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ANGULAR DEPENDENCE AND YIELD OF THE Be^9(d, p) Be^{10} AND Be^9(d, t) Be^8 REACTIONS

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Synopsis

Differential cross-sections have been measured of the $Be^9(d, p)Be^{10}$ and $Be^9(d, t)Be^8$ ground-state transitions at five deuteron energies between 0.30 MeV and 0.62 MeV. The proton angular distributions can be developed into series of Legendre polynomials of which the highest term is a_4P_4 while the developments of the triton distributions above $E_d = 0.45$ MeV need also the terms a_5P_5 and a_6P_6. The total cross-sections of the two reactions are equal within the experimental error below $E_d = 0.45$ MeV while above this energy the $Be^9(d, p)Be^{10}$ reaction predominates.

§ 1. *Introduction.* In a previous paper [1]) the angular distribution has been published of protons from the $Be^9(d, p)Be^{10}$ ground-state transition at an effective deuteron energy of 0.4 MeV. The target used in this experiment was too thick (260 keV) to allow accurate determinations of differential and total cross-sections. Those measurements have now been extended to four more deuteron energies between 0.30 MeV and 0.62 MeV making use of a thin target.

Also tritons have been counted originating from the $Be^9(d, t)Be^8$ ground-state transition. Thus in all five angular distributions can be presented for each reaction, one from the thick target and four from the thin target bombardments. Differential and total cross-sections have been computed from the thin target measurements.

The angular dependence of both reactions mentioned above has also been investigated by Resnick and Hanna [2]) at five deuteron energies between 0.30 MeV and 0.88 MeV. No data have been published on the absolute yields of these reactions at deuteron energies comparable with those of the present experiment.

§ 2. *Experimental procedure.* Details of the experimental arrangement have been given in previous papers [3]) [1]). The thin target was prepared by evaporation in vacuum onto a 7 μ aluminium backing.

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The thickness (70 $\mu g/cm^2$) corresponded to a deuteron energy loss diminishing from 54 keV at $E_d = 0.32$ MeV to 39 keV at $E_d = 0.64$ MeV. These energy losses have been computed for a 45° angle of incidence of the deuteron beam on the target. For a thin target the effective deuteron energy [1]) can be taken equal to the energy of incident deuterons diminished by half the target thickness in kilovolts. In the four bombardments performed the effective deuteron energies amounted to 0.295 MeV, 0.45 MeV, 0.52 MeV and 0.62 MeV. The total deuteron charge collected on the target during these bombardments amounted respectively to 2450 microCoulomb (μC), 1330 μC, 530 μC and 425 μC. These values have already been corrected for the contributions of H_2^+-ions to the mass two beam [4]).

A range analysis of reaction products from a Be + d bombardment has been presented previously [1]). It shows that the average range of protons from the $Be^9(d, p)Be^{10}$ reaction is considerably longer than that of any other particle group, which simplifies the counting of the proton tracks. It is more difficult to count the tritons from the $Be^9(d, t)Be^8$ reaction because their average range in the emulsion does not differ much from that of protons from the $C^{12}(d,p)C^{13}$ and $O^{16}(d, p)O^{17}$ reactions. To avoid as well as possible interference from these neighbouring proton groups the following procedure was adopted. A range analysis was constructed for seven of the fifteen plates together forming one complete set for the measurement of an angular distribution. For one range analysis about 250 tracks were measured with lengths between 20 μ and 80 μ. The minima between the triton group and its two neighbours were then taken as the acceptance limits of triton tracks. The acceptance limits for the eight plates of which no range analysis was measured were found by interpolation. It is estimated that errors in the values of the acceptance limits did not introduce errors in the intensity measurements of the triton group larger than 2%. Altogether the length of about 9000 tracks has been measured for the construction of these range histograms. The average ranges observed for the three particle groups in question were always compared to theoretical values computed [3]) from the Q-value of the reaction, the deuteron energy and the range-energy relation, valid for the emulsion. Measured and computed ranges always agreed to within the experimental error (1 μ), which constitutes a good proof that the assignment of observed particle groups was correct.

The microscope counting technique has also been described previously [1] [3]. A constant area was scanned on all plates of one set. The area was chosen in such a way as to make the average number of tracks counted per plate about 1000. Thus roughly 15000 tracks were counted per angular distribution, while the total number of tracks counted in this investigation amounted to 168,000. The distribution was then corrected for possible eccentricity of the burning mark on the target and finally transformed into the center of mass system. Differential cross-sections and total cross-sections were computed from the observed number of outgoing particles per steradian, from the number of target atoms per square centimeter, obtained by weighing the target, and from the total number of deuterons hitting the target during the exposure.

§ 3. *Experimental results.* In Fig. 1 ten angular distributions are presented, five from the $Be^9(d, p)Be^{10}$ reaction, and five from the $Be^9(d, t)Be^8$ reaction, at effective deuteron energies of 0.295 MeV, 0.395 MeV, 0.450 MeV, 0.520 MeV and 0.620 MeV. They have all been normalized such that the average intensity is equal to unity. The distribution at $E_d = 0.395$ MeV has been measured from the thick target [1], the others from the thin target. Measured points have been represented by circles and statistical errors have been indicated. At four of the five deuteron energies the present measurements could be compared to those of Resnick and Hanna [2]. Their deuteron energies were almost the same as ours viz. 0.3 MeV, 0.4 MeV, 0.5 MeV and 0.6 MeV. It is not stated in their paper whether or not their deuteron energies were effective energies (i.e. whether or not they substracted about half the target thickness in keV from bombarding energy). We took it for granted that they were. Their measured points and corresponding statistical errors have been indicated in Fig. 1 by crosses. It is seen that the agreement is good if it is taken into account that their statistics are considerably worse than those of the present experiment.

The curves drawn in Fig. 1 have been plotted according to expressions of the form: $I(\vartheta) = 1 + \Sigma\, a_n P_n\, (\cos \vartheta)$. The procedure adopted for the determination of the coefficients a_n was the following [5]. First a smooth curve was drawn through the measured points. Then the coëfficients up to and including a_4 were computed by twenty interval numerical integration [1]) from this curve. The expression

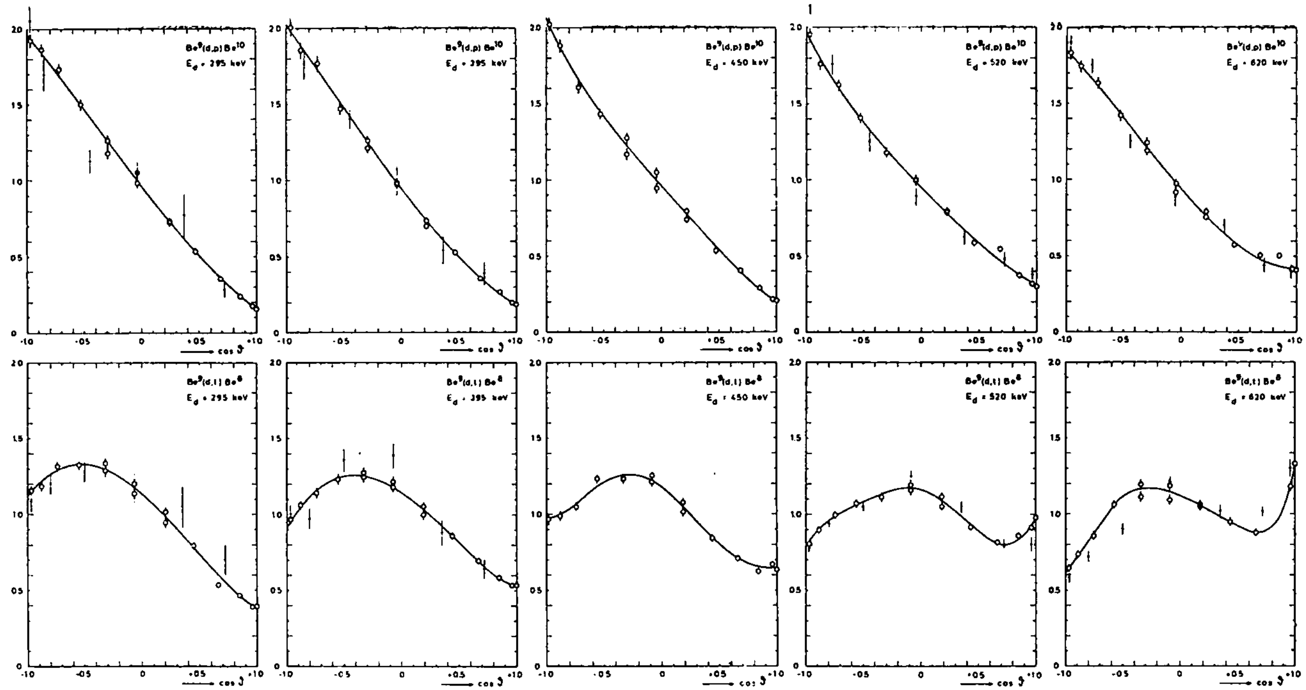

Fig. 1. Angular dependence of the $Be^9(d, p)Be^{10}$ and $Be^9(d, t)Be^8$ reactions at five different deuteron energies. Points measured in the present experiment have been indicated by circles. For comparison points measured by R e s n i c k and H a n n a [2]) have also been plotted indicated by crosses. The curves have been drawn according to expressions of the form $I(\vartheta) = 1 + \Sigma\, a_n P_n (\cos \vartheta)$ in which the coëfficients a_n are given in Table I.

thus obtained for $I(\vartheta)$ was then plotted and compared to the measured points and, if necessary, coefficients were finally sligthly altered so as to obtain a better fit. Only for the triton distributions above 0.45 MeV has it been necessary to include small terms a_5P_5 and a_6P_6 in the analytical expressions for $I(\vartheta)$.

The values of the coëfficients a_n are assembled in Table I together with their respective statistical errors [6]). It is seen that in all proton distributions a_3 and a_4 were already small, of the order of the experimental error. In most triton distributions a_3 and a_4 were fairly large while a_5 and a_6 were of the order of the experimental error. Especially the triton distributions show clearly increasing complexity with increasing deuteron energy. In the same Table the values are given of total cross-sections σ_t computed as indicated in § 2. The total cross-sections from the thick target bombardment at $E_d = 0.395$ MeV have been omitted because of their smaller accuracy.

The errors in the coëfficients given in Table I are only those of a statistical nature resulting from counting a finite number of tracks. The statistical error in each point of an angular distribution amounts on the average to 3%. There is also a personal error of the microscopist (about 2%). Especially when tired he may overlook tracks. The error of 2% introduced by the choice of the acceptance limits for

TABLE I

Total cross-section and coëfficients in Legendre polynomial series representations at five different deuteron energies

			$Be^9(d, p)Be^{10}$ reaction			
$E_{d\ eff.}$	0.295	0.395	0.45	0.52	0.62	MeV.
σ_t	0.51		1.64	3.27	5.26	m. barns
a_0	1.00	1.00	1.00	1.00	1.00	
a_1	—0.93 ± 0.02	—0.95 ± 0.02	—0.90 ± 0.02	—0.81 ± 0.02	—0.78 ± 0.02	
a_2	+0.06 ± 0.02	+0.10 ± 0.02	+0.10 ± 0.02	+0.12 ± 0.02	+0.13 ± 0.02	
a_3	+0.03 ± 0.02	+0.03 ± 0.02	—0.03 ± 0.02	—0.02 ± 0.02	+0.06 ± 0.02	
a_4			+0.03 ± 0.03	+0.02 ± 0.03	0 ± 0.03	
			$Be^9(d, t)Be^8$ reaction			
$E_{d\ eff.}$	0.295	0.395	0.45	0.52	0.62	MeV.
σ_t	0.51		1.57	2.97	4.31	m. barns
a_0	1.00	1.00	1.00	1.00	1.00	
a_1	—0.49 ± 0.02	—0.32 ± 0.02	—0.27 ± 0.02	—0.08 ± 0.02	+0.05 ± 0.02	
a_2	—0.26 ± 0.02	—0.28 ± 0.02	—0.28 ± 0.02	—0.21 ± 0.02	—0.19 ± 0.02	
a_3	+0.12 ± 0.02	+0.13 ± 0.02	+0.15 ± 0.02	+0.14 ± 0.02	+0.28 ± 0.02	
a_4	+0.01 ± 0.03	0 ± 0.03	+0.09 ± 0.03	+0.12 ± 0.03	+0.10 ± 0.03	
a_5			—0.04 ±0.03	+0.04 ± 0.03	+0.03 ± 0.03	
a_6				—0.03 ± 0.03	+0.06 ± 0.03	

the counting of the triton distributions has been mentioned already in § 2. These causes would at most double the statistical errors given in Table I. Total cross-sections however may be wrong by as much as 15% by errors introduced by one or more of the following causes:

1. inhomogeneousness of the target;
2. incomplete suppression of secondary electrons;
3. errors in the calibration of the current integrator;
4. errors in the estimate of the contribution of H_2^+ ions to the mass two beam.

The ratio of $Be^9(d, p)Be^{10}$ over $Be^9(d, t)Be^8$ total cross-sections is affected by none of these latter causes and should be accurate to 2%.

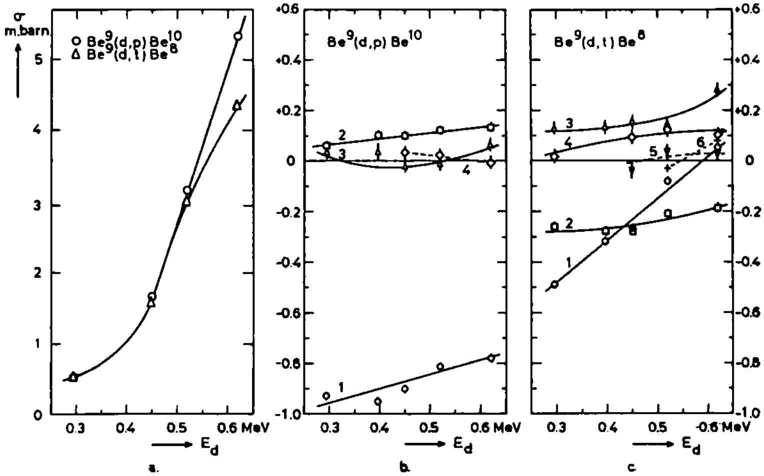

Fig. 2. Total cross-sections in millibarns (Fig. 2*a*) and coëfficients in Legendre polynomial series developments as a function of deuteron energy (Fig. 2*b* and Fig. 2*c*).

The data from Table I have been plotted in Fig. 2. In Fig. 2*a* the total cross-sections are shown as a function of deuteron energy. It is seen that the cross-sections of the two reactions are equal within the experimental error for deuteron energies below about 0.45 MeV. This fact was substantiated by the thick target bombardment at $E_d = 0.395$ MeV (not indicated in Fig. 2) from which measurement also equal cross-sections were found. At deuteron energies above 0.45 MeV the $Be^9(d, p)Be^{10}$ cross-section starts to predominate. The coëfficients a_n have been plotted in Fig. 2*b* and Fig. 2*c*. They are reasonably smooth functions of deuteron energy.

§ 4. *Discussion.* The most important result of the present experiment is the fact that the cross-sections of the $Be^9(d, p)Be^{10}$ and $Be^9(d, t)Be^8$ reactions are equal at deuteron energies below 0.4 MeV. It seems difficult at the moment to explain this equality theoretically but any attempt in this direction might be guided by the remark that spins of outgoing particles are equal ($s = \frac{1}{2}$) in both reactions while the same holds true for spins and parities of the final nuclei ($I = 0^+$). Interesting is also the pronounced anisotropic and asymmetric character of the angular distributions of both reactions at deuteron energies as low as 0.3 MeV.

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Note added in proof.

Lately results were also obtained from a bombardment at an effective deuteron energy of 0.15 MeV. At this energy the differential cross-section of the $Be^9(d, p)Be^{10}$ reaction is given by:

$$\sigma(\vartheta) = (4\pi)^{-1}\, 12.7\, (1 - 0.93\, P_1 + 0.11\, P_2 - 0.08\, P_3)\ \mu \text{ barns/sterad.},$$

while for the $Be^9(d, t)Be^8$ reaction is found:

$$\sigma(\vartheta) = (4\pi)^{-1}\, 12.7\, (1 - 0.55\, P_1 - 0.28\, P_2 + 0.14\, P_3 + 0.04\, P_4)\ \mu \text{ barns/sterad}$$

It is seen that there exists again equality of the total cross-sections. Also very strong deviations from isotropy show up again; the ratio of backward over forward differential cross-sections for the $Be^9(d, p)Be^{10}$ reaction amounts even to 21.

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REFERENCES

1) De Jong, D. and Endt, P. M., Physica **18** (1952) 407.
2) Resnick, I., and Hanna, S. S., Phys. Rev. **82** (1951) 463.
3) Endt, de Jong, Bogaardt and Koudijs, Physica **18** (1952) 399.
4) Endt, Paris, Jongerius and Valckx, Physica **18** (1952) 423.
5) Redman, W. C., Phys. Rev. **79** (1950) 6.
6) Endt, P. M., Physica **18** (1952) 421.