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Angular Yield of Protons, Tritons, and Alphas from the Deuteron Bombardment of Beryllium

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The photographic target chamber incorporating limited magnetic deflection of product particles, which was used to investigate the beryllium plus proton reactions, has been applied to the beryllium plus deuteron reactions. Angular yields of the long and the short range protons, the tritons, and the unresolved alphas were obtained at bombarding energies below 1 Mev. Most of the distributions are fairly complex and energy dependent. The 90° yield of the long range protons increases rapidly with energy up to 900 kev, except for an anomaly at 700 kev. Tritons having a continuous distribution in energy, resulting from the three-particle disintegration $Be^9(d,t)2\alpha$, were observed. Range measurements on the mono-energetic triton group give a $Q=4.61\pm0.04$ Mev for the $Be^9(d,t)Be^8$ reaction.

I. INTRODUCTION

THE bombardment of beryllium by deuterons in the low energy region is of interest in that the compound nucleus formed disintegrates in a relatively large number of ways:[1]

$Be^9(d,p)Be^{10}$, Be^{10*}	$Q=4.58$, 1.20 Mev
$Be^9(d,t)Be^8$	$Q=4.59$ Mev
$Be^9(d,\alpha)Li^7$, Li^{7*}	$Q=7.15$, 6.67 Mev
$Be^9(d,n)B^{10}$, B^{10*}, $\cdots$	$Q=4.31$, 3.60, $\cdots$ Mev
$Be^9(d,t)2\alpha$	$Q=4.68$ Mev.

The present investigation is part of a study of the angular distributions of these reaction products. The nature of these distributions should reveal properties of the participating states of the compound nucleus. It is noteworthy also that in at least three cases the final nucleus may be left in one of its excited states. The angular distributions of this investigation do not directly give information on these states, but it is possible that a careful comparison of the behavior of the long and short range particles, leading, respectively, to the ground and excited states of a nucleus, might uncover pertinent differences between the states. A more direct approach to the problem of the excited states of a residual nucleus is the study of the radiation that is emitted. Such an investigation will be aided, however, by a knowledge of the behavior of the reaction as a whole.

II. METHOD AND PROCEDURE

The photographic method, which was described in connection with the investigation of the proton bombardment of beryllium,[2] is ideally suited to the study of both ranges of protons and the tritons in this experiment. The photographic plate easily resolves these groups of particles from each other and from the other particles of the reaction by the difference in their ranges in the emulsion. Because of the great variety of particles, including the scattered deuterons, however, it is highly desirable, if not essential, actually to separate the groups from each other on the plate. This is accomplished by means of the limited magnetic deflection which is provided in the method. Particles from the target are collimated into narrow beams as they pass through seven radial gaps in a semicircular ring of iron mounted within the target chamber. The internal iron constitutes the yoke of an external electromagnet which produces a magnetic field in the particle gaps. After deflection in the magnetic field, the particles are recorded on the photographic plates mounted in the vacuum behind each gap.

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† Assisted by a contract with the AEC.

[1] Oliphant, Kempton, and Rutherford, Proc. Roy. Soc. (London) **A150**, 241 (1935); Lattes, Fowler, and Cuer, Proc. Phys. Soc. (London) **59**, 883 (1947); Williams, Haxby, and Shepherd, Phys. Rev. **52**, 1031 (1937); E. R. Graves, Phys. Rev. **57**, 855 (1940); T. W. Bonner and G. Brubaker, Phys. Rev. **50**, 308 (1936).

[2] Neuendorffer, Inglis, and Hanna, Phys. Rev. **82**, 75 (1951).

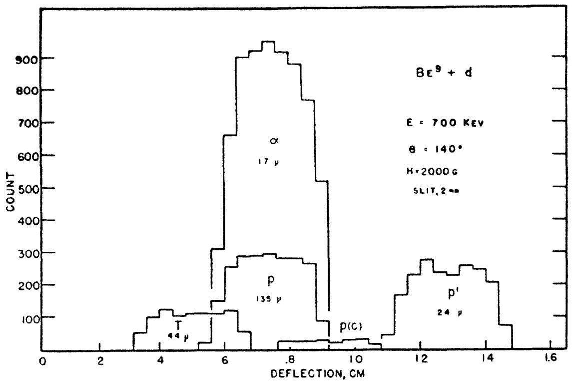

FIG. 1. Typical plate analysis, showing number of particles of each type per microscope swath *vs* deflection along plate. Approximate range in emulsion for each group is recorded.

The experimental detail was similar to that described in reference 2. The Be foil,[3] used as a target for most of the work, was 30 micro-inches thick. The plate emulsions were 100 microns thick. As this was one of the first experiments performed with the apparatus, care was taken to insure satisfactory alignment. The arrangement in the target chamber was adjusted by optical means, and the final alignment tested by exposing plates to the scattering of a beam of protons by a silver foil. A comparison of the results with the Rutherford scattering law showed that the alignment was satisfactory within the statistics of the experiment.

Plates exposed to the bombardment of beryllium by a beam of deuterons were obtained for several deuteron energies. The magnetic spectrum of the reaction is spread lengthwise along each plate, particles having a given momentum and charge appearing in a rather well-defined rectangular area at the appropriate place in the spectrum. The plates were counted in a microscope using a swath method. A record was made of the number of tracks passing a fiducial line in the eyepiece of the microscope as the photographic plate was moved along. The plates were first scanned lengthwise, and the number of tracks in each swath was tabulated. An inspection of these numbers enabled one to select a region of constant particle density across the plate. The plates were then scanned systematically in a transverse direction, the length of each swath being such as to keep within the region of constant density. These data were tabulated (and plotted), and only those swaths which obviously were part of a plateau were used to compute the final yield for each group of product particles. To illustrate the method Figs. 1 and 2 are presented, showing results from two runs under different conditions.

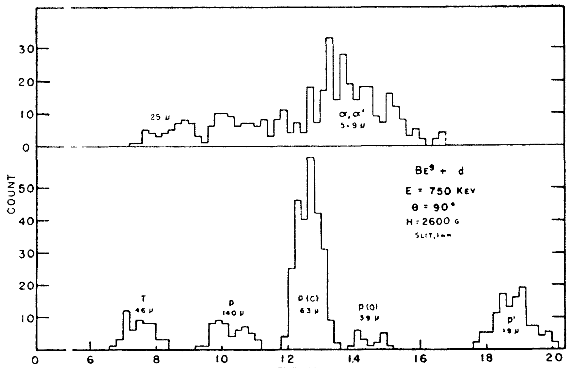

FIG. 2. Plate analysis with apparatus modified to give higher resolution. Background tracks and the alpha-groups are plotted separately from the well resolved groups.

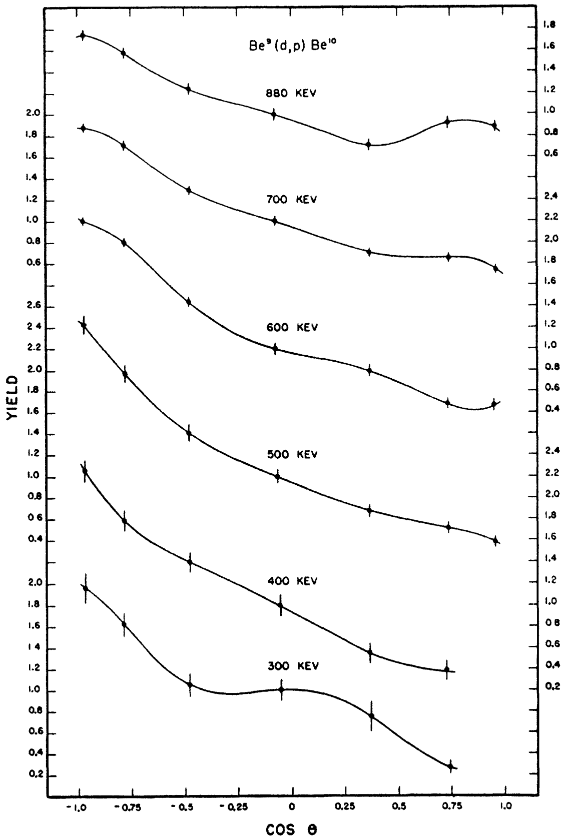

FIG. 3. Angular distributions in the center-of-mass system of the reaction $Be^9(d,p)Be^{10}$. Yields are normalized to unity at the 90° angle of the laboratory system. The curves are sixth-power polynomials having the coefficients given in Table I.

A plate analysis of this type was made at each angle and energy. The number of particles per unit area of plate was computed for each particle group, and these data were used to compute the angular distributions in the center-of-mass coordinate system. Included in the results were small geometrical factors, which corrected for irregularities in the plate distance and inclination in the target chamber. The results are presented in Figs. 3–7.

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[3] These foils were generously supplied to us by Dr. Hugh Bradner of the University of California at Berkeley.

III. DISCUSSION

In Fig. 1, which is representative of most of the runs, it is apparent that the two ranges of alpha-particles were not resolved. The curves in Fig. 6, therefore, give the total alpha-yields, and, for reasons that appear below, are somewhat approximate. An effort to separate the alpha-groups was made in the run illustrated in Fig. 2. The collimating slits were narrowed considerably, a higher magnetic field was used, and 0.2 mil of nickel foil was interposed between the target and the magnetic field. The foil served to decrease the alpha-energies from 4.85 and 4.55 Mev to approximately 2.0 and 1.5 Mev, respectively. It is seen that for the triton group and the various proton groups, shown in the lower part of Fig. 2, the plateaus are about four or five microscope swaths wide. The alpha-groups, plotted in the upper part of Fig. 2, cover a region about twice this wide. However, the resolution is not such as to make a yield determination reliable. Further refinement would have improved the situation were it not for the heavy background of tracks on both sides of, and presumably throughout, the alpha-groups. The background tracks were indistinguishable from the alphas, for the most part, and for this reason further attempts to obtain the angular yields of the separated alphas with this method were abandoned.

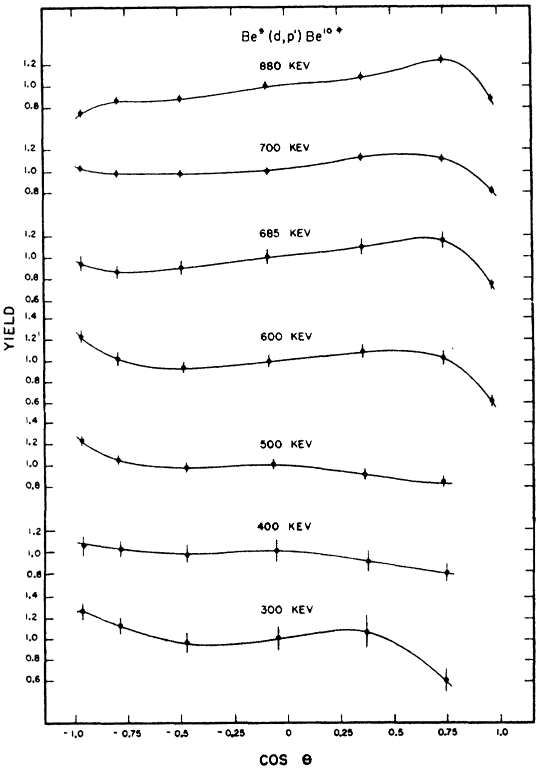

FIG. 4. Angular distributions in the center-of-mass system of the reaction $Be^9(d,p)Be^{10*}$. Yields are normalized to unity at the 90° angle of the laboratory system. The curves are sixth-power polynomials having the coefficients given in Table I.

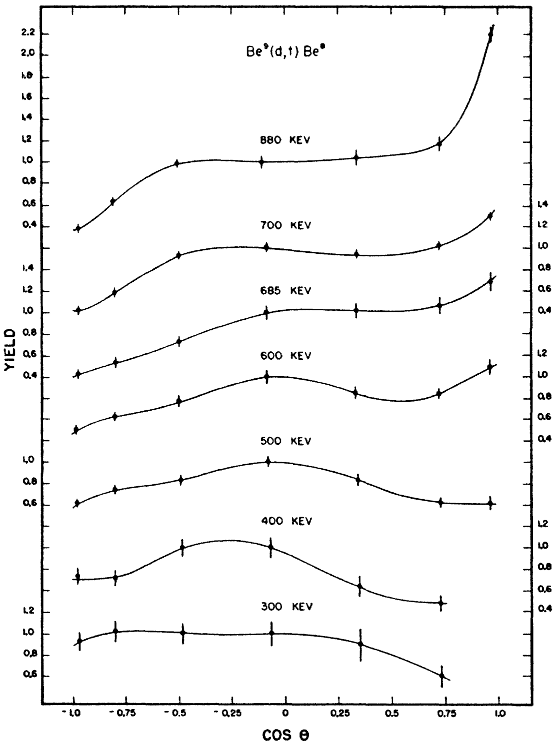

FIG. 5. Angular distributions in the center-of-mass system of the reaction $Be^9(d,t)Be^8$. Yields are normalized to unity at the 90° angle of the laboratory system. The curves are sixth-power polynomials having the coefficients given in Table I.

The background tracks were observed also on the plates exposed without a foil between the target and the deflecting field, but, in general, they were not counted and so were not recorded in Fig. 1. That these particles come from the beryllium plus deuteron reaction and not from some contaminant was established by using a beryllium target prepared in this laboratory in addition to the foils obtained from H. Bradner. The yield of the background particles relative to the yields of other particles was independent of the target used. In addition, all possible contaminants which could have given particles in this region were eliminated by searching for reaction products which the contaminants would have produced had they been present. The range of these particles excludes the possibility that they are protons or deuterons. They cannot be alphas from the beryllium plus deuteron reaction either, since many of them fall on the high energy side of the long range alpha-group. Their range and also their reduction in range on traversing matter indicates that they are tritons.

An extensive range analysis of these background tritons, summarized in Fig. 8, gave evidence of some group structure, but the results were not very reproducible. Furthermore, very little evidence of structure is to be seen in the spectrum of the particles to the left of the alphas in the upper part of Fig. 2. The absorbing

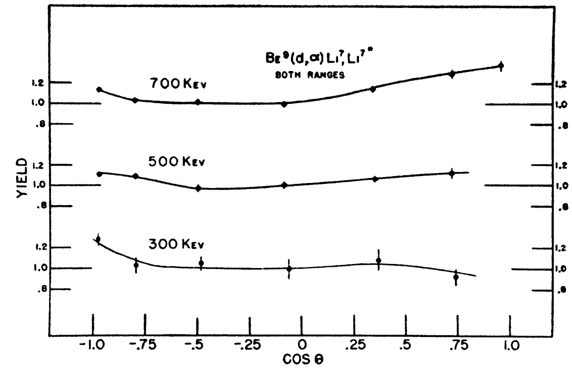

FIG. 6. Approximate angular distributions of the unresolved alpha-groups from $Be^9(d,\alpha)Li^7$, Li^{7*}.

Ni foil used in this run reduced the energy of the alphas relatively more than that of the tritons, so that a greater portion of the triton spectrum could be examined without interference from the alphas. It appears, then, that these tritons have a more or less continuous distribution in energy and arise from the three-particle break-up[4] of the compound nucleus B^{11}. The Q for this reaction is 4.68 Mev and should produce tritons having energies up to and slightly exceeding the energy of the mono-energetic ground-state group. The curves in Fig. 8 are a composite of five plates at various angles and bombarding energy, and the magnetic deflections which were analyzed span the plateau of the ground state triton group. It is interesting to note that the range (energy) of the ground-state tritons remains ostensibly constant throughout the plateau, but that the range of the background tritons decreases with increasing magnetic deflection and finally blends into the strong alpha-particle group (only a portion of which was counted). The apparent increase in intensity of the background tritons, as their energy decreases, can be attributed in large measure to the low resolution of the apparatus. From the accumulated range measurements of the ground-state triton group, we have calculated a Q value for the reaction. The weighted average of six determinations at different angles and energies gives $Q=4.61\pm0.04$ Mev, which agrees with the value of $Q=4.59$ Mev computed from the masses given by Tollestrup, Fowler, and Lauritsen.[5]

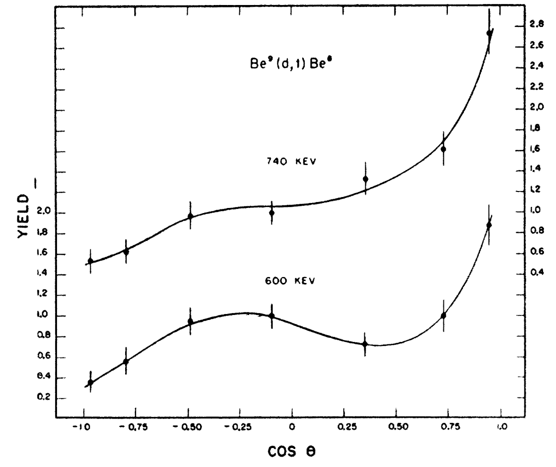

FIG. 7. Angular distributions of the tritons obtained with higher resolution but with greater statistical uncertainty.

The presence of the continuous tritons made it necessary to use care in counting the ground-state tritons. As can be seen from Fig. 8, it was possible to separate them fairly well by their range, at least in the region where the background intensity is appreciable. A suitable range criterion was adopted for accepting or rejecting tracks, and it is believed that serious errors were avoided. However, as a check on the work, the long range tritons (and protons) were counted on the plates taken with the apparatus modified to give higher resolution. The proton distributions obtained from these plates agreed satisfactorily with those in Fig. 3. The triton distributions, however, are reproduced in Fig. 7, since they show some departure from the curves of Fig. 5, notably in the greater increase in yield in the forward direction.

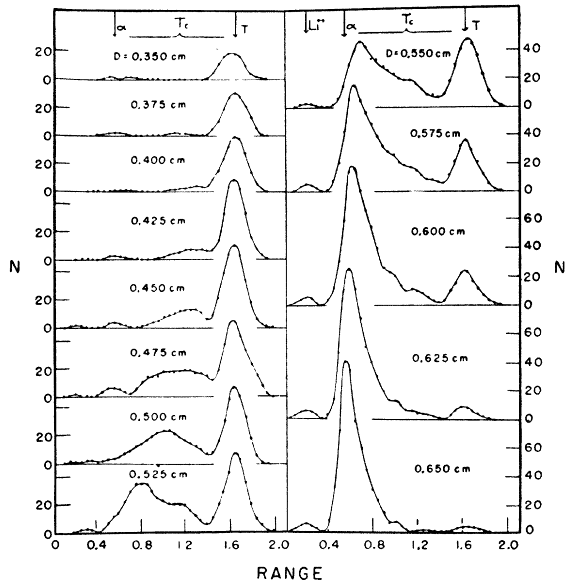

FIG. 8. Range analysis of the ground-state tritons, the continuous tritons, and part of the alphas from Be^9+d. The curves are a composite of five plates at different angles and bombarding energy. The ordinate N represents the number of tracks counted in a small range interval having the average range indicated by the abscissas (arbitrary units). Each curve represents a complete microscope swath at the given plate deflection. The arrows at the top indicate the computed range of the various groups.

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[4] The alpha-particles resulting from the three-particle disintegration were observed recently in this laboratory by D. R. Inglis, Phys. Rev. **78**, 104 (1950), and their magnetic spectrum has subsequently been studied by R. W. Gelinas and S. S. Hanna, Phys. Rev. **82**, 298 (1951).

[5] Tollestrup, Fowler, and Lauritsen, Phys. Rev. **78**, 372 (1950).

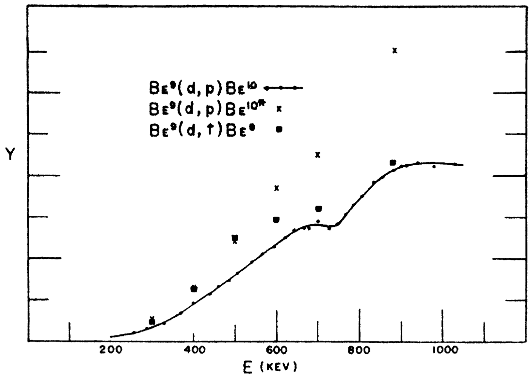

FIG. 9. Energy dependence of the 90° yield of $Be^9(d,p)Be^{10}$, measured with a proportional counter. Also shown are the relative yields of short range protons and tritons, obtained from the photographic plates used in observing the angular yields.

Some effort was made in this work to identify and count particles arising from impurities on the target. The usual proton groups from oxygen and carbon are seen in Fig. 2. The long range oxygen protons were counted on all the plates used in obtaining the angular distributions. This was done in order to obtain an estimate of the number of short range oxygen protons which might have contributed to the measured yield of the short range beryllium protons, since the former could not be distinguished from the latter in the present apparatus. The yields and angular distributions of the oxygen proton groups have not been measured completely in this energy range, and the estimate of the short range yield was based on the observations of Heydenburg and Inglis[6] at somewhat different energies. The estimated contamination is negligible at the low energies and rises to at most 5 percent at the high energies.

The yield measurements obtained with the photographic chamber do not conveniently give the variation of yield with energy for these reactions. The excitation curve for the long range protons, shown in Fig. 9, was obtained with a proportional counter. The yield increases rapidly with increasing energy up to about 900 kev and shows an anomaly at about 700 kev. Because of the very low yield of these reactions at the lower energies, the angular yields measured at 300 and 400 kev were not obtained with high statistical accuracy and are included in the results chiefly to indicate the major trends.

TABLE I. Coefficients in the expansion

$$Y(\cos\theta)=Y(0)\left(1+\sum_{n=1}^{6}A_n\cos^n\theta\right)$$

for both ranges of protons and the tritons from the deuteron bombardment of beryllium.

	300 (kev)	400 (kev)	500 (kev)	600 (kev)	685 (kev)	700 (kev)	880 (kev)
				Long range protons			
A_1	−0.08	−1.18	−0.83	−0.45		−0.70	−0.80
A_2	−1.33	−0.26	0.07	0.54		−0.28	−0.49
A_3	−1.94	0.92	0.19	−1.73		0.06	1.24
A_4	2.99	1.11	1.17	−0.28		2.11	3.28
A_5	1.05	−0.89	−0.12	1.29		−0.07	−0.91
A_6	−1.70	−0.52	−0.77	0.15		−1.61	−2.50
				Short range protons			
A_1	0.38	−0.11	−0.14	0.18	0.16	0.21	0.18
A_2	−0.12	−0.61	−0.51	0.04	−0.02	0.33	−0.35
A_3	−1.75	−0.02	0.22	0.04	0.52	−0.09	0.47
A_4	−0.66	1.22	0.91	−0.05	0.27	−0.64	1.67
A_5	0.84	−0.09	−0.33	−0.62	−0.86	−0.28	−0.62
A_6	0.49	−0.80	−0.38	−0.11	−0.48	0.18	−1.65
				Tritons			
A_1	−0.07	−0.86	−0.10	−0.10	0.25	−0.21	0.03
A_2	−0.46	−0.89	−1.32	−1.53	−0.89	−0.01	0.59
A_3	−0.67	1.82	−0.08	0.45	0.09	1.03	−0.14
A_4	0.33	0.43	1.94	2.82	1.21	−0.92	−2.51
A_5	0.48	−1.17	0.19	−0.00	0.14	−0.33	1.20
A_6	−0.23	0.08	−1.04	−1.52	−0.47	0.87	2.44

The angular distributions have been analyzed into polynomials in cosθ up to the sixth power. The coefficients are given in Table I. An inspection of these coefficients shows that the angular distributions of the beryllium plus deuteron reactions are fairly complex, even at low energies. It is possible, of course, that a less complex (smaller powers of cosθ) analysis might provide a more satisfactory description of the data. Nevertheless, the coefficients are expected still to be large and to show considerable structure in their energy dependence.

We wish to thank Dr. D. R. Inglis for many helpful discussions, and Mr. F. W. Lipps for assistance with some of the calculations.

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