PHYSICAL REVIEW VOLUME 98, NUMBER 1 APRIL 1, 1955

Angular Distribution of Disintegration Products from the $O^{16}(d,p)O^{17}$, $Be^9(d,p)Be^{10}$, and $Be^9(d,t)Be^8$ Reactions

MIRA K. JURIĆ
Institute of Nuclear Sciences "Boris Kidrich," Belgrade, Yugoslavia

(Received October 18, 1954)

The angular distributions of disintegration products from the reactions $O^{16}(d,p)O^{17}$, $Be^9(d,p)Be^{10}$, and $Be^9(d,t)Be^8$ were examined, with deuteron energies from 0.60 to 1.45 Mev. Pronounced asymmetry is found with respect to 90°. The results are analyzed to determine the relative contributions of stripping and compound nucleus formation.

IT would be desirable to be able to make more definite statements about the question as to whether stripping or compound nucleus formation predominates in the reactions with deuterons of energies insufficient to overcome the Coulomb barrier. Therefore, the angular distributions of disintegration products from the reactions $O^{16}(d,p)O^{17}$, $Be^9(d,p)Be^{10}$, and $Be^9(d,t)Be^8$ with deuteron energies from 0.60 to 1.45 Mev were examined in order to determine the extent to which these two processes contribute to these reactions.

The angular distribution of protons from the $O^{16}(d,p)O^{17}$ reaction, produced by deuterons of lower energies, has not yet been published except for 1.07-Mev deuterons on a slightly thick oxide target; the $Be^9(d,p)Be^{10}$ angular distribution has been more investigated, but the $Be^9(d,t)B^8$ angular distribution was measured only for deuterons of 1.3 Mev and below 0.62 Mev.[1–5]

We examined the angular distribution of long-range protons and tritons at bombarding energies of deuterons of $E_d=0.60$, 0.80, 0.90, 1.00, 1.10, 1.20, 1.30, and 1.45 Mev. The bombarding deuterons were produced in the Cockcroft-Walton accelerator of the Institute of Nuclear Sciences "Boris Kidrich" in Belgrade, whose ion source is of relatively high intensity.[6]

The targets were MoO_3 and metallic Be evaporated in vacuum onto a 0.005-mm copper foil. The weight of the targets was 0.136–0.260 mg/cm^2. The target plates were placed at an angle of 45° to the bombarding beam. The angular distributions were measured from 0° to 170° at 10° intervals. The solid angles of 1.87×10^{-3} steradian for each interval were defined by square holes in a ring (150-mm diameter) which surrounded the target.

The reaction products were detected by means of photonuclear emulsions placed around the target in such a way that each plate covered one of the solid angles. The average angle of incidence of particles on the surface of the emulsions was 10°. The plates used were Ilford C_2, 100 μ thick. In order to prevent the blackening of the plates by elastically scattered particles and to reduce the ranges of their tracks, the plates were shielded by 0.005–0.022 mm Al foils, covering the square holes of the collimating ring.

The scanning of the emulsions was performed by means of Leitz immersion microscopes, using the standard methods. The tracks were divided according to length into different groups, and all the tracks of one group were counted in every angle covered by one plate. The total number of tracks per plate varied from 400 to 12 500, according to the energy of deuterons and the position of the plate.

The protons from the $O(d,p)$ reaction, produced from the oxygen layer formed on the target can represent a considerable source of error in the angular distribution from the $Be(d,t)$ reaction. In the region of the energy of the bombarding deuterons ($E_d=0.60$–1.45 Mev), the lengths of the proton tracks from the $O(d,p)$ reaction in photonuclear emulsions at some angles of incidence are equal to the lengths of the triton tracks from the $Be(d,t)$ reactions. However, since at some angles the two groups of tracks were of different length, it was possible to subtract the proton tracks at all angles, because the angular distribution from $O(d,p)$ reaction was already determined (see Fig. 1).

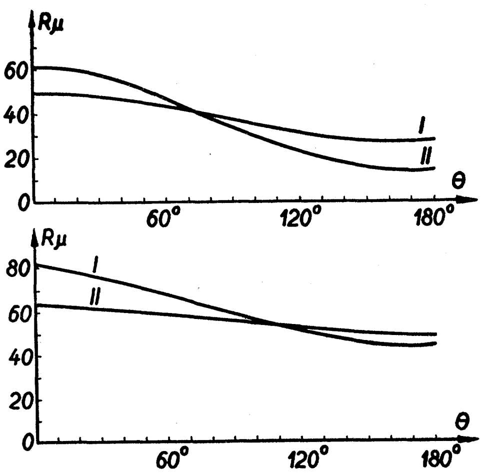

FIG. 1. Abscissa—angles; ordinate—ranges of particles in photonuclear emulsions. I—tritons from $Be(d,t)$ at $E_d=0.8$ and 1.2 Mev; II—protons from $O(d,p)$ reaction at $E_d=0.8$ and 1.2 Mev.

---

[1] N. P. Heydenburg and D. N. Inglis, Phys. Rev. 73, 230 (1948).
[2] J. Resnick and S. S. Hanna, Phys. Rev. 82, 462 (1952).
[3] F. L. Canavan, Phys. Rev. 87, 136 (1952).
[4] D. Jong and P. M. Endt, Physica 18, 679 (1952).
[5] P. Cuer and J. Jung, Phys. Rev. 89, 1151 (1953).
[6] B. Nikolić and M. Crnilović, Bull. Inst. Nuclear Sci., Belgrade 3, 29 (1953).

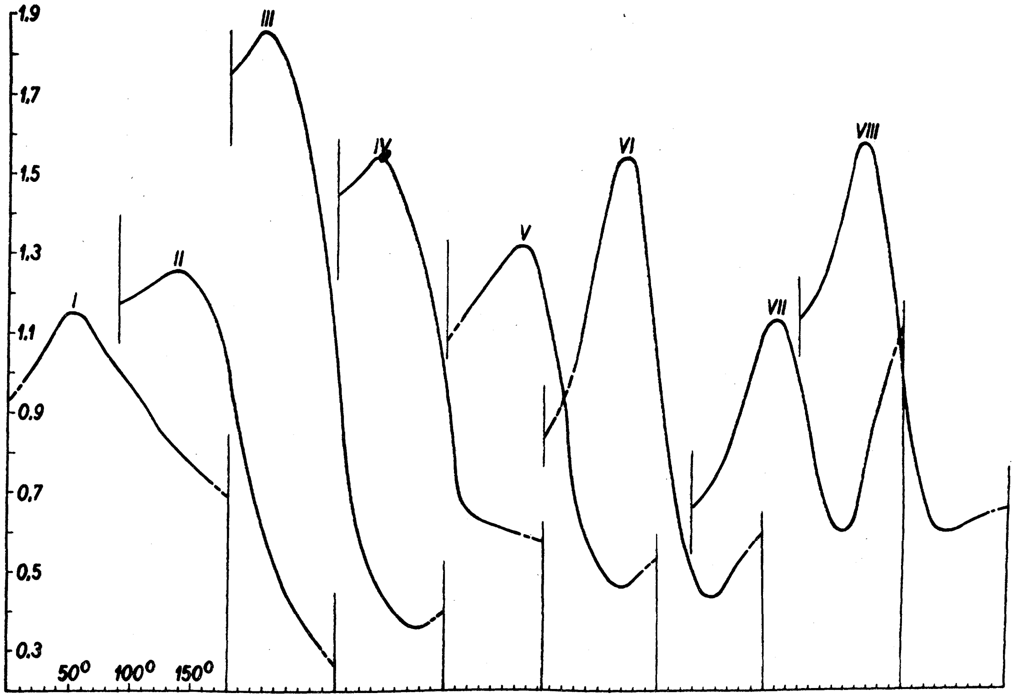

FIG. 2. The angular distribution of protons from the O(d,p) reaction. The curves have been plotted according to the equation:

$$\frac{\sigma(\theta)}{\sigma(90^\circ)}=\sum_{n=0}^{5} A_n P_n.$$

The effective deuteron energy obtained by substracting half the target thickness in kev from the bombarding energy is, in Mev, 0.58 for curve I, 0.76 for curve II, 0.84 for III, 0.98 for IV, 1.05 for V, 1.14 for VI, 1.26 for VII, and 1.40 for VIII.

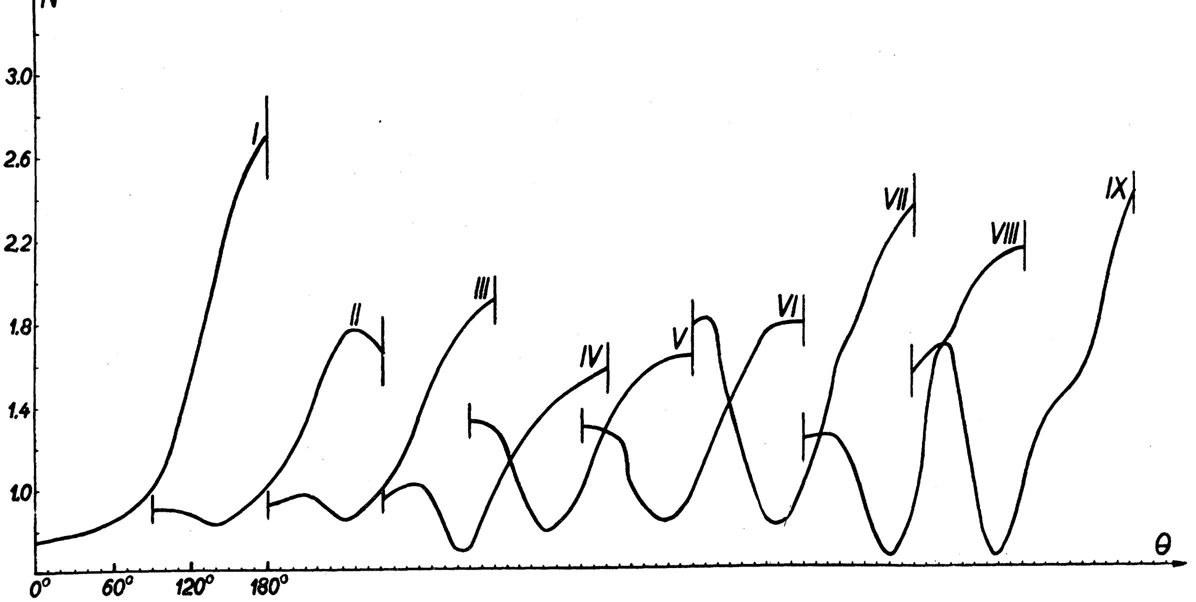

FIG. 3. The angular distribution of protons from the Be(d,p) reaction. The curves have been plotted according to the equation:

$$\frac{\sigma(\theta)}{\sigma(90^\circ)}=\sum_{n=0}^{5} A_n P_n.$$

The effective deuteron energy, obtained by subtracting half the target thickness in kev from the bombarding energy, is, in Mev, 0.62 for curve I, 0.81 for II, 0.90 for III, 0.94 for IV, 1.03 for V, 1.06 for VI, 1.19 for VII, 1.28 for VIII, and 1.403 for IX.

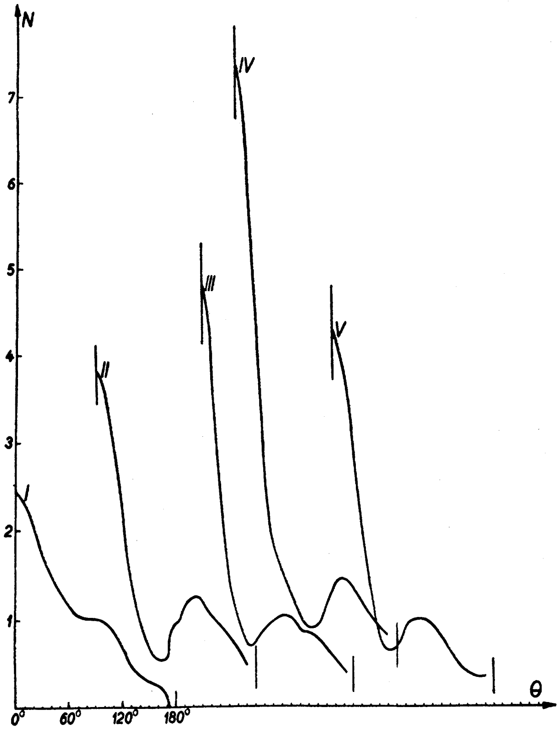

FIG. 4. The angular distribution of tritons from the Be(d,t) reaction. The curves have been plotted according to the equation:

$$\frac{\sigma(\theta)}{\sigma(90^\circ)}=\sum_{n=0}^{7} A_nP_n.$$

The effective deuteron energy, obtained by substracting half the target thickness in kev from the bombarding energy, is, in Mev, 0.58 for curve I, 1.03 for II, 1.19 for III, 1.28 for IV, and 1.40 for V.

The angular distribution of reaction products has been determined by measuring the yields at 18 various angles, and the results have been converted to the center-of-mass coordinate system. The angular distribution obtained in this way is given in Figs. 2, 3, and 4.

These angular distributions have been analyzed in terms of Legendre polynomials:

$$\frac{\sigma(\theta)}{\sigma(90^\circ)}=\sum_{n=0} A_nP_n$$

(P_n=Legendre polynomial). The coefficients A_n of the Legendre polynomials were computed by using an analog computer machine of the Institute "Boris Kidrich," with a total error of approximately ±0.04 (Tables I, II, III). The coefficients A_n in the function for the deuteron energy are shown in Figs. 5, 6, and 7.

TABLE I. The coefficients A_n of the angular distribution for $O^{16}(d,p)O^{17}$.

E_d Mev	A_0	A_1	A_2	A_3	A_4	A_5	A_6
0.58	0.98	0.195	−0.10	−0.06	−0.04	—	—
0.76	0.93	0.53	−0.19	−0.10	0.02	—	—
0.84	1.08	0.94	0.03	−0.25	−0.03	—	—
0.98	1.05	0.60	0.17	−0.16	−0.03	—	—
1.05	0.95	0.53	−0.23	−0.25	0.04	0.03	—
1.14	0.98	0.61	−0.16	−0.49	−0.04	+0.03	—
1.26	0.90	0.15	−0.16	−0.37	0.16	0.00	—
1.40	1.06	0.59	−0.10	−0.43	−0.09	0.09	0.03

TABLE II. The coefficients A_n of the angular distribution for $Be^9(d,p)Be^{10}$.

E_d Mev	A_0	A_1	A_2	A_3	A_4	A_5	A_6	A_7
0.62	1.21	−0.79	0.48	−0.16	0.00	—	—	—
0.81	1.11	−0.48	0.28	0.00	0.02	—	—	—
0.90	1.11	−0.45	0.33	0.00	0.03	—	—	—
0.94	1.10	−0.40	0.26	0.15	0.00	—	—	—
1.03	1.14	−0.35	0.38	0.25	0.00	—	—	—
1.06	1.14	−0.35	0.45	0.20	0.00	—	—	—
1.19	1.13	−0.46	0.74	0.27	0.05	−0.02	—	—
1.28	1.28	−0.65	0.64	0.32	−0.16	−0.16	0.00	—
1.403	1.26	−0.31	0.70	0.27	0.07	−0.36	0.04	—

TABLE III. The coefficients A_n of the angular distribution $Be^9(d,t)Be^8$.

E_d Mev	A_0	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9
0.62	0.97	0.73	0.09	0.34	0.32	0.05	0.03	—	—	—
1.03	1.09	0.44	0.68	1.12	0.25	0.06	0.03	—	—	—
1.19	1.16	0.85	0.95	1.29	0.68	0.36	0.02	—	—	—
1.28	1.45	0.90	1.31	1.5	0.50	0.64	0.59	0.53	0.00	—
1.403	1.03	0.79	0.65	1.08	0.62	0.83	0.01	0.00	—	—

The most remarkable characteristics of the observed angular distributions is their strong asymmetry with respect to the 90° plane which is perpendicular to the incoming deuteron beam. It appears from these results that the reactions produced by deuterons contain contributions from two processes: stripping and com-

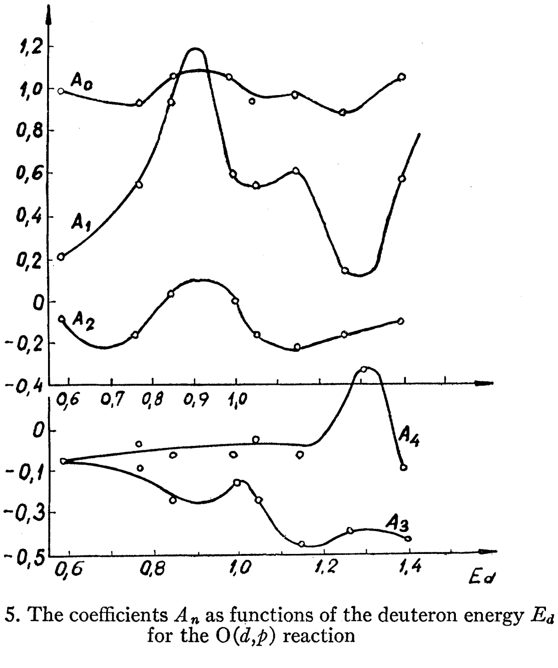

FIG. 5. The coefficients A_n as functions of the deuteron energy E_d for the $O(d,p)$ reaction

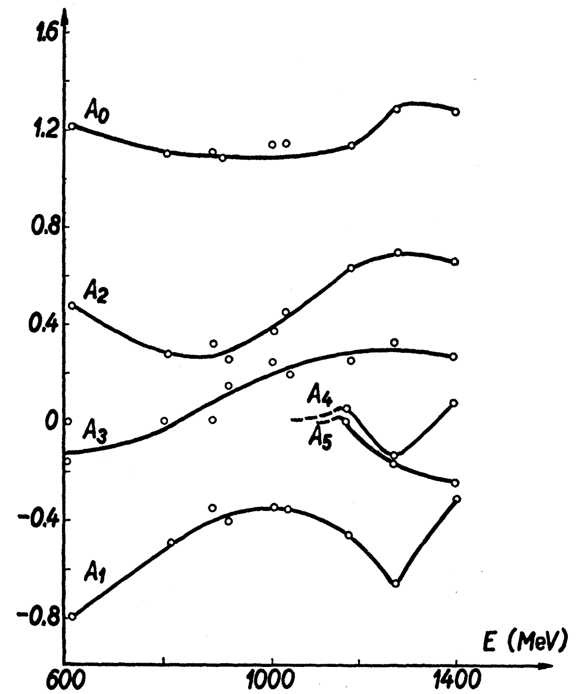

FIG. 6. The coefficients A_n as functions of the deuteron energy E_d for the Be(d,p) reaction.

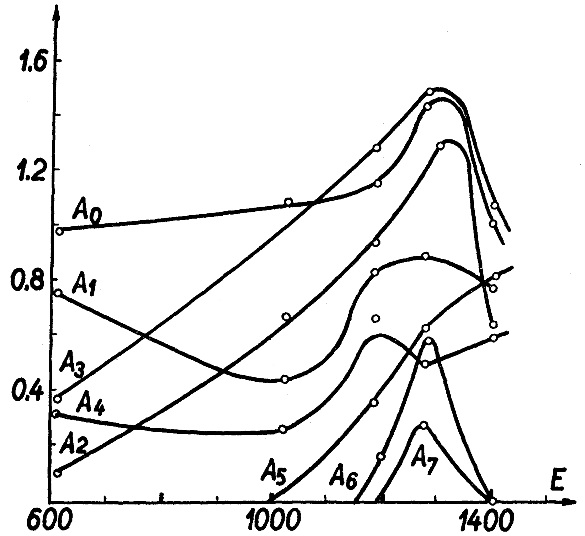

FIG. 7. The coefficients A_n as functions of the deuteron energy E_d for the Be(d,t) reaction.

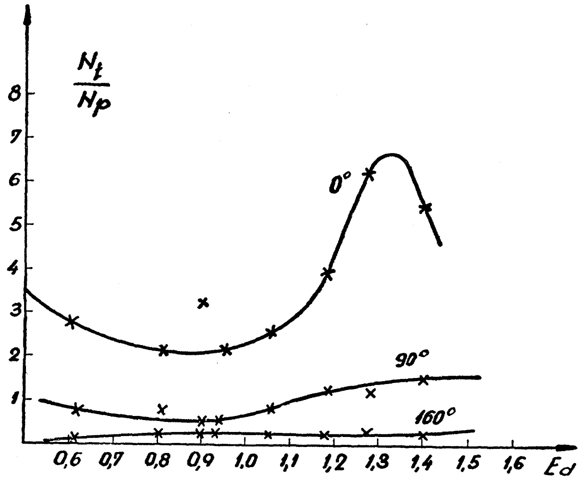

FIG. 8. Abscissa—bombarding energy of the deuteron; ordinate—ratio of the number of tritons to the number of protons in the reactions Be(d,p) and Be(d,t).

pound-nucleus formation. All the shapes of the angular distribution curves for stripping are very similar, showing a strong peak for the forward direction with a maximum at small angles. These peaks, as shown in Figs. 1 and 2, increase with bombarding energy, which means that the relative contribution from the stripping effect increases with deuteron energy.

In addition to the structure which can be attributed directly to the stripping effect, the angular distribution also shows a contribution of the compound-nucleus formation. This contribution will be especially accentuated for the resonance bombarding energies, and the characteristics of the energy levels of the compound nucleus will influence the angular distribution. This may be the case for $E_d=0.84$ Mev and $E_d=1.26$ Mev in the O(d,p) reaction, and for $E_d=1.28$ Mev in the Be(d,p) and Be(d,t) reactions (curves No. III and No. VII, Fig. 2; No. VIII, Fig. 3 and No. IV, Fig. 4). It is of interest to note that the state produced by deuteron energy of $E_d=1.28$ Mev, prefers the Be(d,t) disintegration to the Be(d,p). Figure 8 shows that the yield of the Be(d,t) reaction is higher than that of the Be(d,p) at $E_d=1.28$ Mev, but only for those particles having a forward direction. This resonance could therefore be due to that of the pickup effect.

If we assume that the resonances result only from the effect of the compound-nucleus formation, then the compound nucleus F^{18} has energy levels at about $E_{\text{ex}}=8.38$ Mev and $E_{\text{ex}}=8.76$ Mev, and B^{11} at about $E_{\text{ex}}=16.77$ Mev.

Further work on these subjects is in progress.