV Proton Interactions with Complex Nuclei

The purpose of this report is to provide additional information on the nuclear chemistry experiments included in NAL Proposal No. 81. In Section I a typical example of each kind of experiment is given, together with the technical requirements of the experiments. The experimental equipment that will be needed is described in Section II. A summary of the proton beam requirements--energy, intensity, and time--of the proposed experiments is presented in Section III. The future needs of a nuclear chemistry research program at NAL are discussed in Section IV.

I. Experiments

A. Absolute $C^{12}(p,pn)C^{11}$ Cross Section Measurement

The cross section of the $C^{12}(p,pn)C^{11}$ (20.4-min half life) reaction* has been used as a primary standard for a large number of radiochemical and physical measurements of cross sections for proton interactions up to 30 GeV. We propose to measure the absolute cross section for the $C^{12}(p,pn)C^{11}$ reaction at 50, 100, and 200 GeV initially and at higher energies when possible. It is very important to determine the

*Throughout this report a notation like $C^{12}(p,pn)C^{11}$ is not meant to imply only the emission of a proton and a neutron, but is meant to include any other mechanism for C^{11} formation, such as deuteron emission or processes involving pions, etc.

energy variation of this cross section so that subsequent cross section measurements can be made relative to it in a straightforward manner. Measurements at the three energies indicated are expected to suffice unless unforeseen energy dependence is observed.

For the measurement of the $C^{12}(p,pn)C^{11}$ cross section we will use the technique[1-4] of irradiating a plastic scintillator target and then measuring the induced C^{11} activity. The proton flux incident on the target will be measured directly with a scintillation counter telescope downstream from the target. The target will be a 1/8 in. thick piece of plastic scintillator (carbon content 92%) approximately 3/4 in. in diameter. The loss of C^{11} activity by gas diffusion out of such a target has been shown to be negligible.[5] The arrangement of the target and scintillation counter telescope is shown in Fig. 1 (a). After a short irradiation, the target will be mounted on a phototube and the C^{11} activity will then be measured by internal scintillation counting, which has been shown[2] to be 93% efficient for C^{11}. The amount of C^{11} produced by secondary reactions (from secondaries originating within the target itself) will be determined by irradiating plastic scintillator targets of various thicknesses and extrapolating the C^{11} cross section to zero target thickness. Secondary effects are usually of the order of 1-2% for this type of experiment.

A proton beam intensity of 10^5 to 10^6/pulse will be needed for this cross section measurement. With 1.5 x 10^5 protons per pulse, a C^{11} activity level of ~400 disintegrations/min is expected.* This low level of activity and the short (20.4 min) half life of C^{11} suggests the desirability of setting up a counter as close as possible to the target area for this experiment. At least three irradiations of 5 to 20 min duration will be necessary at each beam energy.

An alternative method that might be used for this C^{11} cross section measurement involves using a thin plastic foil (5-10 mils thick) for a target. The in-beam counter telescope would be used at a low beam intensity to calibrate additional counter telescopes set off to the side of the beam at suitable scattering angles. Then the irradiation would be done at a higher intensity ($\approx 10^7$ protons/pulse) and the out-of-beam counter telescopes would be used to determine the incident proton flux. After the irradiation the C^{11} activity in the plastic foil would be counted in a calibrated NaI(Tl) well-type scintillation counter. This technique has the advantage of utilizing plastic foil targets similar to those that will be used in subsequent relative cross section measurements (see Section IB), thus minimizing effects arising from

*For a product of half-life $t_{\frac{1}{2}}$ minutes, the amount of activity D in disintegrations per minute [dpm] produced at the end of an irradiation of duration t is given by $D = N\sigma I(1 - e^{-0.693t/t_{\frac{1}{2}}})$ where N = number of target nuclei/cm^2, σ= cross section in cm^2, I = beam current in particles/min.

For a 3-mm plastic scintillator target (density ~1.1 g/cm^3), $N = \frac{0.33}{14} \times 6 \times 10^{23} = 1.4 \times 10^{22}$ nuclei/cm^2. For a beam of 1.5×10^5 protons per pulse, $I = 2.25 \times 10^6$/min. Extrapolation from lower-energy data indicates σ of the order of 2.5×10^{-26} cm^2. Thus, for a 20-min irradiation we can expect for the end-of-bombardment C^{11} activity $D = 1.4 \times 10^{22} \times 2.5 \times 10^{-26} \times 2.25 \times 10^6 (1 - e^{-0.69}) \approx 400$ dpm.

the use of targets of different thickness.

This experiment has requirements that are quite similar to those of NAL Proposal Nos. 10 and 56, which are approved experiments that propose to measure total proton cross sections at several energies up to 200 GeV in the Area 2 Meson Lab. We therefore would like to cooperate with Experiments 10 and 56 to whatever extent possible in the use of the same counter telescope equipment for the proton intensity measurements. This C^{11} cross section measurement is the only one of the nuclear chemistry experiments that requires the use of a scintillation counter telescope. We may also wish to expose a few nuclear emulsions for an independent check of the incident proton flux.

When clean beams of particles other than protons become available, e.g. in HEHR and MEHR, this experiment should be repeated to establish the cross sections of the $C^{12}(\pi^-, \pi^- n)C^{11}$, $C^{12}(\pi^+, \pi^+ n)C^{11}$ etc. reactions.

B. Relative Beam Monitor Cross Section Measurements

The half life of C^{11} (20.4 min) limits the use of the $C^{12}(p,pn)C^{11}$ reaction as a beam monitoring reaction to experiments of rather short duration. Other useful beam monitoring reactions that have been frequently used for proton energies up to 30 GeV are: $Al^{27}(p,5p5n)F^{18}$ (110 min); $Au^{197}(p,spallation)Tb^{149}$ (4.1 hr); $Al^{27}(p,3pn)Na^{24}$ (15.0 hr); and $C^{12}(p,3p3n)Be^{7}$ (53.4 days). We propose to measure the cross sections for these reactions at 50, 100, and 200 GeV initially and at higher energies when possible. The technique to be used is foil activation followed by the counting of the induced activity with appropriate detectors.[6] The cross sections will be measured relative to that of the $C^{12}(p,pn)C^{11}$ reaction (see Section I-A) by irradiation of a foil stack including a plastic foil in which the induced C^{11} activity will be measured.

The $Al^{27}(p,3pn)Na^{24}$ cross section measurement will be explained in some detail as an example of these experiments. The target will be a stack of aluminum and polyethylene (or polystyrene) foils arranged as shown in Figure 1 (b). The thick polyethylene foil will be used for the proton flux determination. The thick Al foil will be used for the $Al^{27}(p,3pn)Na^{24}$ cross section measurement. The thin polyethylene and aluminum foils protect the thick foils from recoil contamination and compensate for nuclei recoiling out of the thick foils. The Na^{24} in the thick Al foil will be measured by counting the intact foil with an end-window beta proportional counter or a calibrated Ge(Li) gamma detector. The C^{11} in the thick polyethylene foil will be measured with a well-type NaI(Tl) scintillation counter. All counters will be calibrated in advance for the relevant radiations. The C^{11} and Na^{24} activities will be measured for several half lives and the decay curves fitted with a least squares program to analyze them into their components since other activities, such as 10-min N^{13}, 110-min F^{18}, 53-day Be^{7} and 2.6-y Na^{22}, are also formed in the foils.

In practice, the Au^{197}(p, spallation)Tb^{149} reaction has proved to be very convenient for beam monitoring purposes and has been used extensively at the ZGS and AGS. This cross section will be measured relative to that of the $Al^{27}(p,3pn)Na^{24}$ reaction by irradiating a foil stack consisting of three Al and two Au foils. The intact Au foils will then be counted under standard conditions with internal gas flow alpha counters in order to determine the number of Tb^{149} alpha counts per proton.[7]

Usually several cross section measurements will be done simultaneously by including more of the appropriate foils in the target, but the total target thickness will not exceed 100 mg/cm^2. These experiments could be accomplished in the diffracted proton beam of the Area 2 Meson Lab at a proton intensity of 10^{10}/pulse. At this intensity, all of these relative cross section measurements (except for the C^{12}(p,3p3n)Be^7 and Au^{197}(p,spallation)Tb^{149} reactions) could be performed in six 10 to 20 min irradiations for each proton energy. The C^{12}(p,3p3n)Be^7 and Au^{197}(p,spallation)Tb^{149} cross section determinations will require either several hours of beam time at 10^{10} protons/pulse or,preferably, a few minutes of beam time at 10^{13} protons/pulse.

C. Study of High-Energy Proton Fission Cross Sections

Heavily ionizing particles produce tracks in mica and Lexan plastic that can be made visible by appropriate chemical etching techniques. The use of these track detectors therefore provides a convenient method of determining some of the features of high-energy nuclear reactions.

In this experiment, we propose to determine the cross section for the proton-induced fission of a heavy nucleus, such as Au^{197}, into two or more complementary fission fragments at beam energies from 50 GeV to 200 GeV. This will be accomplished by irradiating a target that consists of a thin layer of metal sandwiched between layers of mica or Lexan plastic. After etching the mica with hydrofluoric acid and the Lexan with sodium hydroxide, the fission fragment tracks will be observed under a microscope in 4π geometry. Mica has a threshold at

$Z \approx 14$ and Lexan at $Z \approx 8$. It is possible to determine not only binary fission, but also ternary and higher order fission cross sections with this technique.[8] In this experiment, the proton flux incident on the target will be determined by measuring the 15-hr Na^{24} activity induced in an aluminum monitor foil by the $Al^{27}(p,3pn)Na^{24}$ reaction.

The fission cross sections of Ag, Au, Bi and U will be measured in this manner. A typical target stack (see Fig. 1(c)) will consist of 5 to 8 sheets of mica (or Lexan), 2 sheets of mylar, and 2 aluminum foils. Thin layers of target material ($\approx 100 \mu g/cm^2$) will be evaporated onto the mica (and Lexan). The total thickness will be ~ 0.5 g/cm^2 and the stack area will be ~ 10 cm^2. Each run will require a beam intensity of 10^7-10^9 protons/$cm^2 \cdot$sec, and a uniformity of at least ±50% over an area of ~ 6 cm^2. Eight hours of beam time will be required at each beam energy--6 hours for alignment and preliminary exposures plus 2 hours for the final irradiations. Runs at 50, 100, and 200 GeV are anticipated. The irradiations can be done in the target chamber described in Section II-A. Target preparation, chemical etching, and track scanning will be done at existing facilities at Brookhaven.

D. Survey of Nuclear Reaction Cross Sections By Direct Gamma Counting of Irradiated Foils

Interactions between high-energy particles and complex nuclei yield product atoms ranging in mass from a few above that of the target down to A = 1. Study of the product mass distribution as a function of target and incident energy at proton energies up to 30 GeV has led to a complex but reasonably well understood picture of nuclear reactions at these energies. The purpose of these experiments is to determine what, if any, changes or modifications of this picture are necessary to describe interactions in the 50-200 GeV region.

The products of the interactions of high-energy particles with complex nuclei are generally described as arising from three processes: fission, spallation, and fragmentation. (The latter process has been invoked to account for products in the mass region of about 20-50, but it is still rather ill-defined and under active investigation.) The detailed understanding of each of these mechanisms is a major goal of high-energy nuclear chemistry research. For all but the heaviest target nuclides (in which fission plays a prominent role) most of the observed yields are products of spallation reactions, where relatively massive residual nuclei remain after the emission of nucleons and small fragments. Detailed calculations of nuclear reactions leading to spallation products have been performed. Since specific nuclear models and detailed dynamics of nucleon-nucleon and nucleon-pion interactions in nuclear matter are the starting point for these calculations, best choices for these various inputs can be made. In this way, nuclear chemists use reaction data from complex reactions to study problems of nuclear structure at high nuclear temperatures.

Spallation data are useful in fields other than nuclear physics and chemistry. For example, the interpretation of cosmic ray induced radioactivity in meteorites and lunar samples requires the knowledge of spallation yields from a variety of target nuclides to deduce information about the flux. Rudstam[9] has shown that spallation data from elements up to $A \sim 100$ bombarded by 0.1-30 GeV protons are reasonably well represented by:

$$\sigma(Z,A) = \text{const.} \times \exp[PA - R|Z - SA + TA^2|^{3/2}]$$

where Z and A are the charge and mass of the spallation product; P is a parameter which defines the slope of the yield curve as one goes from products close to the target towards those of lower mass; and R, S, and T are parameters which define the shape of the isobaric yield curve at each value of A. That is, for a given mass product it yields the distribution as a function of Z.

Recently it has been shown that the above relationship also is adequate in describing the spallation yields from heavy targets such as Au and U up to 30 GeV.[10] Although no physical insight can be obtained in this way, the equation is very useful in estimating unmeasured or unmeasurable yields at energies up to 30 GeV.

We propose to study the yields of radioactive spallation products formed in the interaction of 50 to 200-GeV protons with targets at least as heavy as copper and possibly as heavy as silver. These experiments will be accomplished by irradiating a stack of target and beam monitor foils and then counting the intact foils with high resolution Ge(Li) gamma detectors. The first gamma spectrum will be recorded as soon as possible after the irradiation, and additional spectra will be taken over a period of a few weeks. Different nuclides will be identified by their characteristic gamma ray decay energy and half life properties. This direct gamma counting technique has been successfully used to obtain simultaneously as many as 30 spallation cross sections from the interaction of 30-GeV protons with a copper target. The cross section data obtained in this way will be sufficient to establish what, if any, changes in yield patterns occur between 30 and 200 GeV.

Each irradiation will require 10 to 30 min of beam time at a beam intensity of 10^{10} protons/pulse. The total target thickness will not exceed 200 mg/cm^2. Target recovery should require no more than 10 min. In general, nuclear chemists from several institutions will participate in the analyses of the targets from each irradiation, but it is essential to have the irradiations split up into segments of approximately two hours of beam time each because of the limited amount of counting equipment that will be available at any one time and because of the complexity of the analysis of the wide variety of products formed in these reactions. We therefore request two hours of beam time once a month for these irradiations, which will be done in the target chamber described in Section II-A. These survey experiments will be done at 50, 100, and 200 GeV.

E. Survey of Nuclear Reaction Cross Sections by Radiochemical Techniques

The method of radionuclide assay in activated foils by direct gamma counting (i.e., without chemical separation of elemental fractions) is limited in its ability to distinguish individual nuclides by the complexity of the gamma spectra, and the complex gamma spectra obtained from targets of $A \gtrsim 100$ precludes its general application. Much of the interest in high-energy nuclear reactions is concerned with the fission process and fission-spallation competition in the heavier elements (e.g. Au, Bi, U) and for these, chemical separations are necessary to obtain the reaction cross sections.

Surveys of mass and nuclear charge distributions of the products will be obtained by dissolution of the irradiated target, chemical separation of the elements of interest, and measurement of the radioactivity to establish isotopic identification and to determine the production cross sections. In some cases, even the elemental separation is insufficient to permit accurate assay of the radioactivities in a complex mixture of isotopes, and further separation of the isotopic components of the elements is accomplished by the use of an electromagnetic isotope separator prior to the measurement of the radioactivity. Such separators are in current use at Argonne and at Brookhaven and will be available for study of some of the longer-lived products from NAL irradiations, if necessary.

One of the characteristic features of the nuclear fission reaction is the large kinetic energy of the fragments which results from the Coulomb repulsion of the nuclear charges at scission. The fragments are ejected from the surface of the target and may be caught on catcher foils. Studies of the fraction of the nuclides ejected and the ratio of forward-to-backward ejection give information on the ranges (and, hence, kinetic energies) of the fragments and on the momentum transfer in the initial interaction of the proton beam and target nucleus.[11,12] Previous studies[13-16] have indicated that at bombarding energies above a few GeV the neutron-excess and neutron-deficient nuclides exhibit different recoil behavior. The latter have smaller ranges (~1/2) and are more forward peaked, indicating that the mechanism of their formation probably differs from the usual fission mechanism. Other data on nuclear charge dispersion for the neutron-deficient species also indicates a different mechanism may be contributing at these energies. We propose to continue these studies at NAL in an attempt to characterize these reaction mechanisms further.

Target stacks consisting of beam monitor, guard, target, and catcher foils (Figure 1(d)) will be irradiated for periods of 10-30 min each at an intensity of 10^{13} protons per pulse. The total target thickness will be less than 200 mg/cm^2.* The proton flux incident on the target will be determined from the monitor reaction $Al^{27}(p,3pn)Na^{24}$. The targets will be transported to the chemistry laboratory as quickly as possible after irradiation. (A pneumatic tube system is being planned for loading and unloading targets remotely.) For a recoil experiment the target and catcher foils will be analyzed separately for the nuclides of interest. When a production cross section only is sought, the 3 foils will be combined for analysis. A number of aliquots of the original solution will be taken for simultaneous analysis of different products by cooperating investigators, thus making more efficient use of the irradiations.

These experiments will be carried out at 50, 100, and 200 GeV initially and at higher energies when available. Limitations of manpower and counting equipment make it necessary to space the irradiations over one or two week intervals to allow time for the analysis of one set of data at a time. A total of 1-2 hours of beam time per month is estimated for these experiments on a continuing basis.

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*The usual target stack for heavy element experiments will total 100-150 mg/cm^2. However, more than one element can be irradiated in the same stack, and stacks of closer to 200 mg/cm^2 may be used. The shielding around the target location will, of course, limit the permissible target thickness in a 10^{13} proton/pulse beam and such shielding should be based on a 200 mg/cm^2 target thickness.

II. Experimental Equipment

A. Nuclear Chemistry Experiment Station in a Low Intensity Proton Beam

Experiments A, B, C, and D in Section I (with the two possible exceptions noted in Experiment B--the $C^{12}(p,3p3n)Be^7$ and Au^{197}(p, spallation)Tb^{149} reactions) could all be accomplished in the diffracted proton beam of the Area 2 Meson Lab, which is designed for a maximum proton intensity of 10^{10} protons/pulse and a maximum proton energy of 200 GeV. A suitable location for these irradiations would be a few feet upstream of the location of the liquid hydrogen target in the diffracted proton beam channel of the Area 2 Meson Lab. None of the experiments have to be done in a vacuum, and an 18" space between windowed-off sections of beam pipe (~20 mg/cm^2 windows) would be satisfactory.

Alternatively, a target chamber equipped with thin (~20 mg/cm^2) vacuum windows in addition to, or (preferably) as part of vacuum gate valves could be installed. When experiments were not being done, the chamber would be evacuated and the beam would pass directly through it. The target chamber required for these experiments would be (tentatively) a cubic chamber 18 in. on a side and made of aluminum. A sketch of the rudimentary features of this chamber is shown in Figure 2. Targets would be loaded manually through the access port onto a remotely controlled mechanism capable of moving the target into and out of the beam between beam pulses at the beginning and end of an irradiation.

Target recovery time is important (targets should be available within ~5 min after beam-off), so the target chamber access port would be designed for quick and easy entry. It is essential to have a viewing port for TV monitoring of the target.

B. Nuclear Chemistry Experiment Station in a High Intensity Proton Beam

Experiment E and the 2 exceptions noted in Experiment B require a "clean" beam of 10^{13} protons/pulse and proton energies up to 200 GeV. The target chamber required for these experiments could be made similar to the one shown in Figure 2, with the addition of an airlock and pneumatic rabbit system for target transport. The pneumatic rabbit system would extend through the earth shield and could even be extended for several hundred feet with little difficulty to a local, sheltered station for minimal analysis or from where they could be transported by car to the chemistry lab and counting room. Most of the irradiations will be done by transferring the target through the pneumatic system, but manual access to the target chamber will occasionally be necessary to load and unload delicate target assemblies. It is essential to have viewing ports for TV monitoring of the target in both the airlock and in the beam.

Most of the irradiations in this target chamber will be done with targets less than 100 mg/cm^2. However, we would like to have the capability of using targets up to 200 mg/cm^2 thick.

A suitable location for this target chamber would be near the upstream end of the Area 2 pre-target enclosure, preferably at a location where the chamber could remain undisturbed in the beam line for some length of time. Several inches of local shielding (probably lead bricks) will be needed to prevent undue activation of downstream magnets, etc., but it should be pointed out that the total irradiation time at this experiment station will not exceed more than about two hours per month.

If irradiations at energies greater than 200 GeV become desirable at some future date, it would seem quite feasible to install this same target chamber and pneumatic target transport equipment in a location near the upstream end of the Area 1 pre-target enclosure.

An alternative location for this experiment station would be just inside the Area 2 target box. A sketch of such a system is shown in Figure 3. This experiment station would be designed so that nothing projected out into the target box except during an irradiation. This location would permit the use of targets somewhat thicker than 200 mg/cm^2. The experimental equipment (air lock, pneumatic system, etc.) could be located either on the side of, or on top of the front end of the Area 2 target box.

C. Counting Equipment

The nuclear chemistry research program at NAL will initially require about 600 sq. ft. of counting space for radioactivity measurements. The necessary counting equipment will include the electronics and shielding for two high-resolution Ge(Li) gamma-ray detectors, a well-type NaI(Tl) gamma-ray detector, a 3 x 3 in. NaI(Tl) gamma-ray detector, three gas flow proportional beta counters, two internal gas flow alpha counters, and a semiconductor alpha detector. Two 4096-channel analyzer systems with magnetic tape outputs or a small computer with two ADC inputs and a magnetic tape output will be needed for alpha and gamma spectrum analysis. We will supply all of the counting equipment except for the two Ge(Li) detectors and the two 4096-channel analyzer systems or the computer system. The latter items are essential for our research program (in particular, Experiments D and E in Section I) and would cost about $40,000. Some of this equipment is undoubtedly needed at NAL for the monitoring of beams and general radiation physics studies. A common counting room in which all of the equipment could be shared by the Nuclear Chemistry Users Group and the NAL Radiation Physics Group would seem desirable. This counting room could be located either in a trailer or a temporary building upstream of the target areas (e.g. at the intersection of roads B and A1) or in the NAL village.

D. Chemistry Laboratory

A chemistry laboratory with about 600 sq. ft. of laboratory space is required for target preparation and handling and to carry out chemical analyses as outlined for experiment E. This laboratory will have to be furnished with laboratory benches, one or two radioactive fume hoods and sinks, and equipped with the usual utilities and chemical reagents. The chemistry laboratory, which should be located near the counting area, should contain enough office space for a few people. We will supply the furniture, hood(s), and other equipment for the laboratory. We would expect NAL to furnish an appropriate building and install the equipment.

III. Summary of Experimental Requirements

The following summary refers to the experiments that were listed in Section I.

Experiment A. Absolute $C^{12}(p,pn)C^{11}$ Cross Section Measurement. Requires ≈8 hours of beam time at each of three different energies. (See Table I.)

Experiment B. Relative Monitor Cross Section Measurements. Requires 2 hours of beam time at each of three different energies.

Experiment C. Study of Fission Cross Sections.
Requires 8 hours of beam time at each of three different energies.

Experiment D. Nuclear Reaction Studies by Direct Gamma Counting.
Requires 2 hours of beam time once a month for several months.

Experiment E. Nuclear Reaction Studies by Radiochemical Techniques.
Requires 0.5-1 hour of beam time every other week for several months.

After Experiments A, B, and C are completed, Nuclear Chemistry Users will need 2 hours/month of 10^{10} protons/pulse beam (Expt. D) and 1-2 hours/month of 10^{13} protons/pulse beam (Expt. E).

Table I.

Proton beam intensity and beam energy requirements for the above experiments.

Energy (GeV)	Intensity (protons/pulse)			
	10^6	10^8	10^{10}	10^{13}
50	A	C	B,D	B,E
100	A	C	B,D	B,E
200	A	C	B,D	B,E

IV. Future Needs of Nuclear Chemistry Research at NAL.

The following items, although not included in NAL proposal No. 81, were set forth in a letter of January 7, 1970 from G. Friedlander to R. R. Wilson as being among the eventual requirements of a sustained program of nuclear chemistry research at NAL.

A. Transmission Target Experiment Station

The use of silicon detectors to measure the energy and angular distribution characteristics of nuclear reaction products resulting from the interaction of high-energy protons with complex nuclei provides a powerful tool for the study of nuclear reaction mechanisms. These detectors can be utilized to provide time-of-flight and energy information from which the masses of the fragment can be determined, as well as to provide particle identification (Z and A) for $A \leq 20$.[17] When arranged to record coincident events, they provide a unique means of obtaining energy and angular correlations on an event-by-event basis and supplement the uncorrelated data obtained radiochemically. Such in-beam experiments utilize thin targets ($<10\ mg/cm^2$) and have been successfully run as parasitic experiments at Argonne, Berkeley, Brookhaven and Princeton. These experiments require a clean high intensity proton beam. We may be able to use a beam as intense as the 10^{13} protons/pulse primary beam (a minimum intensity of 10^{11} protons/pulse is required) if it is sufficiently free of secondary particles. These experiments would be completely parasitic and downstream experiments would not be affected. For these experiments, a target chamber (scattering chamber) approximately 2 ft. in diameter and 1 ft. deep would be needed. This chamber would contain a fixed detector and a remotely-controlled detector arm that pivots about the center of the chamber. Access would occasionally be necessary during beam-off periods to change detectors, targets or other components.

B. Internal Irradiation Station

For some studies (e.g., differential recoil studies of low cross section reactions), an internal target is essential to provide the needed high intensity through multiple traversals and to avoid the high flux of secondaries produced from thick targets which would produce the product of interest from competing reactions (and, generally, with a much higher cross section). For differential measurements (angular and energy distributions) it is essential to use targets thin enough to permit the recoils to escape without serious degradation or scattering. Again, multiple traversals are required to provide the necessary intensity in a reasonable time.

For these experiments, target and recoil catcher assemblies would be inserted in a bombardment station airlock in the main ring either manually or by means of an automatic transfer mechanism. Target thicknesses of <0.1 mg/cm^2 would be used. A typical assembly is shown in Figure 4. The orientation of the catcher foils to the target could be in the vertical or horizontal plane and the target need not be integrally attached to the catcher assembly (or even on the same side of the beam) if for some reason another arrangement would prove more satisfactory. It is important, however, to expose the target only to the desired energy beam, and this will require either flipping the target or, preferably (to avoid excessive mechanical shock to the delicate targets), programming the beam cycle to include an RF or magnetic field ramp during flattop to move the beam onto the target. If the latter is possible, the target would remain at the beam vertical center line throughout the cycle, but be radially outside the position of any lower energy beam during the acceleration period.

The internal target station should be in an independent straight section which would permit manual access for target recovery within about 10 min. after an irradiation. No definite plans for internal irradiations have been formulated, but we anticipate that no more than 2 or 3 hours of beam time per month would be desired.

12/10/70/ljc

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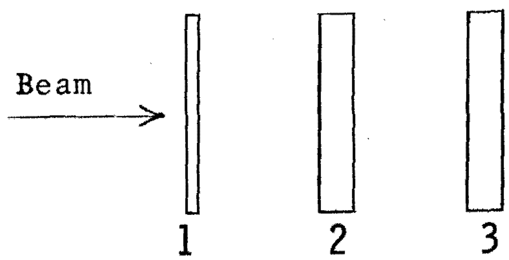
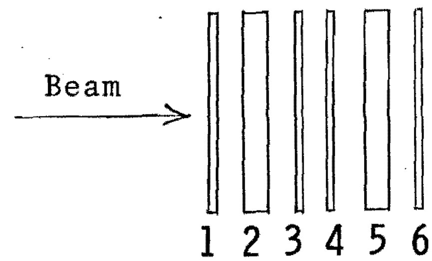


1 - $\frac{1}{8}$ in. thick plastic scintillator target

2 & 3 - Scintillation counter telescope

Fig. 1 (a). Target arrangement for the $C^{12}(p,pn)C^{11}$ cross section measurement.



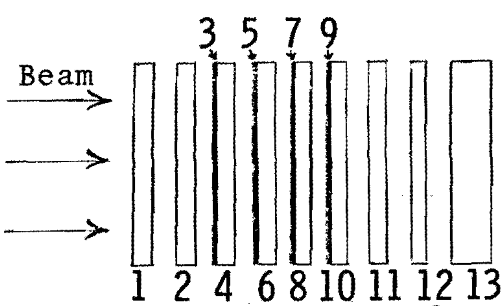
1 & 3 - 2 mil polyethylene (7 mg/cm^2)

2 - 4 mil polyethylene (14 mg/cm^2)

4 & 6 - 1 mil Aluminum (7 mg/cm^2)

5 - 3 mil Aluminum (21 mg/cm^2)

Fig. 1 (b). Target for the measurement of the $Al^{27}(p,3pn)Na^{24}/C^{12}(p,pn)C^{11}$ cross section ratio.



1 & 12 - 4 mil Mylar (14 mg/cm^2)

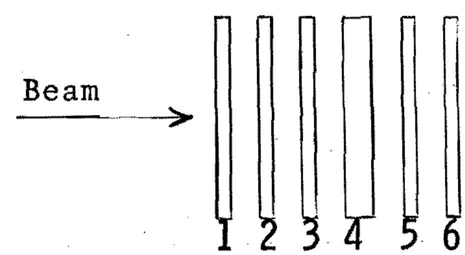
2, 4, 6, 8, 10 - 4 mil Mica (30 mg/cm^2)

11 - 3 mil Aluminum (21 mg/cm^2)

3, 5, 7, 9 - ≈100 μg/cm^2 evaporated layers of U, Bi, Au, Ag.

13 - 10 mil Aluminum (70 mg/cm^2)

Fig. 1 (c). Target for the measurement of high-energy fission cross sections.



1, 2, 3, 5, 6 - 1 mil Aluminum (7 mg/cm^2)

4 - 1-2 mil Uranium (50-100 mg/cm^2

Total = 85-135 mg/cm^2

Fig. 1 (d). Typical target for recoil or cross section measurements by radiochemic analysis.

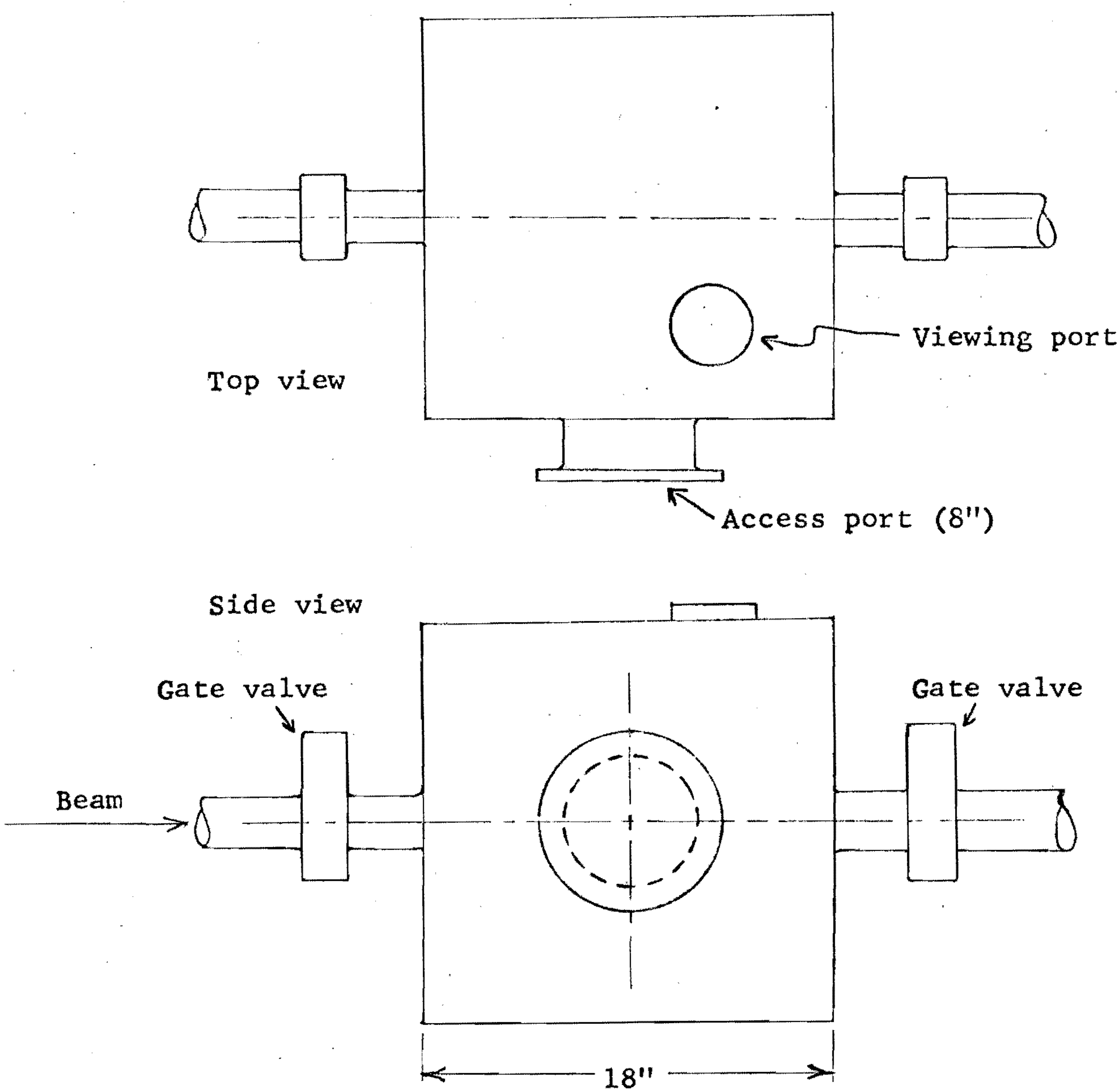


Fig. 2. Nuclear chemistry target chamber schematic. The chamber will contain a mechanical device to move the target in or out of the beam by remote control.

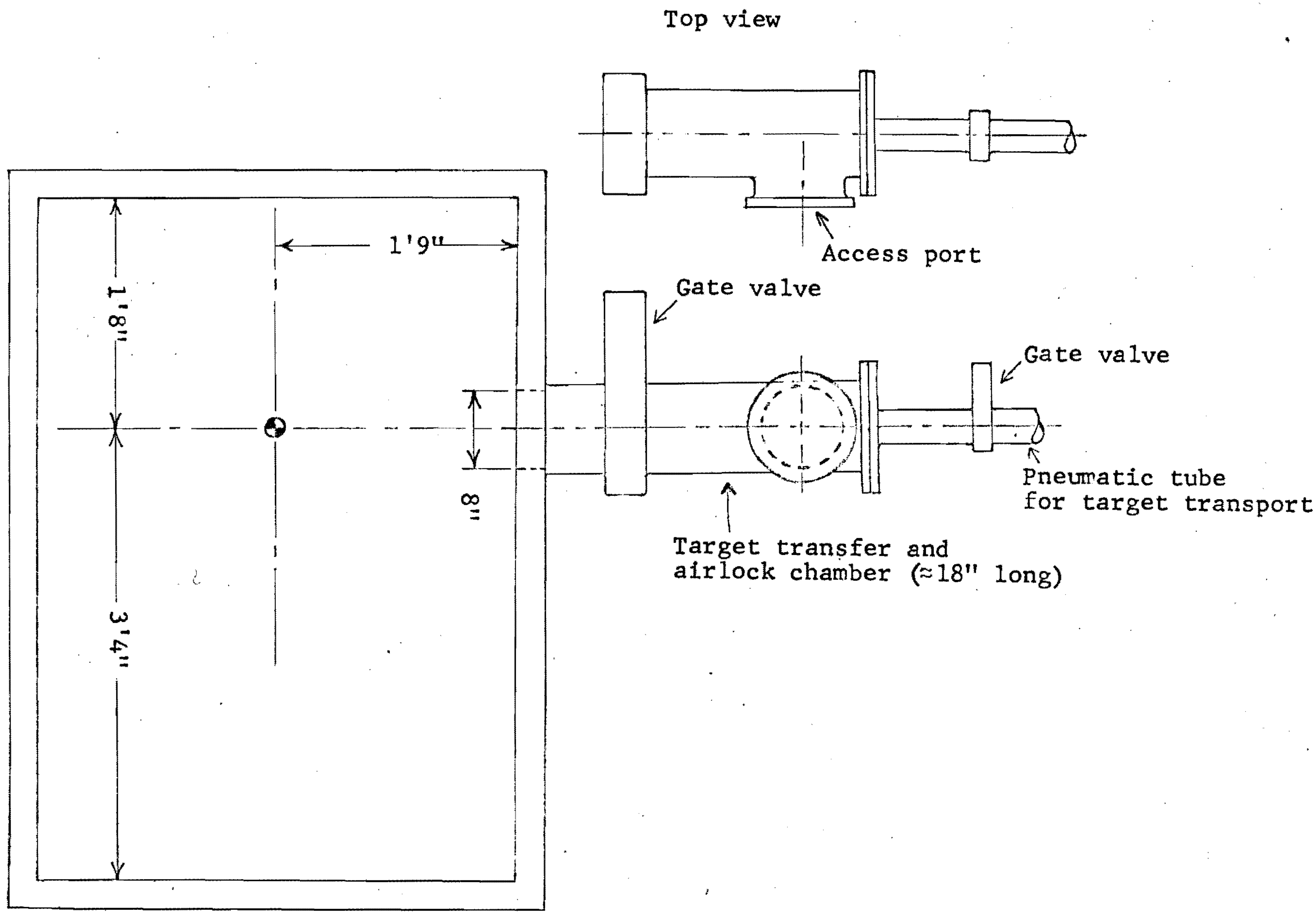


Fig. 3. Schematic of a possible nuclear chemistry experiment station located near the front end of the Area 2 target box. A remotely controlled mechanical device moves the target from the airlock chamber into the beam and back.

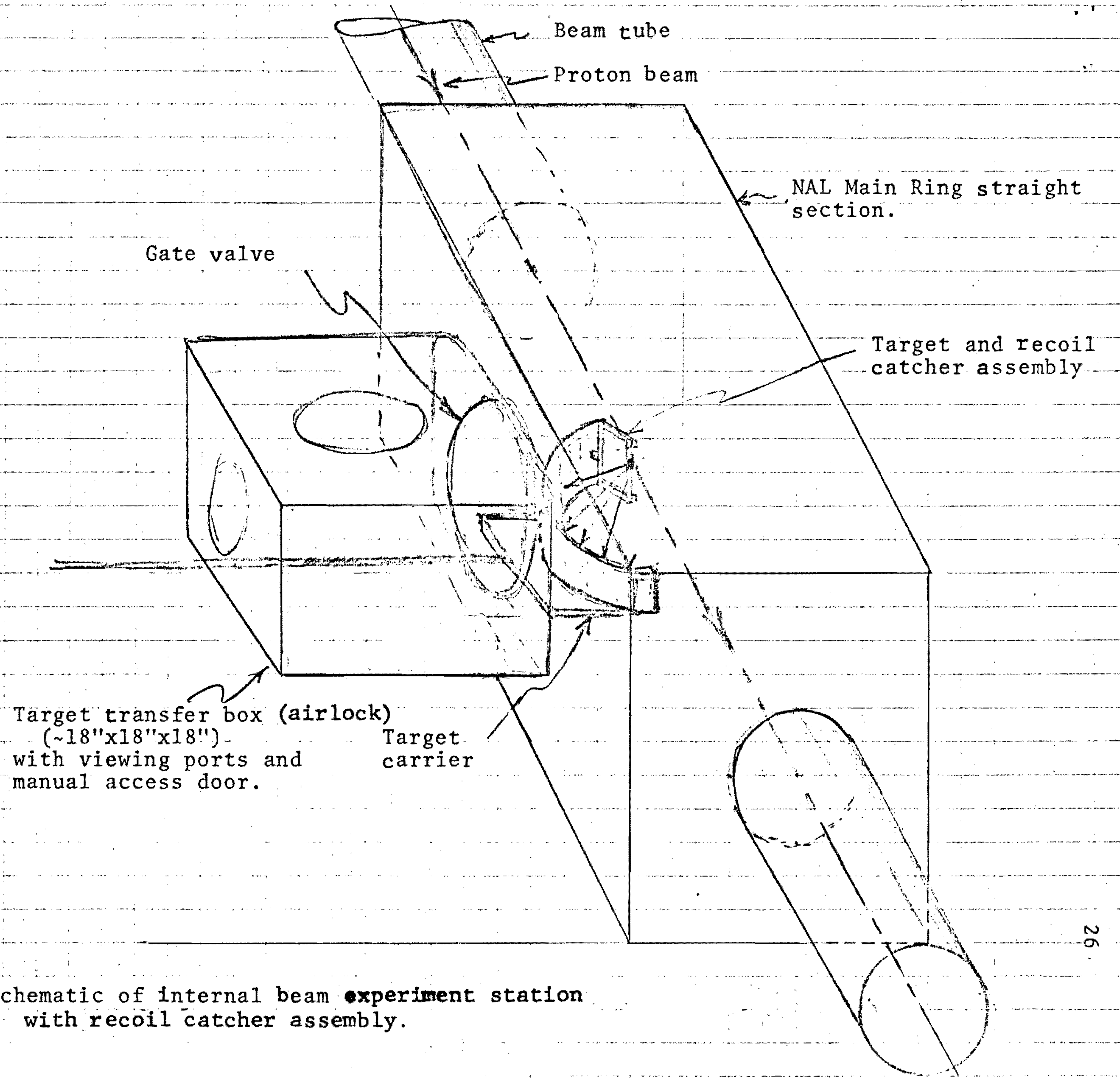


Fig. 4. Schematic of internal beam experiment station with recoil catcher assembly.