The Pickup Reactions $B^{10}(n,d)Be^9$ for 14-Mev Neutrons*

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Measurements have been made of the yields and angular distributions of deuterons resulting from the bombardment of B^{10} by 14-Mev neutrons. The spectrum of charged reaction products was measured by means of a coincidence-telescope spectrometer consisting of two proportional counters and a thin NaI scintillator. The telescope was rotated to obtain measurements at various angles. Deuterons corresponding to the ground state and 2.43-Mev excited state of Be^9 were identified by measurements of both their energy and dE/dx values. The ground-state angular distribution was found to match the expected Butler inverse-stripping curve for $l_p=1$. The Butler analysis for the excited-state deuterons also gave $l_p=1$, corresponding to odd parity and spin 3/2, 5/2, 7/2, or 9/2 for the first excited state of Be^9. In particular, the spin value 1/2, to be expected from the L–S coupling model, is excluded. The cross sections, integrated from zero to 90 degrees (center of mass), are 21 ± 3 and 16 ± 2 millibarns, respectively, for the ground- and excited-state reactions.

INTRODUCTION

THE spins and parities of the energy levels of the Be^9 nucleus have been little investigated. Accurate energy measurements utilizing the $B^{11}(d,\alpha)$ reaction[1] and the $Be^9(p,p')$ reaction[2] showed a narrow (<7 kev) excited level at 2.43 Mev with no further indication of excited states between zero and 5 Mev. A search for α-n and α-γ coincidences from bombardment of B^{11} by deuterons,[3] showed that the 2.43-Mev state decays mainly by neutron emission. In addition to further extensive low-energy inelastic-scattering results[4] on this level, recent inelastic measurements with 32-Mev protons[5] have shown additional levels at 6.8 and 11.6 Mev. The only attempt to determine the spins of excited levels has been that of Mullin and Guth[6] who analyzed the angular distributions and energy variation of the $Be^9(\gamma,n)Be^8$ data and inferred the existence of an $S_{\frac{1}{2}}$ level at about 1.5 Mev with a $D_{\frac{5}{2}}$ level somewhat higher.

Recent work on the disintegration of Li^6 by 14-Mev neutrons[7,8] has shown a striking predominance of the (n,d) pickup reaction, and it was hoped that this process would also be strong in the somewhat analogous case of the $B^{10}(n,d)Be^9$ reaction. Since this is a case of inverse stripping, the well-known theoretical results of Butler[9] on the angular distributions of stripping reactions apply. So long as one considers the same center-of-mass energies for (d,n) and (n,d) reactions, it is clear from the theorem relating inverse nuclear reactions that Butler's stripping curves may be used directly in the case of nucleon pickup. Thus the angular distributions of the deuterons can be used to determine the parities and, within certain limits, the spins of those levels which are excited in the residual Be^9 nucleus.

The object of the present experiment was to measure the differential cross sections of the $B^{10}(n,d)$ reactions to the ground and excited levels of Be^9 and to compare these with Butler's theoretical functions in order to make spin and parity determinations.

APPARATUS

The apparatus for measuring the angular distributions of the charged reaction products from the bombardment of B^{10} by 14-Mev neutrons is shown in Fig. 1. The neutrons bombarded a thin B^{10} radiator, and the charged reaction products emitted into a small solid angle were analyzed by means of a coincidence-telescope spectrometer. The spectrometer was mounted on an indexed stand so that its axis could be rotated in a horizontal plane about a vertical axis lying in the plane of the radiator. The angles made by the reaction products with the incident neutron direction could be read directly from the index of the rotatable stand.

The 14-Mev neutrons were obtained from the $T(d,n)He^4$ reaction by bombarding a thick zirconium-tritium target[10] with the 250-kev monatomic deuteron beam from a Cockcroft-Walton accelerator. The angular position of the boron radiator was 90 degrees with respect to the deuteron beam. At this position the incident neutrons were almost monoenergetic with an energy of 14.10 ± 0.05 Mev. The number of neutrons from the reaction was measured by counting the accompanying alpha particles emitted into a well-defined solid angle.

The radiator was made from 400-mesh amorphous powder containing 98 percent by weight boron enriched to 95.5 percent B^{10}. It was prepared by suspending a small amount of the powder in absolute ethyl alcohol

* Work done under the auspices of the U. S. Atomic Energy Commission.
[1] Van Patter, Sperduto, Huang, Strait, and Buechner, Phys. Rev. **81**, 233 (1951).
[2] Browne, Williamson, Craig, and Donahue, Phys. Rev. **83**, 179 (1951).
[3] G. A. Dissanaike and J. O. Newton, Proc. Phys. Soc. (London) **A65**, 675 (1952).
[4] For a review of the inelastic-scattering results, see F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 342 (1952).
[5] R. Britten, Phys. Rev. **88**, 282 (1952).
[6] C. J. Mullin and E. Guth, Phys. Rev. **76**, 682 (1949).
[7] G. M. Frye and L. Rosen, Phys. Rev. **90**, 381 (1953).
[8] F. L. Ribe, Phys. Rev. **87**, 205 (1952).
[9] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 36 (1951).
[10] Graves, Rodrigues, Goldblatt, and Meyer, Rev. Sci. Instr. **20**, 579 (1949).

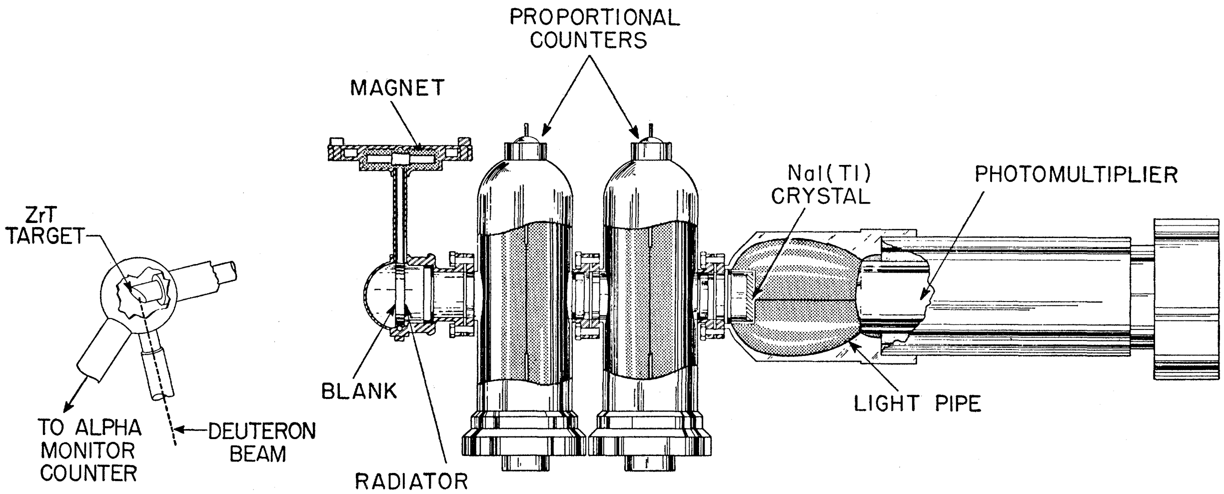

FIG. 1. Apparatus for measuring the $B^{10}(n,d)Be^9$ cross sections, showing $T(d,n)He^4$ neutron source and coincidence-telescope spectrometer.

and allowing the suspension to stand in a vessel, the bottom of which was a detachable platinum disk 0.010 in. thick. When the boron had settled out, the alcohol was drawn off with a pipette and the deposit dried. This deposit was then heated in vacuum to drive off volatile residues, and there resulted a uniform layer which adhered quite well to the platinum backing. The boron radiator thus formed was 2.21 cm in diameter, and its weight was 27.6 mg. The radiator on its platinum backing was attached to one side of a circular collar supported to rotate about a vertical axis as shown in Fig. 1. On the other side of the collar was mounted a platinum blank. At the top of the axle on which the collar was mounted was a small bar magnet which allowed the collar to be rotated inside the spectrometer by means of an external magnet in order to expose either the radiator or the platinum blank to the counters and scintillator of the instrument.

The coincidence-telescope spectrometer consisted essentially of two proportional counters and a thin NaI(Tl) scintillation crystal with light-pipe coupling to a photomultiplier. It operates in the following manner: Neutrons impinge on the boron radiator, and charged reaction products emitted along the spectrometer axis travel through the two counters (which have no foil windows) and strike the NaI crystal of the scintillation detector. The amplified pulses resulting from the ionization in the two proportional counters and from the scintillation of the sodium iodide crystal are fed to a coincidence circuit. An output pulse of the coincidence circuit indicates that a charged particle has traversed the spectrometer. The coincidence output pulse gates open an 18-channel analyzer[11] which records the scintillation pulse in one of its channels. The voltage of this pulse measures the energy of the charged particle traversing the spectrometer. Such a coincidence arrangement is necessary in order to observe the pulse-height spectrum of the reaction products since they occur in the presence of a large (singles) background produced by 14-Mev neutrons and gamma rays striking the scintillator.

The counters were the same as those used by Coon, Bockelman, and Barschall in their n-T scattering experiment.[12] They were filled with 71.5 mm Hg of Kr and 3.5 mm Hg of CO_2 and operated in their proportional range at a multiplication of about 10. With this filling the energy loss by a 9-Mev deuteron in traversing each counter was about 64 kev. Therefore the magnitudes of the counter pulses provided a good measure of the quantity dE/dx for the reaction products.

The NaI crystal was in the form of a cylinder 1 in. in diameter and 2.5 mm thick with the edge polished to transparency in alcohol and toluene and the two flat surfaces freshly cleaved in a dry box before insertion of the crystal into the scintillation detector. The crystal was mounted in a glass cup with a plane bottom which fitted into an oil-filled aluminum light pipe leading to the photocathode of a DuMont type K 1177 photomultiplier, as indicated in Fig. 1. With Pu^{239} (5.16-Mev) alpha particles impinging on the whole surface of the crystal in vacuum the resolution (full width at half-maximum) of the scintillation detector was 6.4 percent. The solid angle subtended at the radiator by the last diaphragm aperture before the crystal was 0.0140 steradian.

TESTS OF SPECTROMETER OPERATION

Using a thin polyethylene radiator with the d-T neutron source, the strength of which was measured to within 4 percent by means of counted alpha particles, the peaked spectrum of recoil protons was observed and counted. From the known incident flux of neutrons,

[11] C. W. Johnstone, Nucleonics **11**, No. 1, 36 (1953).

[12] Coon, Bockelman, and Barschall, Phys. Rev. **81**, 33 (1951).

the weight of the radiator, and the known differential cross section for (n-p) scattering, the solid angle of the spectrometer could be measured. The measured value and the calculated value agreed to within 1 percent.

Still using the polyethylene radiator, the isotropy of the angular distribution for neutron-proton scattering in the center-of-mass system was checked to within 5 percent between zero and 90 degrees. The energy variation of the recoil protons with laboratory angle was found to follow the required $\cos^2\theta$ relation.

The linearity of the system of type 250 preamplifier, amplifier, and pulse-height analyzer for the scintillation detector was tested with an accurate pulser and found to be exact to within 0.5 percent in absolute voltage and about 2 percent in relative channel width. It was also observed that neither the model 250 scintillation amplifier system nor the model 503 counter amplifier system saturated for pulse heights which occurred in the $B^{10}(n,d)$ experiment.

Accidental coincidence counts were observed to be negligible at the counting rates used in the experiment by inserting a 1.3-microsecond delay in the scintillator channel. An additional test was provided by the fact that the recoil-proton counting rate did not change for coincidence-circuit resolving times between 0.35 and 0.80 microsecond. Since scalers were provided on the counter and scintillator channels, the accidentals rate could also be calculated. Neutron fluxes were kept sufficiently low that both the triple-coincidence rate and the double-coincidence rate between the coincidence output and the scintillator singles were negligible.

EFFECT OF THE SPECTROMETER APERTURE

The dimensions defining the angular aperture of the spectrometer were as follows: neutron-source to boron-radiator distance, 13.6 cm; distance from radiator to final scintillator defining aperture, 18.15 cm; radius of radiator, 1.105 cm; and radius of final defining aperture, 1.21 cm. These dimensions were such that the actual scattering angle θ, between an incoming neutron and an outgoing deuteron entering the final defining aperture

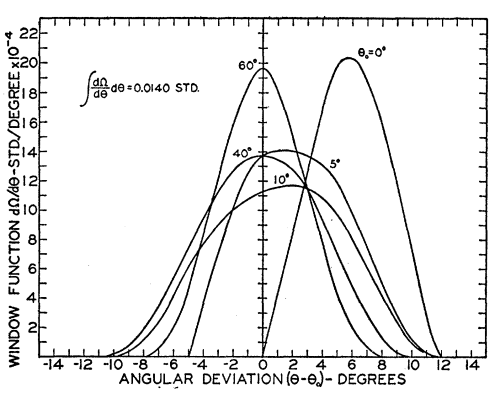

FIG. 2. Window function for counter-telescope spectrometer, showing the effect of finite angular aperture for various angular settings θ_0 of the spectrometer axis.

from some point of the radiator, could differ from the angular setting θ_0 between the spectrometer axis and the line from neutron source to center of radiator by as much as 12 degrees. This lack of perfect angular resolution had the effect of "smearing" the angular distribution so that the measured approximation, $\Delta\sigma/\Delta\Omega(\theta_0)$, to the differential cross section differed somewhat from the true value $d\sigma/d\Omega(\theta)$. Such a large angular aperture was, however, required in order to increase the spectrometer's sensitivity for the present low-yield measurements.

In order to take the smearing effect of the spectrometer aperture into account to close approximation, the "window function" $d\Omega/d\theta(\theta,\theta_0)$ was calculated to first order in the angular deviation $\theta-\theta_0$. Some of the results of the simple but arduous numerical calculations are shown in Fig. 2. Note that the total angular spread of the window function decreases as θ_0 increases. This is due to the fact that the radiator was kept parallel to the scintillation crystal and hence had a smaller projection perpendicular to the neutron direction as θ_0 increased. The fact that one side of the radiator was closer to the neutron source than the other for $\theta_0>0$ and, hence, had a relatively increased neutron flux was also taken into account in the calculation of the window function.

In terms of the window function $d\Omega/d\theta$, the smeared angular distribution is given by

$$\frac{\Delta\sigma}{\Delta\Omega}(\theta_0)=\frac{1}{\Delta\Omega}\int\frac{d\sigma}{d\Omega}(\theta)\frac{d\Omega}{d\theta}(\theta,\theta_0)d\theta, \qquad (1)$$

where $\Delta\Omega$ is the constant total solid angle of the spectrometer. In order to compare the experimental results with Butler's theoretical angular distributions, the theoretical center-of-mass differential cross sections were transformed to the laboratory system and then smeared numerically according to Eq. (1). The resulting smeared theoretical curves, as well as the experimental data, were then transformed back to the center-of-mass system to present the comparison.

Figure 3 shows, in the laboratory system, the theoretical differential-cross-section curves $d\sigma/d\Omega(\theta)$ and the smeared curves $\Delta\sigma/\Delta\Omega(\theta_0)$ calculated for the ground state reaction $B^{10}(n,d)Be^9$ for 14.1-Mev incident neutrons. The unsmeared curves for the three orbital angular momenta 0, 1, and 2 of the picked-up proton have been arbitrarily normalized to the same maximum value. Although the valleys are filled in somewhat and the peaks diminished, the angular locations of the maxima of the curves are not appreciably affected.

DATA AND EXPERIMENTAL PROCEDURE

Identification of the Deuterons from the Reaction $B^{10}(n,d)Be^9$

The data on the yield and energy of the reaction products were obtained as follows. With the boron radiator facing the spectrometer's active volume, bom-

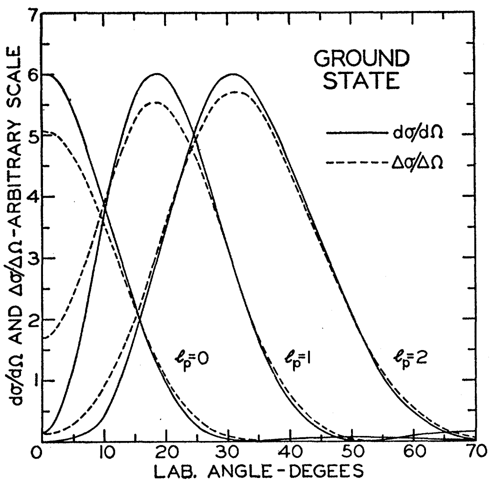

FIG. 3. Theoretical angular distributions for the ground-state $B^{10}(n,d)Be^9$ reaction (solid curves) and the corresponding distributions modified by the effect of finite angular resolution (dashed curves).

bardments were made with an integrated flux of 14.1-Mev neutrons of 1.30×10^9 neutrons/cm^2, and the pulse-height distribution of all charged reaction products which could be recorded for the given proportional-counter biases were recorded on the 18-channel pulse-height analyzer. Using the same integrated flux of neutrons, a bombardment was then made with the platinum blank facing the spectrometer in order to record the background due principally to disintegration of the gas filling of the first counter. This background was then subtracted to give the net pulse-height spectrum of reaction products from the boron radiator. Typical data are shown in Fig. 4 for various angle settings θ_0 of the spectrometer axis. The two peaks due to the (n,d) reaction to the ground and excited states of Be^9 are seen to stand out quite clearly with approximately the resolution to be expected in view of the thickness of the boron radiator—0.56 and 0.75 Mev for the ground- and excited-state deuterons, respectively. The variation of the pulse heights of the groups with θ_0 indicated in Fig. 4 is somewhat arbitrary, since for a given angle setting the scintillator amplifier gain was adjusted to set the deuteron groups comfortably inside the analyzer limits.

In order to determine the energy of the ground-state group of deuterons a thin (4.60 mg/cm^2) radiator of deuterated polyethylene 1.27 cm in diameter was mounted in place of the platinum blank and irradiated at $\theta_0=0$ to determine the pulse-height of the peak due to recoil deuterons of known (12.43-Mev) energy. The boron was then irradiated and the ground-state deuteron pulse-height similarly determined. Comparing the two peaks for five runs, assuming linearity of the NaI crystal, and correcting for radiator half-thickness and energy loss in the counter fillings gave 9.58 ± 0.18 Mev for the forward ground-state deuteron energy. This corresponds to a Q value for the $B^{10}(n,d)Be^9$ ground-state reaction of -4.48 ± 0.18 Mev, in good agreement with the value -4.360 Mev derived from known mass values.[13]

A similar comparison was carried out at $\theta_0=15$ degrees of the pulse heights of the ground-state and excited-state deuteron groups—this time with the platinum blank in order to make background subtractions. Assuming the Q value -4.360 Mev for the ground-state reaction, it was found that the energy of the excited-state group was 7.14 ± 0.12 Mev, corresponding to $Q=-6.85\pm0.12$ Mev and an excited energy of 2.49 Mev, again in good agreement with previously determined values.

It remained to determine the dE/dx values of the deuteron groups in order to identify them positively. This was done by making use of the fact that dE/dx was measured by the proportional counters of the coincidence telescope. A dE/dx comparison was first made between the known recoil deuterons from the deuterated polyethylene radiator and the presumed ground state $B^{10}(n,d)$ deuterons. The numbers of counts in each of the deuteron groups were determined as a function of the common bias of the two proportional-counter

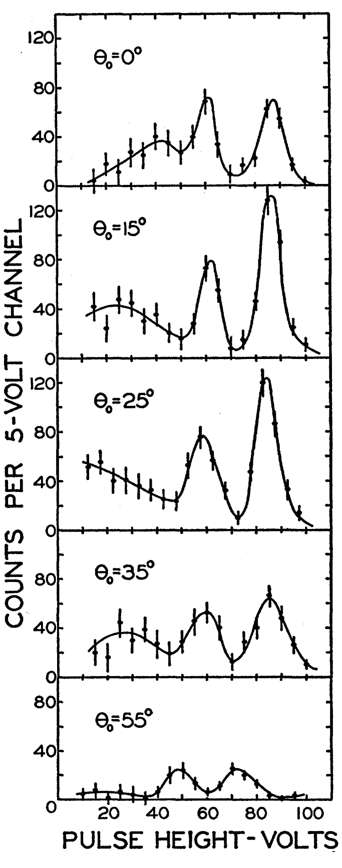

FIG. 4. Scintillator pulse-height distributions for the charged reaction products from the interaction of 14-Mev neutrons with B^{10}, for various spectrometer (laboratory) angles.

[13] Li, Whaling, Fowler, and Lauritsen, Phys. Rev. 83, 512 (1951).

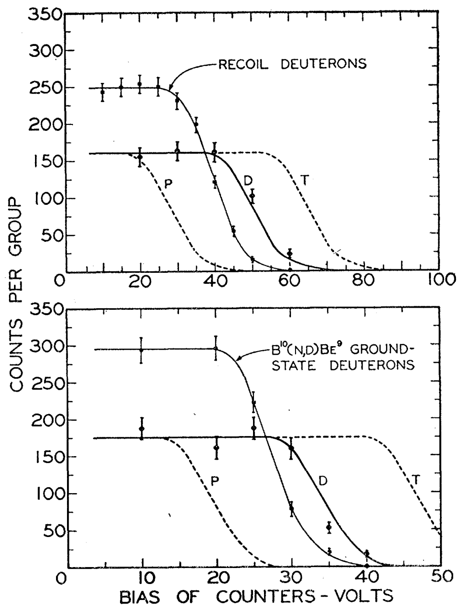

FIG. 5. dE/dx-bias curves used to identify the two principal charged-particle groups as deuterons. The upper curve in each graph corresponds to deuterons of known energy. The lower curves are *calculated* for the particles in question, assuming them to be either protons, deuterons, or tritons.

channels. The resulting bias curves, shown in the upper graph of Fig. 5, show well-defined plateaus. Given the shape of the recoil-deuteron bias curve, one can then calculate the corresponding shape which the bias curve of the lower-energy group should have if it were supposed to be due to protons, deuterons, or tritons. These calculated curves are also shown in the upper graph of Fig. 5, labeled *P*, *D*, and *T*, respectively. It is seen that the experimental points due to the 9.58-Mev group fall closely on the calculated deuteron curve, showing that they are indeed due to deuterons.

A similar comparison for the ground- and excited-state deuteron groups is illustrated in the lower graph of Fig. 5, showing that the excited-state (7.14-Mev) group was also composed of deuterons.

Measurement of the Differential Cross Sections

In order to determine the counts in the ground- and excited-state deuteron groups from data like that shown in Fig. 4, the continuum of counts in the pulse-height spectrum due to competing reactions was subtracted by smoothly interpolating under the peaks. The magnitude of this continuum varied with bias of the proportional counters, and the spectra shown in Fig. 4 represent the condition in which the counter bias was set just below that required to count all the ground-state deuterons.

The magnitude of the platinum-blank background can be inferred from the statistics shown on the points plotted in Fig. 4. Generally this background was about equal to the net boron yield at the lower end of the spectrum and decreased to almost zero at the upper end.

For each angle setting θ_0 of the spectrometer it was ascertained that the counter biases were set at a plateau value as illustrated in Fig. 5. In addition it was determined that no counts were being lost due to undue amounts of delay between the counter and scintillator channels of the coincidence circuit by measuring deuteron-peak counts as a function of the relative delay between the limits ± 0.3 microsecond and observing a well-defined plateau with a width of 0.3 microsecond.

RESULTS

The measured differential-cross-section results are plotted for the ground-state $B^{10}(n,d)Be^9$ reaction in Fig. 6. The errors shown on the experimental points were determined from the statistical spread of the various determinations for each angular setting and include errors due to counting statistics and an allowance for those made in subtracting the continua from the peaks of the pulse-height spectra. The differential-cross-section values have been transformed to the center-of-mass system and correspond to the laboratory angles: 0, 15, 25, 35, 45, 55, and 65 degrees. The (n,d) cross section for the forward hemisphere was obtained by integrating the dashed curve through the experimental points over the solid angle in the center-of-mass system between the angular limits zero and 90 degrees. The resulting integral has the value 21 ± 3 millibarns. The error in this number includes 10 percent due to lack of definiteness in the location of the flat tail, 3 percent due to the effects of smearing by the finite angular aperture, 2 percent in foil-weight determination, 2 percent in solid-angle determination, 4 percent in the flux determination, and 4 percent due to statistics.

The corresponding experimental points for the excited-state differential cross section, also transformed to

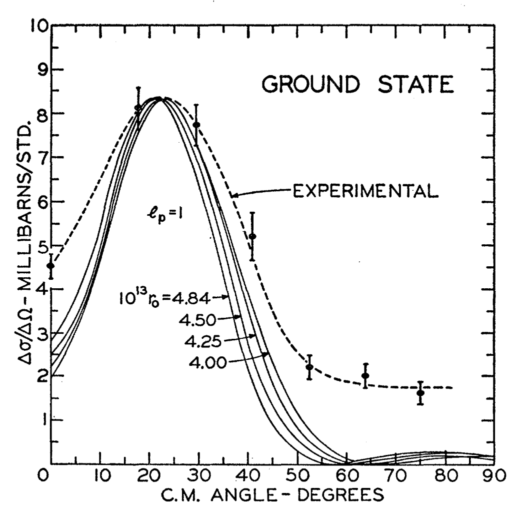

FIG. 6. Experimental and (smeared) theoretical angular distributions for the ground-state $B^{10}(n,d)Be^9$ reaction.

the center-of-mass system, are plotted in Fig. 7. The integrated cross section is 16±2 millibarns.

No group of deuterons corresponding to a state in Be^9 of 1.5-Mev excitation or thereabouts was observed. A differential cross section of as much as 0.4 mb/sterad would have been detected.

DISCUSSION OF RESULTS

When making spin and parity determinations from the angular distributions of (n,d) pickup reactions one is concerned primarily with comparing the observed locations of the forward maxima with those predicted by Butler's theory. As is well known, the angular locations of these maxima vary markedly with the orbital angular momentum l_p of the picked-up proton, leaving little doubt of the proper orbital angular momentum assignment. Following Butler,[9] the conservation of total angular momentum implies

$$\mathbf{l}_p+\mathbf{s}_p+\mathbf{j}=\mathbf{J}, \tag{2}$$

where $\mathbf{s}_p$ is the proton spin angular momentum, $\mathbf{j}$ is the angular momentum of the final nucleus, and $\mathbf{J}$ is the angular momentum of the initial nucleus.

In the case of the B^{10} ground state the spin is known to be 3 and the parity even. Since Be^9 in its ground state has spin 3/2 and odd parity, the value of l_p for the ground-state pickup reaction must be 1, 3, or 5. The cross section for the lowest value is much favored in magnitude, according to the theory, and one, therefore, expects the experimental angular distribution to be fitted by a theoretical curve corresponding to $l_p=1$. This is indeed seen to be the case in Fig. 6 in which are plotted both the experimental data and theoretical curves from Butler's equation (34) for various values of the parameter r_0, the nuclear radius plus the range of nuclear forces. All four (smeared) theoretical curves correspond to $l_p=1$ and have been normalized to the same maximum value as that of the experimental curve.

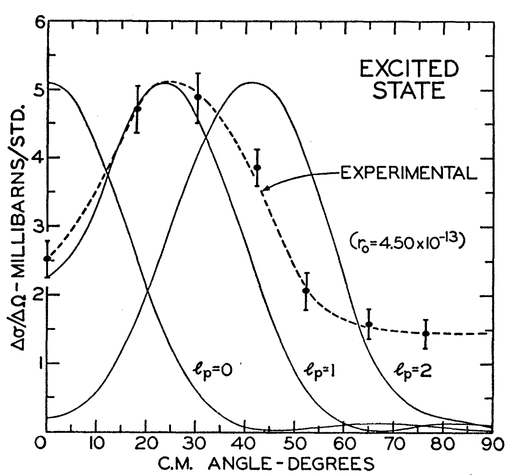

FIG. 7. Comparison of the experimental angular distribution for the excited-state deuteron group with the (smeared) theoretical curves corresponding to various values of the orbital angular momentum of the picked-up proton.

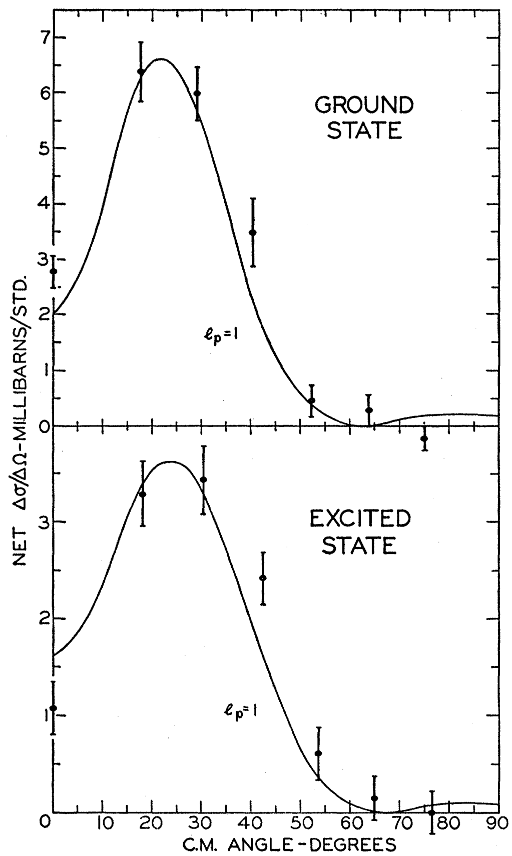

FIG. 8. Comparison with theory of experimental angular distributions after subtraction of isotropic components.

From the total cross section of B^{10} for 14-Mev neutrons[14] one finds $(\sigma/2\pi)^{\frac{1}{2}}=4.84\times10^{-13}$ cm, which one might expect to provide an upper limit for the parameter r_0. It is clear from the curves that the location of the maximum varies little with r_0. Close comparison, however, made it appear that the value 4.50×10^{-13} cm provided the best ground-state fit when an isotropic component equal to the asymptotic-tail value shown was subtracted. This value of r_0 was chosen for calculating the curves corresponding to the 2.43-Mev excited state of Be^9.

In order to study the unknown spin and parity of this excited state, theoretical curves were calculated for the l_p values 0, 1, and 2. A comparison of these curves with the experimental results is given in Fig. 7, where again the theoretical curves have been normalized to the same peak value as that of the experimental results. It is clear that the experimental results correspond to $l_p=1$. Therefore the parity of the 2.43-Mev excited state of Be^9 is odd, and its spin may have any of the values 3/2, 5/2, 7/2, or 9/2.

In both the ground-state and excited-state angular distributions an asymptotic tail of fairly large magnitude occurs, corresponding to an approximately iso-

[14] Coon, Graves, and Barschall, Phys. Rev. 88, 562 (1952).

tropic component of the differential cross section. It is reasonable to suppose that this is due to compound-nucleus formation, as distinct from the pickup process which proceeds without such amalgamation. The theoretical justification for subtracting such an isotopic component from the observed cross section in order to obtain a differential cross section corresponding to a "pure" pickup process is somewhat doubtful. However, the results so obtained by subtracting the asymptotes from the ground- and excited-state results are shown in Fig. 8. It is seen that the experimental points fall quite close to the theoretical curves, again plotted for $l_p=1$ and $r_0=4.50\times10^{-13}$ cm. The isotropic components subtracted amount to 11 and 9 millibarns, respectively, for the ground- and excited-state reactions.

Although the Butler analysis of the first excited state of Be^9 leaves its spin uncertain to within three units, it is significant that the spin value 1/2 for this state is excluded. Thus Be^9 provides the first exception in the sequence of odd light nuclei to the observation that the two lowest-lying levels form an inverted (3/2–1/2) doublet. This spin assignment provides evidence against the L–S coupling model for Be^9, since spin 1/2 is predicted for the first excited level in this case.[15] The experimental result is consistent with the nuclear model involving j-j or strong intermediate coupling[15] which predicts odd-parity levels of spins 7/2 and 5/2 following the spin-3/2 ground state. It is also consistent with the alpha-particle model which identifies the first excited state of Be^9 with one in which the Be^8 core is in its first state of rotational excitation,[16] with odd parity and spin 5/2.

COMPETING REACTIONS

From the pulse-height spectra of Fig. 4 it is clear that the $B^{10}(n,d)Be^9$ reaction was predominant, but one can see that other reactions did enter in the form of a continuous background spectrum beneath the (n,d) peaks. The proportional-counter dE/dx channels were provided with bias settings for both their lower and upper limits of pulse-height acceptance. In order to obtain some idea of the makeup of the continuum, observations at $\theta_0=15°$ were made with various upper- and lower-limit dE/dx settings in order to tell, by their variation with bias, which portions of the continuum were due to tritons, deuterons, and protons. The qualitative conclusions will be discussed in relation to the following possible competing reactions.

$B^{10}(n,\alpha)Li^7$, $Q=2.792$ Mev

All alpha particles produced by this reaction were appreciably degraded in the boron radiator and counter gas. Therefore no attempt was made to observe this reaction, and an upper-limit bias setting prevented any alpha-particle coincidences from registering, due to their large dE/dx values.

$B^{10}(n,t)Be^8$, $Q=0.232$ Mev

Tritons were found between an observed upper energy limit of about 12 Mev down to about 4.7 Mev which was the lowest energy observable, taking account of radiator half-thickness and counter-gas filling. The number of tritons increased with decreasing energy, and the differential cross section in the above energy interval was about 3 mb/sterad. An upper limit could be set on the reaction leading to the ground state of Be^8, giving tritons above 12 Mev. This limit was about 0.3 mb/sterad.

These observations are in agreement with the results of Perkin[17] who observed stars in nuclear plates from the $B^{10}(n,t)Be^8(2\alpha)$ reaction for bombarding neutrons of a continuous energy spectrum extending to 24 Mev. No ground-state reaction was found, and it was observed that the yield of stars increased with excitation of the Be^8 residual nucleus.

$B^{10}(n,dn)Be^8$, $Q=-6.025$ Mev and $B^{10}(n,d)Be^9$, $E_{ex}>2.43$ Mev

No continuum deuterons were observed with energies above about 7 Mev, while below this energy and above the lower limit of the spectrometer of 3.1 Mev, about 4 mb/sterad were observed, again increasing in number toward the lower energies.

The 3.1-Mev lower limit of the spectrometer corresponded to an upper limit on excitation of the Be^9 nucleus of about 7 Mev. However, the resolution for a group from the 6.8-Mev state found in high-energy proton inelastic scattering would have been so poor as to render it impossible to identify. The growth of the continuum toward the lower-energy limit is probably due to this state. It can be stated that no groups of deuterons occurred corresponding to Be^9 excitations of less than 5.5 Mev, other than the group corresponding to the 2.43-Mev level.

$B^{10}(n,p)Be^{10}$, $Q=0.227$ Mev

There was an approximately uniform distribution of protons between the energy limits 2.5 and 12.5 Mev amounting to about 3 mb/sterad. No attempt was made to observe protons from the reaction leading to the ground state of Be^{10}, since these would have been masked by recoil protons from small amounts of hydrogenous matter in the boron radiator.

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[15] D. R. Inglis, Revs. Modern Phys. **25**, 416 (1953).
[16] R. R. Haefner, Revs. Modern Phys. **23**, 228 (1951).
[17] J. L. Perkin, Phys. Rev. **81**, 892 (1951).