UCRL-11856

University of California

Ernest O. Lawrence Radiation Laboratory

TWO-WEEK LOAN COPY

This is a Library Circulating Copy which may be borrowed for two weeks. For a personal retention copy, call Tech. Info. Division, Ext. 5545

STUDY OF NEUTRONS PRODUCED BY THE 31.5-MeV PROTON BOMBARDMENT OF Be^9, N^{14}, AND Al^{27}

Adelson, Bostic, Waddel
1964

Berkeley, California

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

Submitted to Physical Review

UCRL-11856

UNIVERSITY OF CALIFORNIA
Lawrence Radiation Laboratory
Berkeley, California

AEC Contract No. W-7405-eng-48

STUDY OF NEUTRONS PRODUCED BY THE 31.5-MeV PROTON BOMBARDMENT OF Be^9, N^{14}, AND Al^{27}

Harold E. Adelson, Hoyt A. Bostick, and Charles N. Waddell

November 3, 1964

Study of Neutrons Produced by the 31.5-MeV Proton Bombardment of Be^9, N^{14}, and Al^{27} *

Harold E. Adelson† and Hoyt A. Bostick‡

Lawrence Radiation Laboratory
University of California
Berkeley, California

and

Charles N. Waddell

Lawrence Radiation Laboratory and
the University of Southern California,
Los Angeles, California

November 3, 1964

ABSTRACT

Absolute differential cross sections for the production of neutrons with energies greater than 5 MeV by the 31.5-MeV proton bombardment of Be^9, N^{14}, and Al^{27} were measured at 53, 90, and 127 deg (lab). A 4-inch liquid hydrogen bubble chamber was utilized as a neutron spectrometer. Analysis of the neutron energy spectra indicates possible new levels in the residual nuclei B^9 and O^{14}. All the angular distributions were strongly peaked forward, suggesting a direct-interaction mechanism for neutron production at these energies.

I. INTRODUCTION

The study of nuclear energy levels and of reaction mechanisms by measurement of neutron energy spectra and angular distributions has been hampered by the conflicting experimental requirements for good detection efficiency and for high resolution. However, the absence of electric charge, which makes detection of the neutron difficult, simplifies the analysis of the resulting data. In this paper are described the results of an experiment in which the hydrogen bubble chamber was first used as a neutron spectrometer.[1,2]

Absolute differential cross sections for the production of neutrons of energy greater than 5 MeV from the bombardment of thin targets of Be^9, N^{14}, and Al^{27} with 31.5-MeV protons are presented. These yields were measured at three angles (53, 90, and 127 deg) to permit a comparison to the predictions of the compound-nucleus continuum theory[3] and of direct interaction theories.[4,5,6] The neutron yield was strongly peaked forward for each of the targets studied. Considerable structure is apparent in the observed spectra, and the spectra for the two light targets indicate the possible existence of new levels in the residual nuclei, B^9 and O^{14}, as well as previously observed levels. The excitation energies presented here differ from those given in reference 2 because of a calculational error in that work.

The use of the liquid hydrogen bubble chamber as a fast-neutron spectrometer has been described in detail in reference 2.

II. EXPERIMENTAL DETAILS

A. Bubble Chamber

The 4-in. -diameter liquid hydrogen bubble chamber used in this work has been described previously.[2,7] The "sensitive" liquid hydrogen occupied a disk-shaped volume 4 in. in diameter and 2 in. thick. The cylindrical wall of the chamber contained a 7/8-in. -diameter entrance window made of 0.007-in. Mylar. The recoil-proton tracks were photographed by a 35-mm stereo camera located at 90 deg from the incoming neutron direction, with dark-field photography.

In order for the neutron-detection device to be effective, it is necessary to distinguish the recoil protons from the background electrons arising from the conversion of γ rays produced in the target. The use of a magnetic field to make this separation was deemed undesirable because the heating for the magnet coils greatly increased the cycling time of the bubble chamber, and because the magnet also introduced a large neutron-scattering mass near the chamber. By operating the bubble chamber at a lower temperature than normal, it was possible to bias out the minimum-ionizing electrons.[7] The tolerable temperature variation about the selected operating point of 26° K was ± 0.05° K.

B. Experimental Arrangement

The arrangement of the experimental equipment is shown in Fig. 1. The 31.5-MeV protons from the LRL linear accelerator[8,9] were deflected 10 deg by the steering magnet and then focused on the thin targets with a strong-focusing quadrupole triplet. A carbon collimator defined a 1/2-in. -diameter beam spot on the target. The beam was stopped in a carbon Faraday cup. Carbon baffles or collimators were used to prevent the

proton beam from striking the brass walls of the evacuated beam pipe. Provision was made for the dispersion of the beam after it had passed through the target by increasing the diameter of the beam pipe to 8 in. and lining the pipe with polyethylene (CH_2). Carbon was chosen for the collimators and for the Faraday cup because it has a high neutron-production threshold (about 20 MeV)[10] and a low neutron-production cross section.[11]

The bubble chamber was shielded from the γ-ray and neutron background produced in the Faraday cup and the collimators with a 4-in. layer of lead bricks and a 16-in. layer of borated paraffin. This arrangement reduced the target-out background to less than 1% of target-in yield.

C. Neutron Collimation

In the first experimental runs, no neutron collimation was used. An analysis of the angular distribution of the recoil protons indicated a flux of neutrons incident upon the sensitive volume from directions other than that of the target. Subsequent measurements indicated that the major portion of this effect was due to neutrons scattered from the thick glass and steel walls of the chamber itself.

To remove this background the chamber was shielded by a collimator, as shown in Fig. 1. Several collimator shapes were tested,[2] an iron block 25-in. long with a 5/8-in.-diameter axial hole was used in obtaining the data presented here.

D. Data Analysis

A fast data-reduction system (fully described in reference 2) was developed for the analyses of the recoil-proton tracks. A summary of the method of data reduction is given here.

The two-dimensional coordinates of both end points of a track in each stereo view were read with a commercial electronic coordinate-measuring device,[12] and were punched on a data card. Since it was not possible for the readers to determine whether a recoil-proton track was acceptable, all tracks in the central portion of the chamber were measured. Acceptable tracks began within a cylindrical sensitive volume, ended before a plane at the back of the chamber, and had a polar angle $\theta \leq 30$ deg. An IBM 650 digital computer was used to identify acceptable tracks and to compute the corresponding neutron energies. Approximately one out of every five tracks originally measured was accepted.

In calculating the efficiency of the spectrometer it is necessary to take into account the variation of the n-p cross section with energy, the decrease in neutron flux in passage through the hydrogen, the angular distribution of recoil protons, the angular acceptance limits of 0 deg to 30 deg, and the rejection of recoils that start in the sensitive volume but end beyond its limits. A detailed description of the calculation of the efficiency of hydrogen bubble chambers as neutron spectrometers is given in reference 2. The absolute efficiency of the 4-in. hydrogen bubble chamber as it was used in this experiment is shown in Fig. 2.

It was important to determine the energy at which tracks became too short for the readers to find them with 100% efficiency. This lower-energy cutoff was determined in two ways. The first was to have the

readers unknowingly measure the same data and then to compare the number of tracks observed by each reader in different energy regions. The second check was to plot the center-of-mass angular distribution of the observed recoil protons for different energy regions. Since the c. m. distribution is known to be flat, a decrease in reader efficiency would have been shown by a falling off of the distribution as the c. m. angle increased and the proton tracks became correspondingly shorter. Both checks indicated a decrease in reader efficiency for neutrons of energy less than about 7 MeV (lab). Since the decrease in reader efficiency is gradual, the energy spectra were calculated down to 5 MeV in order to look for possible structure in the spectra. The detection efficiency for the 5- to 7-MeV region was estimated to be about 90%.

E. d-T Spectrum and Spectrometer Resolution

Since this was the first time a liquid hydrogen bubble chamber had been used as a neutron spectrometer and because we wished to test the effect of various neutron collimators on the observed spectra, the $T(d,n)He^4$ reaction was used to generate an almost monoenergetic neutron beam. A tritium-titanium target assembly was placed in the target chamber and bombarded with deuterons accelerated to 4 MeV by the Van de Graaff linac injector,[8] and reduced in energy to 2 MeV by a gold foil so that the deuterons would stop within the tritium-titanium target.

The neutron energy spectrum observed at 90 deg with a 7/8-in. -diameter collimator is shown in Fig. 3. This spectrum was obtained from the acceptance of recoils at angles not greater than 30 deg. The full width at half maximum was about twice as large for acceptance of angles up to 45 deg.[2] For the 5/8-in. -diameter collimator the full width at half maximum was 1.5 MeV. Multiple scattering of the deuterons in the target

assembly produces an energy spread of the neutrons of about 0.6 MeV.[2,13] If one assumes that this source spectrum (0.6 MeV full width), the measured spectrum (about 1.5 MeV full width), and the instrumental resolution function of the complete system (including the reading system) all have Gaussian shapes, then the full width at half maximum of the instrumental resolution function is given by

$$R_{1/2} = \left[(1.5)^2 - (0.6)^2\right]^{1/2} = 1.37 \text{ MeV}.$$

Thus, the instrumental resolution of the complete system was about 10% at 14 MeV neutron energy.

III. RESULTS

A. Nitrogen

The cross sections for the production of neutrons from the bombardment of N^{14} with 31.5 MeV protons were measured at laboratory-system angles of 53, 90, and 127 deg. An evaporated, self-supporting target of melamine ($C_3N_6H_6$) of areal density 39.3 mg/cm^2 was used. The proton energy loss with the target at 30 deg with respect to the beam line was 0.8 MeV. A polystyrene (CH) target was bombarded to obtain the carbon spectrum for the necessary subtraction.

The $N^{14}(p,n)$ reaction has a Q value of -5.931 MeV.[10] This reaction was first investigated with 17.3-MeV protons and nuclear emulsions by Ajzenberg and Franzen at 30, 60, 90, and 150 deg (lab).[14] In that work they detected neutron groups corresponding to broad nuclear levels of O^{14} at excitation energies of 6.2, 7.5, and 9.3 MeV as well as a weakly produced ground state.

Towle and Macefield studied the $C^{12}(He^3,n)O^{14}$ reaction, using the slow/fast technique to measure threshold energies for neutron production.[15] States of O^{14} were identified at 5.905 ± 0.012, 6.30 ± 0.03, and 6.586 ± 0.012 MeV. Gale et al. also observed the ground-state neutrons from the $C^{12}(He^3,n)O^{14}$ reaction, using 5.7-MeV He^3 and time-of-flight techniques.[16]

The proton energy of 31.5 MeV and the neutron detection threshold of 5 MeV allowed investigation of O^{14} up to an excitation energy of 18 MeV. In order to facilitate the examination of the neutron spectra for possible level information, the spectra were transformed into the c.m. system. These data are shown in Fig. 4. The solid vertical lines indicate the expected positions of neutron groups from the ground state and the previously identified states of O^{14}.[10] Also indicated are the maximum c.m. energies of neutrons from the (p,pn) and (p,αn) reactions that lead to three-body final states. The neutron spectra from these reactions would be expected to rise smoothly with decreasing neutron energy.

The maximum c.m. neutron energies resulting from the $C^{12}(p,n)$ reaction are shown in Fig. 4. Because the neutron yield from carbon is low,[11,17] the amount of carbon subtraction data obtained was small. Therefore the carbon spectra were smoothed before subtraction, and it is possible for some unobserved structure from the $C^{12}(p,n)$ reaction to appear in the data. The average lab cross sections for the production of neutrons with energy greater than 5 MeV from carbon are 100 μb/sr-MeV at 53 deg (lab), 64 μb/sr-MeV at 90 deg, and 47 μb/sr-MeV at 127 deg.

As can be seen from the neutron spectra shown in Fig. 4, the production of neutrons from N^{14} is strongly peaked forward for the neutron-energy region studied. The $N^{14}(p,n)O^{14}$ ground-state group is found to be weakly produced at all angles of observation (approximately 50 μb/sr). A strong neutron group does appear in the energy region corresponding to the excitation of the lower excited states of O^{14}. Characteristic at all three angles of observation is the increasing yield of neutrons with decreasing energy.

In the previous investigation of the $N^{14}(p,n)O^{14}$ reaction with 17.3-MeV protons, the ground-state neutron group was clearly observed although absolute cross sections and angular distributions were not obtained.[14] To attempt to understand the low yield of the ground-state group produced by 31.5-MeV protons, we may examine the predictions of the Austern-Butler-McManus direct-interaction theory for the (p,n) reaction.[4] Using a radius of 1.4 $A^{1/3}$ F and the lowest allowed ℓ value ($\ell = 0$) for the transition from the $N^{14}(1^+)$ ground state to the $O^{14}(0^+)$ ground state, one finds that the first minimum in the angular distribution is predicted to occur at approximately the most forward angle of observation (55 deg c.m.). The physical arrangement of the bubble chamber did not permit us to measure the neutron yield at smaller angles, at which this theory would predict the largest (p,n) cross sections to occur.

Because of the lack of information concerning the existence of excited states of O^{14} with excitation energies greater than 9.3 MeV, these spectra were examined for evidence of possible unreported excited states. The search for such states was severely limited by the resolution of the bubble

chamber, the statistical accuracy of the data, and by the fact that the neutrons from the (p,pn) and (p,αn) reactions can appear at energies corresponding to excited states of O^{14}, Although the neutron spectra from these three-body final-state reactions are expected to rise smoothly, the presence of these neutrons can mask the structure resulting from the (p,n) reaction because of statistical fluctuations.

The four neutron groups labeled A through D in Fig. 4 may represent transitions to unreported levels of O^{14}. A neutron group was considered to signify a possible level if it appeared at at least two angles with the same c.m. energy. The known energy levels of the mirror nuclei C^{14} and O^{14} are shown in Fig. 5,[10] with the possible energy levels A through D added. An uncertainty of ± 0.8 MeV is assigned to the energy of each of these possible levels because of resolution and range energy uncertainties.

Possible level A (8.3 MeV excitation) appears at 90 and 127 deg, and is consistent with the shape of the forward-angle spectrum. (It is, of course, possible that this level corresponds to the 9.3-MeV level reported by Ajzenberg and Franzen.[14]) Possible level D (16.7 MeV excitation) appears strongly at the forward angle, but the energy spectrum at 127 deg ends before this level because of the c.m. transformation.

B. Beryllium

The cross sections for the production of neutrons from the bombardment of Be^9 with 31.5 MeV protons were measured at lab angles of 53, 90, and 127 deg. The target was 23.8 mg/cm^2 thick and the proton energy loss with the target at 30 deg with respect to the beam line was 0.4 MeV.

The $Be^9(p,n)B^9$ reaction (Q = -1.854 MeV) has been investigated at 6.59 MeV by Ajzenberg and Buechner, using nuclear emulsions.[18] That experiment indicated an excited state at 2.37 MeV in addition to the ground-state neutron group. Using the "counter-ratio" technique for proton energies from 2 to 5.8 MeV, Marion, Bonner, and Cook[19] observed neutron thresholds corresponding to the ground state and the 2.3-MeV level of B^9. For protons from 8 to 14 MeV, and using a fast neutron spectrometer, Saji observed three possible excited states at 3.07, 4.14, and 4.93 MeV excitation energy.[20]

The center-of-mass neutron energy spectra are shown in Fig. 6. The spectra indicate considerable structure, and the neutron yield is strongly enhanced at the forward angle. The 53-deg neutron spectrum does not exhibit the usual increase in neutron yield as the neutron energy decreases--instead, it shows an enhanced yield for the higher neutron energies.

The solid vertical lines in Fig. 6 indicate the expected position of the well-established excited states of B^9.[10] Also indicated are the maximum c.m. neutron energies of neutrons from the (p,pn), (p,αn), and (p,α2n) reactions that lead to multibody final states. Production of the ground-state neutron group is clearly seen at all three angles of observation. The large yield of high-energy neutrons observed at the forward angle may be due to unresolved neutron groups corresponding to the 2.34- and 2.82-MeV levels of B^9.

Because of the lack of information concerning the existence of excited states of B^9 with excitation energies greater than 7 MeV, these spectra were examined for evidence of possible unreported levels. The dashed vertical lines labeled A through F correspond to neutron groups appearing at

at least two angles of observation, and therefore may signify possible levels of B^9. We note that the neutrons from all states of B^9 (including the ground state) are superimposed on the neutron spectra from multi-body final state reactions. However, the indicated possible levels are most clearly resolved in the forward-angle spectrum where the direct-interaction theory would predict the largest (p,n) cross sections to occur, and where the yield is greatest and the statistical errors smallest. Level A (4.7 MeV) is very strongly produced at 53 deg and may correspond to the previously reported 4.1- and 4.9-MeV levels.[20] The known energy levels of B^9 and of the mirror nucleus Be^9 are shown in Fig. 7 where the possible levels A through F have been added. The error assigned to the energy of each possible level because of resolution and range energy uncertainties is $\pm$ 0.8 MeV.

C. Aluminum

The neutron spectra from 31.5-MeV proton bombardment of Al^{27} are shown in Fig. 8. Indicated in Fig. 8 are the expected positions for neutrons produced in the $Al^{27}(p,n)Si^{27}$ ground-state reaction (Q = -5.610 MeV) and for the most energetic neutrons produced in the $Al^{27}(p,pn)Al^{26}$ reaction (Q = -13.05 MeV). It is quite apparent that the ground-state neutron group was produced at all three angles, and that the production was quite strong at the forward angle.

Because the separation of levels in a nucleus as heavy as Si^{27} is smaller than the resolution of the spectrometer system, no attempt was made to interpret the observed spectra

in terms of excitation of specific excited states of Si^{27}. However, aluminum contains enough nucleons to allow a comparison to the predictions of the compound-nucleus continuum theory, since the average excitation energy of each nucleon (about 1 MeV) is much less that the separation energy of a nucleon from the compound nucleus (about 8 MeV). Accordingly, one could expect the energy spectrum of neutrons emitted from the (p,n) reaction to be obtained from the reciprocity theorem,[3]

$$I_N(E)dE = \text{const } E\ \sigma_c(E)\omega(Q)dE, \tag{1}$$

where $I_N(E)$ is the probability of emitting a neutron of energy between E and E + dE; $\sigma_c(E)$ is the capture cross section of a nucleus at excitation energy $Q = E_{max} - E$ for a neutron of energy E; and $\omega(Q)$ is the energy level density in the residual nucleus. By making a Taylor expansion of the logarithm of the level density around the maximum excitation energy of the residual nucleus ($Q_{max} = E_{max}$), Blatt and Weisskopf[3] obtain the "Maxwellian" formula for the neutron spectrum,

$$I_N(E)dE = \text{const } E\sigma_c(E)\ \exp(-E/T)dE, \tag{2}$$

where T, the "Nuclear temperature," is defined by the relationship

$$T^{-1} = \frac{d \ln \omega(Q)}{dE}. \tag{3}$$

Thus, the measurement of the spectra from (p,n) reactions should yield information regarding the energy level densities in excited nuclei. It should be emphasized, however, that the (p,n) reaction is not the only possible--nor the most likely--neutron-producing reaction for 31-MeV protons. Table

I lists the several possible reactions that may contribute to the observed spectra, together with their Q values and the maximum lab neutron energy at the forward angle of observation (53 deg lab). The Q values were obtained from Endt and Braams[21] or were calculated by using data from Wapstra.[22]

Thus, over most of the neutron energy range studied in this experiment, multiple particle emission is possible, and the expressions given in Eqs. (1) and (2) are not directly applicable. However, it has been customary to fit emission spectra to Eq. (2), extracting experimental values of "T" in order to facilitate the comparison of spectra obtained under differing experimental conditions.

The "nuclear temperature" T can be determined from an emission spectrum by plotting the quantity $I_N(E)/E\sigma_c(E)$ versus E on semilog paper. If the spectrum has a "Maxwellian" form, the data will lie on a straight line whose negative slope is T. Semilog plots of this relation for the c.m. spectra of aluminum for the three angles of observation are shown in Figs. 9, 10, and 11. The values of $\sigma_c(E)$ were obtained from Blatt and Weisskopf,[3] and the energy width of the data points was doubled to 0.8 MeV to remove some of the structure in the spectra. The straight lines were fitted to the data for neutron energies between 5 and 12 MeV (c.m.). The empirical "temperatures" T determined for the angles were 4.3 MeV at 53 deg, and 3.3 MeV at both 90 and 127 deg.

The spectral shapes are fairly well represented by the straight line; the major departure occurs for the highest neutron energies at the forward angle. Only the (p,n) reaction

contributes to this region, and only the lower-lying states of Si^{27} are involved.[23] Bloch,[24] Rosenzweig,[25] Critchfield and Oleska,[26] and Beard and McClellan[27] have emphasized the level density dependence on nucleon shell configuration at excitations of only a few MeV, and therefore one would anticipate a departure from a straight line for the highest-energy neutrons. Also, the direct-interaction mechanism for the (p,n) reaction preferentially produces the lower excited states of the residual nucleus, since the core of the nucleus is undisturbed.[4]

While the "temperatures" obtained at 90 and 127 deg were the same, the production of neutrons was not; the 90-deg yield was much larger than the 127-deg yield. The integrated differential cross sections for the production of neutrons with energy greater than 5 MeV (lab) are listed in Table II for the three observation angles; the ratio, from forward to backward angles, is approximately 5:3:1. This strong forward asymmetry is in direct contradiction to the predictions of the compound-nucleus continuum theory. Wolfenstein has shown that the angular distributions predicted by the statistical model will be symmetric about 90 deg for high excitations of the compound nucleus into a region of many overlapping levels.[28] The 30-MeV proton bombardment of Al^{27} would produce the compound nucleus Si^{28} with an excitation of about 40 MeV; hence the continuum criterion should be well satisfied. Furthermore, Hauser and Feshbach have pointed out that the angular distributions should be isotropic for high excitations of the residual nucleus.[29] This should then be the case for the 5- to 10-MeV neutrons in this experiment, since the residual nucleus--for the (p,n)

reaction--is left with 15 to 20 MeV excitation. The spectra in Fig. 8 indicate, however, that the neutron production is strongly peaked forward even at the lowest emission energies studied, where the reactions involving three-body final states are important. Hence, it would appear that both types of reactions--two- and three-body--proceed primarily through a direct-interaction mechanism.

It is of interest to compare the empirical "temperatures" T obtained from this experiment with those from previous experiments on aluminum. A compilation given by Gugelot has been used,[30] to which have been added the results from a 23-MeV (p,n) experiment by Cohen,[31] and the results of this experiment. In Table III the following quantities are listed: the type of reaction studied; E_{max}, the maximum energy of an emitted nucleon; ΔE, the energy interval of the emitted nucleon over which T was computed; and ΔQ, the corresponding excitation energy interval of the residual nucleus for the two-body reaction.

Comparison of the three (p,n) experiments shows an increase in T with increase in bombarding energy. In Cohen's experiment,[31] as in this one, it was found that higher temperatures were obtained for the highest-energy neutrons and for the forward angles of observation. The angular distributions obtained by Cohen were peaked forward for neutron energies greater than 9.5 MeV; the ratio of the neutron intensities at 53, 90, and 127 deg were approximately 6:3:2. This is quite similar to our results at a higher bombarding energy.

The forward production of the emitted neutrons and the energy spectra indicate that the direct-interaction mechanism

is important for the neutron energy region studied (i.e., $E_N > 5$ MeV lab). In Table II are listed the estimated total cross sections for neutrons with energy greater than 5 MeV (39 mb) and the measured total cross section for the production of neutrons from thin targets (273 mb).[17] Thus, only about 1/7 of the total neutron production was studied in this experiment, and there is no experimental information regarding the spectrum and angular distribution of the more abundant lower-energy neutrons.

IV. DISCUSSION

The forward peaking of the neutron yield for all the targets studied indicates that the direct-interaction mechanism is important for neutron-producing reactions at this proton energy. It has been found that the ground-state neutron group is very weakly produced in the $N^{14}(p,n)O^{14}$ reaction, whereas it is strongly produced in the $Be^9(p,n)B^9$ and $Al^{27}(p,n)Si^{27}$ reactions. It has been suggested that the reason for this low yield (for N^{14}) could be that the Austern-Butler-McManus theory of direct interactions predicts the largest neutron yields to occur at angles smaller than the most forward angles of observation.[4] However, this strong forward peaking should occur for all three reactions, and, in fact, the forward peak should be sharpest for the $Al^{27}(p,n)Si^{27}$ reaction.

Bloom, Glendenning, and Moszkowski[5] have shown that the (p,n) reaction connecting ground states of mirror nuclei singles out the isotopic spin exchange part of the effective neutron-proton interaction in the nucleus. The "direct" part of the

matrix element, which refers to the charge-exchange process in which the charge on the incident proton is transferred to a bound neutron, is dominant for mirror nuclei because of the good overlap of the wave functions for the initial and final bound states. Anderson and collaborators[36,37] have found that the isotopic spin exchange part of the effective n-p interaction is also important for the (p,n) reaction connecting non-mirror medium-weight nuclei since the residual nuclei are preferentially left in an excited state which is the isobaric analog of the ground state of the bombarded nucleus. In a related paper, Lane has shown[6] that it is possible to describe the (p,n) reaction with the optical model if the isotopic spin dependence of the potential is taken into account.

The $Be^9(p,n)B^9$ and the $Al^{27}(p,n)Si^{27}$ reactions connect mirror nuclei. The $N^{14}(p,n)O^{14}$ reaction, however, does not--the isobaric analog of the N^{14} ground state in O^{14} is forbidden by the Pauli principle. Therefore, the isotopic spin exchange part of the interaction should not be expected to dominate the $N^{14}(p,n)O^{14}$ ground-state reaction. The low yield of the ground-state group is thus in agreement with the predictions of the above-mentioned theories.[6,7]

V. ACKNOWLEDGMENTS

We wish to thank Professor Burton J. Moyer for his constant support and encouragement.

Essential to this experiment was the aid of the Lawrence Radiation Laboratory Bubble Chamber Group; in particular, Mr. Arnold Schwemin effected several modifications in the bubble chamber which made it suitable for use as a neutron spectrometer. We gratefully acknowledge the generous assistance of Mr. J. Sirois and the crew of the linear accelerator. It is a pleasure to thank Dr. Klaus Dietrich for helpful discussions on this work.

FOOTNOTES AND REFERENCES

* Work supported by the U. S. Atomic Energy Commission.

† Present address: General Dynamics-Astronautics, San Diego, California.

‡ Present address: Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts.

1. Harold E. Adelson, Ph.D. Thesis, Lawrence Radiation Laboratory Report UCRL-8568, Dec. 11, 1958 (unpublished). (The paper is based in part on this thesis.)
2. H. E. Adelson, H. A. Bostick, B. J. Moyer, and C. N. Waddell, Rev. Sci. Instr. 31, 1 (1960).
3. J. M. Blatt and V. F. Weiskopf, Theoretical Nuclear Physics (John Wiley and Sons, New York, 1962).
4. N. Austern, S. T. Butler, and H. McManus, Phys. Rev. 92, 350 (1953); W. Tobocman, Theory of Direct Nuclear Reactions (Oxford University Press, London, 1961).
5. S. D. Bloom, N. K. Glendenning, and S. A. Moszkowski, Phys. Rev. Letters 3, 98 (1959).
6. A. M. Lane, Phys. Rev. Letters 8, 171 (1962).
7. D. Parmentier and P. Schwemin, Rev. Sci. Instr. 26, 954 (1955).
8. L. W. Alvarez, H. Bradner, J. V. Franck, H. Gordon, J. D. Gow, L. C. Marshall, F. Oppenheimer, W. K. H. Panofsky, C. Richman, and J. R. Woodyard, Rev. Sci. Instr. 26, 111 (1955).
9. This proton linear accelerator is now at the University of Southern California, Los Angeles, California.
10. F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. 11, 1 (1959).

11. G. P. Millburn, Ph. D. Thesis, University of California Radiation Laboratory Report UCRL-3320, 1956 (unpublished); Y. K. Tai, G. P. Millburn, S. N. Kaplan, and B. J. Moyer, Phys. Rev. 109, 2086 (1958).

12. Oscar, Model N-2, manufactured by the Benson-Lehner Corporation, Los Angeles, California.

13. J. Benveniste and J. Zenger, University of California Radiation Laboratory Report UCRL-4266, 1954 (unpublished).

14. F. Ajzenberg and W. Franzen, Phys. Rev. 94, 409 (1954).

15. J. Towle and B. Macefield, Proc. Phys. Soc. (London) 77, 399 (1961).

16. N. Gale, J. Garg, J. Calvert, and K. Ramavataram, Nucl. Phys. 20, 313 (1960).

17. T. M. Henderson, P. S. Lewis, and C. N. Waddell, Neutron Yields from Thin Targets, to be submitted to Nucl. Phys.

18. F. Ajzenberg and W. W. Buechner, Phys. Rev. 91, 674 (1953).

19. J. B. Marion, T. W. Bonner, and C. F. Cook, Phys. Rev. 100, 91 (1955).

20. Y. Saji, J. Phys. Soc. Japan 15, 367 (1960).

21. P. M. Endt and C. M. Braams, Rev. Mod. Phys. 29, 683 (1957).

22. A. H. Wapstra, Physica 21, 367 (1955).

23. Nuclear Data Sheets (National Research Council, Washington, D. C.).

24. C. Bloch, Phys. Rev. 93, 1094 (1954).

25. N. Rosenzweig, Phys. Rev. 105, 950 (1957); 108, 817 (1957).

26. C. Critchfield and S. Oleska, Phys. Rev. 82, 243 (1951).

27. D. Beard and A. McClellan, Phys. Rev. 130, 962 (1963).

28. L. Wolfenstein, Phys. Rev. 82, 690 (1951).

29. W. Hauser and H. Feshbach, Phys. Rev. 87, 366 (1952).

30. P. C. Gugelot, Phys. Rev. 93, 425 (1954).

31. B. L. Cohen, Phys. Rev. 108, 768 (1957).

32. E. Graves and L. Rosen, Phys. Rev. 89, 343 (1953).

33. B. G. Whitmore and G. E. Dennis, Phys. Rev. 84, 296 (1951).

34. R. Britten, Phys. Rev. 88, 283 (1952).

35. P. C. Gugelot, Phys. Rev. 81, 51 (1951).

36. J. D. Anderson and C. Wong, Phys. Rev. Letters 8, 171 (1962).

37. J. D. Anderson, C. Wong, and J. D. McClure, Phys. Rev. 126, 2170 (1962); 129, 2718 (1963).

Table I. Neutron-producing reactions for the proton bombardment of Al^{27}.

Products of Al^{27} + p	Q (MeV)	Highest lab. neutron energy (53 deg) (MeV)
Si^{27} + n	-5.610	25.6
Al^{26} + p + n	-13.049	18.0
Mg^{23} + α + n	-14.93	16.1
Si^{26} + 2n	-16.27	14.7
Mg^{25} + 2p + n	-19.59	11.2

Table II. Cross sections for the production of neutrons by the 31.5-MeV proton bombardment of N^{14}, Be^{9}, and Al^{27}.

Target	Integrated differential cross sections[a] (mb/sr)			Estimated total cross section[a] (mb)	Thick-target total cross section[b] (mb)	Thin-target total cross section[c] (mb)
	53 deg	90 deg	127 deg			
N^{14}	4.6	1.7	1.1	32	108	---
Be^{9}	11.7	2.9	2.6	78	339	330
Al^{27}	5.2	3.0	1.2	39	234	273

[a] For neutrons with lab energy greater than 5 MeV.

[b] Reference 11. For Ep = 18 to 32 MeV.

[c] Reference 17. For Ep = 31.5 MeV.

Table III. Empirical "temperatures" determined from aluminum bombardments.

Reaction	E_{max} (MeV)	ΔE (MeV)	ΔQ (MeV)	T (MeV)	Reference
Al(n,n)	13	1-2	12-9	1.0	32
Al(n, n)	14	1-4	13-10	1.1	33
Al(p, p')	17	5-7	12-10	1.3	30
		8-12	9-5	2.7	
Al(p, p')	28	10-25	18-3	3-6.5	34
Al(p,n)	11	2-5	9-6	1.3 (0 deg)	35
				1.34 (0 deg)	
		≈ 3	≈ 14	1.1 (90 deg)	
				1.05 (150 deg)	
Al(p, n)	17				36
				2.6 (0 deg)	
		≈ 10	≈ 7	2.2 (90 deg)	
				1.9 (150 deg)	
				4.3 (53 deg)	
Al(p, n)	25	5-12	20-13	3.3 (90 deg)	This work
				3.3 (127 deg)	

FIGURE CAPTIONS

Fig. 1. Diagram of experimental arrangement showing the location of magnets, collimators, shielding, and the 4-in. hydrogen bubble chamber.

Fig. 2. Absolute efficiency for the detection of neutrons by the 4-in. bubble chamber as it was used in this experiment.

Fig. 3. Measured spectrum of neutrons from the $T(d,n)He^4$ reaction observed at 90 deg with 7/8-in. neutron collimator.

Fig. 4. Center-of-mass neutron energy spectra from the bombardment of N^{14} by 31.5-MeV protons. The solid vertical lines indicate the expected positions of neutron groups from previously identified excited states of O^{14}. Also shown are the maximum c.m. energies of neutrons from the (p,pn) and (p,αn) reactions. The dashed vertical lines indicate the positions of possible new energy levels of O^{14}.

Fig. 5. Energy-level diagram of the mirror nuclei C^{14} -O^{14}. The possible new energy levels of O^{14} are labeled A,B,C, and D to correspond to the positions indicated in Fig. 4.

Fig. 6. Center-of-mass neutron energy spectra from the bombardment of Be^9 by 31.5-MeV protons. The solid vertical lines indicate the expected positions of neutron groups from previously identified excited states of B^9. Also shown are the maximum c.m. energies of neutrons from the (p,pn), (p,αn), and (p,α2n) reactions. The dashed vertical lines indicate the positions of possible new energy levels of B^9.

Fig. 7. Energy-level diagram of the mirror nuclei Be^9 -B^9. The possible new energy levels of B^9 are labeled A, through F to correspond to the positions indicated in Fig. 6.

Fig. 8. Differential cross sections for the production of neutrons at 53, 90, and 127 deg (lab) by the 31.5-MeV proton bombardment of Al^{27}. The maximum lab neutron energies of neutrons from the (p,pn) reaction are indicated by the vertical solid lines.

Fig. 9. Plot of $I_N(E)/E\ \sigma_c(E)$ versus c.m. neutron energy for Al^{27} at 53 deg (lab). The maximum c.m. neutron energy from the (p,pn) reaction is indicated by the vertical line. The slope of the straight line was determined from the data between 5 and 12 MeV.

Fig. 10. Plot of $I_N(E)/E\ \sigma_c(E)$ at 90 deg (lab). The slope of the straight line was determined from the data between 5 and 12 MeV.

Fig. 11. Plot of $I_N(E)/E\ \sigma_c(E)$ at 127 deg (lab). The slope of the straight line was determined from the data between 5 and 12 MeV.

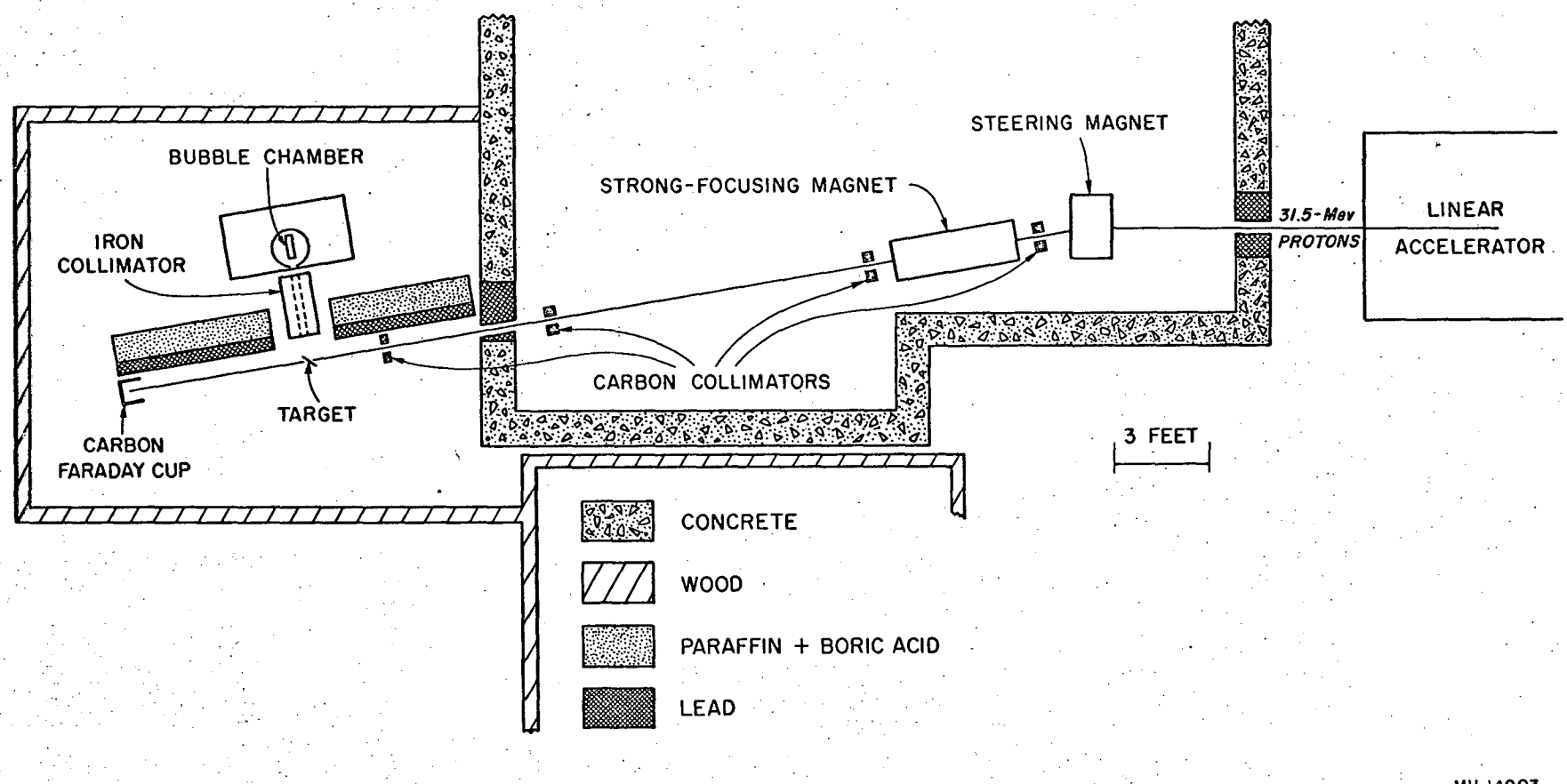
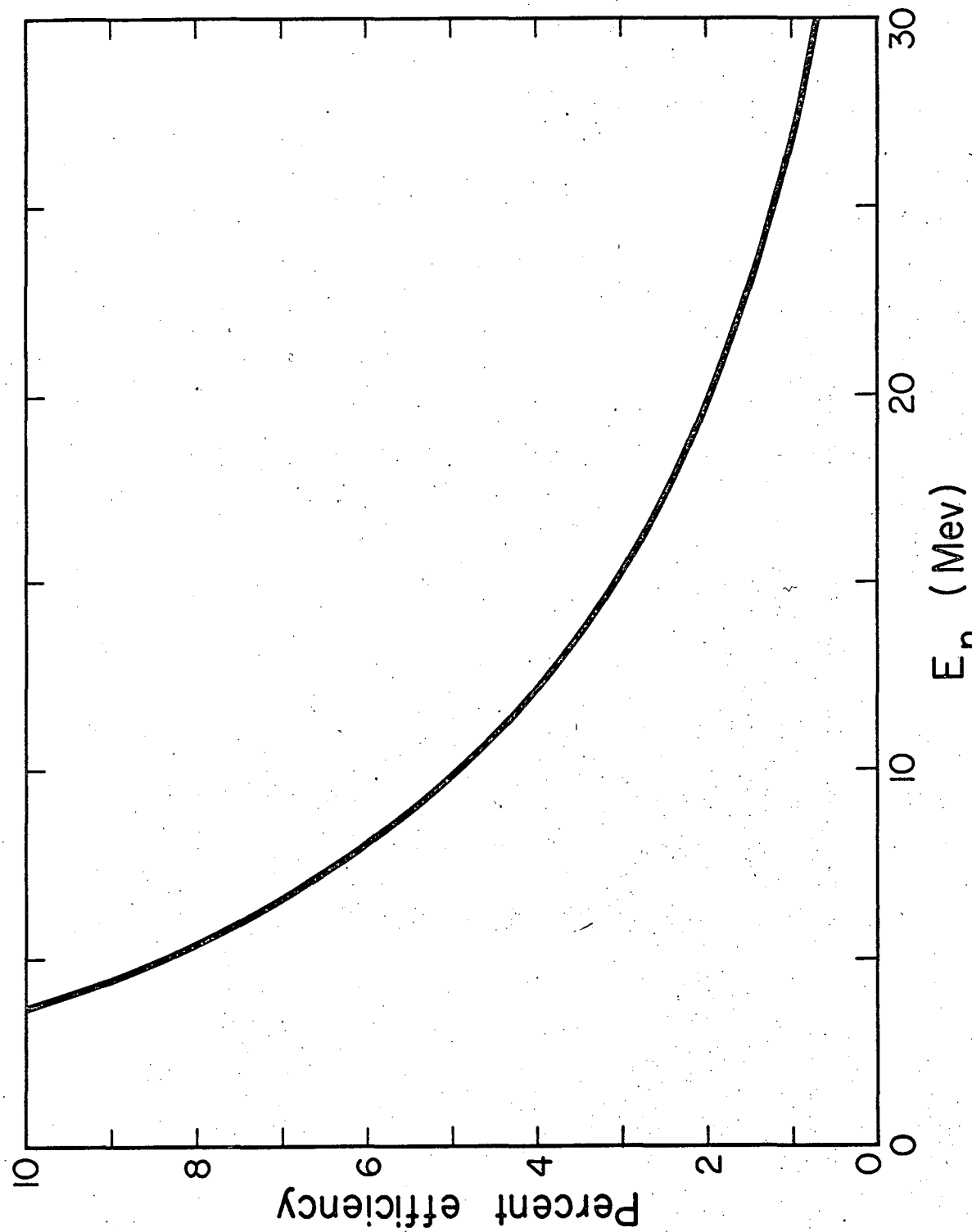

BUBBLE CHAMBER
IRON COLLIMATOR
TARGET
CARBON FARADAY CUP
STRONG-FOCUSING MAGNET
STEERING MAGNET
CARBON COLLIMATORS
31.5-Mev PROTONS
LINEAR ACCELERATOR
3 FEET
CONCRETE
WOOD
PARAFFIN + BORIC ACID
LEAD
MU-14903

Fig. 1



MU-14944

Fig. 2

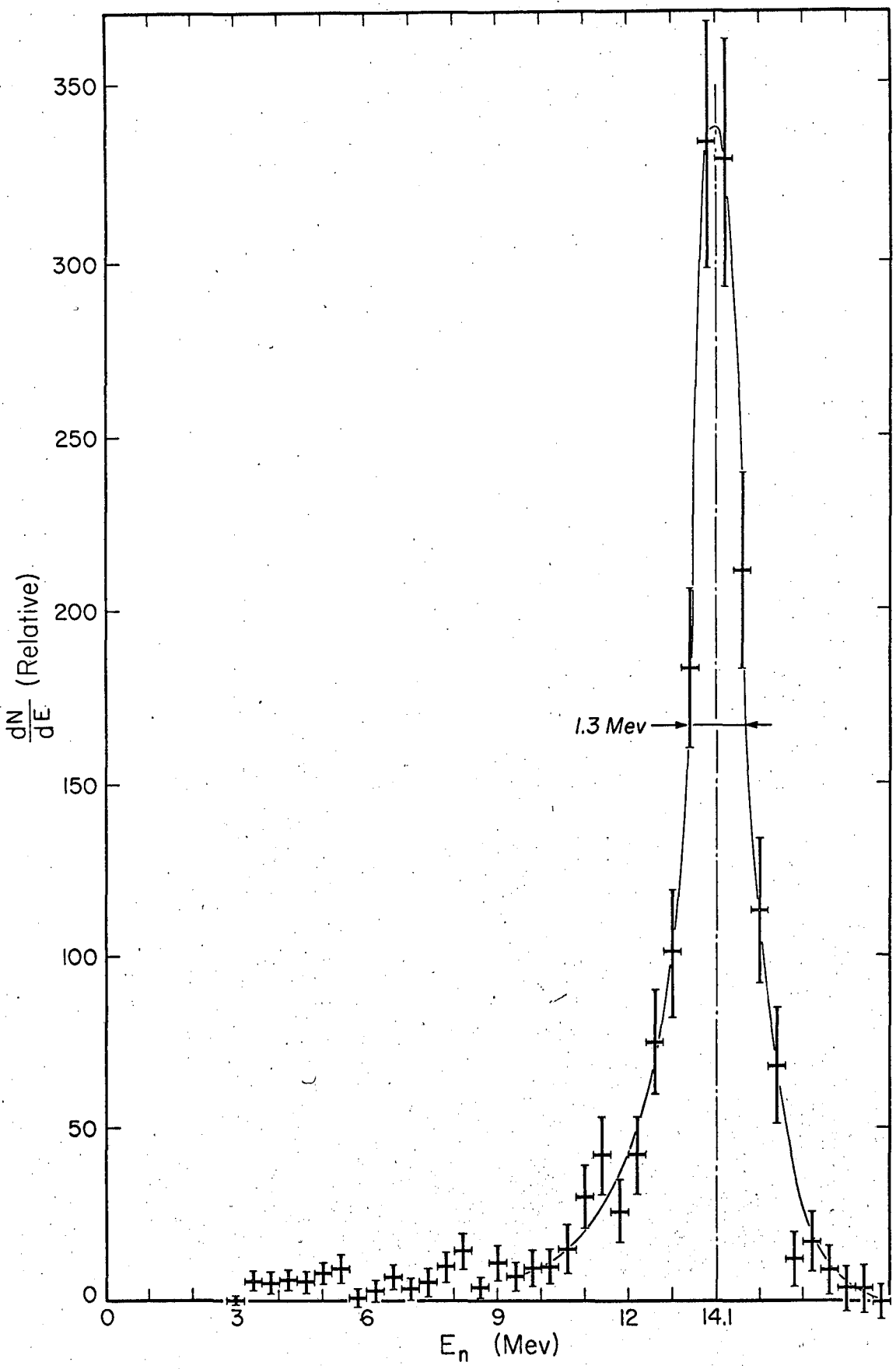
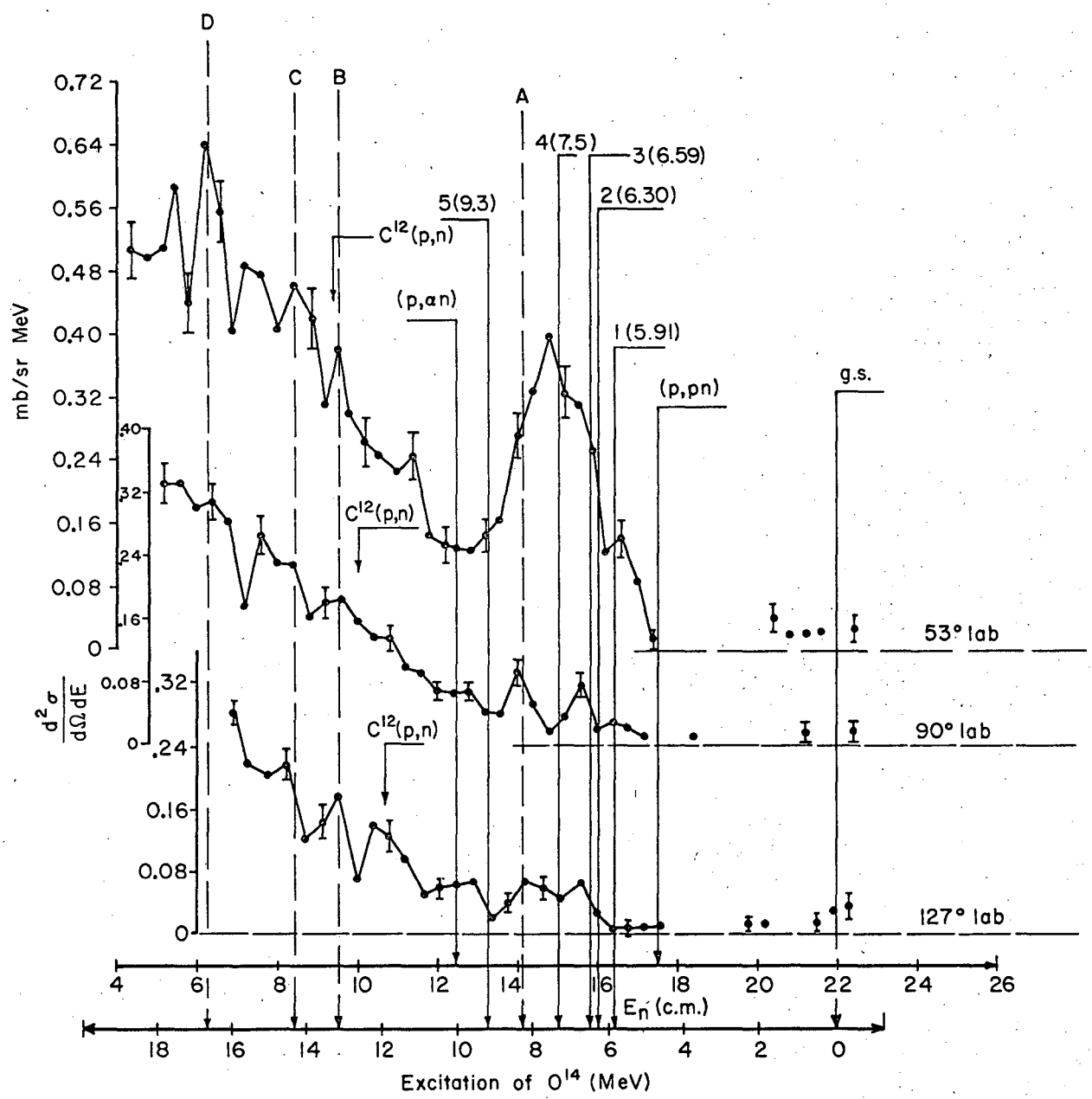

350
300
250
200
150
100
50
0
dN/dE (Relative)
1.3 Mev
0
3
6
9
12
14.1
E_n (Mev)

Fig. 3

T & 90°



MUB-2770

Fig. 4

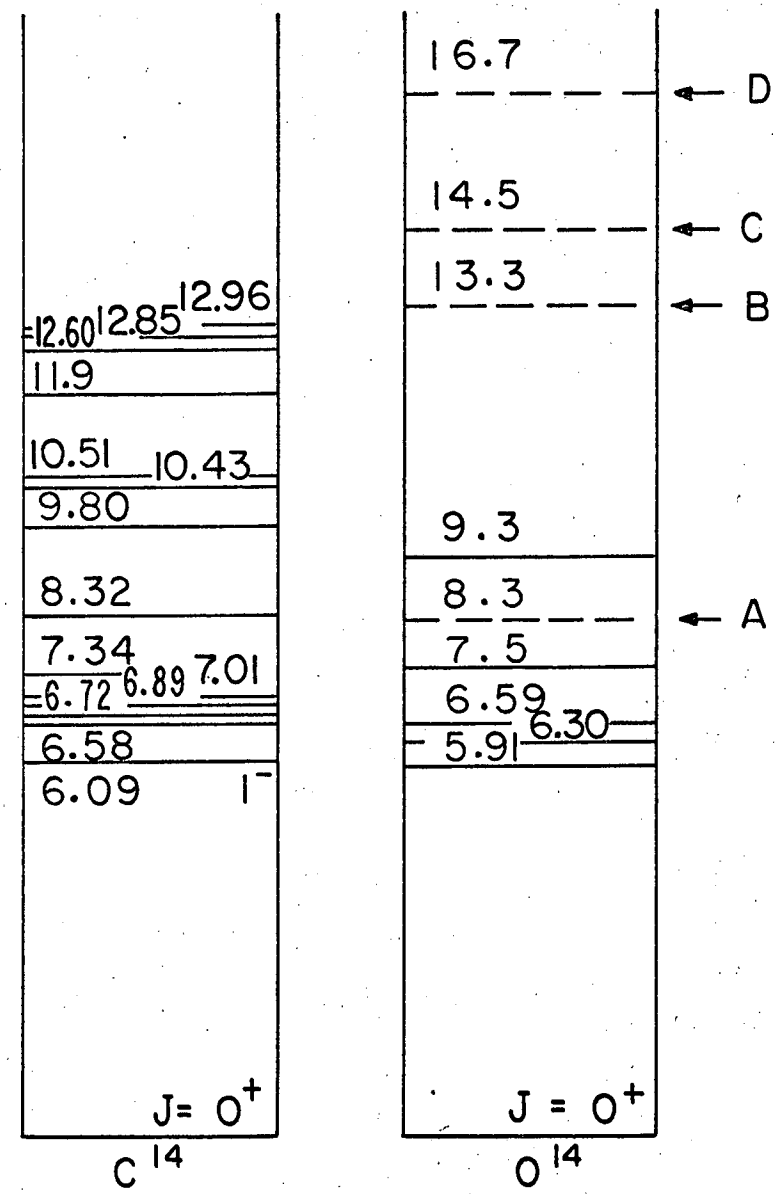


Fig. 5

MUB-4513

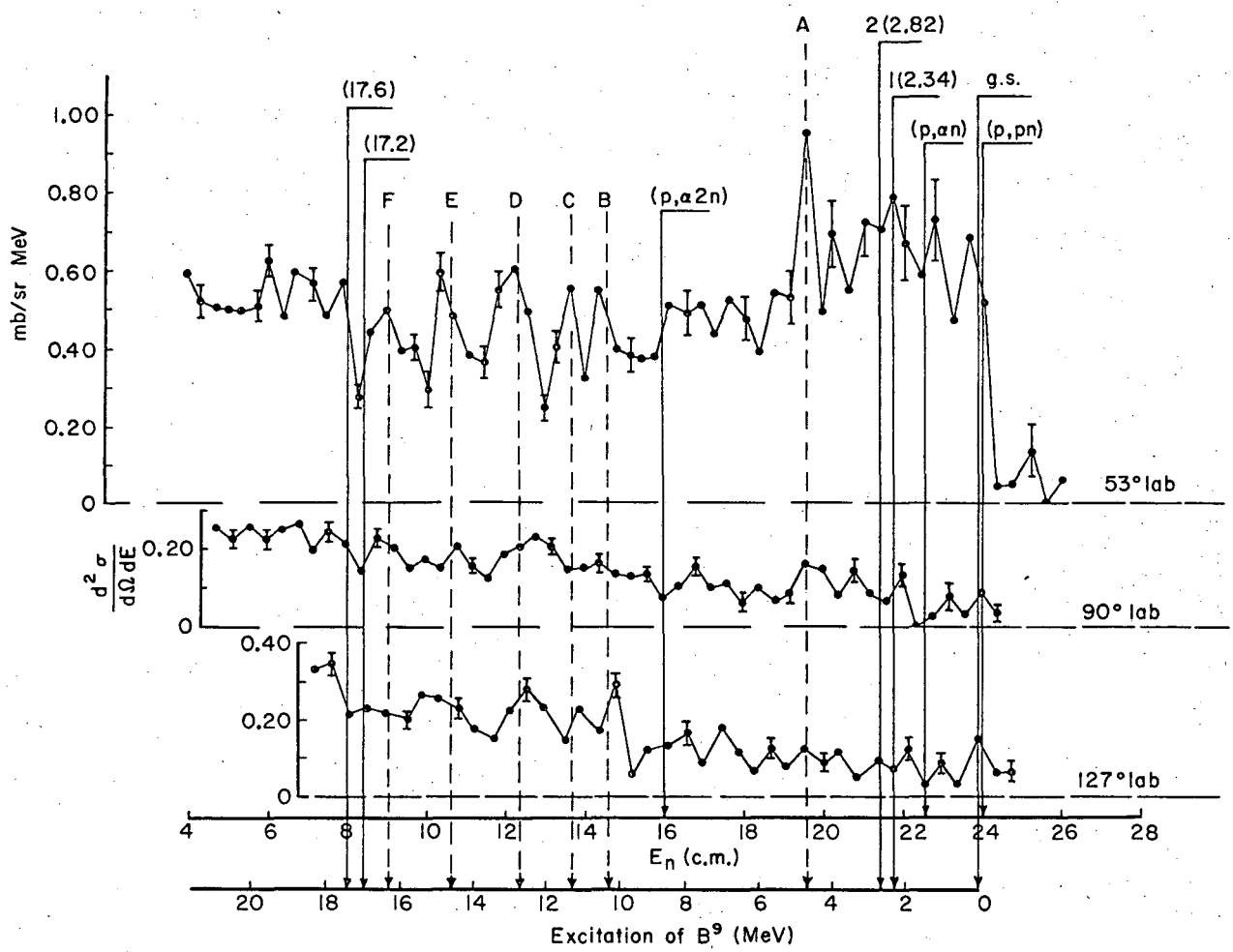


Fig. 6

MUB-2771

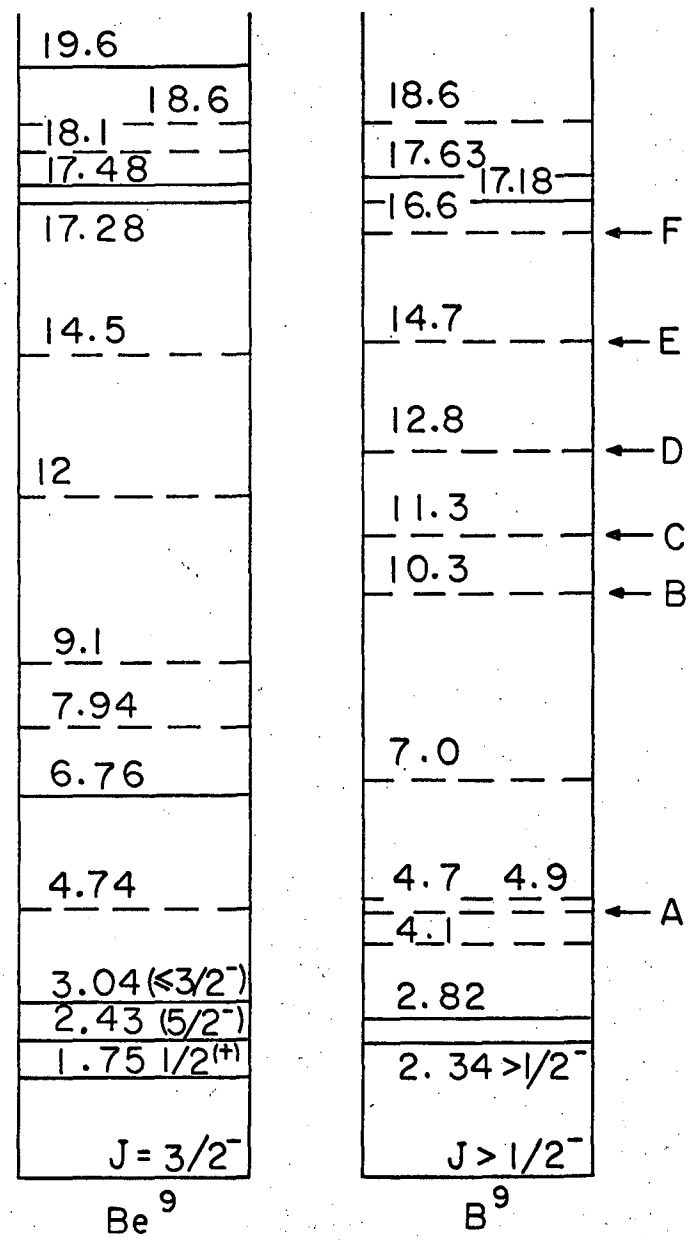
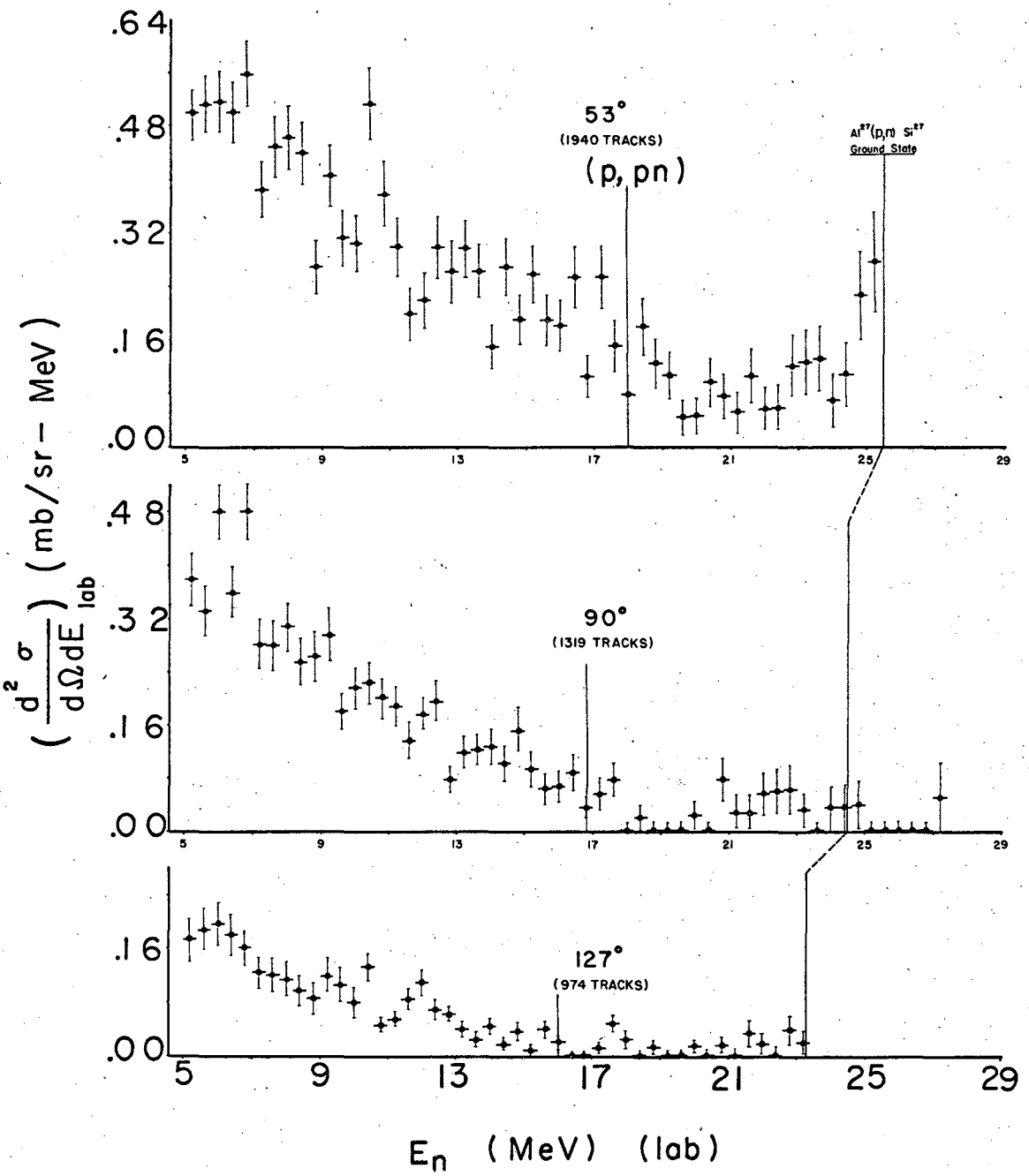


Fig. 7

MUB-4514



MUB-4515

Fig. 8

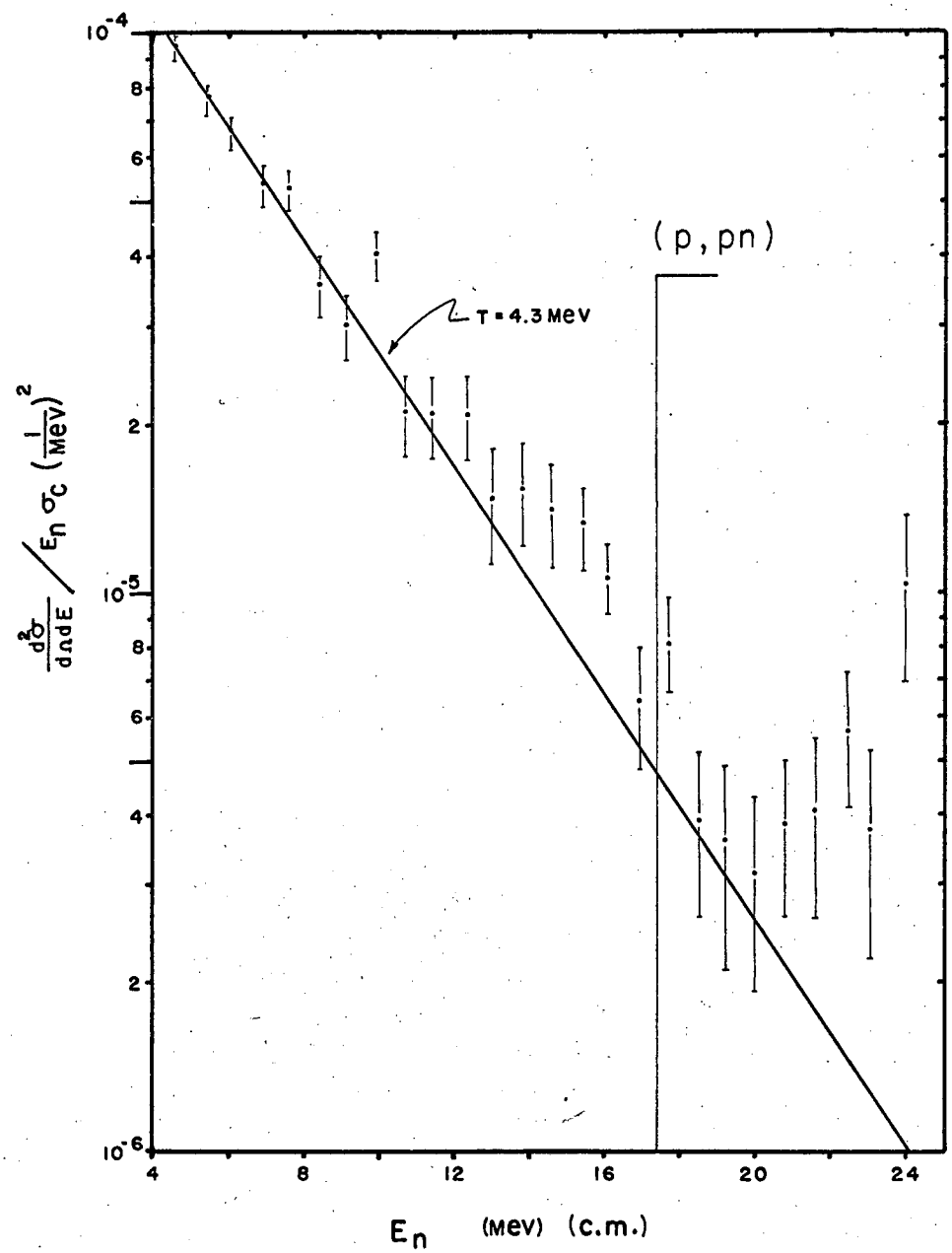


Fig. 9

MUB-4516

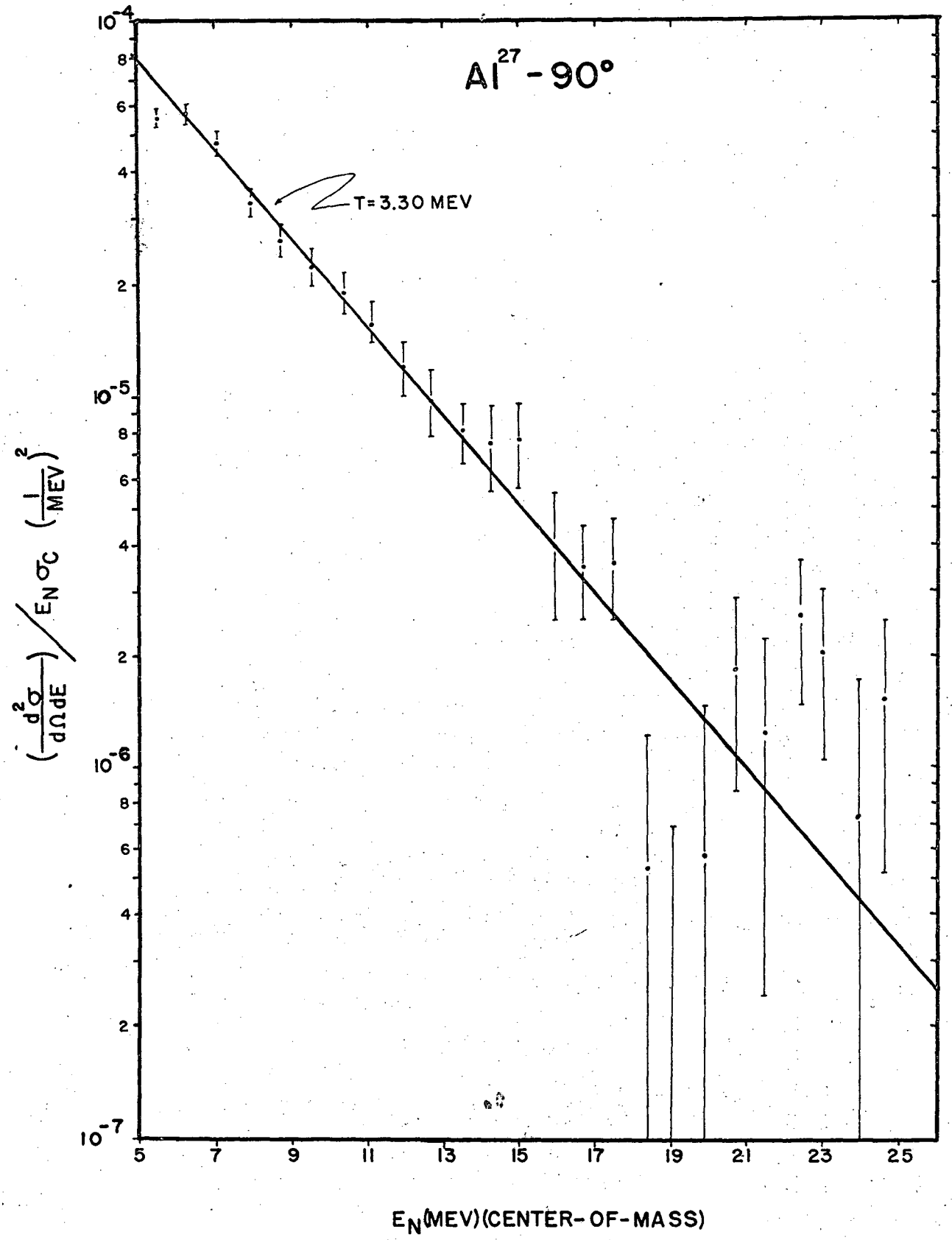


Fig. 10

MU-16515

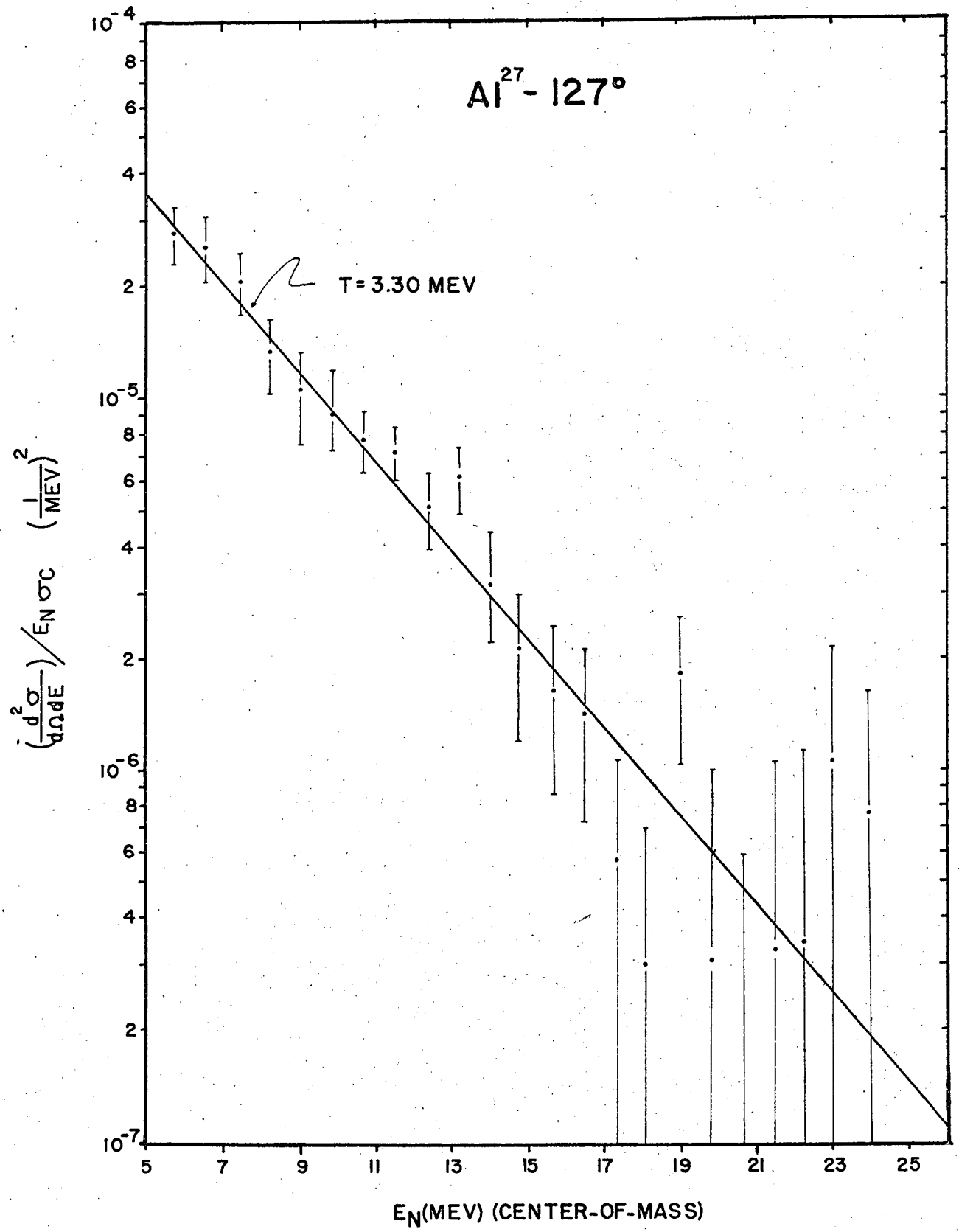


Fig. 11

MU-16516

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.