

ANGULAR DISTRIBUTION OF LONG RANGE  
PROTONS FROM THE  $\text{Be}^9(d, p)\text{Be}^{10}$  REACTION

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**Synopsis**

With the equipment described in the preceding paper the angular distribution has been measured of long range protons from the  $\text{Be}^9(d, p)\text{Be}^{10}$  reaction at a deuteron bombarding energy of 470 keV. The distribution shows a pronounced maximum in backward direction. Series expansion of the distribution into spherical harmonics is shown to be simple, terms containing  $P_4(\cos \theta)$  or higher being negligible. A short discussion is given of the theoretical implications of the observed distribution.

§ 1. *Introduction.* The  $\text{Be}^9(d, p)\text{Be}^{10}$  ground-state transition was chosen as a suitable reaction to test the equipment for the measurement of angular distributions described in the previous paper<sup>1)</sup>.

Several reasons can be given for this choice:

a) the  $Q$ -values for this reaction and for competing  $\text{Be} + d$  reactions have been measured accurately<sup>2)</sup>, which makes it easy to assign the observed particle groups. The assignment is further simplified by the fact that beryllium has only one stable isotope ( $\text{Be}^9$ );

b) at a deuteron bombarding energy of 470 keV the range of protons from the  $\text{Be}^9(d, p)\text{Be}^{10}$  ground-state transition can be expected to be well different from that of particles from competing reactions or from that of any conceivable contaminant groups;

c) even at low deuteron energies the yield of the  $\text{Be}^9(d, p)\text{Be}^{10}$  reaction can be expected to be sufficient for the present measurements because of the low atomic number of beryllium.

In § 2 of this paper details are given of the experimental procedure.

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When this investigation was started no previous measurements had been published of the angular distribution of the  $\text{Be}^9(d, p)\text{Be}^{10}$  reaction. During the course of the present experiments a paper appeared by Resnick and Hanna<sup>3)</sup> on the same subject. In § 3 of this paper the results of the present investigation are compared to theirs and it is shown that good agreement exists. In the same paragraph an expansion of the observed distribution into spherical harmonics is presented showing rapid convergence.

In § 4 some theoretical considerations are given regarding the observed distribution. In particular it is shown that no agreement exists with the angular distributions derived by Butler<sup>4)</sup> for the stripping process. This is not surprising since the theory is restricted to deuteron energies large compared to the potential barrier of the initial nucleus which condition is certainly not fulfilled in our experiments.

§ 2. *Experimental procedure.* General features of the experimental arrangement are given in the previous paper<sup>1)</sup>.

Beryllium targets were prepared by evaporation of beryllium metal in vacuum onto thin aluminium foils. To this purpose boat-shaped strips of molybdenum containing small chips of the beryllium metal were heated electrically. Two targets have been used with thicknesses of  $0.027 \text{ mg/cm}^2$  and  $0.37 \text{ mg/cm}^2$  corresponding to an energy loss for 470 keV deuterons of 16 keV and 255 keV. The energy loss has been calculated from Warsaws data<sup>5)</sup>, taking into account the fact that the deuteron beam hits the target under an angle of  $45^\circ$ . It was found difficult to prepare still thicker targets by evaporation because then the beryllium is apt to scale off in small flakes from the aluminium backing.

Nuclear emulsions were used with a thickness of  $100 \mu$ . Also  $50 \mu$  emulsions have been tried but it was found that then an appreciable number of long-range protons from the reaction  $\text{Be}^9(d, p)\text{Be}^{10}$  (maximum range in forward direction about  $150 \mu$ ) scattered over small angles in the emulsion have their endpoint in the glass backing rather than in the emulsion. For particles incident on the surface of the emulsion at  $15^\circ$ , as in these experiments, it seems a good rule to choose an emulsion with a thickness at least 40% of the maximum tracklength.

In Fig. 1 a range analysis is presented of 930 tracks of particles

leaving the target in forward direction. The thin beryllium target mentioned above was exposed to  $300 \mu\text{C}$  of 470 keV deuterons. Tracklength was measured with a total magnification of 250 for tracks longer than  $21 \mu$  and a magnification of 1350 for shorter tracks.

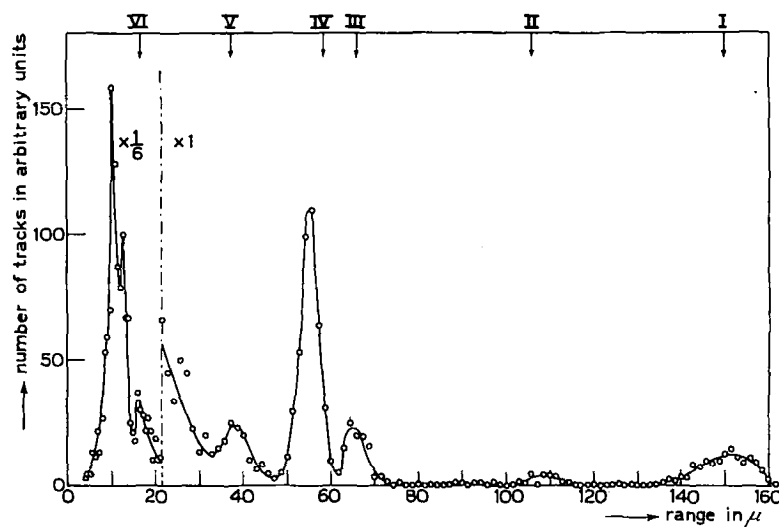


Fig. 1. Range analysis in nuclear emulsion of  $\text{Be} + d$  reaction products at  $E_d = 470$  keV. Groups I, II, III, V and VI are protongroups, group IV a tritongroup. They are assigned to the following reactions: I  $\text{Be}^9(d, p)\text{Be}^{10}$ , II  $\text{D}(d, p)\text{T}$ , III  $\text{C}^{12}(d, p)\text{C}^{13}$ , IV  $\text{Be}^9(d, t)\text{Be}^8$ , V  $\text{O}^{16}(d, p)\text{O}^{17}$ , VI  $\text{Be}^9(d, p)\text{Be}^{10*}$ . The arrows indicate ranges calculated from  $Q$ -values for the groups indicated above.

The six groups in Fig. 1 numbered I through VI can be attributed to the following reactions:

I. $\text{Be}^9(d, p)\text{Be}^{10}$	$Q = 4.585 \pm 0.008 \text{ MeV},$
II. $\text{D}(d, p)\text{T}$	$Q = 4.030 \pm 0.006 \text{ MeV},$
III. $\text{C}^{12}(d, p)\text{C}^{13}$	$Q = 2.716 \pm 0.005 \text{ MeV},$
IV. $\text{Be}^9(d, t)\text{Be}^{10}$	$Q = 4.597 \pm 0.013 \text{ MeV},$
V. $\text{O}^{16}(d, p)\text{O}^{17}$	$Q = 1.917 \pm 0.005 \text{ MeV},$
VI. $\text{Be}^9(d, p)\text{Be}^{10*}$	$Q = 1.201 \pm 0.007 \text{ MeV}.$

The  $Q$ -values quoted have all been measured <sup>2)</sup> by Buechner's group at the M.I.T., Cambridge (Mass.). Groups III and V originate from unavoidable contamination layers on the target. Group II is caused by the fact that during long bombardments an ap-

preciable quantity of deuterium is shot into the target. Besides these six groups four tracks were found in the scanned area of about  $220\ \mu$  range. They can be assigned to the  $C^{13}(d, p)C^{14}$  reaction ( $Q = 5.948 \pm 0.008\ \text{MeV}$  <sup>2)</sup>), the  $C^{13}$  being part (1.1%) of the natural carbon contamination on the target. The intensive group with ranges between  $4\ \mu$  and  $14\ \mu$  consists chiefly of alpha-particles from the reactions  $Be^9(d, \alpha)Li^7$  ( $Q = 7.150 \pm 0.008\ \text{MeV}$  <sup>2)</sup>) and  $Be^9(d, \alpha)Li^{7*}$  ( $Q = 6.668 \pm 0.007\ \text{MeV}$  <sup>2)</sup>), but it probably also contains a certain number of protons from the  $O^{16}(d, p)O^{17*}$  reaction ( $Q = 1.049 \pm 0.007\ \text{MeV}$  <sup>6)</sup>). The resolving power of the present range measurements is not sufficient to separate these three groups. Finally the continuum of tracks with ranges between  $20\ \mu$  and  $39\ \mu$  must be attributed <sup>3)</sup> to tritons from the three-body break-up  $Be^9(d, t)2\alpha$ .

The assignment of the six groups I through VI has been performed by computing the ranges as indicated in the previous paper<sup>1)</sup>. These calculated ranges are shown by arrows in Fig. 1. It is seen that the agreement between measured and calculated ranges is satisfactory.

The intensity of group I in Fig. 1 seems rather low e.g. compared to that of group IV. Actually the total yield (integrated over solid angle) for these two groups is very nearly the same. It must be kept in mind however that the angular distribution of group I shows a minimum in the forward direction (see Fig. 2).

After the preliminary exposure from which the range analysis of Fig. 1 was obtained the thick beryllium target of  $0.37\ \text{mg/cm}^2$  was bombarded with  $700\ \mu\text{C}$  of  $470\ \text{keV}$  deuterons from which exposure a complete angular distribution was obtained. Because of the energy loss of deuterons in the target the "effective" bombarding energy (= average energy of reacting deuterons) is calculated to be only  $400\ \text{keV}$  taking into account the energy dependence of the total yield of the  $Be^9(d, p)Be^{10}$  reaction <sup>3)</sup>. At least 1000 tracks of long range protons from the  $Be^9(d, p)Be^{10}$  reaction (group I in Fig. 1) were counted on each plate. A microscope magnification of 1000 was used. Plates were scanned in swaths  $15\ \text{mm}$  long and of  $29\ \mu$  width perpendicular to the direction of the incident particles (parallel to the axis of the plate-holder). The distance between adjacent swaths was  $0.1\ \text{mm}$ . The total number of swaths counted on one plate varied from 5 to 43.

The angular resolution obtained in this way, about  $3^\circ$ , is determined primarily by the width of the beam hitting the target (1.5 mm). For the plate detecting protons ejected in the forward direction the angular resolution is determined also by the height of the beam (5 mm). This plate was counted in swaths parallel to the long side. The angular resolution is here  $6^\circ$ .

The angular distribution thus obtained is given in Fig. 2. A small correction is included for variable distance from the center of the target to the center of the counted area on a plate. The distribution has been transformed into the center of mass system.

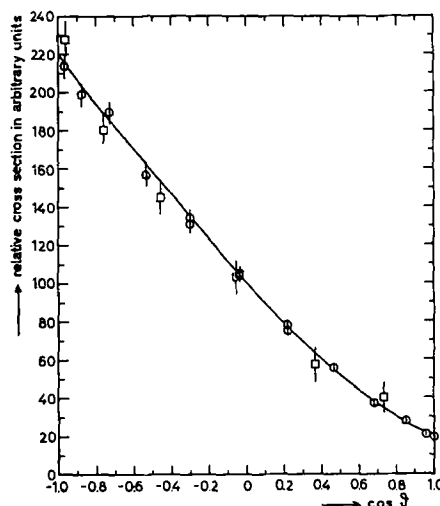


Fig. 2. Angular distribution of long range protons from the  $\text{Be}^9(d, p)\text{Be}^{10}$  reaction in center of mass system at an effective bombarding energy of  $E_d = 400$  keV. Circles (O) correspond to the data of the present experiment, quadrangles (□) denote points measured by Resnick and Hanna<sup>3)</sup> at a deuteron bombarding energy of  $E_d = 400$  keV. Their yield has been normalized so as to obtain the best fit with the present measurements. The curve has been drawn according to the expression:

$$I(\theta) = a_0(1 - 0.95 P_1 + 0.10 P_2 + 0.03 P_3).$$

The errors indicated are only statistical errors.

The distribution has not been plotted in absolute measure (barns/steradian) because the target was considered too thick, causing a rather large uncertainty in effective deuteron energy. Because the total cross-section is a steeply rising function of

deuteron energy the corresponding uncertainty in cross-section would also be large. The thickness of the target however does not seriously affect the shape of the distribution in relative measure because the shape varies only slowly with deuteron energy. At the moment measurements are in progress of  $\text{Be}^9(d, p)\text{Be}^{10}$  angular distributions from thin targets at deuteron bombarding energies of 300 keV, 450 keV and 600 keV. Absolute yields will be presented shortly from these measurements.

§ 3. *Discussion of results.* In Fig. 2 also the results obtained by Resnick and Hanna<sup>3)</sup> at 400 keV deuteron bombarding energy have been plotted. Their yield has been normalized so as to obtain the best fit with the present measurements. It is seen that there is agreement within the statistical errors indicated in Fig. 2.

The measured distribution may be expanded into spherical harmonics:  $I(\vartheta) = \sum_n a_n P_n(\cos \vartheta)$ . The coefficients  $a_n$  were computed by numerical integration from:  $a_n = \frac{1}{2}(2n+1) \int_{-1}^{+1} I(\vartheta) P_n(\cos \vartheta) d(\cos \vartheta)$ . The result is given by:

$$I(\vartheta) = a_0 \{1 - 0.95 P_1(\cos \vartheta) + 0.10 P_2(\cos \vartheta) + 0.03 P_3(\cos \vartheta)\}. \quad (1)$$

The coefficients  $a_4$ ,  $a_5$  and  $a_6$  were also computed but they are smaller than 3% of  $a_0$  and were neglected. It is seen that the series thus obtained converges rapidly. The curve drawn in Fig. 2 has been plotted according to expression (1).

§ 4. *Comparison with stripping theory.* The most remarkable characteristics of the observed angular distribution are its strong anisotropy and its pronounced asymmetry in respect to the 90° plane perpendicular to the incoming beam.

The distribution would be isotropic if only deuterons with zero orbital momentum would participate in the reaction. It can be computed however that the penetrability of the  $\text{Be}^9$  Coulomb barrier for  $P$ -deuterons of 400 keV is not negligible. It is still about 5% of that for  $S$ -deuterons. This makes it understandable that anisotropic distributions are found even for deuteron energies as low as 400 keV.

Symmetry in respect to the 90° plane would be expected if only one level of the compound nucleus is excited or if more levels

are excited all of the same parity. Asymmetric distributions are caused by interference from at least two levels of different parity in the compound nucleus. It is difficult to make more specific predictions about the angular distribution if nothing is known about positions, spins and parities of the compound nucleus  $\text{B}^{11}$ . By deuteron capture this nucleus is excited to about 16 MeV. In general it may be expected that levels in this region are close and broad. Experimentally only a small anomaly in the yield at  $90^\circ$  of long range protons has been found by Resnick and Hanna<sup>3)</sup> at  $E_d = 0.7$  MeV.

It is not certain however that a proper compound nucleus is formed. An alternative mechanism is the Phillips–Oppenheimer or stripping process, where the deuteron as a whole does not enter the nucleus. A successful theory of angular distributions based on the stripping process has been given by Butler<sup>4)</sup>. The applicability of his theory is limited to high deuteron energies because Coulomb interaction between nucleus and in- and outgoing particles is neglected.

Notwithstanding the fact that the deuteron bombarding energy in the present experiment (0.4 MeV) was well below the Coulomb barrier (1.8 MeV for  $\text{Be}^9$ ) it was thought worthwhile to apply Butlers stripping theory to the  $\text{Be}^9(d, p)\text{Be}^{10}$  reaction. His formula (34) becomes fairly simple if it is kept in mind that the neutron produced by deuteron break-up outside the nucleus enters the nucleus with orbital momentum  $l_n = 1$ . This follows from the fact that  $\text{Be}^9$  has spin  $J = \frac{3}{2}$ , odd, while  $\text{Be}^{10}$  has spin  $J = 0$  and even parity. The angular distribution computed from Butlers formula (34) does not agree with the present experiment. It shows a maximum in forward and a minimum in backward directions with  $I(0^\circ)/I(180^\circ) = 4$ . In the present experiment this ratio is 0.09. Of course this bad agreement is not surprising because the neglect of Coulomb interaction is not justified at low deuteron bombarding energies.

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