PHYSICAL REVIEW VOLUME 87, NUMBER 1 JULY 1, 1952

The Angular Distribution and Excitation Function of the Long-Range Protons from the $Be^9(d,p)Be^{10}$ Reaction*

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(Received November 29, 1951)

The angular distribution of the long-range protons from the deuteron bombardment of Be^9 has been investigated over the deuteron energy range from 1.0 to 2.2 Mev using a photographic technique. The excitation function has been measured from 0.55 to 2.95 Mev using a proportional counter. On the basis of a compound nucleus model, the fact that six terms are required to fit the observed distributions with a series of Legendre polynomials indicates the presence of overlapping levels of the compound nucleus in the region with both even and odd parities, and that both d and f deuterons enter into the reaction at these energies. There is, however, some evidence that the reaction proceeds in part by a stripping process with the transfer of a neutron with $l=1$ to the target nucleus. This stripping becomes relatively more important as the deuteron energy is increased. The excitation function shows evidence of broad, overlapping resonances.

I. INTRODUCTION

THE angular distribution of the reaction products from the deuteron bombardment of beryllium has been studied at The Johns Hopkins University using the magnetic bombarding chamber developed there.[1] Since these observations extended only up to deuteron energies of 880 kev, it was thought worth while to undertake the present investigation extending the observation of the angular distribution of the long-range protons from the reaction over the range from 1.0 to 2.2 Mev. It is hoped that these angular distributions, together with the previous data and an excitation curve which was run in the course of the present work, will provide a large body of experimental data whereby the analysis of the reaction leading to the production of the long-range protons may be carried on.

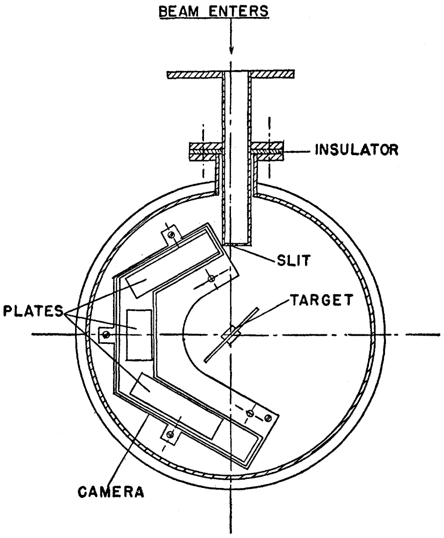

FIG. 1. Schematic diagram of the basic bombardment chamber.

II. EXPERIMENTAL PROCEDURE

Through the courtesy of Dr. Tuve and Dr. Heydenberg of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, the large, pressurized statitron at the DTM was used as a source of high energy deuterons. The basic target chamber used was that developed by Talbott and the Catholic University Group for their precise investigation of the lithium—two alpha-reaction.[2] This chamber is shown in Fig. 1. The deuteron beam enters through the slits and strikes the target at the center of the chamber. The target holder is mounted on a sylphon toggle and can be turned from outside the chamber. The removable box or camera, shown in position in the left side of the chamber, contains three plate holders arranged in a semicircle around the target and holding the plates at an angle of 45° to the plane of the incident beam. Windows in the side of the camera in front of each of the plate holders can be covered with various thicknesses of absorbing foils to discriminate against unwanted reaction products. The whole chamber is covered with a lucite lid and sealed with a Neoprene gasket.

When Be^9 is bombarded with deuterons, two groups of protons are produced, a long-range group with a Q-value of 4.58 Mev, and a short-range group with a Q-value of 1.20 Mev.[3] In addition short-range alphas, neutrons, and tritons are produced.[4] The following reactions also occur because of contamination of the target by deuterons from the beam, carbon from the pump oil, and oxygen that appears to be in the crystal structure of the beryllium:

$$D^2(d,p)T^3, \quad Q=3.98 \text{ Mev};$$
$$C^{12}(d,p)C^{13}, \quad Q=2.76 \text{ Mev};$$
$$O^{16}(d,p)O^{17}, \quad Q=1.95 \text{ Mev}.$$

Since in the present experiments only the long-range protons from $Be^9(d,p)Be^{10}$ were being examined, it was

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* Taken from a dissertation submitted to the faculty of the Graduate School of Arts and Sciences of the Catholic University of America in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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[1] I. Resnick and S. S. Hanna, Phys. Rev. **82**, 463 (1951).

[2] Talbott, Busala, and Weiffenbach, Phys. Rev. **82**, 1 (1951).

[3] W. W. Buechner and E. N. Strait, Phys. Rev. **76**, 1547 (1949).

[4] W. F. Hornyak and T. Lauritsen, Revs. Modern Phys. **20**, 191 (1948).

necessary to insert absorbers in the various windows of such thickness that only the desired protons would reach the plates at each angle. The ranges in aluminum were computed for each group of protons and graphs drawn showing the ranges of the different proton groups *versus* angle for each of the energies studied. From these graphs the amount of absorbing foil required at each camera window at each energy could be readily determined. To check the computed absorber thicknesses, an auxiliary camera was devised as shown in Fig. 2. This camera holds a single plate at an angle of 5° to the plane of the incident deuteron beam giving the particles a long range in the emulsion and making possible their identification by the range energy relationships. This camera may be placed in three positions corresponding to the three windows of the large camera. An exposure was first made with a thin window in the auxiliary camera and the particle spectrum observed by plotting a histogram as shown in Fig. 3. A check was usually run with the calculated absorber thickness in the window of the auxiliary camera to insure the fact that only the desired protons were penetrating to the plate.

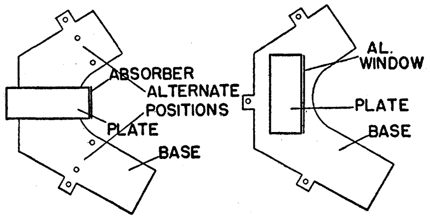

FIG. 2. Schematic diagram of the auxiliary cameras. The camera on the left was used to calibrate the absorbing foils. The camera on the right covered the blind spots of the large camera.

Since the camera used by Talbott's group did not cover the angles between 50° and 80°, another auxiliary camera was devised. This is also shown in Fig. 2 and holds a single plate at angle of 45° to the plane of the incident beam and covers the angles between 65° and 115°.

Towards the end of the work it became evident that the distribution at very small angles was of special importance in determining the coefficients of the series fitted to the angular distributions. The forward plate holder of the large camera was moved to the forward position and by allowing the protons to penetrate the tungsten target backing measurements were made at angles down to 0°. The combination of cameras used enabled the author to take measurements of the relative yield at close intervals from 0° to 160° with enough common points among the cameras to insure consistency.

The targets used were thin films of beryllium evaporated on 1-mil tungsten foils. The target alignment was checked by replacing the target with a 1-mil foil painted with a thin coat of zinc-sulfide in shellac. The zinc-sulfide fluoresced strongly when hit by the deuteron beam and the target holder was adjusted until the point of impact of the beam on the target remained the same on rotation of the target. This assured that the beam was hitting the target at the geometrical center of the chamber. This alignment was also checked by observing the plates for perpendicularity of the tracks at angles corresponding to the normals to the plates.

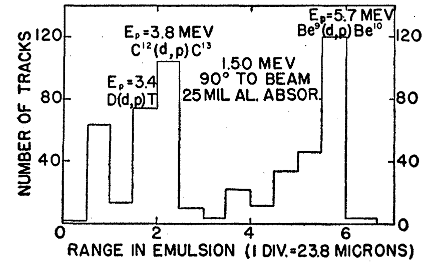

FIG. 3. Typical histogram obtained using the calibrating camera. The various proton groups are indicated. $E_d = 1.50$ Mev.

Eastman NTA plates with an emulsion 25 microns thick were used to record the proton tracks. Some difficulty was experienced with the plates peeling in the evacuated chamber during the early test runs; but this trouble was overcome by painting the edges of the plates with a thin coat of shellac before putting them into the chamber. To gauge bombardment time so as to secure optimum track density for counting purposes, a current integrator utilizing a Los Alamos type circuit was used as an exposure meter.

The plates were scanned using a binocular microscope with an adjustable mechanical stage. From the geometry of the bombardment chamber stage settings corresponding to the desired angles in the laboratory system of coordinates were worked out. Using a Whipple disk and a 100× magnification, a square millimeter of the plate was defined at each desired angle and the number of proton tracks appearing in this area counted. Frequent repetition of counts showed that the error introduced by the counting was less than 1 percent. Track density was kept fairly low to facilitate accurate counting and the statistics improved by taking several runs with each camera at each energy. The plates from the calibrating camera were scanned with a magnification of 430× and the number of tracks of each length observed in a swath 0.1 mm wide down the center of the plate were plotted on a histogram as shown in Fig. 3.

III. DATA AND ERRORS

The raw data obtained from an examination of the plates was transformed from the laboratory coordinate system to the center-of-mass system using the transformations derived by Heydenberg and Inglis.[5] A geometrical correction was also necessary since, as one moves along the plate away from the normal, both the

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[5] N. P. Heydenberg and D. R. Inglis, Phys. Rev. 73, 230 (1948).

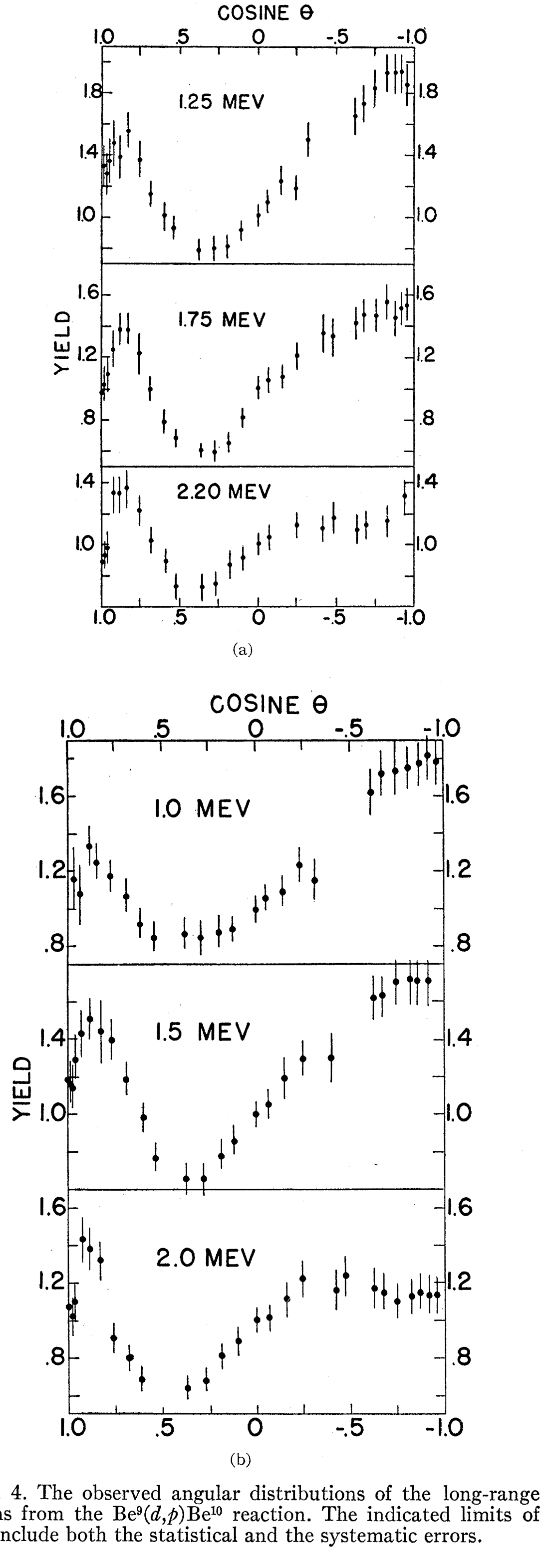

FIG. 4. The observed angular distributions of the long-range protons from the $Be^9(d,p)Be^{10}$ reaction. The indicated limits of error include both the statistical and the systematic errors.

distance from target to plate and the solid angle subtended by a unit area of the plate increase. Both of these corrections are included in an additional correction factor $1/\cos^3\phi$, where ϕ is the angle between the normal and the angle at which the count is made.

The observed angular distributions at the 6 energies studied are shown corrected for geometry and transformed to the center-of-mass system in Fig. 4. The indicated error included the following statistical and systematic errors:

(1) Statistical error estimated as equal to the square root of the number of tracks counted.

(2) The error introduced by multiple, small-angle, Coulomb scattering at the absorbing foils.[6] This tends to spread the proton beam so that some protons originally headed for one section of the plate are scattered into another section. From the number of tracks deviating significantly from the prevalent track direction at each angle, 2 percent seems a reasonable estimate of the error from this source.

(3) Possible displacement of the target from the geometrical center of the chamber is estimated as the source of an error of 1 percent.

(4) Another 1 percent is allowed for possible movement of the emulsions and for the effect of recoil protons caused by the neutron flux present. This last effect is very small as was checked by placing enough absorber in the camera windows to keep out all protons from the target and observing plates exposed in this way for tracks.

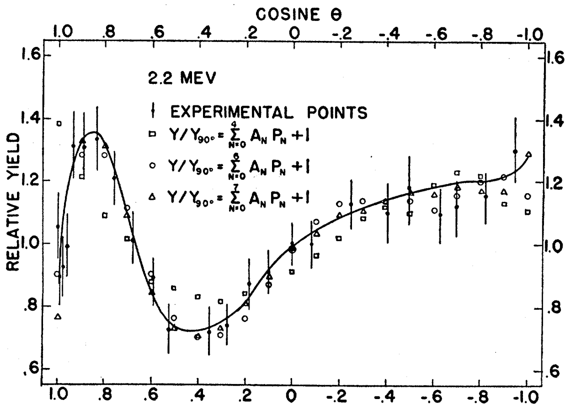

FIG. 5. Typical fit of an experimentally observed distribution with a series of Legendre polynomials, showing the effect on the fit of the addition of further terms in the series. $E_d=2.20$ Mev.

(5) A final 1 percent was allowed for errors in counting.

IV. NUMERICAL TREATMENT

In order to obtain a quantative picture of the complexity of the observed angular distributions, these experimentally determined distributions have been expanded in a series in terms of the ordinary Legendre polynomials. This series has the form

$$Y_\theta/Y_{90°}(\cos\theta)=1+\sum_{l=0}^{n} A_l P_l(\cos\theta),$$

where

$$A_l=\tfrac{1}{2}(2l+1)\int_{-1}^{+1} Y_\theta/Y_{90°}(\cos\theta)P_l(\cos\theta)d\cos\theta.$$

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[6] Breit, Thaxton, and Eisenbud, Phys. Rev. 55, 1013 (1938).

The coefficients have been evaluated by a process of numerical integration using Simpson's rule. An interval of $\cos\theta = 0.1$ was taken between the adjacent points to which the series was fitted. This required that the value of $Y_\theta/Y_{90°}$ be known at 21 equally spaced points between $\cos\theta = 1$ and $\cos\theta = -1$. These values were obtained by drawing a smooth curve through the experimental points and extending it by eye to $\cos\theta = -1$. Figure 5 shows the increasingly better fit to the observed angular distributions obtained by adding further terms in the series of polynomials. The series terminating with the fourth Legendre polynomial does not fit the observed complexity. The series terminating with the sixth fits within the experimental error; and the series terminating with the seventh gives a close fit to the smooth curve. Since a fit better than the experimental points themselves is not meaningful, it seems best to say that a series of at least six Legendre polynomials is required to fit the observed angular distributions. Table I shows the coefficients of the series fitted to the observed distributions at the energies studied. The energy dependence of these coefficients is presented in a graph in Fig. 6.

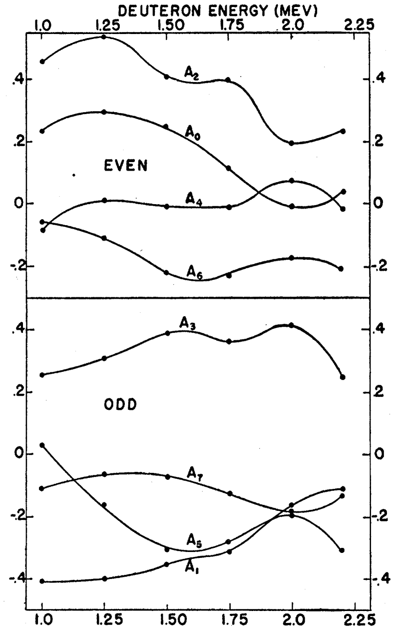

FIG. 6. The energy dependence of the coefficients of the series of Legendre polynomials fitted to the observed data.

TABLE I. The coefficients of the series of Legendre polynomials fitted to the observed angular distributions at the various energies studied.

$$Y_\theta/Y_{90°}(\cos\theta) = 1 + \sum_{l=0}^{n} A_l P_l(\cos\theta).$$

E	A_0	A_1	A_2	A_3	A_4	A_5	A_6	A_7
1.00	0.23	−0.41	0.45	0.25	−0.08	−0.03	−0.06	−0.11
1.25	0.30	−0.41	0.54	0.30	0.02	−0.15	−0.10	−0.06
1.50	0.24	−0.35	0.41	0.38	−0.01	−0.30	−0.22	−0.07
1.75	0.12	−0.32	0.40	0.36	−0.02	−0.29	−0.23	−0.13
2.00	−0.01	−0.16	0.19	0.42	0.09	−0.19	−0.17	−0.19
2.20	0.04	−0.11	0.23	0.25	−0.03	−0.27	−0.21	−0.13

V. EXCITATION FUNCTION

The excitation function for the long-range protons was measured over the energy range from 0.55 to 2.95 Mev. This measurement was made with a proportional counter to permit a more rapid and complete survey of the region of interest. The experimental arrangement for making this measurement is shown in Fig. 7. Deuterons entered the chamber, which was insulated from ground and served as a Faraday cage, through the slit system shown at the top of the diagram. A Be-on-tungsten target was placed in a holder at an angle of 45° to the direction of the deuteron beam. An auxiliary quartz disk could be substituted for the target holder to insure alignment of the beam in the center of the chamber. The reaction products emerging through a thin window in the side of the bombardment chamber were passed through a series of calibrated aluminum foils which cut off all but the long-range protons. These were allowed to pass through a small window into a proportional counter filled with argon at 5-cm pressure and mounted at 90° to the direction of the incoming deuteron beam. The protons were allowed to pass completely through the counter to obtain pulses of uniform strength. The counter pulses were passed through a preamplifier, amplifier, and discriminator into a scaler. All these circuit elements were of conventional design. A Los Alamos type current integrator was used to monitor the reaction; and considerable difficulty was experienced in getting this integrator to behave in a satisfactory manner. The trouble was apparently caused by secondary emission at the slits

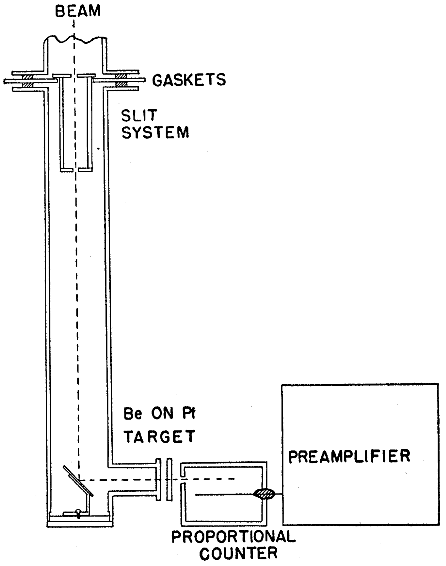

FIG. 7. The experimental arrangement for measuring the excitation function. Note that the slit system is grounded and the rest of the chamber insulated from ground and connected to the current integrator.

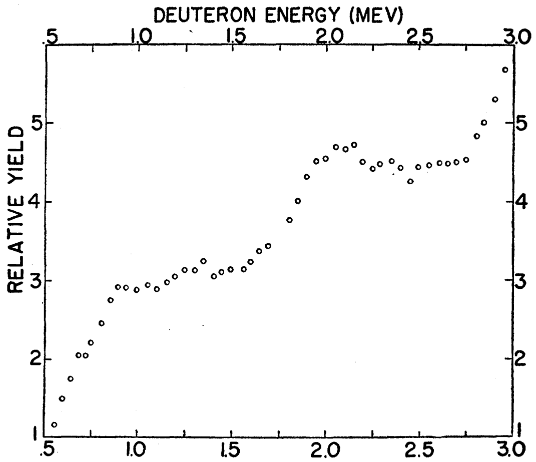

FIG. 8. Observed excitation function for the long-range protons from the $Be^9(d,p)Be^{10}$ reaction. Observations were made at 90° to the incident beam in the laboratory coordinate system.

and by leakage in the integrator circuit. The latter difficulty was overcome by using an air dryer in the bombardment room, and the secondary emission obviated by modification of the slit system. Observations were made at intervals of 50 kev over the range studied. In Fig. 8, the number of protons observed for a fixed amount of beam current is plotted as a function of the deuteron energy.

VI. DISCUSSION

While the complete theoretical interpretation of these angular distributions is beyond the scope of the present paper, there are certain general features of the experimental results that are worthy of note. Heretofore angular distributions in this energy region have been interpreted completely in terms of compound nucleus formation. If this model is used in the discussion of the present work, as the predominance of proton emission in the backward direction at lower energies would seem to indicate, then the certain appearance of terms as high as P_6 in the series fitted to the experimental data would mean that both *d* and *f* deuterons take part in the reaction leading to the emission of the long range protons. The appearance of both the odd and even polynomials would indicate the presence of at least two states of the compound nucleus with opposite parity in this energy region.[7] This is in accord with the complexity of the angular distributions observed for the same reaction at lower energies.[1]

Butler,[8] however, has been quite successful in explaining angular distributions resulting from (d,p) reactions in terms of a stripping process whereby the neutron is stripped from the deuteron as it passes the target nucleus. While Butler's theory was formulated for cases where the incident deuterons had energies between 7 and 15 Mev, he feels that the essential features of the theory will be preserved even at lower energies. The peaks observed at small forward angles in the present work are similar to the forward peaks predicted by Butler on the basis of the stripping theory. Dr. Leo Diesendruck has been kind enough to extrapolate the Butler theory to our energies, and has found that the position of the observed forward peaks agrees with that predicted by the stripping theory for the transfer of a neutron with $l=1$ to the target nucleus. This forward peak is just beginning to appear at 880 kev, the highest deuteron energy studied by Resnick and Hanna,[1] and becomes relatively more important as the energy of the incident deuterons is increased. At the same time the emission of protons in the backward direction becomes less predominant. This would seem to indicate that in this range of energies, both the stripping process and compound nucleus formation are operative; and that the stripping process gradually assumes a more dominant role as the deuteron energy is increased. It is hoped that it will be possible to subtract the effect of the stripping process from the total distribution, and to thus arrive at distributions that may be more simply explained on the basis of the compound nucleus theory. Dr. Diesendruck has undertaken this calculation, and results should be forthcoming shortly.

The generally complicated nature of the excitation curve is indicative of broad, overlapping resonances in the region studied. The small step at 0.7 Mev agrees with the phenomenon previously observed at this energy,[1] although the anomaly is within the error of the experiment. Since the excitation curve was taken at 90° in the lab coordinate system, it should show very little contribution from the stripping process and should be of use mainly in the interpretation of the residual distributions on the basis of the compound nucleus model.

The author is grateful to Dr. F. Leo Talbott for advice and direction, to Dr. Leo Diesendruck and Dr. S. S. Hanna for helpful discussions, and especially to Dr. N. P. Heydenberg and Mr. Charles Little of the DTM for invaluable assistance in the operation of the statitron.

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[7] See L. Diesendruck, thesis (Johns Hopkins University, 1949).

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