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Energy and Angular Distribution of Neutrons Emitted in the Be^9 (d, n) B^{10} Reaction

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The energy spectra and angular distributions of neutrons from the $Be^9\ (d,n)\ B^{10}$ reaction have been investigated at deuteron energies of 0.5, 0.8, 1.0, 1.2, 1.4 and 1.6 Mev. The excitation curve for this reaction indicates a resonance at 1 Mev in the compound nucleus, B^{11}. The angular distribution corresponding to an excited state in B^{10} with excitation energy $E_x = 3.62$ Mev points to the existence of a stripping mechanism. The angular distributions of reactions involving the formation of compound nuclei are appreciably distorted on passage through a resonance.

1. INTRODUCTION

THE experimental study of spectra and of angular distributions of neutrons emitted when light nuclei are bombarded by charged particles, for instance by deuterons, yields useful information on the excited states of the residual nucleus and on the mechanism of the nuclear transmutation. In this work*, the reaction $Be^9\ (d,\ n)\ B^{10}$ was investigated. Lately a number of authors[1-3] have published results on the investigation of this reaction for deuteron energies less than 1 Mev. Five energetic neutron groups were observed. The angular distributions indicate a stripping mechanism only for the fourth excited state of B^{10}, for the other states a substantial contribution from the formation of the compound nucleus is presented.

This work is believed to be more detailed investigation of the energy spectra and the angular distributions of the neutrons from the reaction $Be^9\ (d,\ n)\ B^{10}$ as a function of the incident deuterons in the range of 9.5 to 1.6 Mev.

2. EXPERIMENTAL SET-UP.

A beam of fast deuterons, obtained from the tube of an electrostatic generator, hit a thin metallic beryllium foil after magnetic analysis. The energy of the incident deuterons had values of 0.5, 0.8, 1.0, 1.2, 1.4 and 1.6 Mev. The voltage of the electrostatic generator was determined with the help of a generating voltmeter, calibrated with the reaction $F^{19}\ (p\ \alpha\gamma)\ O^{16}$. The voltage stabilization was carried out with the help of a corona triode for which the signal was the beam passing through the magnetic analyzer.

The focussed deuteron beam falling on the target had a diameter of about 5 mm. The neutrons from the reaction were detected by means of proton recoil tracks in photoemulsions. The surface of the photoemulsions was placed parallel to the direction of the incoming neutrons coming out of the target. The NIKFI photographic plates with 200 μ thick emulsions were placed at various angles to the direction of the incident deuteron beam in a ring-like hermetically closable duraluminum chamber (Fig. 1). The inside diameter of the chamber was 140 mm, the outside diameter was 170 mm. The

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*This work was carried out in 1950-1952

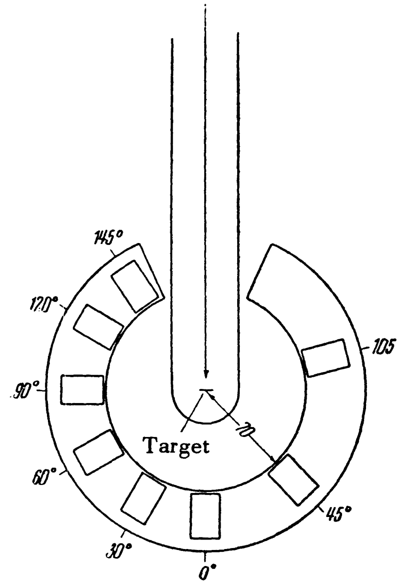


FIG. 1. Experimental Set-Up.

chamber was fastened at the end of the pipe through which the deuteron beam was brought, in such a way that the beryllium target was at the center of the chamber. The thickness of the chamber (wall) was 4 mm which excluded the possibility of charged particles reaching the photoplates.

The photoplates had dimensions of 20 × 30 mm. At each angle, two plates were placed with the emulsions one on top of the other and separated by a 0.1 mm aluminum foil (this was done in case one of the plates was spoiled during development and use). It was checked that the average number of proton recoil tracks was the same on both plates. The distance beteeen the forward edge of the plate and the center of the target was 70 mm for all angles.

The current of the incident beam was measured with a current integrator consisting of a Faraday cup and electronic equipment. The number of deuterons falling on the target at each energy was 1.1×10^{17} (that is, 26.3×10^3 μQ) which gave a sufficient number of proton recoil tracks in the photoemulsions. The target was prepared from pure beryllium (99.99% pure) by evaporation in vacuum and its deposition onto a platinum disk of 16 mm diameter and of 0.2 mm thickness. The target had a glossy metallic finish. The weight of the target was 0.1 mg/cm^2 which corresponded to an energy loss for 1-Mev deuterons of approximately 30 kev.

After exposure, all the photoplates are processed at the same time with an amidol developer. The simultaneous processing of all the plates assured obtaining the same shrinkage of the emulsion layer after drying. The dried photoplates were examined with a microscope. We used binocular microscopes of the "Liuminan" and MBI-2 types, working with a magnification of 7 × 1.5 × 90.

Only those proton recoil tracks were measured which were entirely within the emulsion and which made with the assumed direction of the neutrons (leaving the target under a given angle) a horizontal angle not larger than 5° to the right or to the left and also a dip angle in the emulsion not larger than 5°.

Thirty three plates were examined by us. At each plate the same surface of 36 mm^2 was examined in 3000 fields of view. On the average 400 to 800 proton recoil tracks were measured on each photoplate.

3. NEUTRON ENERGY SPECTRA

The energy spectra are presented in Figs. 2 to 4. They show the number of tracks, counted at each angle and collected as a function of energy in 100-kev intervals (the spectra for deuteron energies of 0.8, 1.2 and 1.4 Mev are not shown, since their appearance is similar to the spectra shown on Figs. 2 to 4). The experimentally obtained number of neutrons was corrected for the neutron-proton scattering cross section according to the formula of Smorodinskii[4] to take into account neutron-proton scattering in the emulsion, and it was also corrected for the probability of the proton leaving the emulsion.

Five groups of neutrons, corresponding to five states of the residual nucleus B^{10}, are well resolved at all angles. The reaction energy Q, was calculated for each maximum on all plates. The average values of Q, are given below in the table for the determined values of the deuteron energies, E_d. The table also shows the corresponding values of the excitation energies E_x for five states of B^{10}.

The results of our measurements are in good agreement with the results published earlier[1-3]. The values of the errors shown for Q were determined from the deviations at various angles and the uncertainly in the range-energy determination connected with the determination of the average values of E_d. For the determination of the neutron yields for each group and also of the total yield of neutrons in a given deuteron energy region, spectra were constructed for each bombarding energy in the center of mass system by summing the data obtained at all angles. These spectra are shown in Fig. 5 for energies of 0.5, 1.0 and 1.6 Mev (the data for 0.8, 1.2 and 1.4 Mev are not presented because they do not differ appreciably from those presented on Fig. 5). On the basis of these spectra, curves were plotted showing the yield for each of the five neutron groups (Fig. 6) and the total yield (Fig. 7).

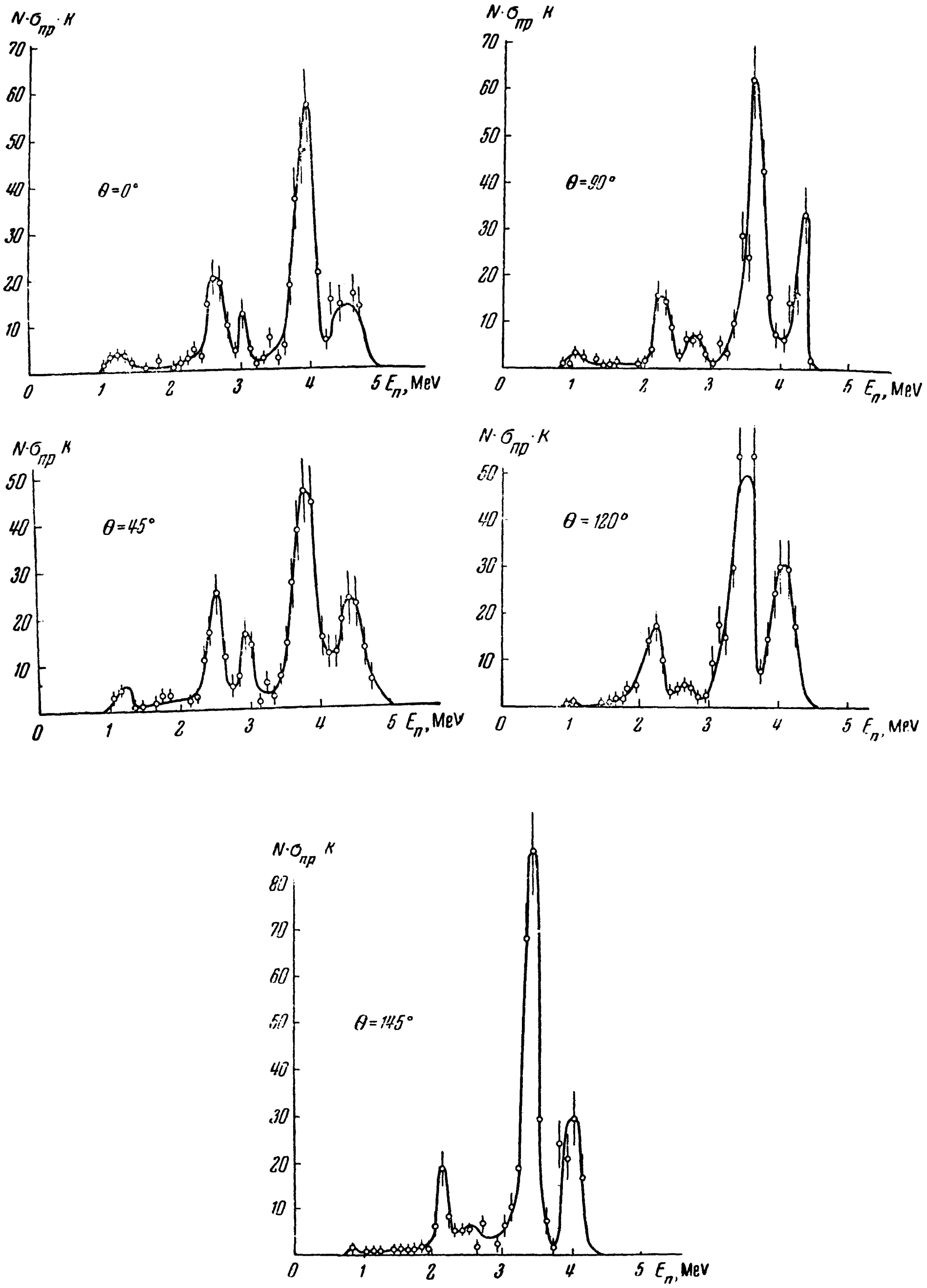


FIG. 2. The neutron spectra from the reaction Be^9 (d, n) B^{10} at $E_d = 0.5$ Mev at various angles (in the laboratory system).

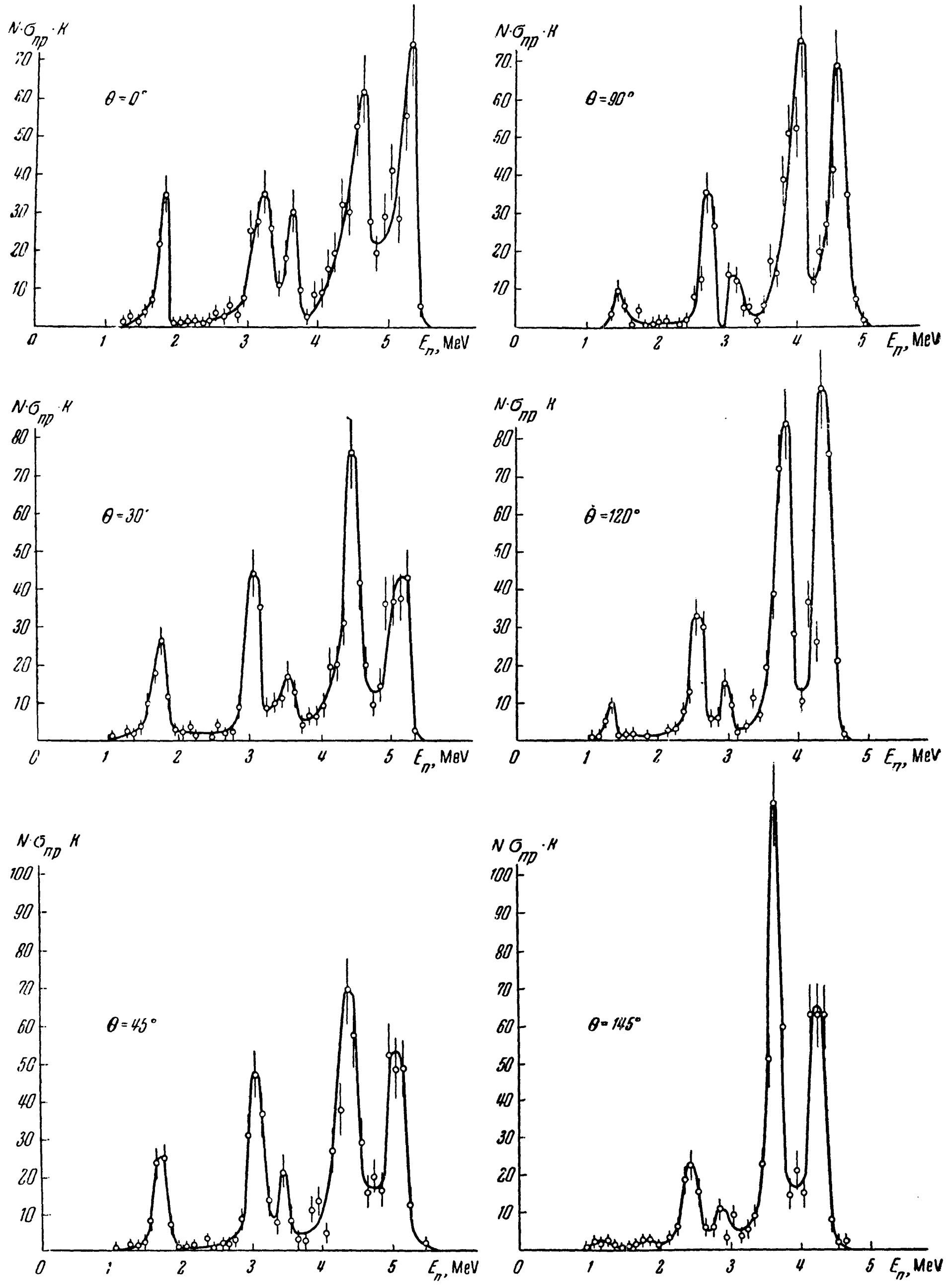


FIG. 3. The neutron spectra from the reaction Be^9 *(d, n)* B^{10} at $E_d=1$ Mev at various angles (in the laboratory system).

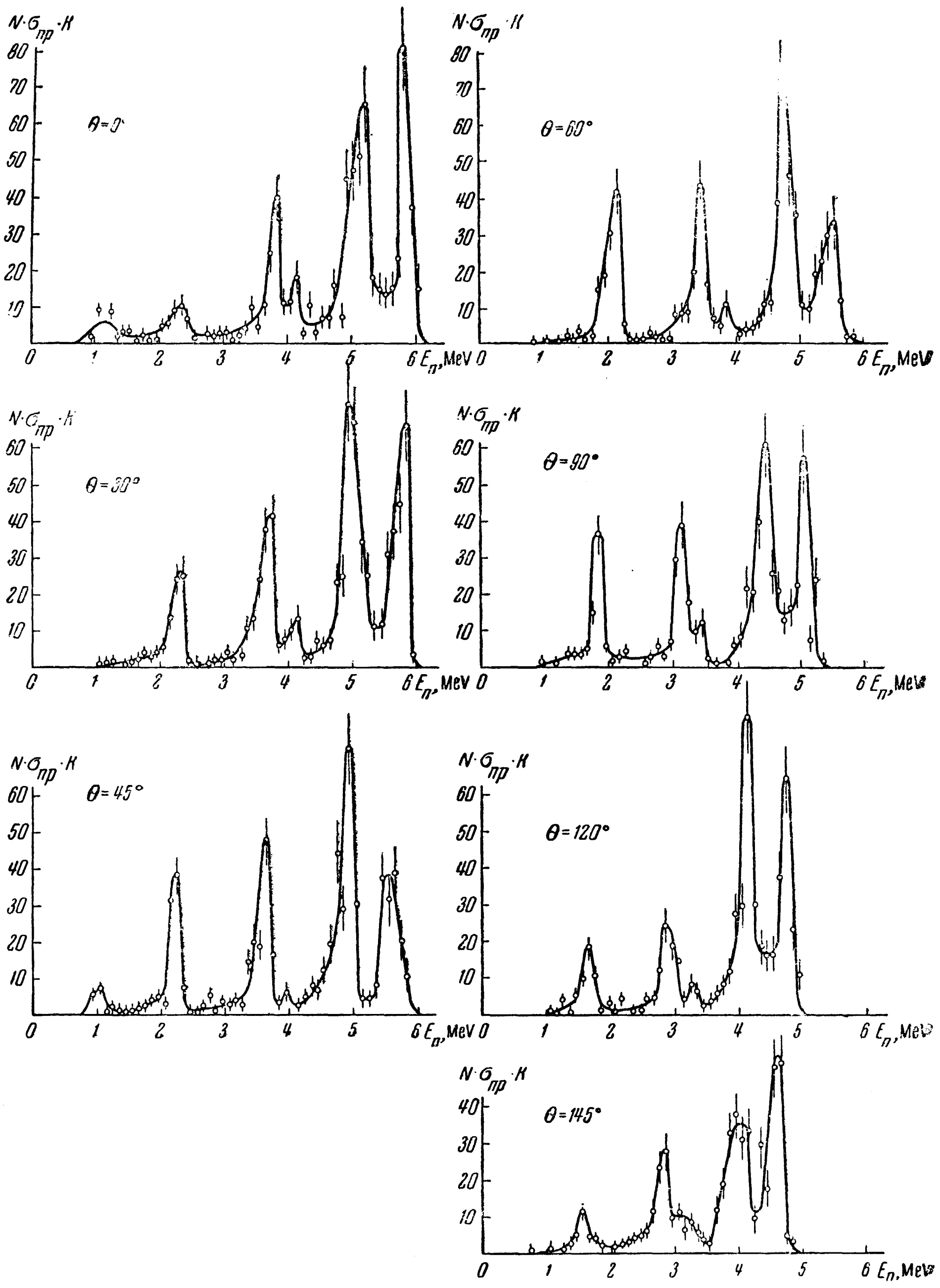


FIG. 4. The neutron spectra from the reaction Be^9 (d, n) B^{10} at E_d=1.6 Mev at various angles (in the laboratory system).

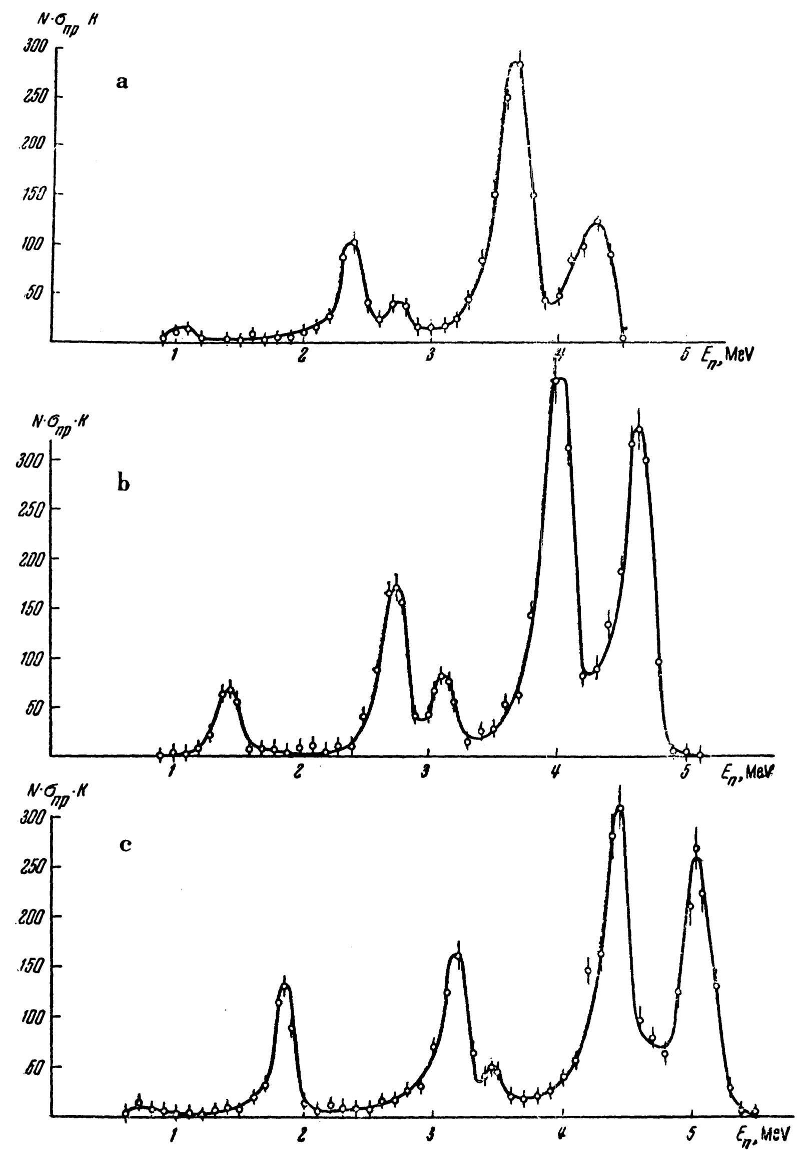
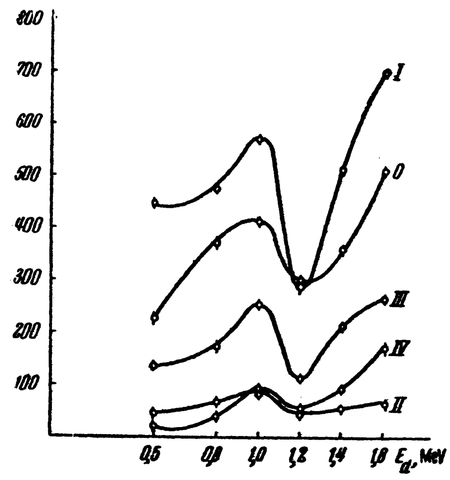


FIG. 5. Neutron spectra from the Be^9 (d, n) B^{10} reaction (in the center of mass system) summed over all angles: $a - E_d = 0.5$; $b - E_d = 1.0$, $c - E_d = 1.6$ Mev.



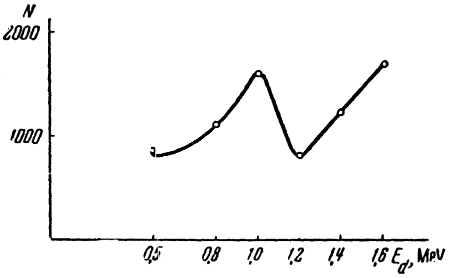


FIG. 7. Total neutron yield corresponding to five energetic groups from the Be^9 (d, n) B^{10} reaction.

FIG. 6. Excitation curves for five neutron groups from the Be^9 (d, n) B^{10} reaction

E_d, MeV	Q	E_x	E_d, MeV	Q	E_x
0,5	4,33±0,04	0,00	1,2	4,32±0,07	0,00
	3,56±0,04	0,77±0,06		3,55±0,06	0,77±0,09
	2,57±0,03	1,76±0,05		2,56±0,05	1,76±0,08
	2,13±0,03	2,20±0,05		2,12±0,05	2,20±0,08
	0,71±0,03	3,62±0,05		0,70±0,05	3,62±0,08
0,8	4,31±0,05	0,00	1,4	4,38±0,07	0,00
	3,54±0,05	0,77±0,07		3,61±0,07	0,77±0,10
	2,55±0,04	1,76±0,07		2,62±0,06	1,76±0,09
	2,11±0,04	2,20±0,07		2,18±0,06	2,20±0,09
	0,69±0,04	3,62±0,07		0,76±0,06	3,62±0,09
1,0	4,37±0,06	0,00	1,6	4,33±0,09	0,00
	3,60±0,06	0,77±0,09		3,56±0,08	0,77±0,12
	2,61±0,05	1,76±0,08		2,57±0,07	1,76±0,11
	2,17±0,05	2,20±0,08		2,13±0,06	2,20±0,10
	0,75±0,05	3,62±0,08		0,71±0,06	3,62±0,10

As can be seen from the results which were obtained, a maximum is observed for a deuteron energy of 1 Mev, which indicates the presence of a resonance for the compound nucleus, B^{11}, at 1 Mev. Evidence on the presence of this resonance has been obtained in work published earlier[5-6] on γ-ray yields. Comparison of the neutron yield curve, shown in Fig. 7, with the results obtained earlier[7-8], does not appear to be possible, because it was not possible by our method to register neutrons of low energy (lower than 1 Mev).

4. THE ANGULAR DISTRIBUTIONS OF THE NEUTRONS

The angular distributions for five states of B^{10} are shown on Fig. 8 (where for the first four states the angular distributions are not shown for the 1.2 and 1.4-Mev energies because they are similar to the angular distribution at 1.6 Mev; for the same reasons, the angular distribution at the 0.5-Mev energy is not shown for the fifth state).

It is seen from the curves that only the fourth excited state with E_x=3.62 Mev is formed as the result of a stripping mechanism. The angular distributions of this group of neutrons have an appreciable maximum in the forward direction, for example at 50°, which is characteristic for an angular distribution in a stripping process. Comparison of these distributions with the Bhatia-Butler theory[9,10] gives good agreement. Results of theoretical calculations carried out with the formula of Bhatia and a nuclear radius R =6.2×10^{-13}cm, for an l= 1 momentum, are shown on the diagrams as black dots.

The shapes of the angular distributions of the other four groups of neutrons are characteristic of processes involving the formation of the compound nucleus, but indicate interference with the stripping mechanism (to the extent that both these mechanisms are coherent). Moreover the angular distributions for these four groups of neutrons in the energy region to 1 Mev coincides with the angular distributions in (previous) work[1-3]. In passing through the maximum at about 1 Mev an appreciable deformation is observed in the angular distribution of these groups of neutrons, which is not detected for the group which is formed by the stripping mechanism.

5. DISCUSSION OF THE RESULTS AND CONCLUSIONS

The results of the investigation show convincingly the presence of the resonance for the compound nucleus B^{11} at an energy of 1 Mev. The angular distribution of the neutrons during passage through the resonance appreciably changes in the case of the formation of the compound nucleus. Such a change in the angular distribution is not observed in the case of a stripping mechanism. This can be seen in Fig. 8 and also in Fig. 9 were relative (with respect to the total neutron yield) yield curves are plotted for each group. As can be seen from the curves, the relative yield of neutrons from the fourth excited state of B^{10} smoothly increases with an increase in the deuteron energy.

Comparison of the curves for the other groups shows that the lower the excitation energy of the residual nucleus, the stronger is the influence of the resonance on the angular distribution. Analysis of the angular distributions in terms of a formula of the type $A + B\cos\theta + C\cos^2\theta$ shows that the

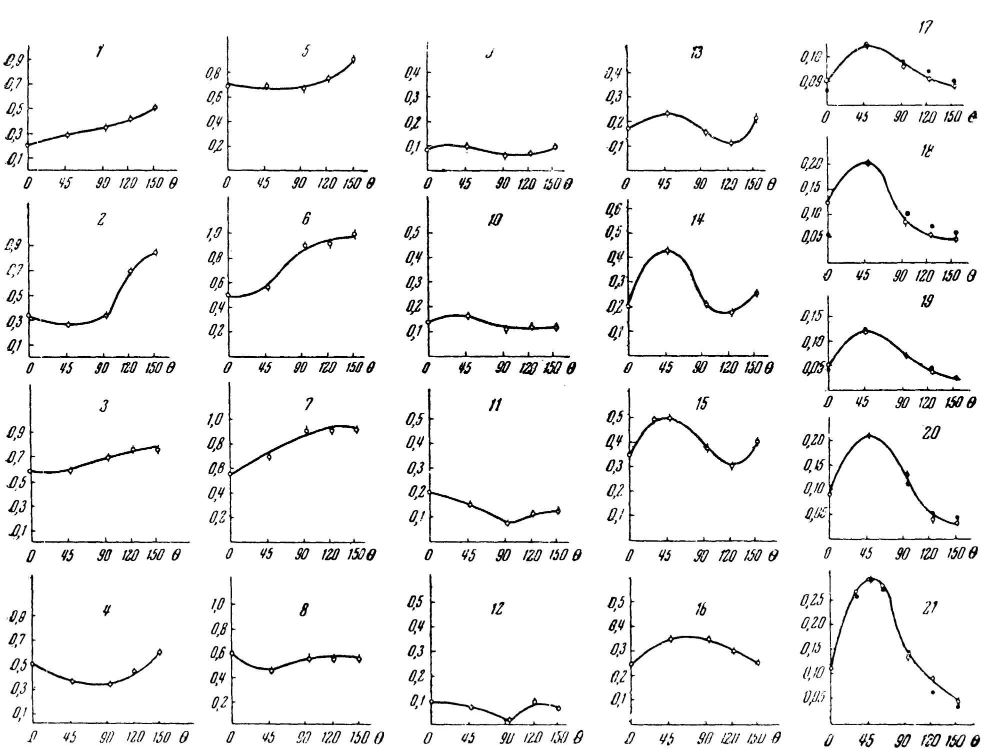


FIG. 8. Angular distributions of neutrons from the Be^9 (*d*, *n*) B^{10} reaction (the angles are in the c. of m. system). For 1, 2, 3, 4 $E_x=0$; for 5, 6, 7, 8 $E_x=0.76$ Mev; for 9, 10, 11, 12 $E_x=1.76$ Mev; for 13, 14, 15, 16 $E_x=2.2$ Mev; for 17, 18, 19, 20, 21 $E_x=3.62$ Mev; for 1, 5, 9, 13 $E_d=0.5$ Mev; for 2, 6, 10, 14, 17 $E_d=0.8$ Mev; for 3, 7, 11, 15, 18 $E_d=1.0$ Mev; for 19, $E_d=1.2$ Mev; for 20, $E_d=1.4$ Mev; for 4, 8, 12, 16, 21, $E_d=1.6$ Mev.

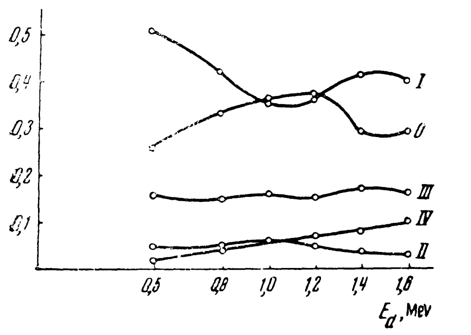


FIG. 9. Yield of individual neutron groups relative to the total yield (the total yield is taken to be unity).

experimental curves of the angular distributions for the ground state of B^{10} and for the first excited state are in good agreement with such a distribution. This calculation is more difficult for the case of the second and third excited states because of the interference process between the formation of the compound nucleus and the stripping reaction.

Spins and parities for this reaction are given in the review article[11].

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