PHYSICAL REVIEW VOLUME 108, NUMBER 1 OCTOBER 1, 1957

Angular Distributions of Neutrons from Al^{27}(*d*,*n*)Si^{28}[†][*]

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(Received June 27, 1957)

By using the method of proton recoils in nuclear emulsions, angular distributions of neutrons emitted to low-lying states of Si^{28} in the reaction Al^{27}(*d*,*n*)Si^{28} have been obtained at deuteron energies of 2.16 and 6.00 Mev. As might be expected, the angular distributions obtained at $E_d=2.16$ Mev show considerable deviations from the predictions of the simple Butler stripping theory. The angular distributions obtained at $E_d=6.00$ Mev have been analyzed by means of the Butler theory to obtain parities and limits on the spins of Si^{28} states. These results are, for the ground state, $J^\pi=0^+$, 1^+, 4^+, or 5^+; 1.78-Mev state, $J^\pi=2^+$ or 3^+; 4.62-Mev state, $J^\pi=1^-$ to 4^-; 6.24-Mev state, $J^\pi=2^+$ or 3^+; 6.88-Mev state, $J^\pi=(1^-$ to $4^-)$; 7.90-Mev state, $J^\pi=2^+$ or 3^+; 8.57-Mev state, $J^\pi=2^+$ or 3^+; 9.39-Mev state, $J^\pi=2^+$ or 3^+. It is pointed out that the odd parity of the 4.62-Mev state of Si^{28} is consistent with the possible shell-model states of a spheroidal nucleus.

INTRODUCTION

THE angular distributions of neutrons emitted to resolved levels in (*d*,*n*) reactions have been studied in about a dozen cases. An early experiment by Ajzenberg[1] showed the usefulness of the Butler theory in interpreting (*d*,*n*) reactions at low bombarding energies. Subsequently a number of other neutron angular distributions were obtained for the purpose of studying nuclear levels (see, e.g., the work of Middleton *et al.*[2,3]). Pruitt, Hanna, and Schwartz[4] found considerable deviations from the Butler predictions[5] at bombarding energies below the Coulomb barrier of the target. Later experiments at bombarding energies below the Coulomb barrier[6,7] have confirmed the fact that the simple Butler theory is not adequate to explain the observed angular distributions. It has also been found from experiment that the angular distributions of protons from (*d*,*p*) reactions below the Coulomb barrier are not well described by the simple Butler theory.[8–10] Below the Coulomb the reaction mechanism is obscure, and one may anticipate a considerably different reaction mechanism for proton and neutron emission.[11] There are three approaches which have been used to interpret stripping angular distributions below the Coulomb barrier. The first is the assumption that part of the reaction takes place by means of the compound-nucleus mechanism. Interference between compound-nucleus state amplitudes was postulated in the analysis[12] of the experiment of Canavan,[8] because after a stripping angular distribution was subtracted, the remainder of the angular distribution was not symmetric about 90 degrees, as required of a compound-nucleus angular distribution, in the absence of interference. The second method is that used by Tobocman and Kalos[13] and Grant,[14] in which the Coulomb and nuclear effects omitted in the simple stripping theory are taken into account. The angular distributions of Canavan were again analyzed by Grant with this method, but the rise in the cross section at backward angles could not be explained. The third effect is stripping of the emitted particle from the target with the subsequent absorption of the deuteron. In the center-of-mass system it makes little difference which particle is called the target and which the bombarding particle, so that it is quite reasonable that either may be subject to stripping. This effect is called heavy-particle stripping.[15] Owen and Madansky have fitted[15] the angular distribution from the reaction B^{11}(*d*,*n*)C^{12} over a deuteron energy range from 0.6 to 4.7 Mev,[7] with the assumption of deuteron and heavy-particle stripping, and without taking into account compound-nucleus, Coulomb, or nuclear scattering effects. The relevant question at present is for what targets and at what bombarding energies the three effects discussed above become important.

We decided to obtain neutron angular distributions for a number of levels to see whether any simple interpretations were possible. In the present work angular distributions of neutrons emitted to levels of Si^{28} from the reaction Al^{27}(*d*,*n*)Si^{28} have been obtained at energies below and above the Coulomb barrier, which for

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[†] Supported by the U. S. Air Force through the Air Force Office of Scientific Research of the Air Research and Development Command.

[*] Submitted in partial fulfillment of the requirements for the Ph.D. degree at Boston University.

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[1] F. Ajzenberg, Phys. Rev. **88**, 298 (1952).

[2] Middleton, El Bedewi, and Tai, Proc. Phys. Soc. (London) **A66**, 95 (1953).

[3] Evans, Green, and Middleton, Proc. Phys. Soc. (London) **A66**, 108 (1953).

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[12] W. W. True and L. Diesendruck, Phys. Rev. **87**, 381 (1952).

[13] W. Tobocman and M. H. Kalos, Phys. Rev. **97**, 132 (1955).

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$Al^{27}+d$ is ~3.6 Mev. The bombarding energies were 2.16 and 6.00 Mev. At the 6.00-Mev bombarding energy the Butler stripping-theory analysis of the neutron angular distributions reliably provides the parities and limits on the spins of the Si^{28} states. The bombardment at the energy below the Coulomb barrier was carried out in order to obtain the excitation energies of the Si^{28} states, in addition to the angular distributions at $E_d=2.16$ Mev. At this lower energy, the energies of neutrons emitted to low-lying states of Si^{28} were sufficiently lower that the neutron energy resolution of the nuclear-emulsion technique employed was appreciably better. Having obtained the level energies, one is better able to separate the neutron energy spectra obtained at the higher bombarding energy into discrete energy groups, for the purpose of obtaining angular distributions. Also, once one knows from the higher bombarding energy experiment the orbital angular momentum of the captured proton leading to a particular state of Si^{28}, one can construct the stripping-theory angular distributions expected at the lower bombarding energy. In this way, deviations from the stripping angular distributions become apparent.

EXPERIMENTAL PROCEDURES

A. $E_d=2.16$-Mev Experiment

The experimental arrangement has been described in detail in a previous report[16] on the levels of Si^{28}, but a brief review is in order. A thin Al foil target was bombarded with 2.16-Mev deuterons from the MIT Rockefeller Van de Graaff generator. Ilford C-2 emulsions, 400 microns thick, were used as detectors, and were placed at nine angles to the incident beam. Neutron spectra at 0°, 10°, 20°, 30°, 45°, 60°, 90° and 120° were obtained by recoil-proton measurements in the emulsions. From these spectra the excitation energies of low-lying Si^{28} states were found at 1.78±0.10, 4.54±0.20, 4.95±0.20, 6.24±0.06, 6.88±0.06, 7.39 ±0.06, 7.89±0.06, 8.31±0.10, 8.57±0.08, 9.37±0.04, 10.00±0.10 and 10.25±0.06 Mev. The best values for the Si^{28} levels taken from our work, the gamma-ray measurements of Bent *et al.*,[17] the measurement of the excitation of the second excited state by Endt and Paris,[18] and of the first excited state by Motz and Alburger[19] are 1.78±0.01, 6.24±0.06, 6.88±0.06, 7.39±0.06, 7.90±0.05, 8.28±0.06, 8.57±0.08, 9.39 ±0.04, 10.00±0.10, and 10.25±0.06 Mev.

To obtain an angular distribution from the experimentally observed number of neutrons in an energy group at various angles, the following corrections are made; (a) correction for variation of the *n-p* scattering cross section with energy, (b) geometry correction, to take account of the finite thickness of the emulsion, and, (c) correction for variation of the emulsion area scanned at different angles. The angular distributions obtained are then transformed to the center-of-mass system.[20] Representative examples of the angular distributions thus obtained are shown in Figs. 1–5. The error shown is the statistical error only. Another important error enters into the estimation of the number of tracks in an energy group. If one refers to the neutron spectra,[16,21] one can see that some of the neutron groups are not resolved at one or more angles. When the resolution is poor, i.e., for the states at 6.88, 7.39, and 8.28 Mev, a

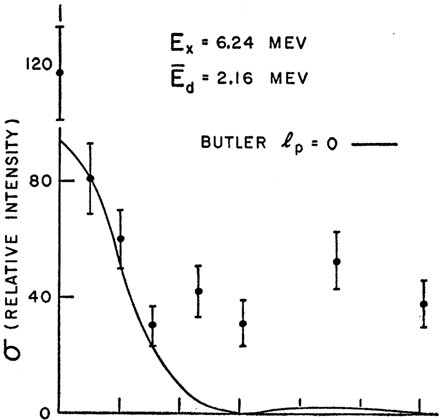

FIG. 1. The angular distribution of neutrons emitted to the 6.24-Mev state, at $E_d=2.16$ Mev. The solid line is the Butler-theory prediction, with $r=5.36\times10^{-13}$ cm. The errors indicated are statistical errors only.

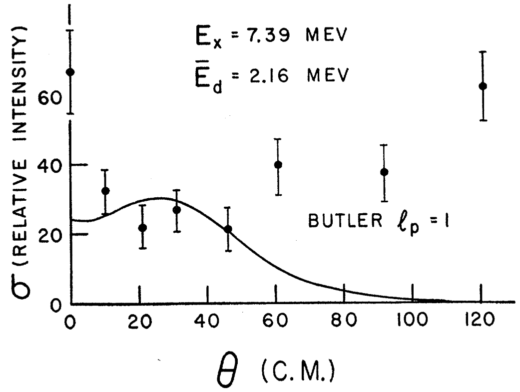

FIG. 2. The angular distribution of neutrons emitted to the 7.39-Mev state, at $E_d=2.16$ Mev. The solid line is the Butler-theory prediction, with $r=5.36\times10^{-13}$ cm.

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[16] Rubin, Ajzenberg-Selove, and Mark, Phys. Rev. **104**, 727 (1956).

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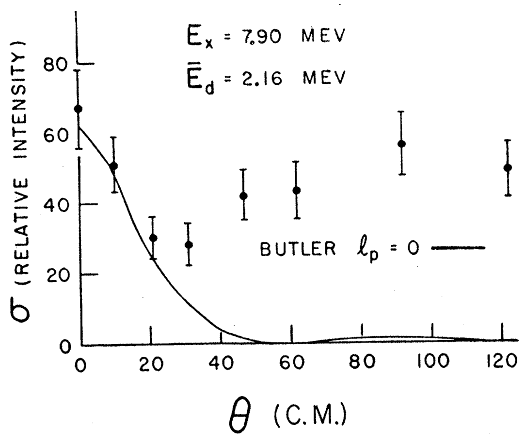

FIG. 3. The angular distribution of neutrons emitted to the 7.90-Mev state, at $E_d=2.16$ Mev. The solid line is the Butler-theory prediction, with $r=5.36\times10^{-13}$ cm.

consistent procedure was adopted for estimating the number of tracks in an unresolved group. The energy interval defining a neutron group was taken from an adjacent angle, at which the group was resolved, and all of the neutrons in this energy interval were assigned to the group. The error in the number of neutrons in an energy interval, estimated by this procedure, may be large and cannot be estimated accurately.

The energy resolution to be expected in this experiment has been calculated. The major contribution to the group width at half-maximum below 5-Mev neutron energy is the range straggling of protons in the emulsion. Above 5 Mev, the geometrical error, assuming that neutrons are incident on the emulsion from a fixed direction, becomes important. In general, the length and angle measurement errors contribute less than 10% to the total group width. The theoretical group width at half-maximum decreases from 170 kev at 1 Mev to 101 kev at 3 Mev, and then increases to 260 kev at 10-Mev neutron energy. The best experimental group widths are about 50 kev greater than the expected group widths,[21] perhaps because of emulsion distortion, which was not considered. Because the statistics are in general rather poor, groups must be separated by about twice the width at half-maximum of a group in order to be resolved. The states which may be unresolved are discussed in the section on "Results."

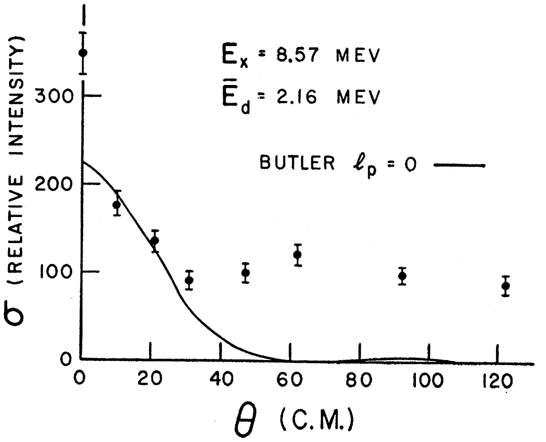

FIG. 4. The angular distributions of neutrons emitted to the 8.57-Mev state, at $E_d=2.16$ Mev. The solid line is the Butler-theory prediction, with $r=5.36\times10^{-13}$ cm.

It is possible that states reached by capture of protons with l values greater than zero are unresolved from neighboring states reached with higher cross sections. The angular distributions obtained will then represent the state reached with highest cross section, despite the possible unresolved levels.

For purposes of comparison, Butler-theory curves have been drawn using the l values obtained from the 6.00-Mev bombardment, except for the 8.28-Mev level distribution. At the higher bombarding energy, the 8.28-Mev level was not resolved. It is to be noted that for the state at 9.39 Mev the angular distribution is very close to the Butler-theory curve for small angles near the principal maximum, but that the experimental cross section is considerably higher than the Butler prediction for larger angles. The same qualitative behavior holds for the 6.24- and 8.28-Mev state angular distributions. For the lower excited states, the angular distributions are nearly isotropic within statistics. Further understanding of these angular distributions can come only from a fuller analysis by means of a more complete stripping theory.

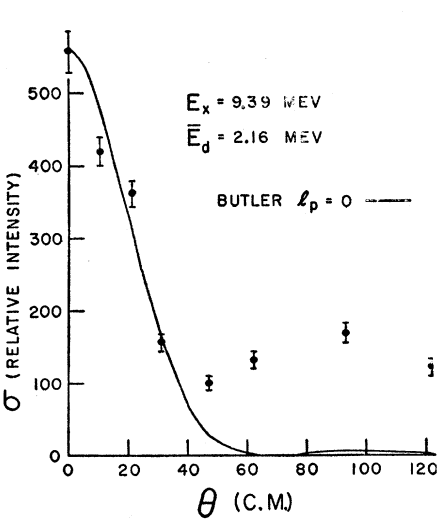

FIG. 5. The angular distribution of neutrons emitted to the 9.39-Mev state, at $E_d=2.16$ Mev. The solid line is the Butler-theory prediction, with $r=5.36\times10^{-13}$ cm.

B. $E_d=6.00$-Mev Experiment

The Coulomb barrier of the $Al^{27}+d$ system, for an Al radius of 4.3×10^{-13} cm and an effective deuteron radius of 1.1×10^{-13} cm is 3.6 Mev. In order to obtain

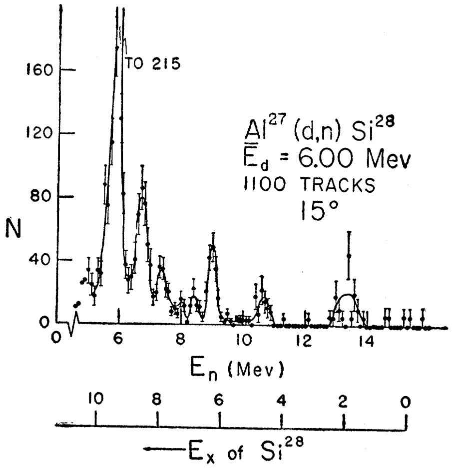

FIG. 6. The neutron spectrum at 15° for $E_d=6.00$ Mev.

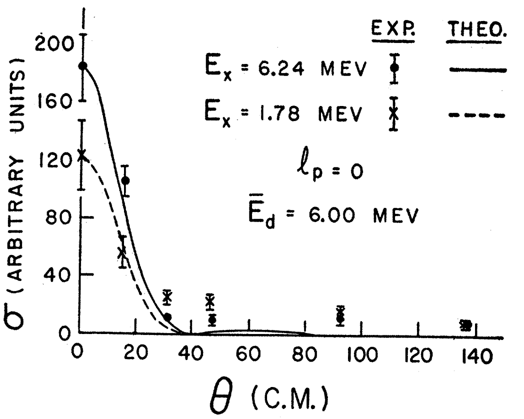

FIG. 8. The angular distributions of neutrons emitted to the 1.78- and 6.24-Mev states, at $E_d=6.00$ Mev. The curves are the Butler-theory predictions, with $r=5.1\times10^{-13}$ cm.

valid stripping angular distributions, a bombarding energy of 6.00±0.005 Mev, considerably in excess of the Coulomb barrier, was chosen. The exposure was 1500 microcoulombs, and a potential of 300 volts was used for electron suppression. An Al foil target, weighing 0.23 mg/cm^2 was used, with a backing of 10-mil tantalum. As before, nuclear emulsions were employed for neutron energy measurement. The plate camera[22] is an aluminum ring of 7-in. radius, with blades set at 15° intervals, onto which emulsions, wrapped in aluminum foil, are attached with binder clips. Neutron spectra at 0°, 15°, 30°, 45°, 90°, and 135° with respect to the incident beam were obtained by measuring proton recoil tracks in the emulsions. A Leitz binocular microscope, equipped with a Heine stage, was used for track measurement. Only long tracks, corresponding to neutron energies greater than 4.5 Mev, and excitation energies in Si^{28} less than 10.5 Mev, were scanned, to correspond to the excitation region explored in the lower bombarding energy experiment. 1000 tracks were scanned at each of those forward angles where the track density made it possible, while fewer were scanned at higher angles where the track density was very low, about 100 acceptable tracks per cm^2 of emulsion. A typical neutron spectrum obtained at $E_d=6.00$ Mev is shown in Fig. 6 (see also, reference 21). In the 2.16-Mev deuteron energy spectra, the neutron group with $E_n\sim1.8$ Mev was identified as due to carbon contamination. This carbon group appears much less strongly in the 6.00-Mev deuteron energy spectra, ($E_n\sim5.4$ Mev). Angular distributions of neutrons emitted to Si^{28} states were obtained from these spectra by the method described in the previous section. Figures 7–11 show the angular distributions obtained. The ordinates of the angular distribution curves are in

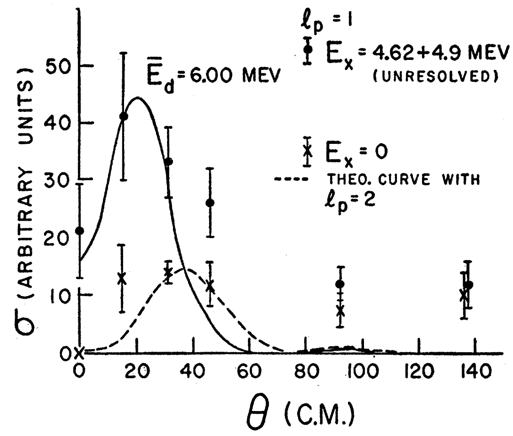

FIG. 7. The angular distribution of neutrons emitted to the ground state, and the combined angular distribution of neutrons emitted to the states at 4.62 and 4.9 Mev, at $E_d=6.00$ Mev. The solid and dashed curves are the Butler-theory predictions, with $r=5.1\times10^{-13}$ cm.

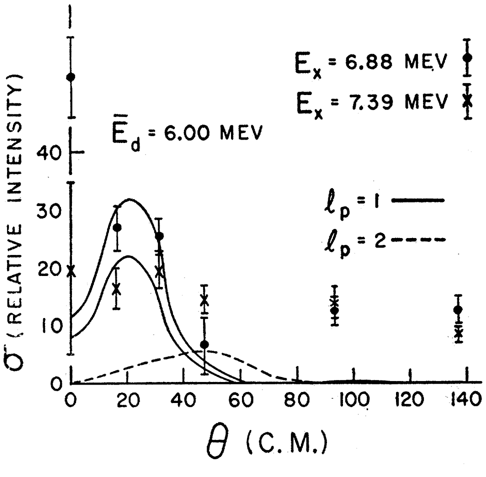

FIG. 9. The angular distributions of neutrons emitted to the 6.88- and 7.39-Mev states, at $E_d=6.00$ Mev. The curves are the Butler-theory predictions, with $r=5.1\times10^{-13}$ cm.

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[22] Ajzenberg-Selove, Bullock, and Almquist (unpublished).

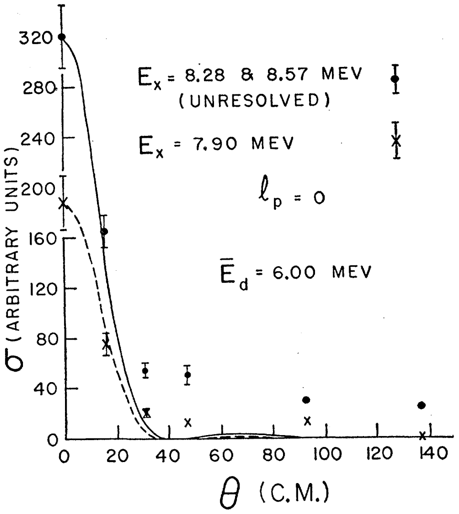

FIG. 10. The combined angular distribution of neutron emitted to the states at 8.28 and 8.57 Mev, and the angular distribution of neutrons emitted to the 7.90-Mev state, at E_d=6.00 Mev. The curves are the Butler-theory predictions, with $r=5.1\times10^{-13}$ cm.

arbitrary units, which directly correspond to absolute cross sections. The cross section for emission of neutrons at 0° to the 9.39-Mev state(s) was computed using the formulas of Rosen,[23] and is 31±8 mb/steradian. The error quoted involves 10% errors in the incident flux, the number of tracks in an energy group, target thickness, and average attenuation of the neutron flux in the emulsion.

For unresolved neutron groups, corresponding to unresolved Si^{28} states, the composite angular distribution of the unresolved neutron groups was obtained. The 8.28- and 8.57-Mev levels were unresolved, as were the 4.62- and 4.9-Mev levels. For these cases it proved possible to establish the fact that the largest contribution to the cross section came from just one of the states, so that the angular distribution obtained describes this state primarily. This was done by obtaining the mean energy of the composite neutron group, and from this the mean excitation energy in Si^{28}, to which it corresponded. If the mean excitation came out much closer to that of one level than of the other, the cross section for production of Si^{28} in the corresponding state contributes the major portion of the observed cross section. For the combined states at 8.28 and 8.57 Mev, the mean excitation of the composite group which corresponds to them is 8.50 Mev at 0° and 8.59 Mev at 15°, indicating that the angular distribution obtained is mainly that of the 8.57-Mev state. Similarly for the states of 4.62 and 4.9 Mev the mean excitation energy of the composite group at 0° is 4.6 Mev; at 15°, 4.68 Mev; at 30°, 4.65 Mev; and at 45°, 4.55 Mev. The angular distribution obtained therefore is primarily that of the 4.62-Mev state.

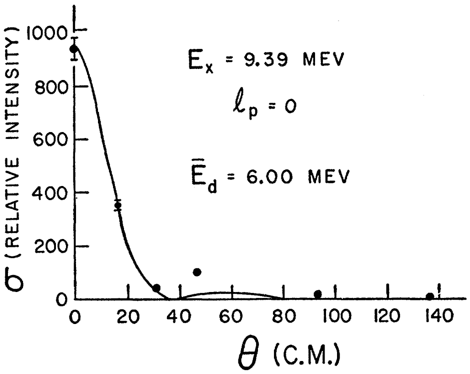

FIG. 11. The angular distribution of neutrons emitted to the 9.39-Mev state(s), at E_d=6.00 Mev. The curve is the Butler-theory prediction, with $r=5.1\times10^{-13}$ cm.

The angular distributions obtained are compared with Butler-theory curves drawn with the aid of nomographs[24] and the more recent tables[25] of Lubitz and Parkinson. The amplitudes of the theoretical curves were chosen to fit the experimental amplitudes at the position of the principal peaks. A radius of 5.1×10^{-13} cm sufficed to fit all of the experimental angular distributions, and was chosen by varying the radius and seeing which radius fit two of the experimental curves best.

RESULTS

Since the ground state of Al^{27} is $5/2^+$,[26] the parity of a Si^{28} state is even if the orbital angular momentum of the captured proton is even, and odd if l is odd. Capture of $l=0$ protons leads to states whose total angular momentum is 2 or 3; capture of $l=2$ protons leads to states of angular momentum between 0 and 5, but more likely, 0, 1, 4, or 5 because 2 and 3 can be reached by $l=0$, which has a larger cross section. In the following discussion, an "$l=0$ angular distribution" is the angular distribution of neutrons emitted to a state which is formed when protons of angular momentum zero are captured.

Ground State (Fig. 7)

As expected from the theory of even-even nuclei, the ground state is 0^+,[26] which would lead to an $l=2$ angular distribution. At E_d=6.00 Mev we find an angular distribution which is consistent with $l=2$, because of the zero point at 0°, but the statistics are too poor to regard this as a confirmation. At E_d=2.16 Mev, the angular distribution is isotropic within statistics.

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[23] L. Rosen, Nucleonics **11**, 38 (1953).

[24] C. R. Lubitz and W. C. Parkinson, Rev. Sci. Instr. **26**, 400 (1955).

[25] C. R. Lubitz, "Numerical table of Butler-Born approximation stripping cross sections," University of Michigan, 1957 (unpublished).

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1.78-Mev State (Fig. 8)

The spin and parity of this state are 2^+.[26] We find an $l=0$ angular distribution, verifying this result. At $E_d=2.16$ Mev the angular distribution is isotropic within statistics.

4.62-Mev State (Fig. 7)

From the measurements of Rutherglen *et al.*[27] the 4.62-Mev level can have a spin of 2, 3, or 4 and either even or odd parity. Gove[28] reports that the direct transition from this level to the ground state is not observed, necessitating a spin of at least two. As mentioned previously, we have obtained a composite angular distribution of neutrons emitted to the 4.62- and 4.9-Mev states, but consideration of the mean excitation energies in Si^{28} corresponding to the mean neutron energies incicates that the angular distribution corresponds to the 4.62-Mev state. It is described by an $l=1$ Butler curve, except at 45°, where the experimental point is high. The high point at 45° could be due to an admixture of an $l=2$ or higher distribution of the 4.9-Mev state neutrons, but such a definite statement cannot be justified on the basis of one point. The 4.62-Mev state probably has $J=1^-$ to 4^- from the angular distribution but the absence of the direct ground state transition indicates that 1^- is extremely unlikely and that 3^- or 4^- are favored. At $E_d=2.16$ Mev the angular distribution is isotropic within statistics.

4.9-Mev State

The spin and parity of the 4.9-Mev state cannot be identified on the basis of this work or of previous work.

6.24-Mev State (Figs. 1 and 8)

The neutron group corresponding to the 6.24-Mev state has $l=0$ angular distributions at $E_d=2.16$ and 6.00 Mev and is thus 2^+ or 3^+.

6.88-Mev State (Fig. 9)

The 6.88-Mev state angular distribution has been compared with an $l=1$ Butler curve. At 0°, the experimental point is considerably higher than is consistent with the $l=1$ curve, but the discrepancy may be due to the overlapping of the 6.88-Mev state neutron group with the group of neutrons emitted to the 6.24-Mev state. The magnitude of the cross section makes it unreasonable to assume the 6.88-Mev state to have an $l=0$ angular distribution, and the fact that there certainly are a significant number of tracks at zero degrees eliminates the $l=2$ possibility. The $l=1$ assignment is not certain.

7.39-Mev State (Figs. 2 and 9)

The 7.39-Mev state neutron angular distribution does not have the character of a stripping distribution at either 2.16- or 6.00-Mev deuteron energy, and its spin and parity cannot be identified on the basis of the present work. Because the cross section at $E_d=6.00$ Mev, for large angles, is consistently greater than the Butler prediction, it is possible that there is an unresolved state near the 7.39-Mev level, reached by $l\geq 2$.

7.90-Mev State (Figs. 3 and 10)

The 7.90-Mev state neutron angular distribution is $l=0$, at $E_d=6.00$ Mev, so that this state has spin and parity 2^+ or 3^+. At $E_d=2.16$ Mev the angular distribution does not follow a simple stripping pattern, and the cross section is anomalously low.

8.28-Mev State (Fig. 10)

The 8.28-Mev state angular distribution can be seen only as a distortion of the angular distribution of the 8.57-Mev state angular distribution, in the composite angular distribution of the two states (see earlier discussion). The 8.28-Mev state contributes to high points in the experimental angular distribution at 30° and 45°, and so is most likely $l=1$ or $l=2$. No identification of the character of this state can be made on the basis of the present work.

8.57-Mev State (Figs. 4 and 10)

The 8.57-Mev state angular distribution is described by an $l=0$ Butler distribution, except at 30 and 45 degrees, where the experimental points are high, as discussed above. The 8.57-Mev state is therefore 2^+ or 3^+.

9.39-Mev State (Figs. 5 and 11)

The 9.39-Mev state angular distribution is described by an $l=0$ angular distribution, and therefore is 2^+ or 3^+. The calculation of Wilkinson[29] indicates that the first $T=1$ level of Si^{28} is at 9.4 Mev, and reference to the Al^{28} spectrum shows that there is a 2^+ excited state 29 kev above the 3^+ ground state. The 9.39-Mev level is thus a composite of the two levels in Si^{28} analogous to the $T=1$ ground state and the first excited state of Al^{28}, in addition to an unknown number of $T=0$ states.

DISCUSSION

A striking feature of the 2.16-Mev deuteron energy $l=0$ angular distributions is the decrease in zero-degree amplitude with increasing neutron energy. This behavior is easily explained by calculating the Butler cross section at zero degrees as a function of emergent neutron energy. From purely kinematic considerations the emission of lower energy neutrons is favored. The

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[27] Rutherglen, Grant, Flack, and Deuchars, Proc. Phys. Soc. (London) **A67**, 101 (1954).

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[29] D. H. Wilkinson, Phil. Mag. **2**, 1031 (1956).

fact that the neutron energy corresponding to the 9.39-Mev state is 2 Mev, and that it in fact is composed of two unresolved levels reached by capture of $l=0$ protons explains the predominant cross section for formation of this state.

There exists no reliable method for separating angular distributions into portions due to stripping and portions due to compound-nucleus formation. However a possible upper limit to the contribution of the compound-nucleus mechanism can be obtained by assuming the isotropic portion of the angular distribution to be the portion contributed by the compound-nucleus reaction. At $E_d=2.16$ Mev, about half the cross section for formation of the 9.39-Mev state(s) forms the upper limit to the compound-nucleus contribution. For states of lower excitation, for which the stripping cross section is lower, and which exhibit larger isotropic portions of the cross section, the limit is larger. At $E_d=6.00$ Mev, the $l=0$ angular distributions have essentially no isotropic background, although for some angles and for some of the levels the cross section away from the forward maximum is slightly higher than the Butler prediction.

The odd parity of the 4.62-Mev level is Si^{28} is something of a problem. Si^{28} is an alpha-particle nucleus, and the alpha-particle model, in general, can lead to low-lying odd-parity levels. No calculation of the levels of Si^{28} have been made on the alpha-particle model. If one wishes to explain the spins and parities of excited states by means of the simple shell model, the simplest assumption is that one nucleon at a time is raised into the next available shell-model state, in the same shell as the ground state. However, the odd-parity 4.62-Mev second excited state cannot be explained in this way, because there are no odd-parity shell-model states available in the *d* shell. Brink[30] has pointed out however that the odd parity of the 4.62-Mev state can be accounted for within the framework of the shell model if one assumes a nonspherical potential. Evidence that nuclei between oxygen and silicon have stable nonspherical shapes comes from the success in matching the level schemes of F^{19} and Al^{25} with rotational levels based on a spheroidal potential by Paul,[31,32] and from the successful predictions of the binding energies of nuclei between oxygen and silicon by Brink and Kerman,[33] based on the level scheme and allowed-particle states in a spheroidal potential. With increasing nuclear distortion the shell-model states, which are degenerate, split up, and the *z* component of the particle angular momentum along the nuclear symmetry axis becomes the only good quantum number. For a prolate nuclear shape the substates with $j_z<j$ become depressed with respect to their positions based on a spherical potential, the decrease in energy becoming greater with increasing nuclear distortion. The $1/2^-$ substate of the $f_{7/2}$ shell-model state, for great enough nuclear distortion of Si^{28}, will lie lower in energy than the $d_{3/2}$ substates. If one assumes the ground state of Si^{28} to be made up of particles in the $d_{5/2}(5/2)$ state, then a low excited state available is a 2^- state, formed by the combination of one particle in the $d_{5/2}(5/2)$ state and another in the $f_{7/2}(1/2)$ state.[30] The spheroidal-potential shell model thus provides a natural explanation of the odd parity of the 4.62-Mev state of Si^{28}, and predicts a spin of 2. To conclude, angular distributions have been obtained for neutrons emitted to resolved states of Si^{28}, at a bombarding energy below the Coulomb barrier. Although the stripping mechanism is certainly responsible for a large portion of the cross section, deviations from the stripping angular distributions remain to be explained.

ACKNOWLEDGMENTS

I am grateful to Professor F. Ajzenberg-Selove for suggesting this investigation and for her help in carrying it out, and to Professor W. W. Buechner for making this work possible. I wish also to thank Dr. Harold Enge, Mr. Anthony Sperduto, Dr. N. S. Wall, Dr. R. K. Nesbet, and Dr. D. M. Brink for their advice and aid, and the Brookhaven National Laboratory, where part of this work was done, for its hospitality.

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