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Evidence for Direct Interactions at Low Energy*

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The angular distributions of protons corresponding to the first excited-state transition in the reaction $Mg^{24}(p,p')_{1.38\text{ Mev}}$ have been measured for bombarding energies between 5.0 and 6.2 Mev. The angular correlations between the gamma rays emitted from the first excited state of Mg^{24} and the inelastically scattered protons have been measured at two different bombarding energies and for three proton detection directions. The angular correlation data are fitted to curves of the form $A+B\sin^2[2(\theta-\theta_q)]$, where θ_q is the momentum transfer direction for the reaction. The angular correlation data are consistent with predictions of the direct-interaction theory.

INTRODUCTION

THE differential cross sections for inelastic reactions such as (p,p'), (α,α'), and (n,p), leading to residual nuclei in low-lying excited states, have shown a behavior different from that predicted on the basis of statistical models of the nucleus. In particular, for bombarding energies between 10 and 30 Mev, the differential cross sections are usually peaked in the forward direction and are not symmetric about 90°. There is now considerable experimental evidence for such reactions which seems to indicate the presence of a direct-interaction mechanism rather than the formation of a compound nucleus.[1] In his analysis of direct-interaction processes, Butler[2] has shown that reactions proceeding to the low-lying levels of the residual nucleus should be dominated by direct reactions if the bombarding energy is high enough to excite many levels of the residual nucleus. For, if the bombarding energy is sufficiently high, the probability that the compound states would decay to highly excited states of the residual nucleus where level densities are large should be greater than the probability of decay to low-lying states of the residual nucleus where level densities are small. At lower bombarding energies, it is expected that the relative contribution of compound-nucleus decay to direct reaction through the first excited state should increase due to the limited number of channels available for compound-nucleus decay. However, results that can be interpreted in terms of direct-reaction mechanisms have been reported at energies as low as 5.0 Mev by von Herrmann and Pieper[3] in the $B^{10}(\alpha,p)Ne^{22}$ reaction, at 6.0 Mev by Pieper and Heydenburg[4] in the $F^{19}(\alpha,p)C^{13}$ reaction, and be Seward[5] in (p,p') reactions at energies from 3.5 to 7.0 Mev. In the present paper we wish to present evidence for the presence of direct-reaction mechanisms at proton bombarding energies of from 5.0 to 6.2 Mev. The reactions investigated were the angular distributions of protons scattered inelastically from Mg^{24} in the $Mg^{24}(p,p')_{1.38\text{ Mev}}$ reaction, and the angular correlation between the de-excitation gamma rays from this state and the inelastically scattered protons.

EXPERIMENTAL APPARATUS

The experimental layout is shown in Fig. 1. The Ohio State University cyclotron is used to accelerate protons to an energy of 6.2 Mev. The proton beam is extracted from the cyclotron and enters a 2-inch brass pipe which passes through the fields of a pair of quadrupole focussing magnets and a 15° sector-type deflecting magnet. The deflected beam then passes through the target, which is located in the center of the scattering chamber, and is finally collected in a Faraday cage. A high-resolution double-focussing spectrometer magnet is under construction and will be used to analyze charged particles emitted from bombarded targets.

The scattering chamber is constructed from a 10-inch-diameter brass cylinder and is capped with flat brass lids on both ends. Four fixed access ports are soldered into the brass cylinder in the plane of the reaction. The top lid is mounted on ball bearings so that it may be rotated while under vacuum. A scintillation crystal is mounted on a lucite rod which passes vertically through the top lid. A multiplier phototube is mounted to the top lid in optical contact with the Lucite rod. By rotation of the lid, the detector angle may be changed continuously from 0° to 160° with respect to

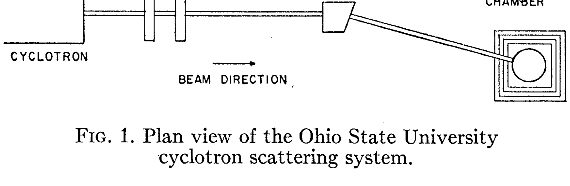

FIG. 1. Plan view of the Ohio State University cyclotron scattering system.

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[*] Supported in part by the U. S. Atomic Energy Commission.

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[1] R. Sherr, *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), p. 361.

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

[3] P. von Hermann and G. F. Pieper, Phys. Rev. **105**, 1556 (1957).

[4] G. F. Pieper and N. P. Heydenburg, Phys. Rev. **111**, 265 (1958).

[5] F. D. Seward, Bull. Am. Phys. Soc. Ser. II, **3**, 200 (1958).

the incident beam direction. A second multiplier phototube is located in one of the access ports and serves as a fixed detector. The angle of this detector may be varied from 68° to 120° with respect to the incident beam direction. The beam is defined by two apertures located 15 inches apart. The first is a circular aperture of 0.20 inches diameter and the second is a rectangular aperture of width 0.10 inch by $\frac{3}{8}$ inch. The final aperture is located one inch from the target. Protons scattered from the final collimator are prevented from hitting the detector by an antiscattering shield. In this way the detector is prevented from seeing the final aperture for detector angles greater that 13°. Targets were prepared from magnesium ribbon and were 0.0003 inch thick.

For the angular distribution experiments, thin CsI(Tl) crystals were affixed to both the fixed and movable detectors. The outputs of each detector went separately to linear amplifiers and single-channel pulse-height analyzers. The fixed-detector analyzer was biased so that it counted all pulses corresponding to protons elastically scattered from magnesium as well as pulses corresponding to protons inelastically scattered leaving Mg^{24} in its first excited state. The window of the movable-detector analyzer was set so that it completely bracketed the peak corresponding to the proton group which leaves Mg^{24} in its first excited state. The counting rate of the movable detector was then recorded for a fixed number of counts in the fixed detector. The beam energy was degraded by placing varying thicknesses of aluminum foil between the last beam aperture and the target.

For the correlation experiments a "fast-slow" coincidence circuit was used designed by P. S. Jastram of this university. A schematic diagram of the circuit is shown in Fig. 2. The circuit employs both time and pulse-height coincidence and has a measured resolving time of 20 millimicroseconds. Beam currents for the coincidence experiments were reduced by a factor of 100 below that used for the angular distributions in order to obtain a favorable ratio of true to accidental coincidences. True to accidental rates of from 10:1 to 20:1 were used throughout the runs. A NaI(Tl) crystal,

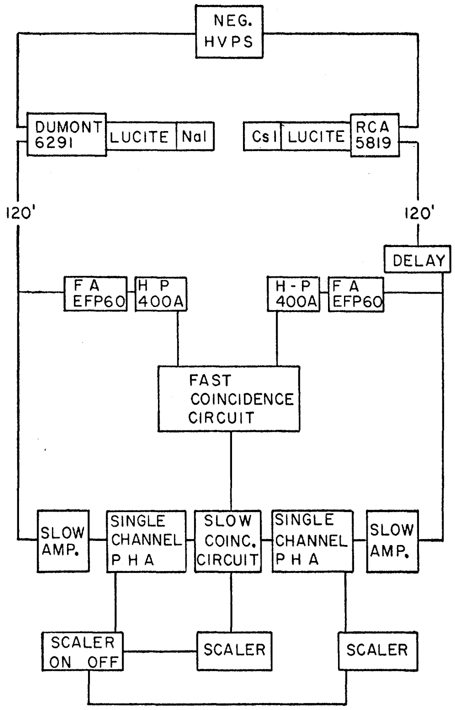

FIG. 2. Block diagram of the "fast-slow" coincidence circuit.

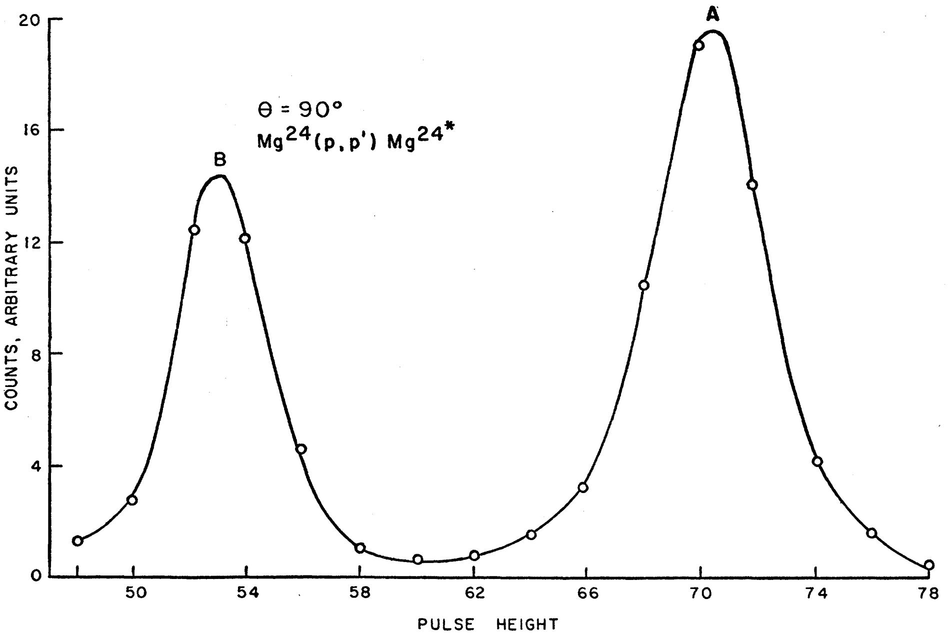

FIG. 3. Differential pulse-height spectrum of 6.2-Mev protons scattered from magnesium. Peak *A* is the proton group corresponding to elastic scattering from magnesium. Peak *B* corresponds to protons inelastically scattered from Mg^{24} leaving the residual state at an excitation of 1.37 Mev.

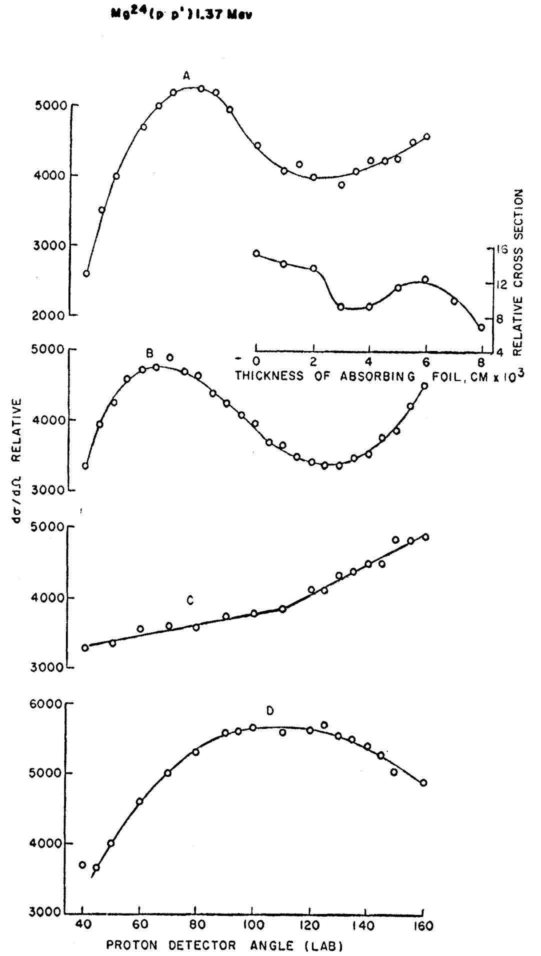

FIG. 4. Curves *A*, *B*, *C*, and *D* are the angular distributions of inelastically scattered protons from Mg^{24}. Aluminum foils of thickness 0.0, 0.02 mm, 0.038 mm and 0.06 mm were used to degrade the incident beam energies. The insert shows the energy dependence of the inelastic scattering cross section at 90°.

1 inch in diameter and 2 inches long, was attached to the Lucite pipe of the movable detector and was located approximately 1 inch from the target. The fast coincidence circuit was checked and calibrated by using both a mercury switch pulser and the annihilation gamma rays from a Na^{22} source. This source was also used to secure an energy calibration of the gamma-ray detector. The coincidence counts were normalized against a predetermined number of counts in the fixed proton detector. Peak coincidence counting rates were of the order of from 3 to 5 counts per second.

THEORY

The first theoretical treatment of a direct-reaction process was proposed by Butler[6] for the analysis of deuteron stripping reactions. The possibility that inelastic reactions of the form (p,p') (n,n'), (p,α), etc., might proceed by a direct process was considered by Austern, Butler, and McManus.[7] Recently, Butler[2] has proposed a theory of direct reactions which include stripping as a special type of a more general class of reactions. The angular-dependent terms in the differential cross sections predicted for these direct-reaction processes contain a characteristic oscillatory term of the form

$$[j_l(Q_R)]^2,$$

where j_l is the spherical Bessel function of order l, R is the interaction radius, and Q is the magnitude of the momentum transfer, which for (p,p') reactions is given by

$$Q = |\mathbf{k}_p - \mathbf{k}_p'|.$$

$\mathbf{k}_p$ and $\mathbf{k}_p'$ are the wave vectors for the incident and outgoing protons. The angular distributions predicted on the basis of the direct-reaction mechanism are dependent on the spins and parities of the initial and final nuclear states involved, and are thus capable of yielding information regarding these parameters. The agreement between inelastic scattering experiments above 10 Mev and the predictions of Butler's theory are excellent. At lower bombarding energies, where the probability of compound-nucleus formation is high, the angular distributions of inelastically scattered particles do not agree very well with predictions of the direct-reaction process. However, the differential cross sec-

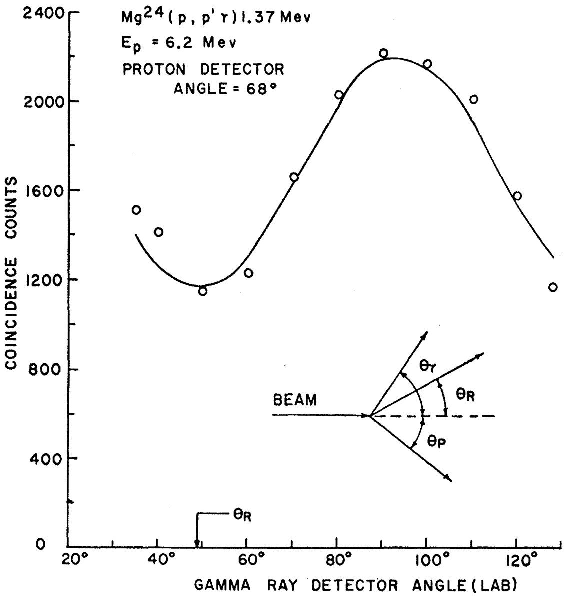

FIG. 5. The angular correlation between gamma rays and inelastically scattered protons from the first excited state of Mg^{24}. The gamma-ray detector is located in the plane determined by the incident beam direction and the proton detector direction. The angle of recoil of the residual nucleus is 49°. The proton detector angle is 68° with respect to the incident beam direction.

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[6] S. T. Butler, Proc. Phys. Soc. (London) **A208**, 559 (1951).

[7] Austern, Butler, and McManus, Phys. Rev. **92**, 350 (1953).

tions observed also do not exhibit the symmetries predicted on the basis of the statistical models of the nucleus.

An additional test for measuring the presence of direct-reaction mechanisms in inelastic scattering processes is measurement of the angular correlation between the inelastically scattered particles and the radiative decay of the excited residual nucleus state. This process was first studied theoretically by Satchler,[8] using a description in which the initial and final nucleon states are represented by plane waves. He showed that the proton gamma angular correlation is symmetric about the nuclear recoil direction. For the case of a target nucleus of ground-state spin 0, excited by inelastic scattering to an excited state of spin 2, decaying to the ground state by the emission of quadrupole radiation, the angular correlation is given by $\sin^2[2(\theta-\theta_q)]$, where θ is the angle between the gamma-ray and the initial proton beam direction and θ_q is the classical nuclear recoil direction or momentum-transfer direction. Sherr and Hornyak[9] investigated the angular correlation of gamma rays from the 4.45-Mev state of C^{12} excited by 16.2-Mev protons. The angular-correlation function was fitted to a distribution of the form

$$A+B\sin^2[2(\theta-\theta_0)],$$

where θ_0 refers to the axis of symmetry. Banerjee and Levinson [10] analyzed these data considering the effects of the distortions of the plane waves on the angular correlation. They found that the angular correlation function could be represented as $A+B\sin^2(\theta-\theta_0)$, where the symmetry axis θ_0 coincided only approximately with the nuclear recoil direction for all scattering angles.

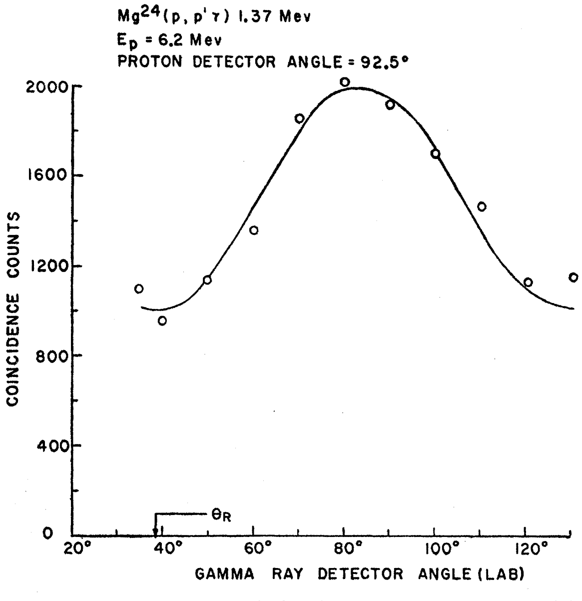

FIG. 6. The angular correlation between gamma rays and inelastically scattered protons from the first excited state of Mg^{24} for a proton detector angle of 92.5°. The angle of recoil of the residual nucleus is 38.5°.

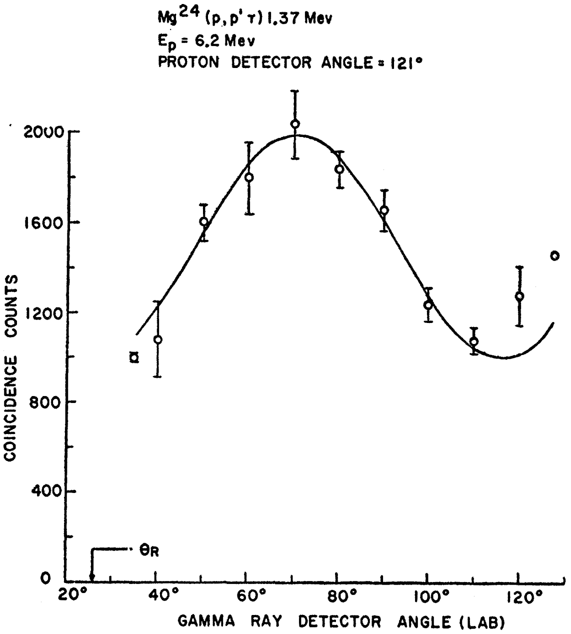

FIG. 7. The angular correlation between gamma rays and inelastically scattered protons from the first excited state of Mg^{24} for a proton detector angle of 121°. The angle of recoil of the residual nucleus is 26°.

RESULTS

A typical differential pulse-height spectrum of the protons scattered from the magnesium target is shown in Fig. 3. The proton group corresponding to Mg^{24} in its first excited state is seen to be well resolved from the elastically scattered proton group. A differential yield curve for the inelastically scattered protons was observed, and it was decided that the angular distributions of most interest would be those corresponding to the peaks and valleys of this curve. Accordingly, angular distributions were measured for foil thicknesses of 0, 0.02 mm, 0.038 mm, and 0.06 mm. These distributions are shown in Fig. 4. A curve based upon Butler's theory for direct reactions was calculated using a nuclear radius of 5.5×10^{-13} cm. The experimental curves A and B of Fig. 4 agree with the theory in the positions of the peaks, but not in details of the distributions, such as the increase in yield in the backward angles. The forward peaking in the distribution has disappeared completely at a foil thickness of 0.038 mm. Finally, at a foil thickness of 0.06 mm there is a very broad peak centered at about 115°. In all cases observed the angular distributions fail to be symmetric

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[8] G. R. Satchler, Proc. Phys. Soc. (London) **A68**, 1037 (1955).

[9] R. Sherr and W. F. Hornyak, Bull. Am. Phys. Soc. Ser. II, A, 197 (1956).

[10] M. K. Banerjee and C. A. Levinson, Ann. Phys. N.Y. 2, 499 (1957).

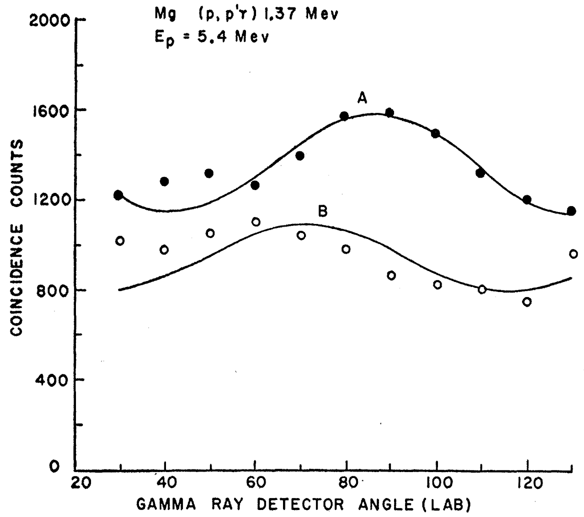

FIG. 8. The angular correlation between gamma rays and inelastically scattered protons from the first excited state of Mg^{24} at a proton bombarding energy of 5.4 Mev. Curve A was taken for a proton detector angle of 90° whereas curve B was taken for a proton detector angle of 121°.

about 90° (c.m.). This would seem to rule out the case of pure compound-nucleus formation in which one or more distinct levels of the compound nucleus are formed.

Two possible explanations for the asymmetries observed and the rapid variation of the angular distributions with energy are (a) interference between direct-reaction processes and decays through one or more levels of the compound nucleus, and (b) interference between states of the compound nucleus of opposite parity. The level spacings in Al^{25} at these excitation energies is not known; consequently, one cannot evaluate the relative strength of the interference between compound-nucleus levels. However, the results of the angular correlation measurements seem to indicate the presence of direct reactions. Thus it appears likely that some, if not all, of the asymmetries observed in the angular distributions are due to interferences of type (a).

The results of the angular correlation experiments are shown in Figs. 5, 6, 7, and 8. The angular correlation measurements were performed at incident beam energies of 5.4 and 6.2 Mev and at laboratory proton detector angles of 68°, 92.5°, and 121°. The experimental data were corrected for accidental counts but not for the finite detector geometry. The standard deviations associated with the experimental points were determined by averaging the data from three to six separate angular correlation runs. The solid curve in each correlation is not the best fit to the experimental data, but is of the form

$$A+B\sin^2[2(\theta-\theta_R)],$$

where θ is the gamma-ray detector angle with respect to the incident beam direction, and θ_R is the classical residual-nucleus recoil direction or laboratory momentum transfer direction. The momentum transfer directions for the data of Figs. 5, 6, 7 are, respectively, 49°, 38.5°, and 26°. The results of the 6.2-Mev correlation data appear to be consistent with symmetries about the momentum transfer directions. The A/B ratio for the 6.2-Mev data is, within experimental precision, equal to 1. While the strong angular asymmetries observed appear to be "washing out" at bombarding energies of 5.4 Mev, it is striking to observe that the data are still consistent with the symmetries predicted on the basis of the direct-reaction mechanism.

CONCLUSIONS

The purpose of our experiment was to investigate the presence of direct-reaction mechanisms at low particle bombarding energy. While it was not expected that angular distribution experiments at these low energies would permit an unambiguous determination of the presence of direct-reaction mechanisms, it was felt that this information plus the more definitive angular correlation experiments would serve to determine the existence of direct reactions. The results of the angular correlation experiments are in agreement with predictions of Satchler,[8] and Banerjee and Levinson,[10] based on direct-reaction mechanisms. It has been pointed out by Satchler and Biedenharn[11] that the momentum transfer direction Q has no significance in compound-nucleus processes. The possible symmetries that might exist for compound-nucleus processes are the incoming beam direction or the outgoing particle direction in the center-of-mass coordinates. For the angular correlation experiments, only the data for a proton detector angle of 92.5° are consistent with compound-nucleus symmetries, since the peak of the $\sin^2[2(\theta-\theta_R)]$ distribution, computed for the appropriate momentum transfer direction at this detector angle, is within experimental accuracy also symmetric about the outgoing proton direction. However, for proton detector angles of 68° and 121° the data are consistent only with the direct-reaction mechanism.

The angular correlation data indicates the presence of direct-reaction processes even at these low incident bombarding energies. A possible explanation for the observed energy dependence of the angular distributions is that there is interference between compound-nucleus decay and direct-reaction processes. In this case the nature of the experimental distributions observed depend upon the detailed nature of the compound-nucleus levels excited. At these low bombarding energies it does not appear that angular distribution experiments alone will yield decisive quantitative information either concerning the nature of the reaction mechanisms or the parameters of the residual states excited. However, with sufficiently good energy resolu-

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[11] Biedenharn, Boyer, and Charpie, Phys. Rev. **88**, 517 (1952).

tion of the incident beam and for compound-nucleus states well resolved in energy, an analysis of the interferences between compound-nucleus decay and direct processes could lead to information concerning the spins and parities of the compound-nucleus states involved in the reaction.

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PHYSICAL REVIEW VOLUME 114, NUMBER 2 APRIL 15, 1959

Excitation Function of the Reaction $Zn^{64}(n,p)Cu^{64}$ with Neutrons of Energies between 2 and 3.6 Mev

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The relative cross section for $Zn^{64}(n,p)Cu^{64}$ has been measured by an activation method for neutron energies of 2.0 to 3.6 Mev. The absolute cross section at 3.55-Mev neutron energy is found to be 56.4 ± 9.0 mb by comparing the Cu^{64} positron activity with the amount of Si^{31} formed in the $P^{31}(n,p)Si^{31}$ reaction, which has a previously known cross section of 96.2 ± 9.0 mb. The cross section rises monotonically with increasing energy from a value of 12 mb at 2.0 Mev. The experimental results are compared with the predictions of statistical theory; experimental level densities are used in the calculations, but even so the predicted yield is too small. An upper limit of 2 mb is assigned to the cross section for $Zn^{68}(n,\gamma)Zn^{69*}$ at 3 Mev.

INTRODUCTION

THE excitation function of the reaction $Zn^{64}(n,p)$-Cu^{64} is of interest from the various standpoints of fast-neutron detection, reactor design, and nuclear theory. Previously the reaction has been investigated by Bretscher and Wilkinson, who measured the relative yield of the Cu^{64} beta activity at neutron energies between 2 and 3.5 Mev.[1] However, no attempt was made to determine the cross section. The reaction cross section was measured by a number of authors[2] at 14-Mev incident neutron energy.

The reaction $Zn^{64}(n,p)Cu^{64}$ has a positive Q value of 0.20 Mev, and the product Cu^{64} decays with a half-life of 12.8 hours.[3] The decay of Cu^{64} consists of 19% positron emission and 42% of K-capture to the ground state of Ni^{64}, and 39% electron emission to the ground state of Zn^{64}. This paper reports positron activation measurements of the relative yield of the $Zn^{64}(n,p)Cu^{64}$ reaction at neutron energies in the range from 2.0 to 3.6 Mev. The absolute cross section is obtained by comparing the Cu^{64} positron activity with the amount of Si^{31} formed in the $P^{31}(n,p)Si^{31}$ reaction, which has a cross section of 96.2 ± 9.0 mb at 3.56 Mev neutron energy.[4]

EXPERIMENTAL PROCEDURE

The 800-kev Philips cascade generator of the University of Chile delivering an ion beam of about 1 milliampere was used to obtain neutrons by means of the reaction $H^2(d,n)He^3$. The accelerating voltage of the deuterons is controlled by a rotating voltmeter, the scale of which was calibrated previously in terms of energy through the resonances in the $Al^{27}(p,\gamma)Si^{28}$ reaction.[5]

The target was a deuterium self-regenerating target, water-cooled at a speed of two liters per minute. From a systematic study of deuterium self-regenerating targets, Fiebiger concluded that the highest neutron yield was given by a gold target.[6] Our experience is that the best results could be obtained with a sandwich-type target, in which consecutive thin layers of gold, palladium, and gold are evaporated onto a 1-mm copper backing. Saturation in the neutron yield from a freshly prepared target occurred after $1\frac{1}{2}$ hours of continuous bombardment giving total neutron outputs up to 3.5×10^8 neutrons/sec at 600 kev deuteron bombarding energy. These targets appeared to be very stable and bombardment with currents up to 1 milliampere hardly deteriorated the target. In order to make an estimate of the target thickness, a similar target has been prepared in which the lower gold layer was replaced by one of aluminum. This target was bombarded with protons and from the displacement of the resonance in the $Al^{27}(p,\gamma)Si^{28}$ reaction, we obtained an estimate of the

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[1] E. Bretscher and D. H. Wilkinson, Proc. Cambridge Phil. Soc. **45**, 141 (1949).

[2] E. B. Paul and R. L. Clarke, Can. J. Phys. **31**, 267 (1953); L. Rosen and A. H. Armstrong, Bull. Am. Phys. Soc. Ser. II, **1**, 224 (1956); H. G. Blosser (private communication); D. L. Allan, Proc. Phys. Soc. London **A68**, 925 (1955).

[3] Strominger, Hollander, and Seaborg, Revs. Modern Phys. **30**, 585 (1958).

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[6] K. Fiebiger, Z. Naturforsch. **11a**, 607 (1956).