PHYSICAL REVIEW VOLUME 115, NUMBER 4 AUGUST 15, 1959

Angular Distributions of Proton Groups from the $Al^{27}(n,p)Mg^{27}$ Reaction at 14 Mev*

O. E. OVERSETH, JR.,† AND R. A. PECK, JR.
Brown University, Providence, Rhode Island

(Received March 18, 1959)

A study has been made of the high-energy proton groups from the $Al^{27}(n,p)Mg^{27}$ reaction at 14 Mev with emulsion detectors, continuous survey being made in the interval 10°–70° (lab system). Proton groups corresponding to the residual Mg^{27} nucleus left in the ground state and at excitations of 1.0, 1.6, 2.1, 2.8, and 3.5 Mev are identified. Several of these groups are characterized by a pronounced peaking in forward directions characteristic of direct interaction processes. The protons leading to the ground-state form a peak in the vicinity of 30°, those to the 1.0-Mev level at 36°, and those to the 1.6-Mev level at about 50°. The 3.5-Mev group is not resolved from known close-lying levels and the cluster exhibits an isotropic distribution. The 2.1-Mev and 2.8-Mev groups, corresponding to no previously reported levels in Mg^{27}, also display an isotropic distribution and probably represent several unresolved levels. The three lowest-lying levels shown approximate fits to theoretical curves consistent with reactions proceeding either by direct collision or by excitation of collective modes.

INTRODUCTION

MEASUREMENTS made in the past few years on nuclear reactions at intermediate energies have indicated serious discrepancies with the predictions of the statistical model of nuclear reactions.[1] In particular, angular distribution measurements of inelastically scattered protons,[2] neutrons,[3] deuterons,[4] and alpha particles[5] leading to low-lying levels have generally shown strong peaking in the forward directions. It has been proposed that such reactions proceed in part by either a direct collision of the incoming nucleon with a nucleon of the target nucleus,[6] or by excitation of rotational collective modes of the target nucleus.[7]

Recent studies of (n,p) reactions at 14 Mev have also indicated that a non-compound-nucleus mechanism is operative in these reactions. Such evidence has come from measurements of cross sections,[8] excitation functions,[9] energy spectra,[10,11] and angular distributions for gross portions of the spectrum.[12–15] Perhaps the strongest indication of direct interaction behavior has come from the angular distribution studies where it generally appears that the high-energy protons emitted are characterized by a forward peaking. However, no work has appeared giving quantitative information about the distribution of these protons associated with a single final state of the residual nucleus. The present experiment is an attempt to gain some information on the mechanisms involved in (n,p) reactions at intermediate energies by studying the angular distributions of the high-energy protons emitted in the forward directions from the $Al^{27}(n,p)Mg^{27}$ reaction induced by 14-Mev neutrons. The measurements are confined to approximately the first 4 Mev of excitation of the residual nucleus and to angles less than about 70° (lab system).

The Q value for the reaction is -1.811 Mev,[16] and levels in Mg^{27} at 0.99, 3.50, 3.56, 3.76, and 4.13 Mev have been established from $Mg^{26}(d,p)Mg^{27}$ reaction studies.[17] Most proton spectra published [11,14,15] for the $Al^{27}(n,p)Mg^{27}$ reaction have been confined to residual excitations above 4 Mev, but examination of the low-excitation portion of the spectrum[14] has shown that the low-lying levels can be identified by the corresponding proton groups. In the latter study the level at 1.0 Mev and a cluster at 3.5 Mev were confirmed ,and a level at 1.6 Mev reported. The protons from these groups were

---

* Supported in part by the U. S. Atomic Energy Commision.

† Submitted in partial fulfillment of the requirements for the Ph.D. degree at Brown University. Present address: Palmer Physical Laboratory, Princeton University, Princeton, New Jersey.

[1] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics*, (John Wiley & Sons, Inc., New York, 1952).

[2] See, for example, Schrank, Gugelot, and Dayton, Phys. Rev. **96**, 1156 (1954); Berveniste, Finke, and Martinelli, Phys. Rev. **101**, 655 (1956); H. E. Conzett, Phys. Rev. **105**, 1324 (1957); R. W. Peelle, Phys. Rev. **105**, 1311 (1957); Kikuchi, Kobayashi, and Matsuda (to be published).

[3] Anderson, Gardner, McClure, Nakada, and Wong, Phys. Rev. **111**, 572 (1958).

[4] Freemantle, Gibson, and Rotblatt, Phil. Mag. **45**, 1200 (1954); J. W. Haffner, Phys. Rev. **103**, 1398 (1957); Hinds, Middleton, and Parry, Proc. Phys. Soc. (London) **A70**, 900 (1957); R. G. Summers-Gill, Phys. Rev. **109**, 1591 (1958).

[5] P. C. Gugelot and M. Rickey, Phys. Rev. **101**, 1613 (1956); H. J. Watters, Phys. Rev. **103**, 1763 (1956); Seidlitz, Bleuler, and Tendam, Phys. Rev. **110**, 682 (1958).

[6] Austern, Butler, and McManus, Phys. Rev. **92**, 350 (1953); S. T. Butler, Phys. Rev. **106**, 272 (1957).

[7] S. Hayakawa and S. Yoshida, Proc. Phys. Soc. (London) **A68**, 656 (1955); Progr. Theoret. Phys. (Kyoto) **14**, 1 (1955).

[8] E. B. Paul and R. L. Clarke, Can. J. Phys. **31**, 267 (1953).

[9] A. V. Cohen and P. H. White, Nuclear Phys. **1**, 73 (1956).

[10] L. Colli and U. Facchini, Nuovo cimento **4**, 671 (1956); Badoni, Colli, and Facchini, Nuovo cimento **4**, 1618 (1956); Colli, Facchini, and Micheletti, Nuovo cimento **5**, 502 (1957); Colli, Pignanelli, Rytz, and Zurmuhle, Nuovo cimento **9**, 280 (1958).

[11] L. Colli and U. Facchini, Nuovo cimento **5**, 309 (1957).

[12] R. A. Peck, Jr., Phys. Rev. **106**, 965 (1957).

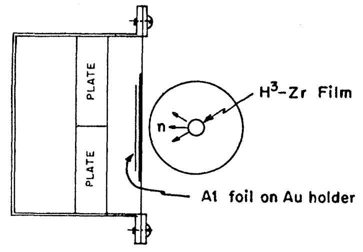
[13] D. L. Allen, Proc. Phys. Soc. (London) **A68**, 925 (1955); **A70**, 195 (1957); Nuclear Phys. **6**, 464 (1958). Verbinski, Hurliman, Stephens, and Winhold, Phys. Rev. **108**, 779 (1957); Colli, Facchini, Ioni, Marcazzan, Sona, and Pignanelli, Nuovo cimento **7**, 400 (1958); P. V. March and W. T. Morton, Phil. Mag. **3**, 143 (1958); **3**, 577 (1958).

[14] Haling, Peck, and Eubank, Phys. Rev. **106**, 971 (1957).

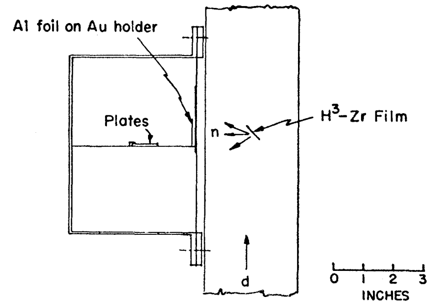
[15] Brown, Morrison, Muirhead, and Morton, Phil. Mag. **2**, 785 (1957).

[16] P. M. Endt and C. M. Braams, Revs. Modern Phys. **29**, 683 (1957).

[17] J. R. Holt and T. N. Marsham, Proc. Phys. Soc. (London) **A66**, 258 (1953); Hinds, Middleton, and Parry, Proc. Phys. Soc. (London) **71**, 49 (1958).



HORIZONTAL SECTION



VERTICAL SECTION

FIG. 1. Experimental arrangement of the second exposure.

observed to have a greater yield in the forward than in the backward hemisphere, as has also been reported to be the case for the higher energy protons from gross portions of the spectrum not associated with resolvable levels.

EXPERIMENT

Neutrons were produced by bombardment of a tritiated zirconium foil with 175-kev deuterons in a Cockcroft-Walton accelerator.[18] The energy profile of the neutron beam was determined by emulsions to have a leading edge at 14.1 Mev and to have a half-width of about 0.6 Mev. The target was commercial aluminum foil, 99.45% pure, and 4.7 mg/cm^2 thick which is equivalent to an energy loss of 0.14–0.19 Mev for proton energies corresponding to 0 to 4 Mev excitation. Ilford *C*2 emulsions 400 microns thick were employed as detectors and processed by a two-solution temperature-controlled method.[19]

Since the cross section for any proton group was expected to be of the order of millibarns or less, an extreme form of "poor geometry" was adopted. However, because of the geometrical information implicit in a proton track, the disadvantage of poor geometry can be removed analytically in the processing of the data. Two exposures are represented in the final data, the first in the geometry of reference 12, and the second in that of Fig. 1. The two arrangements are qualitatively similar, the second involving the higher recording efficiency, particularly for the smaller angles. In each arrangement two plates were used, their emulsions normal to the target plane, and close to it. An evacuated chamber containing the plates, target, and target backing, was positioned close to the neutron source with no collimation of the neutron beam attempted. In Run I, the target was 2 in.×2 in., supported on lead, 20 cm from the neutron source, and 4.6 cm from the near edge of the plates; in Run II, the target was 1 in.×3 in. (the larger dimension parallel to the emulsion surface), supported on gold, 5 cm from the neutron source, and 3 cm from the plates. The exposures were to 5.6×10^8 and 2.1×10^9 neutrons/cm^2, respectively, determined by emulsion recoil measurements and checked by a calibrated BF_3 long counter. Bombardment times, and hence the number of reaction protons recorded in the emulsions, were limited by the density of recoil proton tracks in the emulsion volume caused by the incident neutron beam which made the emulsions unreadable. The two exposures contributed roughly equal number of tracks to the final data set as different areas were scanned; separate background exposures were made for the two cases. Symmetrical areas were read on the two plates in each exposure.

Tracks were measured with a Zeiss *W* microscope using oil immersion and 1000× magnification. Selection criteria were designed to select tracks originating at the emulsion surface, terminating within the emulsion, oriented within the solid angle defined by the aluminum target, and falling in the energy range 7 to 13 Mev. These energy limits allow a generous latitude for the unbiased recording of protons reflecting the first 5 Mev of excitation while excluding any contributions from (n,np), (n,d), and (n,α) reactions in the target. The angular limits were reduced in analysis to exclude protons ostensibly originating in the outermost $\frac{1}{8}$-in. strip of the target. The criterion that the proton track start at the surface of the emulsion was applied in the strictest possible sense in order to discriminate against any recoil protons originating near the surface. In the application of this criterion many bona fide reaction protons were undoubtedly rejected as recoils through failure to cause grain development at the resolvable surface of the emulsion. As a result this experiment can only give information on minimum values of the reaction cross sections. However, this rejection of some of the reaction proton tracks introduces no systematic bias in the angular distributions. Much of the area scanned was studied twice to check reproducibility in the location, acceptance, and measurements of tracks; it was found that angles were reproduced to within 1° and energies to within 0.1 Mev. A total emulsion area of 21.8 cm^2 was scanned yielding over 1600 measured tracks, of which 650 survived all final screening and fell within the excitation range (0.0 to 4.3 Mev) of interest. On the average about one hour was devoted to the location and measurement of each acceptable track.

---

[18] R. A. Peck, Jr. and H. P. Eubank, Rev. Sci. Instr. **26**, 441 (1955).

[19] J. C. Allred and A. H. Armstrong, Los Alamos Scientific Laboratory Report LA-1510, 1951 (unpublished).

ANALYSIS

From the measurements on each accepted track the following quantities were computed: local emulsion shrinkage factor, full emulsion range, proton energy,[20] point of origin in the target plane, space angle between neutron and proton directions, and the Q value of the proton. The calculations were performed on an IBM-605 card-punch computer, and required approximately 20 seconds per track. In this analysis the neutrons were assumed to be emitted from a point source at the center of the tritium-zirconium button where previous studies showed that the deuteron beam was well concentrated due to collimation and focusing. The calculated target points at which the reactions occurred were plotted and for both exposures gave a uniform scatter diagram within the imposed target limits, indicating the absence of strong contributions from any nonuniform target contamination, and of any effective directional bias in the microscopic analysis. Background contributions evaluated from the background exposures were found to be negligible except for energies corresponding to $Q \geqslant -1.7$ Mev, a region irrelevant to the analysis of the reaction.

As a check on the efficacy of the microscopic discrimination against recoil protons originating in the top micron or so of the emulsion, the full set of proton data were separated analytically into two groups, according to whether or not they energetically could represent such recoils within the full latitude permitted by the observed energy width of the primary neutron beam and the maximum possible extension of the source of neutrons. Separate plots of these groups as total spectra showed essentially the same peak positions and peak-to-valley ratios except near the ground-state peak where there exists the possibility of some contribution of background recoil protons.

In the geometry employed, the recording efficiency of the emulsions is angle dependent in a manner itself dependent on the extent and location of emulsion area scanned. The angular bias function (fraction of all protons emitted from the target at a given reaction angle which are detected in the portion of the emulsion scanned) was computed by numerical analysis based on sixty uniformly distributed target loci for each exposure. This correction function varies by less than a factor of two over the range 3° to 50° for the first exposure, and 4° to 62° for the second, and should be quantitatively reliable over larger angular range. All angular distributions displayed here have been corrected for this detector anisotropy. Moreover, all distributions shown represent the combination of results of the two runs, each track being appropriately weighted according to the efficiency of the detector at the particular reaction angle of the track for the particular run. Results of the two runs were analyzed separately and the similarity of distribution argues favorably for the reproducibility of the experiment.

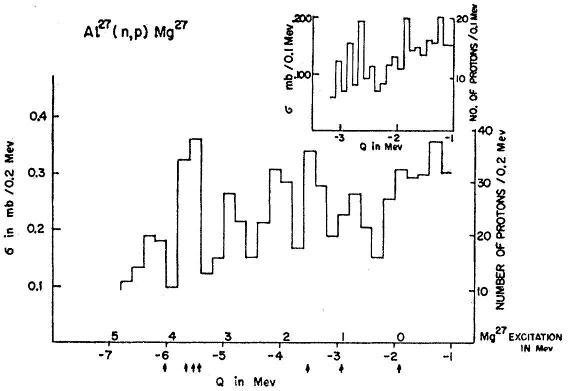


FIG. 2. Proton energy distribution as a function of excitation. The arrows mark the energies corresponding to previously reported levels of Mg^{27}, and the vicinity of the ground state is shown with smaller energy intervals as an insert. For reasons discussed in the text all experimental cross sections reported here are to be regarded as minimum values.

RESULTS

The total spectrum of acceptable tracks, integrated over angles from 5° to 70°, is presented in Fig. 2, with the vicinity of the ground state also being shown with smaller energy intervals as an insert. The proton energy dependence on reaction angle has been removed by plotting the tracks as a function of their Q value. The corresponding excitation energy of the residual Mg^{27} nucleus is also indicated on the abscissa. Arrows mark the energies corresponding to excitations of known levels (0.00, 0.99, 1.60, 3.50, 3.56, 3.76, and 4.13 Mev). Corresponding proton groups appear to be as well defined as can be expected with these separations and the known energy spread in the primary neutron beam (0.6 Mev at half maximum), and these groups are in satisfactory agreement with the known levels of Mg.[27] Groups corresponding to excitations at 1.0, 1.6, 3.5, and 4.1 Mev are quite reasonably marked, and the fine-structure spectrum shows fair evidence of a ground-state contribution, presumably superimposed on recoil contamination.

Two additional groups appear quite strongly at excitations around 2.1 and 2.8 Mev, corresponding to no previously reported levels, although Haling's $Al(n,p)Mg^{27}$ spectrum[14] suggests the possibility of further structure between the 1.6- and 3.5-Mev groups in view of the anomalous width of the 1.6-Mev group. The $Mg^{26}(d,p)Mg^{27}$ investigations[17] tended to be obscured in this excitation region due to strong proton contributions from (d,p) reactions in the oxygen to the MgO targets and in a target contaminate attributed to carbon.

Although both resolution and statistics are limited, the definition of these groups appears adequate for the identification of protons associated with specific final states of Mg^{27}, and the angular distributions (in the lab

---

[20] The range-energy tables given in Appendix A of reference 19 were used.

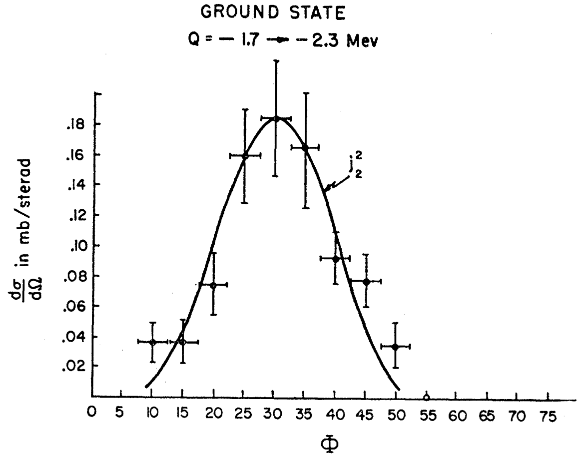


FIG. 3. Angular distribution of protons leading to the ground state. All angles in Figs. 3 through 7 are in the laboratory system. The solid curve is $j_2^2(KR)$ for $R=7.4\times10^{-13}$ cm.

system) of several of these groups are displayed in Figs. 3–6. Protons for these distributions were selected within energy limits chosen to exclude the region of confusion between adjacent groups, and the data have been combined in 5° intervals for the graphical presentation. The angular distribution of all protons in the energy interval studied is given in Fig. 7.

The angular distributions for the ground and 1-Mev level are characterized by a distinct peaking in the vicinity of 30° and 36°, respectively. Although there is the possibility of recoil contamination in the group state group, this group exhibits the clearest peak. The distribution for the 1.6-Mev group has a less well-defined maximum, but appears to peak in the vicinity of 50°. With the decreased level spacings expected at higher excitations and the limited resolution of this experiment, it is quite possible that some of the protons in this interval represent transitions to nearby levels. The distributions for the 2.1-, 2.8-, and 3.5-Mev groups are not characterized by any peaking, and appear essentially isotropic. As an example of the type of distribution resulting for these groups, the angular distribution for the 3.5-Mev group is presented in Fig. 6. This group is assumed to contain protons corresponding to transitions to several close lying unresolvable levels, and it is quite possible that this is also the case for the 2.1- and 2.8-Mev groups. The distribution for all protons in the energy interval studied is characterized by isotropy for angles greater than 30° with a decreasing cross section in the extreme forward directions.

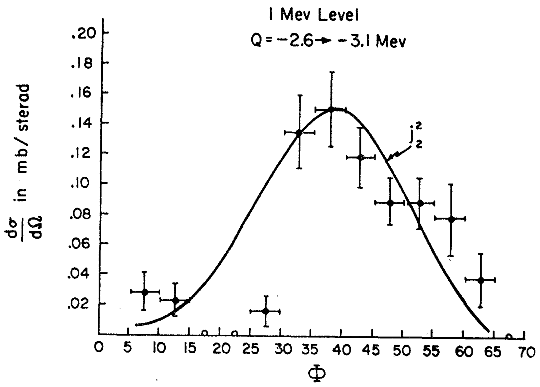


FIG. 4. Angular distribution of protons leading to the 1-Mev level. The solid curve is $j_2^2(KR)$ for $R=6.5\times10^{-13}$ cm.

A summary of the experimental results is presented in Table I. It has already been noted that due to the particular stringency of screening procedures adopted the experimental cross sections resulting from this study must be regarded as minimum values for the reaction, and it is estimated that they may easily be too low by a factor of two.

The uncertainty in the relative cross sections for the groups due to statistical probable errors are generally of the order of 10%. The vertical error flags in the angular distributions are statistical probable errors, and the uncertainty in the angle determinations is the result of the point-source approximation for the neutron source. This latter approximation can introduce a maximum uncertainty of 0.2 Mev for the Q value of any measured track.

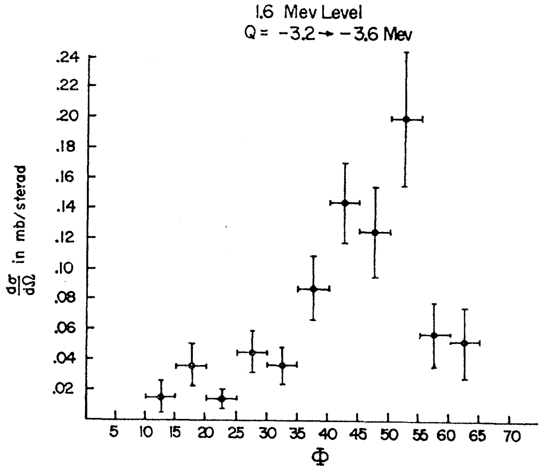


FIG. 5. Angular distribution for protons leading to the 1.6-Mev level.

DISCUSSION

The angular distributions of the protons associated with the three lowest lying levels give strong evidence that the (n,p) reaction leading to these states has proceeded by a direct interaction mechanism. These distributions are characterized by a pronounced peaking in the forward directions, with the angle of peaking increasing with the excitation of the level as might be expected of a direct collision process. Moreover, the cross section for the protons associated with the first 4 Mev of excitation has been found to be at least an order of magnitude greater than the statistical theory would predict.

The theory of direct interaction processes as proposed by Austern, Butler, and McManus[6] predicts that the angular distributions for the high-energy proton groups should be given by $j_l^2(KR)$, where K is the absolute value of the momentum transfer vector, R is the interaction radius, and the parameter l characterizing the distribution is limited by the shell model selection rule, for this case, to $l_n+l_p \geqslant l \geqslant |l_n-l_p|$ where l must be even if there is no change of parity, and odd if there is. The derivation of this form for the distribution is based on the assumptions (1) that a single collision between the incident nucleon and one of the target nucleons occurs in a region near the surface of the nucleus, and (2) that the incident and outgoing particles may be represented by plane waves. Although the validity of these assumptions is open to question in the reaction under consideration, the distributions determined in this experiment appear to show rough fits to a distribution of this type.

TABLE I. Summary of experimental results.

Level (Mev)	$\sigma_{\min}$ (mb)	Angular distribution
Ground state	0.86	Maximum at 30° (lab)
1.0	0.69	Maximum at 36°
1.6	0.67	Maximum at 50°
2.1	0.51	Isotropic
2.8	0.58	Isotropic
3.5	0.78	Isotropic
0 to 4.9	5.7	Isotropic for $\Phi>30°$

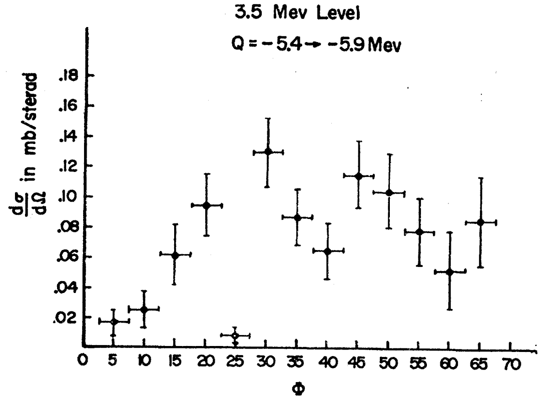


FIG. 6. Angular distribution for protons leading to levels around 3.5 Mev.

From the Butler theory it is expected that the angular distribution for the ground state should be given by $j_2^2(KR)$. The spins of the Al^{27} and Mg^{27} ground states have been measured to be $\frac{5}{2}$ and $\frac{1}{2}$, respectively, each with positive parity.[16] According to the shell model the emitted proton can be expected to come from a $d_{\frac{5}{2}}$ shell and the captured neutron to enter an $s_{\frac{1}{2}}$ orbit, in which case the selection rule allows only $l=2$. The distribution for the ground state gives a fairly satisfactory fit (see Fig. 3) to j_2^2, but requires the unorthodox radius of 7.4×10^{-13} cm. The distribution can also be fit with the $l=1$ curve for the more plausible radius of 4.7×10^{-13} cm, but since no change in parity is involved, l must be even and $l=1$ rejected. That such a large interaction radius must be used to fit the data to the theoretical curve means that the experimental distribution peaks at a smaller angle than the Butler theory would predict. Similar behavior has also been found to be the case in some (p,p') scattering, where it has been found that the experimental data can be successfully accounted for by a distorted-wave calculation.[21] The results of such calculations, in which the influence of the nuclear and Coulombic potentials on the incoming and outgoing waves are considered, generally appear to shift the angles of peaking to smaller values.[22] Thus, the possibility exists that the experimental distribution found here may reflect the inadequacy of the plane-wave approximation in the Butler theory. However, as has already been pointed out, the ground-state group may contain background contribution from recoil protons which would accentuate smaller angles. The Q interval was chosen to discriminate against this background, and the clean peaking of the angular distribution argues for its success; still the possibility exists that the peaking of the experimental curve at smaller angles than the Butler theory predicts may result from a background contribution.

The angular distribution for the 1.0-Mev group can also be best fit by the j_2^2 curve (see Fig. 4), requiring a radius of 6.5×10^{-13} cm, where, as with the ground state, the radius has been determined by matching the maxima. The distribution for the 1.6-Mev group has a less well-defined maximum, but if we take the maximum as occurring at 50°, the maximum of the theoretical curve for $l=1$ could only be matched using a radius of 3.3×10^{-13}

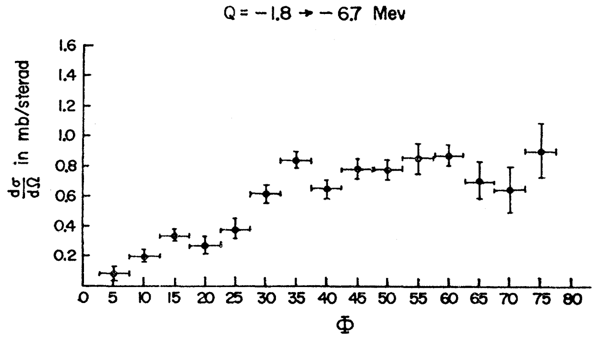


FIG. 7. Angular distribution of all protons corresponding to the first 4.9 Mev of excitation.

---

[21] C. A. Levinson and M. K. Banerjee, Ann. Phys. **2**, 471 (1957); **3**, 67 (1958). S. Yoshida, Proc. Phys. Soc. (London) **A69**, 668 (1956).

[22] For example, distorted-wave calculations by K. W. Ford and N. K. Glendenning (private communication) for the (n,n') reaction in light elements at intermediate energies result in $l=2$ curves peaking at 0°.

cm, and the $l=2$ curve fitted using a radius of 5.3×10^{-13} cm. Hence it would appear that this distribution might also be best fitted by the $l=2$ curve. Although this region of the periodic table has not been very thoroughly studied in terms of the shell model, it appears that such assignments are not inconsistent with it. In contrast with the three lowest-lying levels, the angular distributions for the 2.1-, 2.8-, and 3.5-Mev groups are not characterized by any particular peaking. This may be expected for the 3.5-Mev group which is known to consist of protons corresponding to several close-lying unresolvable levels each having a different configuration. Since the distributions of the 2.1- and 2.8-Mev groups also show no particular peaking this may be regarded as an indication that these groups also may consist of two or more levels not resolved in this experiment.

Recently several nuclei in the vicinity of $A=27$ have been examined on the basis of the Bohr-Mottelson collective model. In particular, the known level structures of Mg^{25} and Al^{25},[23] and Al^{28},[24] have been accounted for by this model. Accordingly, the possibility that a direct interaction has proceeded by an excitation of rotational collective modes must be considered for this reaction. This theory[7] predicts that to first order in the deformation parameter, such a collective behavior results in angular distributions given by $j_2^2(KR)$. The results of this experiment are entirely consistent with this prediction.

The only other angular distribution available for comparison with the results of this experiment is the distribution given for this reaction at 13.2 Mev by the Glasgow group[15] for all protons in the energy range $Q=-1.7$ to -6.2 Mev. The two distributions are consistent for angles greater than 30°, but disagree at the extreme forward directions. The Glasgow determination shows a rising differential cross section at the extreme forward angles (points at 20° and 10°) to a maximum of roughly twice the isotropic value, while the present observation shows the opposite behavior forward of 30°. The basis of this discrepancy is not clear.

ACKNOWLEDGMENTS

We are indebted to Dr. H. P. Eubank for extensive assistance in conducting this experiment and would also like to acknowledge the assistance of the staff of the Brown University Computer Laboratory in the programming and running of the data processing calculations. One of us (O. E. O.) would also like to thank Dr. C. A. Levinson for many informative conversations on the theory of direct interaction processes, and to acknowledge the Ohio Oil Fellowship held in 1956–1957.

---

[23] H. E. Gove, *Proceedings of the University of Pittsburgh Conference on Nuclear Structure, 1957*, edited by S. Meshkov (University of Pittsburgh and Office of Ordnance Research, U. S. Army, 1957).

[24] R. K. Sheline, Nuclear Phys. **2**, 382 (1956).