Neutron Thresholds in Light Elements*†

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An investigation of the neutron thresholds obtained by deuteron bombardment of lithium, beryllium, boron (natural and enriched[1]), carbon, and lead fluoride targets has been carried out. Thresholds have been reported previously at deuteron energies of 920, 990, and 1920 kev[2–4] for the reaction $Be^9(d,n)B^{10}$ and at 1.84 Mev[4] for $O^{16}(d,n)F^{17}$. A number of (p,n) thresholds have also been investigated.[4,5]

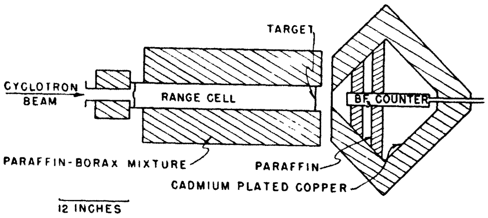

FIG. 1. Apparatus for detection of neutron thresholds.

The apparatus used (Fig. 1) was complicated by the high neutron background and the need for varying the deuteron energy. In addition to the shielding shown in the diagram almost a ton of water was found necessary to cut down the background from the cyclotron, and even so the background level was high. The range cell for varying the bombarding energy was filled with helium. The average values of stopping power of helium needed in calculations were obtained by numerical integration of Mano's results.[6,7] In order to check on these calculations two experimental evaluations were made of the stopping power of helium relative to air. A direct comparison of deuteron ranges in helium and in air was made, and a value of stopping power was also calculated from the experimental threshold results assuming the previously published value of the lowest $Be^9(d,n)B^{10}$ threshold (920 kev). Both of these determinations were slightly higher than the average stopping power calculated from Mano's work but were within the estimated experimental errors.

The experimental curves (Fig. 2) show neutron yield plotted against average deuteron energy, using a value of atomic stopping power of helium relative to air of 0.350. The values assigned to the thresholds are calculated, using the extrapolated beam energy (3.9 Mev) and stopping powers which depend on the energy range concerned (the maximum variation from the value 0.350 is about 2 percent). The probable error is estimated in all cases to be ±0.15 Mev. The yield curve for carbon shows only resonance peaks, as can be seen by comparison with previous results.[8] The detection system is such that both resonances and thresholds can be observed. In general, it is expected that the thresholds will show a sharper increase than the resonances, and when using a homogeneous beam the over-all shapes of response should differ considerably. Another method of distinguishing between the two types of yield is to compare fast neutron yield curves with BF^3 counter yield curves. The yield obtained from a lithium target (not illustrated) could also be attributed to previously reported resonance levels.[9] The results obtained for the reaction $Be^9(d,n)B^{10}$ indicate two levels. The lower threshold has a value of 0.91 Mev, in good agreement with previous work.[2–4,10,11] The upper inflection point at 2.3 Mev might well be due to a resonance level judging by its sharpness. Ajzenberg[11] has obtained levels in B^{10} at 6.37, 6.57, and 6.81 Mev but finds them weak compared with levels at 5.91 and 6.11 Mev. Owing to poor resolution (the width of the deuteron beam at half-maximum was 150 kv) a combination of these levels might account for the response observed. Bonner,[4] however, obtains a threshold at a deuteron energy of 1.920 Mev.

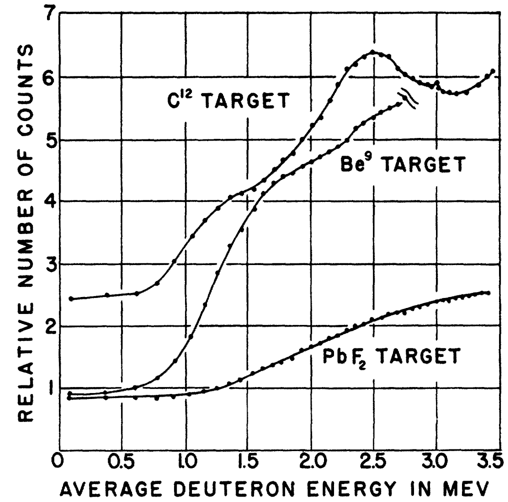

FIG. 2. Relative number of neutron counts *versus* mean deuteron energy for C^{12}, Be^9, and PbF_2 targets. For relative yields from the different targets multiply yield for Be^9 by 4, PbF_2 by 2. The ordinate then represents hundreds of counts on a scale of 256. The Be^9 curve has been terminated at 2.7 Mev to prevent confusion. No beryllium thresholds were observed above this energy.

The curve for $F^{19}(d,n)Ne^{20}$ indicates an increase in yield at 1.3 Mev and a steady increase thereafter. No fast neutron yield curve has been obtained for this reaction, but the shape of the yield indicates a broad resonance in Ne^{21} about 20 Mev above ground. An exact value cannot be given because no yield maximum is obtained. If it is a true neutron threshold, this would indicate that close spaced levels begin in Ne^{20} at 11.9 Mev above ground (see reference 12 for energy level diagram of Ne^{20}).

Yields from targets of natural and enriched boron (96 percent B^{10}) are compared in Fig. 3. It appears that the reaction $B^{11}(d,n)C^{12}$ is responsible for the entire yield. Results[13] on the fast neutron yield from $B^{11}(d,n)C^{12}$ indicate that the first slow increase (about 1.3 Mev) is due to a resonance level in C^{13}. The 1.9-Mev threshold agrees very well with the 1.84 threshold for $O^{16}(d,n)F^{17}$. The fact that this threshold is observed for both targets seems to indicate an oxygen contamination. The rise at

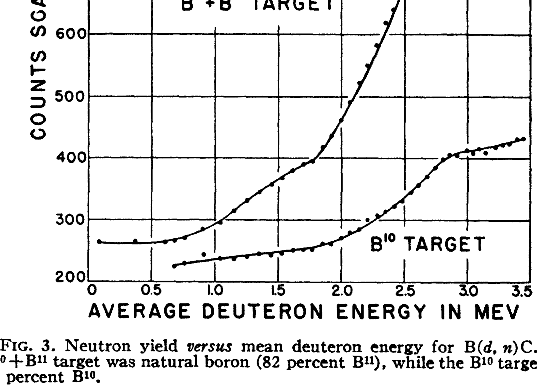

FIG. 3. Neutron yield *versus* mean deuteron energy for $B(d,n)C$. The $B^{10}+B^{11}$ target was natural boron (82 percent B^{11}), while the B^{10} target was 96 percent B^{10}.

the end of the curve is not complete enough to obtain an accurate threshold energy, but an approximate value of 3.4 Mev is assigned to it. There is no way of determining whether this last rise is due to a resonance level or not. The fast neutron yield curve[13] referred to above does not reach this energy.

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Alpha-Particle Range-Energy Curve for Kodak NTA Emulsions*

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The range-energy curves for Ilford B1 emulsions reported by Lattes, Fowler, and Cuer[1] have been used as standards for several years. Recent observations, however, indicate that the alpha-particle curve rises too steeply at the higher energies. Berlman[2] has modified the proton curve for use with alpha-particles and obtained a curve suitable for Ilford E1 plates. A modified curve has been derived for Kodak NTA emulsions at this laboratory.

The stopping power of the emulsion relative to air for alpha-particles was calculated as a function of the energy by using the procedure outlined by Webb.[3] The emulsion is approximated by a homogeneous compound having the composition given by Rotblat.[4] The atomic stopping powers used were interpolated from plots of stopping power *versus* atomic number and energy, as constructed from Bethe's[5] semi-empirical tabulation. This data was then combined with Bethe's[6] range curves for air, and the resultant curve of range in emulsion *versus* alpha-particle energy shown in Fig. 1 was obtained. Points were calculated at 0.5-Mev intervals, representative values being given in Table I. The curve rise is less steep than indicated by Lattes, Fowler, and Cuer, and there appears to be good agreement with the recent work of Rotblat. The agreement of this curve with experimental data has been obtained in this laboratory, extending the accurate measurement of tracks to 14.9 Mev. Experimental points were taken using natural alpha-particles from polonium and thorium-active deposit sources and the two long-range alpha-groups in the $Al^{27}(d, \alpha)Mg^{25}$ reaction, observed at various angles under Bethe's conditions of good geometry. The Q-values[7] and deuteron energy are known by magnetic analysis to 10 and 40 kev, respectively. The angle of observation was accurate to 15 minutes. Data obtained using this curve agree very well with published work using aluminum foils and counters.[8] Curves showing some of the alpha-groups obtained in these experiments are given in Fig. 2. The calibration points on the range-energy curve were obtained by taking the average value from several plates to obtain good statistics. The position of the peaks was observed not to shift as a function of time of exposure in vacuum over the range of several minutes to one hour.

TABLE I. Calculated and observed α-particle ranges.

Calculated		Observed		
Alpha-energy Mev	Range microns	Source	Energy Mev	Range microns
2.07	6.88	Po	5.30	21.2
3.00	10.44	ThC	6.06	26.8
4.00	14.50	ThC′	8.78	47.1
5.00	19.6	$Al^{27}(d, \alpha)Mg^{25}$		
6.00	25.6			
7.00	32.2	(0) 124°	13.77 ±0.08	91.3
8.00	39.5	(I) 90°	13.83	96.6
9.00	47.3	(I) 89°	13.87	97.4
10.00	55.6	(0) 90°	14.34	101.6
11.00	65.0	(I) 60°	14.36	103.9
12.00	74.9	(0) 89°	14.38	103.0
13.00	85.2	(0) 60°	14.87	109.9
14.00	96.4			
15.00	108.7			

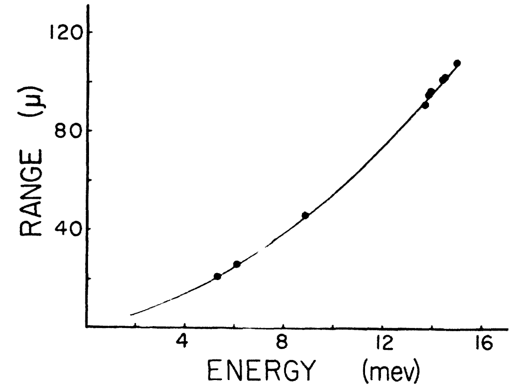

FIG. 1. Calculated alpha-particle range-energy curve for Kodak NTA emulsions, with experimental check points.

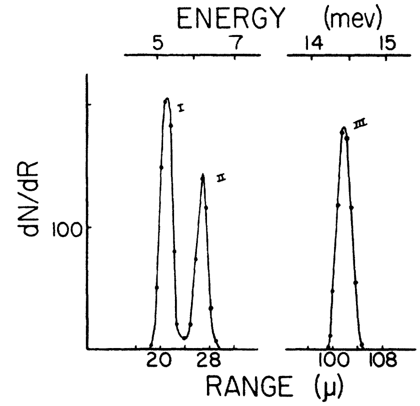

FIG. 2. Typical data obtained from plates. Peak I, Po; II, ThC; III, $Al^{27}(d, \alpha)Mg^{25}$. The energy scale is plotted above for comparison.

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