the previous distribution is immediately obvious, as both of these groups show very large back-angle peaks that are characteristic of the heavy-particle stripping mechanism. Neither of these states can be populated by the neutron-pickup mechanism if they are describable as single-particle excited states from the *p*-shell ground state, as concluded by Warburton and Pinkston.[9] Since the angular distribution of the 5.69-MeV level could be symmetric about 90°, a 90° excitation curve is included in Fig. 7. It shows no evidence of strong resonance structure. It seems likely that heavy-particle stripping is dominating these two reactions. It is also worth noting that the cross sections for these two reactions are considerably larger than the average.

It is surprising that the pair of states at 4.91 and 5.10 MeV, which belong to the same configurations[9] as the 5.69- and 5.83-MeV pair, respectively, but couple to different spins, have such comparatively small cross sections for population by this reaction. Perhaps the clustering amplitudes for heavy-particle stripping are considerably larger for the angular momentum couplings associated with the higher lying pair of final states.

VII. CONCLUSIONS

On the basis of this experiment, the existence of states in N^{14} at 6.70-, 7.40-, and 7.60-MeV excitation is to be doubted. The absence of a state near 7.60 MeV means that the extrapolation of the $C^{13}(p,\gamma)N^{14}$ reaction rate to the low energy of stellar interiors made on the assumption that no resonance exists for low proton energies is correct. The minimum observed C^{12}/C^{13} abundance ratios are then consistent with the value to be expected from the CNO cycle. Alternatively, of course, one could interpret the large amounts of C^{13} observed in the cool carbon stars as evidence that the $C^{13}(p,\gamma)N^{14}$ reaction is nonersonant at low energies. Because of the conflicting evidence regarding the N^{14} energy levels, however, it is important that the $N^{14}(p,p')N^{14*}$ reaction be repeated with more modern techniques to either confirm or refute the earlier evidence for these states.

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Reaction Mechanism in $Mg^{24}(p,p'\gamma)$ at Low Energies*

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The excitation function for the inelastic scattering of protons to the first level of Mg^{24} has been measured for bombarding energies between 2.7 and 4.2 MeV, using an electrostatic accelerator. The 1.37-MeV gamma rays resulting from inelastic scattering were measured at 0°. Six resonances occur in this energy interval, corresponding to levels in Al^{25} at excitation energies of 4.93, 5.09, 5.14, 5.75, 5.81, and 6.15 MeV. Angular distribution measurements were made of the two reaction products, both on and off resonance, and the coefficients of the Legendre polynomial expansions determined. The character of the distributions indicates the adequacy of the compound nucleus model with no evidence of direct interaction effects; the nuclear barrier height thus seems to set an approximate lower limit for the onset of direct interactions. The use of an electrostatic analyzer allowed an energy resolution of 0.05%, and calibration against the Li(p,n) threshold resulted in an absolute energy uncertainty of ± 2 kV; this energy calibration allows some simplification of the level scheme in Al^{25}, particularly for excitation energies near 5 MeV.

INTRODUCTION

A NUMBER of reports have appeared recently concerning the reaction mechanism involved in the inelastic scattering of protons at low energy.[1–4] The nucleus Mg^{24} is of particular interest because of the low binding energy for an added proton, (2.29 MeV), allowing one to reach low-lying, widely separated levels in the compound nucleus when low bombarding energies are used. For energies below 3 MeV, Litherland *et al.*[5] have found their results to be well fitted by a collective model which ascribes a prolate distortion to the Mg^{24} ground state. The excitation is then described as a collective excitation of the nucleus, causing it to rotate or vibrate about its spheroidal ground-state shape. For bombarding energies near 7 MeV, Seward interprets his results as indicating a direct interaction of the type

* Supported by the U. S. Atomic Energy Commission at Duke University.
[1] Frederick D. Seward, Phys. Rev. **114**, 514 (1959).
[2] H. A. Lackner, G. F. Dell, and J. Hausman, Phys. Rev. **114**, 560 (1959).
[3] H. J. Hausman, G. F. Dell, and H. F. Bowsher, Phys. Rev. **118**, 1237 (1960).
[4] H. F. Bowsher, G. F. Dell, and H. J. Hausman, Phys. Rev. **121**, 1504 (1961).
[5] A. E. Litherland, E. B. Paul, G. A. Bartholomew, and H. E. Gove, Phys. Rev. **102**, 208 (1956).

proposed by Butler,[6] while his results at 5.4 MeV indicate a mixture of direct interaction and compound nucleus effects. Seward also suggests that the amount of direct interaction in a (p,p') reaction may depend on the nuclear barrier height. Lackner *et al.*[2] find, in the region between 5 and 6 MeV, that their angular correlation data are consistent with predictions of a modified direct-interaction theory. This is somewhat surprising, in view of the analysis of direct-interaction processes by Butler, which shows that direct-interaction processes should predominate in a reaction only if the bombarding energy is high enough to excite many levels of the residual nucleus. It is the purpose of this paper to complete the excitation function for the reaction $Mg^{24}(p,p'\gamma)$ by filling in the region from 2.7 to 4.2 MeV, to investigate the angular distributions in this region, and to study the extent to which direct interaction mechanisms contribute to the reaction for energies just below the nuclear barrier height.

The plan of approach was to measure the yield of gamma radiation at 0° with respect to the incident beam, and then to determine the angular distributions of the reaction products at salient points of the excitation curve. In order to measure the excitation function exactly, it was desirable to use a thin target; it is important to note that both Seward and Lackner used a thick target (on the order of 200 keV) for their cyclotron work mentioned above. When a prominent resonance occurs superimposed on a nonresonant contribution, the use of a thin target should enable one to obtain information concerning the relative importance of compound nucleus formation and direct interaction mechanism by determining the angular distributions below, above, on the sides, and on the peak of the resonance.

The analysis of results in this region of excitation energy is difficult because more than one compound nucleus state may contribute to the reaction, but not enough states contribute to allow the application of the statistical model; also, the degree of direct interaction is not known. However, if only one compound nucleus state contributes at a given energy, analysis might be possible, since the long lifetime of the compound nucleus state as compared to the direct interaction time should result in the incoherency of the separate contributions.

Six resonances were observed in the energy region from 2.7 to 4.2 MeV; at five of the six resonances, it was possible to measure angular distributions of both the 1.37-MeV gamma rays and the inelastically scattered protons. However, at the lowest resonance energy, the yield of inelastic protons was so low that no distribution could be obtained.

The energy scale as measured in our laboratory was found to differ from some previous work.[1,5] For this reason a calibration of the electrostatic analyzer used for energy selection was carried out using the $Li(p,n)$ threshold, resulting in an absolute energy uncertainty of ± 2 keV; this calibration allows some simplification of the level scheme in Al^{25}, particularly for excitation energies near 5 MeV.

APPARATUS

The proton beam from the electrostatic accelerator was passed through a steering magnet into a 90° electrostatic analyzer, thereby determining the incident proton energies in terms of the $Li(p,n)Be$ threshold. The energy resolution of the analyzer varied from 0.066 to 0.05%; in particular, the region below 3 MeV was studied at a resolution of 0.05%. After leaving the analyzer, the beam was collimated and passed into a small steel chamber of cylindrical symmetry. The target was supported at the center of this chamber.

Fifty milligrams of separated Mg^{24} isotope in the form MgO were available. Targets were prepared by converting the MgO to $MgNO_3$, (which is highly soluble in water), dissolving in distilled water, and spraying onto a backing kept above the boiling point of water. Temperatures near 300° produced the most satisfactory targets. Tantalum was used as a backing below 3.0 MeV, but the rising yield from the contaminant fluorine made it unsatisfactory above 3.0 MeV. Freshly turned lead was used as a backing for the targets used above 3.0 MeV for the data presented in Fig. 1. Using the narrow resonance in $Mg(p,p'\gamma)$ at 2.41 MeV, which is known to have a width of less than 500 eV, the measured thickness of the tantalum-backed target was found to be 4.2 keV, and that of the lead backed target 6.0 keV. Thicker targets were used for angular distribution measurements on the broad resonances, in order to reduce the counting time required for the desired statistical accuracy.

The 1.37-MeV gamma rays were detected by a 2-in.×2-in. cylindrical NaI scintillator mounted on a 2-in. photomultiplier. A cylindrical lead shield of 2-in. thickness surrounded the entire scintillation counter. The energy resolution of this counter for the Cs 0.66-MeV gamma ray was 8%. The pulses from this detector were fed into a 10-channel pulse-height analyzer which was controlled by the beam integrator, and monitored by an oscilloscope.

For the proton inelastic scattering, the steering magnet was used to deflect the proton beam from the accelerator directly into a large steel scattering chamber without passing through the electrostatic analyzer. A thin target of naturally abundant magnesium evaporated onto thin films of Formvar was supported at the center of this chamber. The beam passed through several collimators, through the target, and into a collector cup. The photomultiplier was inserted through the lid, and a 90° prism attached to the photocathode. A thin piece of CsI was mounted onto the prism, so that it looked directly at the target. The angle of the counter with respect to the incident beam could be changed by rotating the entire lid of the chamber by means of a ring and gear

[6] S. T. Butler, Phys. Rev. **106**, 272 (1957).

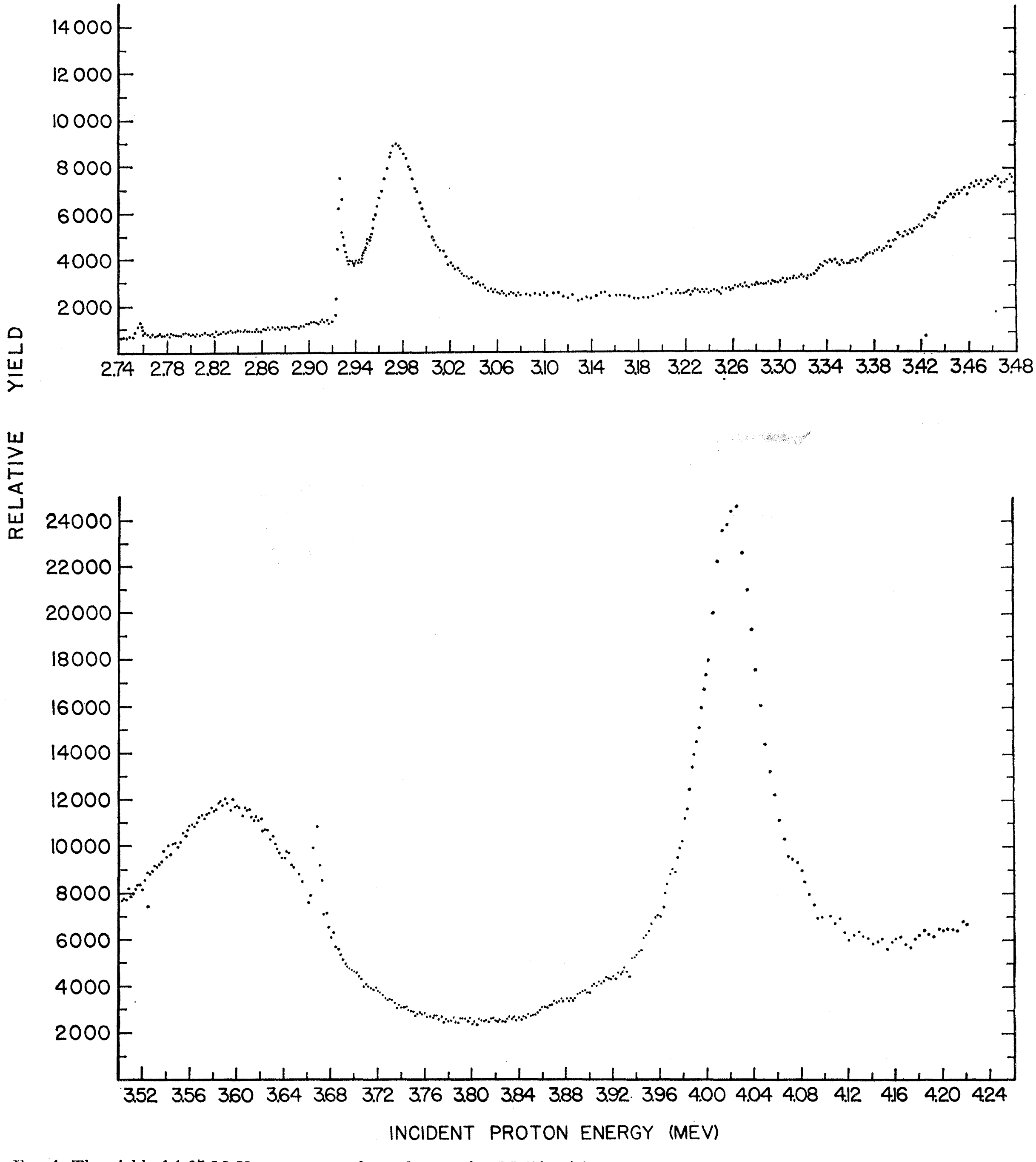

FIG. 1. The yield of 1.37-MeV gamma rays from the reaction $Mg^{24}(p,p'\gamma)Mg^{24}$ as a function of incident proton energy between 27. and 4.2 MeV. Energy intervals are 2 keV except for the region 2.92 to 2.95 MeV, where intervals are 1 keV, and above 4.0 MeV, where the intervals are 4 keV.

arrangement, thus moving the lid and the counter. The target was supported by the fixed floor of the chamber. The counting system had an energy resolution of 10% for 3.0-MeV protons. These pulses were fed into the 10-channel pulse-height analyzer and monitored on the oscilloscope. The resulting distributions are shown in Fig. 2.

EXPERIMENTAL PROCEDURE

For the bombarding energies used in this experiment, the inelastic scattering process $Mg^{24}(p,p'\gamma)$ results in the emission of the 1.37-MeV gamma ray and no other, since the second level in Mg^{24} is at 4.12 MeV. The yield of this gamma ray as a function of energy is shown in Fig. 1. The experimental points were taken at intervals

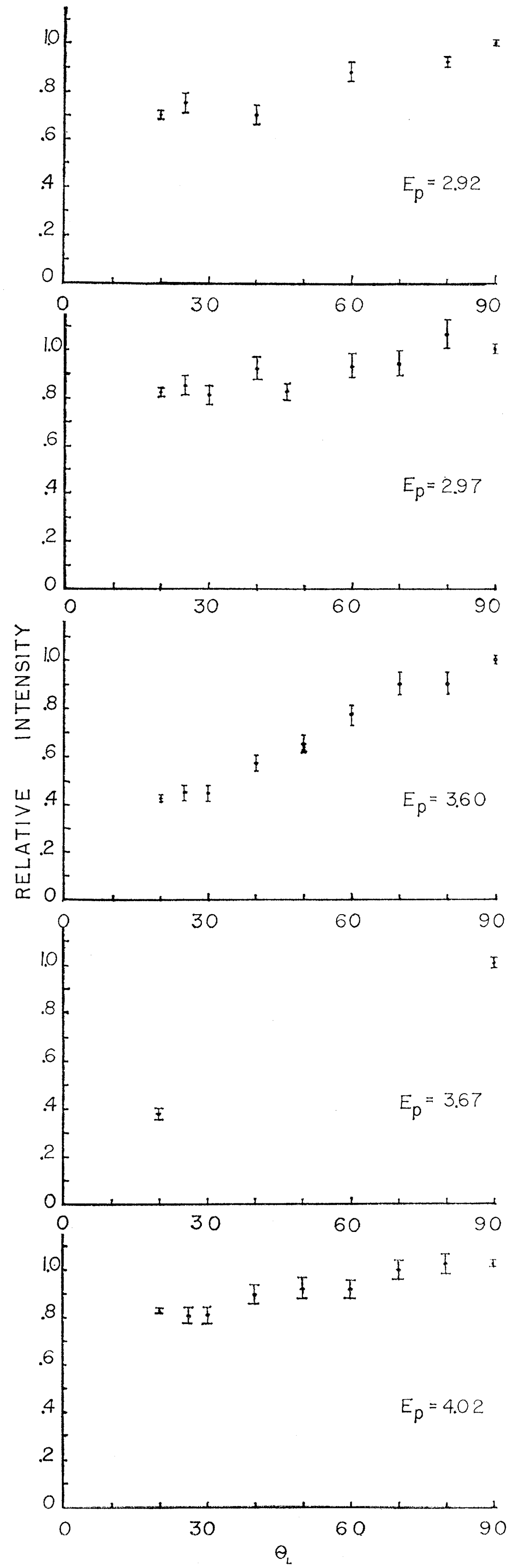

FIG. 2. Angular distributions of the inelastically scattered protons from the $Mg^{24}(p,p'\gamma)Mg^{24}$ reaction, at various incident proton energies.

TABLE I. Angular-distribution measurements of gamma rays and inelastic protons from $Mg^{24}(p,p'\gamma)$. The coefficients of P_2 and P_4 are listed for gamma rays, and the coefficient of P_2 is listed for the inelastic protons. The distributions are written in standard form, $W_\gamma=P_0+(a_2/a_0)P_2+(a_4/a_0)P_4$, and $W_p=P_0+(b_2/b_0)P_2$. The standard deviation (S.D.) for each coefficient is also listed.

Energy (MeV)	a_2/a_0	S.D.	a_4/a_0	S.D.	b_2/b_0	S.D.
2.92	0.054	0.03	0.005	0.03	−0.175	0.03
2.97	0.322	0.03	0.404	0.03	−0.072	0.05
3.12	0.240	0.03	0.238	0.03		
3.60	0.105	0.03	0.405	0.04	−0.499	0.04
3.67	0.072	0.03	0.192	0.04	−0.554	0.05
4.02	−0.005	0.03	0.012	0.03	−0.066	0.04
4.12	0.132	0.03	0.383	0.03		

of 2 keV up to 4.0 MeV and at 4-keV intervals from 4.0 to 4.2 MeV. (See Fig. 1.) Between the 2.92-MeV resonance and the 2.97-MeV resonance points were taken at intervals of 1 keV. The gamma-ray spectrum was quite clean, except for some gamma rays of approximately 1.5-MeV energy which appeared at about 3.0 MeV when the tantulum-backed target was used, and increased with energy. By the use of the freshly turned lead backing, this radiation was kept below 6%. These gamma rays are attributed to the reaction $Fl(p,p'\gamma)$.

The gain of the pulse amplifier was adjusted occasionally so as to keep the output pulse peaked in the same analyzer channel. This peak reading was then used as the yield measurement at that energy. The distribution of the gamma rays with respect to the incident beam was measured by replacing the large shield with a smaller shield of 1-in. thickness, and mounting the shielded counter on a selsyn-controlled arm which allowed the positioning of the counter at any desired angle about the target. The distance from the front face of the counter to the target was 8 cm or 15 cm. A complete spectrum was taken at several angles during each run. In those cases for which a background correction was necessary, the entire 10 channels were recorded at each angle. The shape of the distribution was found by running from 0° to 160° and back with statistical error of about 4%; this also showed the existence of fore-and-aft symmetry in every case. Distribution measurements were then repeated to reduce the statistical uncertainty to 2%. No higher terms than $\cos^4\theta$ appeared in the gamma distributions. (See Fig. 3.) Table I lists the coefficients found by fitting the gamma-ray distributions to the Legendre polynomial expansion

$$W_\gamma=P_0+(a_2/a_0)P_2+(a_4/a_0)P_4.$$

Pulses from the inelastically scattered protons were displayed on the 10 channel analyzer and all 10 channels recorded in order to permit correction for the flat background present in the region of the inelastic group. The gain of the amplifier was adjusted to compensate for the change in gain of the nonmagnetically shielded photomultiplier as the lid of the chamber was rotated. The proton distributions were found to contain no term higher than $\cos^2\theta$; Table I lists the coefficients found by fitting the proton distributions to the Legendre polynomial expansion

$$W_p = P_0 + (b_2/b_0)P_2.$$

DISCUSSION

The resonance energies given above are found to differ considerably from those given in the review article by Endt and Braams.[7] Because of this confusion, the electrostatic analyzer was calibrated on the $Li(p,n)$ threshold, so that the energy scale of Fig. 1 is believed to be accurate within 2 keV. The energy scale of this report is in agreement with that given by Mooring *et al.*[8] in an elastic scattering experiment [$Mg^{24}(p,p)$]. The energy scale of reference 5, therefore, seems to be incorrect by approximately 35 keV in the region above 2.5-MeV bombarding energy. Also, the energy scale of reference 1 is displaced to low energies by about 200 keV (4 MeV on his scale is about 4.2 MeV). The excitation function of Fig. 1 has also been observed earlier[9] for targets of naturally abundant magnesium; while the general features are unchanged, the presence of many small resonances for the reaction $Mg^{25}(p,p'\gamma)$ masks the smaller resonances at 2.96 MeV and 3.34 MeV.

The resonance energies given by Endt and Braams can be corrected as follows: The "2.72-MeV" resonance is the 2.76-MeV resonance of Fig. 1, the "2.89-MeV" resonance is the 2.92-MeV resonance of Fig. 1, and the "2.93-MeV" resonance is the 2.97-MeV resonance of Fig. 1. A previous report[9] by the authors on the broad 3.60-MeV resonance was erroneously assumed to apply to the 3.67-MeV resonance. Both levels are distinctly evident in Fig. 1. Small resonances are evident at 2.96 MeV and 3.34 MeV, and the asymmetry of the 3.60-MeV resonance indicates the presence of another level on the low side. Figure 4 is a summary of the levels in Al^{25} above 4.2-MeV excitation energy.

The distributions measured at seven different energies are given in Table I. Many other distributions were measured at points between resonances and on the slopes of the resonance; in no case was a rapid change with energy noted. That is, as the energy is moved to cross a given resonance point by point, the distributions show the contribution from the resonance to be proportional to the resonance yield as shown in Fig. 1.

The observed symmetry of the gamma-ray distribution about 90° with respect to the incident beam is consistent with a compound nucleus (CN) model; such a model is also indicated by the inelastic proton distributions. These statements are true for the entire energy region of this report, whether on or off resonance. Seward has concluded that direct interaction (DI) effects are important in the analysis of his data between

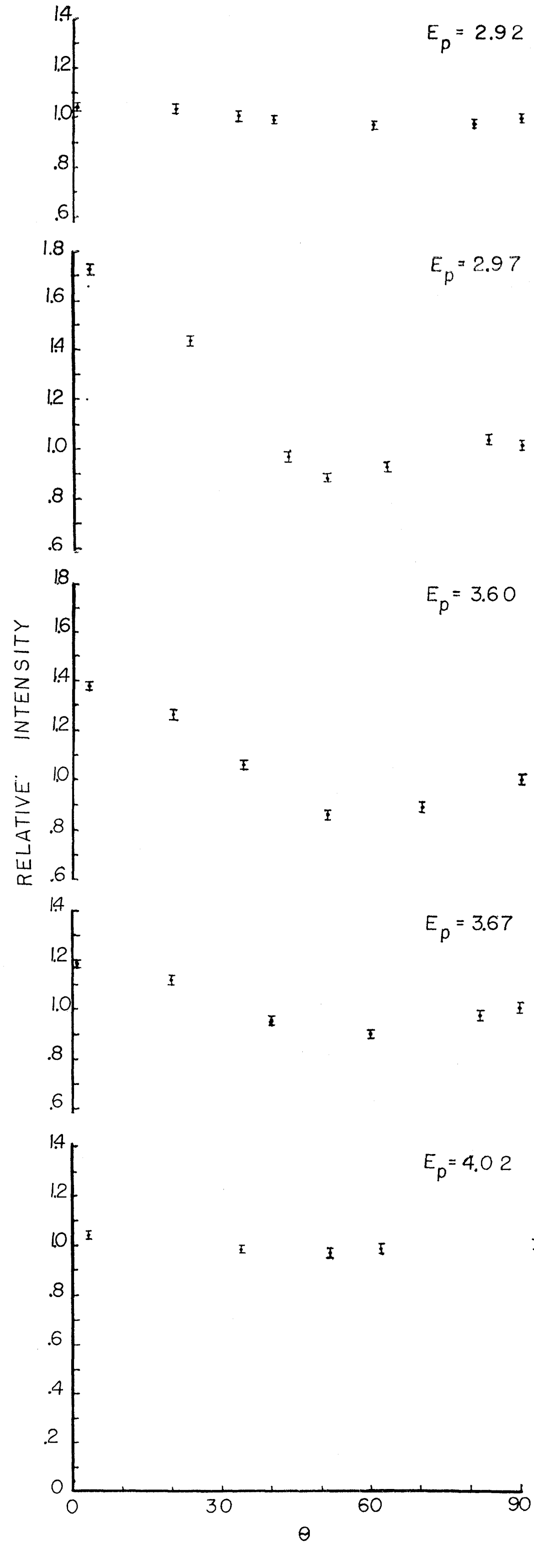

FIG. 3. Angular distributions of the 1.37-MeV gamma rays from the $Mg^{24}(p,p'\gamma)Mg^{24}$ reaction, at various incident proton energies.

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[7] P. M. Endt and C. M. Braams, Revs. Modern Phys. 29, 683 (1957).
[8] F. P. Mooring, L. J. Koester, E. Goldberg, D. Saxon, and S. G. Kaufmann, Phys. Rev. 84, 703 (1951).
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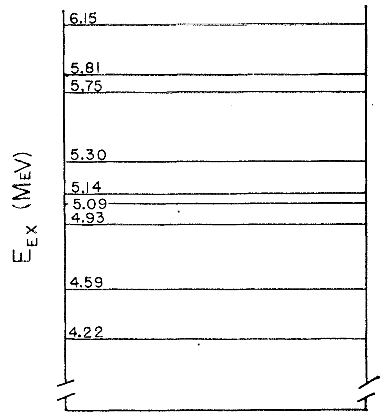

FIG. 4. Summary of the levels in Al^{25} above 4.2 MeV, as measured by $Mg^{24}(p,p'\gamma)Mg^{24}$. The energy scale is that of this work and reference 8.

5 and 7 MeV. The apparent absence of such effects below 4.2 MeV indicates that the nuclear barrier height may be an important factor in the extent to which DI may enter into a reaction. At an energy of 4 MeV, which is just below the nuclear barrier height, no DI effects are observed, while some DI occurs at 5 MeV[2] and DI dominates at 7 MeV.[1] Apparently, the nuclear barrier height sets a lower limit to the energy which must be given to the incident particle if DI effects are to take place.

It is interesting to speculate that the nonresonant portion of the yield curve may be due to DI, with CN contributing only when a strong resonance occurs. As the respective contributions from DI and CN are expected to be incoherent, one could then subtract the nonresonant contribution from the total yield in the region of a resonance, and analyze the resulting CN contribution by the usual CN theory.[10] However, if the excitation curve of Fig. 1 is joined to that of Seward, it is evident that the tails of the large resonances between 5 and 7 MeV are more than adequate to supply the "nonresonant" yield observed from 3 to 4 MeV. Since thick targets have been used for all published reports in this region, it would be desirable to extend the excitation curve from 4 to 8 MeV using a precisely defined beam energy and a thin target. The resonance structure might offer more clearcut evidence concerning the origin of the "nonresonant" yield observed from 3 to 4 MeV. Also, the thick targets used earlier cast some doubt on the validity of the DI interpretation of the results, since the overlapping of a finite number of excited CN states of different parities could give rise to the observed results. It would seem to be important to measure both angular distributions and angular correlations for many energies between 4 and 7 MeV while using a thin target and a precise beam energy, selecting points of interest from the thin target excitation curve. This information would be of great help in deciding whether or not DI actually occur in this energy region, and, if so, in measuring the contribution from DI relative to CN.

In summary, the measured distributions up to 4.2 MeV can be interpreted by a CN model for the reaction. Several strong CN resonances are observed, and the nonresonant yield in this region may be attributed to the tails of the large resonances above 4 MeV found by Seward. If the analyses of the inelastic scattering between 5 and 7 MeV referred to above[1,2] are correct in attributing DI effects to this region, it appears that the incident particle must have an energy equal to or greater than the nuclear barrier height if DI effects are to contribute appreciably to the reaction.

ACKNOWLEDGMENTS

The author wishes to thank the nuclear physics group for its assistance in taking the experimental measurements.

[10] A. A. Kraus, J. P. Schiffer, F. W. Prosser, and L. C. Biedenharn, "Angular Correlation for the $(a,b\gamma)$ Type Reaction" (circulated privately by Rice Institute, Houston, Texas).