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On the Scattering of Fast Neutrons by Protons and Deuterons

M. Ageno,[*] E. Amaldi,[*] D. Bocciarelli,[†] and G. C. Trabacchi[†]
Instituto Superiore di Sanità, Roma, Italia

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The scattering cross sections of the proton, deuteron, and the carbon nucleus have been determined for 4.1-, 12.5-, and 13.5-Mev neutrons by detecting the corresponding recoil protons. A coincidence set of three proportional counters was used. Similar measurements were made with 14-Mev neutrons from the reactions D+Li. These were detected by the 9.9-min. activity arising from the reaction ${}_{29}\mathrm{Cu}^{63}+{}_0n^1\rightarrow{}_{29}\mathrm{Cu}^{62}+2{}_0n^1$. The $n-2n$ disintegration of the deuteron has been investigated for 14-Mev neutrons and cross section found to be of the order of 9–4 $\times10^{-26}$ cm². The scattering cross sections at 4.1, 12.5, and 13.5 Mev are, respectively, for H 1.73, 0.69, 0.694×10^{-24} cm²; for D 1.79, 0.78, 0.864×10^{-24} cm²; for C 1.99, 1.40, 1.23×10^{-24} cm². The experimental results are compared with those of other experimenters and with theoretical predictions.

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1. INTRODUCTION

INFORMATION about the nuclear forces can be deduced by comparing the experimentally determined energy-dependence of the neutron-proton scattering cross section with the corresponding theoretical predictions. The more valuable experiments for such a purpose are those carried on with mono-energetic neutrons. Such neutrons are produced according to reaction

$$ {}_1\mathrm{D}^2+{}_1\mathrm{D}^2\rightarrow{}_2\mathrm{He}^3+{}_0n^1, \tag{1}$$

whose spectrum energy is variable with both the observation angle and the voltage used to accelerate the impinging deuterons.

Of the numerous experiments performed with reaction (1) we shall mention that of Aoki[1] who, by changing the observation angle, was able to determine the proton-neutron cross section for five different values of the energy of the impinging neutrons ranging between 2.14 and 2.76 Mev. Other experiments performed with reaction (1) refer to neutron energies varying, from case to case, between 2.4 and 3 Mev.[2] Besides these measurements and those performed with slow neutrons,[3] there have been others carried on with neutrons of about 0.2–0.3 Mev produced by nuclear photo-effect[4] or by the reaction[5]

$$ {}_1\mathrm{D}^2+{}_6\mathrm{C}^{12}\rightarrow{}_7\mathrm{N}^{13}+{}_0n^1. \tag{2}$$

For energies larger than 3 Mev there is a lack of published experimental data. As far as we know only Salant, Roberts, and Wang[6] and Salant and Ramsay[7] have performed measurements with the neutrons from the reaction

$$ {}_1\mathrm{D}^2+{}_3\mathrm{Li}^7\rightarrow{}_4\mathrm{Be}^8+{}_0n^1 \tag{3}$$

detected by means of the activity of 9.9-min. period, produced in copper according to the reaction

$$ {}_{29}\mathrm{Cu}^{63}+{}_0n^1\rightarrow{}_{29}\mathrm{Cu}^{62}+2{}_0n^1, \tag{4}$$

$$ {}_{29}\mathrm{Cu}^{62}\rightarrow{}_{28}\mathrm{Ni}^{62}+e^+. \tag{5}$$

It is to be noticed that reaction (4) has an appreciable yield only for energies of the impinging neutron larger than 11 Mev,[8] so that the results of these authors refer to neutrons of about 14 Mev.

Finally, considering all the measurements performed up to the present, it is to be noticed that the experimental methods are different for different energy, excepting the measurements of

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[*] Instituto di Fisica dell' Università, Centro di Fisica Nucleare del C.N.R.

[†] Instituto Superiore di Sanità.

[1] H. Aoki, Phys. Rev. **55**, 795 (1939).

[2] E. T. Booth and C. Hurst, Proc. Roy. Soc. **A161**, 248 (1937); R. Ladenburg and M. H. Kanner, Phys. Rev. **52**, 911 (1937); W. H. Zinn, S. Seely, and V. W. Cohen, Phys. Rev. **56**, 260 (1939).

[3] E. Amaldi and E. Fermi, Ricerca Scient. 7–1, 223, 393 (1936); Phys. Rev. **50**, 899 (1936); L. Simons, Phys. Rev. **55**, 792 (1939); Kgl. Danske Vid. Sels. Math.-Fys. Medd. 16 (1940); V. W. Cohen, H. H. Goldsmith, and J. Schwinger, Phys. Rev. **55**, 106 (1938); H. B. Hanstein, Phys. Rev. **57**, 1045 (1940).

[4] A. Leipunski, L. Rosenkewitsch, and D. Timoschuk, Phys. Sov. **10**, 625 (1936); W. E. Good and G. Scharff-Goldhaber, Phys. Rev. **58**, 89 (1940).

[5] E. Amaldi, D. Bocciarelli, and G. C. Trabacchi, Ricerca Scient. **11**, 121 (1940).

[6] E. O. Salant, R. B. Roberts, and P. Wang, Phys. Rev. **55**, 984 (1939).

[7] E. O. Salant and N. F. Ramsay, Phys. Rev. **57**, 1075 (1940).

[8] R. Sagane, Phys. Rev. **53**, 492 (1938).

Aoki, which cover a rather narrow energy interval.

For a strict comparison with theory it would be very convenient to have measurements performed with mono-energetic neutrons whose energy could be varied within wide limits.

In Section 2 we shall explain a method which satisfies rather well such a condition; it has been applied to the determination of the scattering cross sections of hydrogen, deuterium, and carbon for 4.1-, 12.5-, and 13.5-Mev neutrons.

In other sections we attempt to clarify some interesting points about the neutron-proton and neutron-deuteron collisions.[9]

2. THE METHOD

Our experimental arrangement is shown in Fig. 1. Neutrons emitted by the source S impinge on the paraffin layer P whose thickness (2 mm) is negligible with respect to the absorption of neutrons and large with respect to the range of recoil protons. Protons projected in the forward direction and fast enough to go through the Al-absorber A, are registered by a coincidence-set of three proportional counters, $c_1c_2c_3$.

The triple coincidences are caused only in part by protons recoiling from P; in part they are caused by random coincidences whose number, depending on the type of neutron source and on the geometry of the arrangement can be determined by inserting in position O' an absorber thick enough to stop all recoil protons. Therefore, all measurements were performed by counting the triple coincidences with this last absorber in position O (obturator opened) and then in position O' (obturator closed) and taking the difference between the two numbers so obtained.

The absorber A determines the minimum energy E_0 of the registered recoil protons. All the measurements were performed with protons scattered in the forward direction; hence, the energy of recoil protons is equal to the energy of the impinging neutrons. If $E_{\max}$ is the maximum energy of the neutrons emitted by the source S, the difference between the numbers of triple coincidences counted with obturator open and closed is caused only by recoil protons from neutrons whose energy lies in the interval $E_0-E_{\max}$. That is, our apparatus is a detector sensitive only to neutrons lying in a narrow energy interval close to the end of the spectrum of the neutrons from the source. This last limitation can be eliminated by replacing the thick obturator with another one chosen in such a way that only protons of energy equal or larger than E' can be registered when both the absorber A and the new obturator are in the path of the particles recoiling from P.

Under these last conditions the difference between the numbers of triple coincidences counted with this new obturator open and closed is caused only by recoil protons from neutrons whose energy lies between the two arbitrarily fixed values E_0 and E'.

As we shall see in Section 4, our measurements of the cross sections have been performed, by means of the first of these methods, for neutrons of energy equal to 4.1, 12.5, and 13.5 Mev.

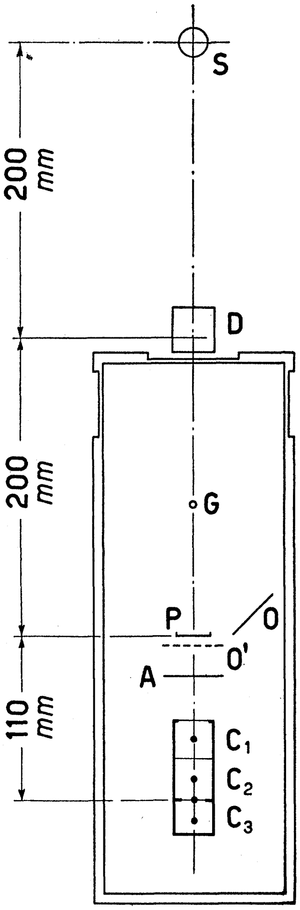

FIG. 1. Arrangement of source and scattering chamber.

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[9] M. Ageno, E. Amaldi, D. Bocciarelli, and G. C. Trabacchi, Naturwiss. **31**, 231 (1943); Nuovo Cimento **1**, 253 (1943).

With the second method a measurement at 8 Mev was attempted; however, the result was rather uncertain on account of the large statistical error affecting a rather small difference between large numbers.

In order to determine the total (transmission) cross section of a given element for neutrons of the chosen energy interval, it is sufficient to insert, at about half-way between S and P, a scatterer D containing that element. The ratio of the numbers of recoil protons observed with and without such a scatterer in the position shown in Fig. 1, gives the transmitted fraction of impinging neutrons which is connected by a simple well known relation to the desired total cross section.

In conclusion for every value of both the energy E_0 (and E_{max}) and the thickness of the scatterer, we must perform four measurements under the following conditions: with obturator open and without scatterer: OO; with obturator open and with scatterer: OS; with obturator closed and without scatterer: CO; and with obturator closed and with scatterer: CS.

TABLE I. Data on scattering as determined by recoil proton. Each transmission determination is the result of 200 measurements except as indicated.

Scatterer	Thickness (cm)	Thickness (g/cm²)	Number of recoil protons OO	OS	CO	CS	Transmission T
D+Be; $E_0=3.2$ Mev; $E_{\text{max}}=4.6$ Mev; $\bar{E}=4.1$ Mev							
$C_{32}H_{66}$	1.6	1.4	6601	4802	732	659	0.706 ±0.016
	2.95	2.6	6055	3381	727	538	0.534 ±0.014
	6.0	5.2	6403	2235	791	454	0.317 ±0.011
$C_{35}D_{72}$	3.0	2.94	5836	3329	698	475	0.555 ±0.015
	4.85	4.74	6305	2602	743	545	0.370 ±0.012
C	4.0	6.34	6010	3336	702	526	0.529 ±0.014
	6.0	9.51	6345	2808	720	541	0.403 ±0.012
	8.0	12.68	6208	2191	753	515	0.307 ±0.011
D+B; $E_0=9.4$ Mev; $E_{\text{max}}=13.2$ Mev; $\bar{E}=12.5$ Mev							
$C_{32}H_{66}$	6.0	5.2	2815	1683	923	655	0.543 ±0.022
$C_{35}D_{72}$	4.85	4.74	2647	1795	889	692	0.627 ±0.024
C	4.0	6.35	2843	2036	853	753	0.644 ±0.024
D+Li; $E_0=11.5$ Mev; $E_{\text{max}}=14.5$ Mev; $\bar{E}=13.5$ Mev							
$C_{32}H_{66}$	2.95	2.6	13706	10382	5343	4128	0.748 ±0.019
	6.0	5.2	13094	7322	5369	3318	0.518 ±0.016[1]
	8.95	7.8	9462	4354	3664	1773	0.445 ±0.016[2]
$C_{35}D_{72}$	3.0	2.94	14063	10269	5096	3970	0.702 ±0.017
	4.85	4.74	13027	8054	5462	3512	0.600 ±0.018
C	2.0	3.17	12211	10183	4248	3680	0.817 ±0.020[3]
	6.0	9.5	13560	8366	5136	3469	0.581 ±0.016
	10.0	15.9	8461	3350	3018	1456	0.385 ±0.015[4]

[1] Result of 160 measurements.
[2] Result of 150 measurements.
[3] Result of 210 measurements.
[4] Result of 130 measurements.

3. THE EXPERIMENTAL ARRANGEMENT

The experimental arrangement was about the same as that used in an earlier research[10]; therefore, details of the construction and the voltage (2140 v) applied to the counters and on the registering set will not be given here.

The scattering chamber was changed as shown in Fig. 1. The paraffin arc used in our preceding research was taken away from its support G and replaced by a 2-mm thick paraffin layer P of 25×40 mm² area, supported by a brass plate 1 mm thick.

The distance between the paraffin surface and the first wall of the third counter was 110 mm. The walls of the counters were of Al 1.93 mg/cm² thick. The scattering chamber was filled with commercial argon at atmospheric pressure. As shown in Fig. 1 the distances between the source S and scatterer $D(d_1)$ and between scatterer D and paraffin $P(d_2)$ were both 200 mm.

The neutron source S was a target of Be, B, or Li bombarded with deuterons of 0.8 Mev produced by the one million-volt equipment of the Istituto Superiore di Sanità. The target was reduced to a disk of 20-mm diameter by means of an iron screen. The neutrons were observed at 90° with respect to the direction of the impinging deuterons.

The scatterers had an area equal to 30×30 mm² and thicknesses varying between 20 and 90 mm.

In order to count the triple coincidences alternatively in the four conditions OO, OS, CO, CS, we have used the same automatic device used in our preceding research, conveniently modified[10]: the scattering chamber containing the paraffin P and the counters remained in a fixed position while the scatterer D, supported by a long 2 mm thick aluminum arm, was periodically inserted and taken away from the path of the neutrons coming from S and impinging on P.

The triple coincidences were registered for 28 sec. in each of the four above-mentioned arrangements; then the arrangement was changed automatically in 2 sec. By alternating so frequently the four measurements, the effect of slow varia-

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[10] E. Amaldi, D. Bocciarelli, B. Ferretti, and G. C. Trabacchi, Naturwiss. **30**, 582 (1942); Ricerca Scient. **13**, 502 (1942).

tions of the neutron emission or detection sensitivity was made as small as possible. By means of a convenient caliper the distances and the alignment were frequently checked during the measurements.

4. THE MEASUREMENTS

The measurements were performed with neutrons from the three reactions Be(D, n), B(D, n), Li(D, n). The more critical point in all measurements of the transmitted fraction of neutrons is to ascertain that the number of neutrons scattered by the surrounding materials and room-walls is negligible with respect to the number of neutrons impinging on the detector directly from the neutron source.

Although the experiments described in subsection (6a3) and (6a4) of our earlier paper[10] had given very satisfactory results on this point, we performed two more checks with D+Li neutrons at $E_0=11.15$ Mev.

(a) We have verified that the number of registered protons varies proportionally to the square of the distance $r=d_1+d_2$ of the paraffin P from the source S. By increasing this distance from $r'=16.6$ cm to $r''=29.6$ cm, the number of registered protons decreased by a factor 3.12 ± 0.15, in satisfactory agreement with $(r''/r')^2=3.18$.

(b) In our apparatus the target was cooled by means of a water layer about 2 mm thick which could give rise to a few scattered neutrons. In order to check this point we substituted for the scattered D a 6-cm thick paraffin ring whose inner and outer diameter were, respectively, 4.5 and 9.0 cm. We found that the paraffin ring increased the number of registered protons by a factor 1.109 ± 0.031. Considering the thickness and the geometrical disposition of the water-cooling, we can conclude that it gives rise to a negligible number of neutrons scattered to the detector with energy high enough to be registered.

We measured the fraction of neutrons transmitted by scatterers of light paraffin, heavy paraffin, and graphite. The melting point of the light paraffin was between 68° and 70°C so that we can assume the formula $C_{32}H_{66}$. The melting point of heavy paraffin was higher than 77°C so that we can assume the formula $C_{35}D_{72}$; the graphite used was "Acheson."

In the measurements with neutrons from Be, B, and Li the Al absorber A was, respectively, 0 mg/cm², 124 mg/cm², and 175.5 mg/cm² thick. Taking into account the thickness of the five counter-walls ($5\times1.93=9.6$ mg/cm² Al), the distance (11 cm of argon) between the paraffin P and the first wall of the third counter, and the stopping-power of aluminum,[11] we found that the minimum ranges of recoil protons, in the three above-mentioned conditions, were, respectively, 17.5, 103, 140 air cm, corresponding to $E_0=3.2$, 9.4, 11.15 Mev.

The results of our measurements are given in Table I; in addition to the minimum energy E_0, the maximum energy $E_{\max}$, and the mean energy $\bar{E}$ are also given. For the neutrons from B and Li $E_{\max}$ was deduced from the absorption curves of recoil protons given in our earlier paper.[10] A similar curve was measured in the case of the neutrons from Be which turned out to agree very well with the results of other authors.[12]

The mean energy $\bar{E}$ was calculated by formula (11) of our earlier paper from the above-mentioned absorption curves for B and Li neutrons, and the spectrum of Bonner and Brubaker for Be neutrons. In Table I, besides the thickness of the scatterers, we give the numbers of recoil protons registered in the 4 dispositions $OO\ OS\ CO\ CS$, and the transmitted fraction

$$T=(OS-CS)/(OO-CO). \qquad (6)$$

The errors are calculated from the square root of the number of counted pulses, by means of the usual propagation rule. In some cases we have calculated the standard deviation which turned out to be about 1.3 times the error calculated from the square root of the number of pulses.

In the case of the neutrons produced by means of reaction

$$_1D^2+{}_5B^{10,\,11}\rightarrow{}_6C^{11,\,12}+{}_0n^1, \qquad (7)$$

the measurements were performed for a single value of the thickness of the scatterer because the mean energy of these neutrons does not differ very much from that of neutrons produced in reaction (3) which has the advantage of a much higher intensity.

We have also attempted to measure the transmitted fraction of the neutrons of the second group of reaction (7) which extends between 7.3 and 9.1 Mev. For such a purpose the obturator was replaced by an Al absorber 60.6 mg/cm²

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[11] M. S. Livingstone and H. A. Bethe, Rev. Mod. Phys. 9, 276 (1937),

[12] T. W. Bonner and W. M. Brubaker, Phys. Rev. 50, 308 (1936).

thick; the Al absorber A was 54.8 mg/cm^2 thick; and the paraffin P 43 mg/cm^2, corresponding to 43 cm air. Under these conditions with obturator open and closed we counted only recoil protons whose range was equal or larger than, respectively, 66 cm of air (7.3 Mev) and 97 cm of air (9.1 Mev); the calculated mean energy $\bar{E}$ was 8 Mev.

From these measurements we found, for each scatterer studied, a result intermediate to that obtained at $\bar{E}=4.1$ Mev (D+Be) and at $\bar{E}=13.5$ Mev (D+Li). However, the statistical errors were appreciably higher than that reported in Table I, as we must expect, taking into account that in this case we deal with relatively small differences between rather large numbers. Therefore we do not report in detail these results which, although in agreement with all other measurements, are not usable for a strict comparison with theory.

In order to check our results by a different method we repeated the measurements of the transmitted fraction of the D+Li neutrons, using, as detector, the activity induced in copper according to reaction (4). This method [6, 7] is very simple; it is, however, to be noticed that the value of the threshold of reaction (4) is rather uncertain and the dependence of its cross section on the energy of the impinging neutrons is practically unknown. For this reason the agreement between the results obtained by detecting fast neutrons by means of recoil protons and by means of the copper activity, must be considered as a reciprocal check of the two methods.

In order to have geometrical conditions similar to those used in the preceding measurements, the copper detectors were plates, 1 mm thick, bent in the form of cylinders 25 mm in diameter and 40 mm long so that their section (25×40 mm^2) was equal to the area of the paraffin sheet of Fig. 1. The distance between source and detector was again 40 cm and the scatterer was placed at half this distance.

TABLE II. Scattering of neutrons from the D+Li reaction detected by use of the Cu^{62} 9.92-min. activity.

cm	g/cm^2	Number of counts without scatterer	Zero effect	Number of counts with scatterer	Zero effect	Transmission	
						T'	T
				Scatterer $C_{32}H_{66}$			
2.95	2.6	28016	4820	21696	4970	0.721±0.009	0.748±0.019
6.0	5.2	25829	4900	16848	4857	0.573±0.009	0.518±0.016
8.95	7.8	29768	5170	15648	5060	0.430±0.008	0.445±0.016
				Scatterer $C_{35}D_{72}$			
3.0	2.94	29592	5530	23190	5530	0.730±0.009	0.702±0.017
4.85	4.74	27597	5150	18640	5160	0.592±0.008	0.600±0.018
				Scatterer C			
2.00	3.17	25944	5080	22576	4980	0.843±0.011	0.817±0.020
6.0	9.5	27746	5000	17712	4870	0.564±0.008	0.581±0.016
10.0	15.9	28202	4980	13840	4910	0.384±0.007	0.385±0.015

To reduce, as much as possible, the number of scattered neutrons, all surrounding materials were removed; the scatterer and the detector were supported by an aluminum plate, 1 mm thick and 3 cm wide, marked with convenient lines, which permitted the distances and the alignment of scatterer and detector in the successive experiments to be reproduced accurately. During irradiation the detector was screened with cadmium 0.78 g/cm^2 thick to eliminate the copper activity of 5-min. period produced by slow neutrons.

The influence of slow intensity-variation in the neutron emission was eliminated by irradiating at the same time two copper detectors placed at the same distance from the source, in two directions forming an angle of about 30°: the scatterer was placed in the path of the neutrons impinging on one of these two copper cylinders.

After ten minutes irradiation, the two detectors were placed around two thin-walled glass counters and the number of pulses was registered by means of a "scale-of-16" and a "scale-of-8." The counting continued for 19 minutes, starting one minute after the end of irradiation. The measurement was repeated with the same scatterer placed in the path of the neutrons impinging on the other copper cylinder and the results of the two measurements were added together. The zero effect was measured before and after each measurement.

The results are summarized in Table II; the values given are the sum of the pulses counted in four measurements. In column 8 we give the transmitted fraction T' deduced from the preceding data, while in column 9 we reproduce, for comparison, the transmitted fraction of neutrons T deduced by means of (6) from the recoil-proton measurements (Table I, D+Li).

The agreement is very satisfactory so that it seems to us reasonable to assume that the meas-

TABLE III. Scattering cross sections from the data of Tables I and II.

Scatterer	Δ	K'	K''	$T-K$	$\sigma\times10^{24}$	Molecular $\sigma\times10^{24}$ (average)	Atomic $\sigma\times10^{24}$ (average)
				D+Be $\bar{E}=4.1$ Mev			
C	6.34	0.003	0.003	0.523	2.04± 0.08		$\sigma(C)=1.99$ ±0.04
$\Lambda=6.5$ cm	9.51	0.004	0.007	0.392	1.99± 0.07		
protons	12.68	0.005	0.012	0.290	1.97± 0.06		
$C_{35}D_{72}$	2.94	0.003	0.003	0.549	192± 8.7	199±5.4	$\sigma(D)=1.79$ ±0.08
$\Lambda=4.9$ cm	4.74	0.004	0.008	0.358	204± 7.0		
protons							
$C_{32}H_{66}$	1.4	0.003	0.000	0.703	188±12	178±4	$\sigma(H)=1.73$ ±0.06
$\Lambda=4.9$ cm	2.6	0.006	0.001	0.527	185± 7.6		
protons	5.2	0.008	0.006	0.303	173± 5.2		
				D+B $\bar{E}=12.5$ Mev			
C	6.35	0.003	0.001	0.640	1.40± 0.12		$\sigma(C)=1.40$ ±0.12
protons							
$C_{35}D_{72}$	4.74	0.003	0.002	0.622	95± 7.7		$\sigma(D)=0.78$ ±0.12
protons							
$C_{32}H_{66}$	5.2	0.006	0.002	0.535	90.5± 6		$\sigma(H)=0.69$ ±0.11
protons							
				D+Li $\bar{E}=13.5$ Mev			
$\bar{E}=13.5$ Mev	3.17	0.001	0.000	0.816	1.29± 0.16	1.22±0.037	$\sigma(C)\doteq1.23$ ±0.015
C	9.5	0.003	0.002	0.576	1.17± 0.06		
$\Lambda=10.6$ cm	15.9	0.004	0.008	0.373	1.25± 0.05		
protons							
$\bar{E}=14$ Mev	3.17	0.001	0.000	0.842	1.09± 0.08	1.23±0.016	
C	9.5	0.003	0.002	0.559	1.23± 0.03		
Cu	15.9	0.004	0.008	0.372	1.24± 0.02		
$\bar{E}=13.5$ Mev							
$C_{35}D_{72}$	2.94	0.002	0.001	0.699	115±10	107±5.1	$\sigma(D)=0.864$±0.028
$\Lambda=9.2$ cm	4.74	0.003	0.002	0.595	104± 6		
protons							
$\bar{E}=14$ Mev	2.94	0.002	0.001	0.727	102± 4	105±2.2	
$C_{35}D_{72}$	4.74	0.003	0.002	0.587	106± 2.7		
Cu							
$\bar{E}=13.5$ Mev	2.6	0.003	0.000	0.745	84.5± 7.3	86.5±2.6	$\sigma(H)=0.694$±0.019
$C_{32}H_{66}$	5.2	0.006	0.002	0.510	97.2± 4.5		
$\Lambda=9.4$ cm	7.8	0.007	0.004	0.434	80.5± 3.5		
protons							
$\bar{E}=14$ Mev	2.6	0.003	0.000	0.718	95.2± 3.5	85.0±1.35	
$C_{32}H_{66}$	5.2	0.006	0.002	0.566	82.2± 2.3		
Cu	7.8	0.007	0.004	0.419	83.8± 1.9		

urements, performed with both methods, cannot be affected by serious systematical errors.

As a further check of the measurements performed with a copper detector, we have plotted, on a semilogarithmic scale, the decay curve of Cu obtained by adding the pulses counted in each minute, in all the measurements used to deduce Table II. Such a decay curve turned out to be a straight line corresponding to a half period of 8.3±0.4 min. As this value is appreciably lower than that obtained by Crittenden[13] (9.92 ±0.05), one could suspect a slight influence, in our measurements, of the 5-min. period. Although our decay curves can be analyzed only with difficulty into two exponentials of 5- and 9.9-min. periods, we have calculated under this assumption the percentage of the total number of pulses which could be attributed to slow neutrons. We found less than five percent so that we considered it unnecessary to introduce any correction for this reason.

5. RESULTS

If the transverse dimensions of neutron-source *S*, detector *P* and scatterer *D* are negligible with respect to the distances d_1, d_2, the percentage

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[13] E. C. Crittenden, Phys. Rev. 56, 709 (1939).

of the transmitted neutrons varies exponentially with the thickness z of the scatterer

$$e^{-z/\Lambda}. \tag{8}$$

$\Lambda=1/N\sigma$ is the mean free path, σ the total cross section, and N the number of nuclei per cm^3.

If δ and M are the density and the atomic weight of the scatterer we have

$$\frac{z}{\Lambda}=\frac{z\delta\sigma}{M1.67\times10^{-24}}=\frac{\delta}{M}\frac{\sigma}{1.67\times10^{-24}} \tag{9}$$

where $\Delta=z\delta$ is the thickness of the scatterer in g/cm^2.

In our experimental disposition the transverse dimensions of the neutron source and detector were small but not negligible with respect to d_1 and d_2. Therefore we must introduce two corrections caused by:

(1) "scattering in," that is, neutrons which are scattered through such a small angle that they still impinge on the detector.

(2) "double scattering," that is, neutrons which impinge on the detector on account of a second collision in the scatterer.

Both these effects increase the percentage T of the transmitted neutrons with respect to the value (8) one would expect under ideal geometrical conditions. Therefore we can write

$$T(z)=e^{-z/\Lambda}+K'+K'', \tag{10}$$

where K' and K'' correspond to the above-mentioned effects.

By simple geometrical considerations we found for our experimental conditions

$$K'=0.007\frac{\sigma(0)}{\bar{\sigma}}(1-e^{-z/\Lambda}) \tag{11}$$

for scatterer of atomic weight larger than 1, and

$$K'=0.014\frac{\sigma(0)}{\bar{\sigma}}(1-e^{-z/\Lambda}) \tag{12}$$

for hydrogen. $\sigma(0)$ is the differential cross section in the forward direction and $\bar{\sigma}$ is the differential cross section averaged over all directions. If the scattering is isotropic in the center of gravity system we have $\sigma(0)/\bar{\sigma}=1$.

In practice, we have used for D and C,

$$K'=0.007(1-T); \tag{11'}$$

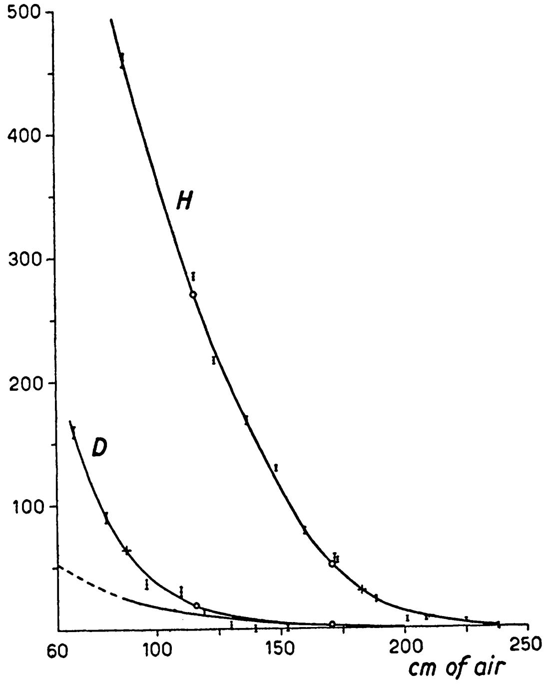

FIG. 2. Absorption curves of recoiling particles.

for H

$$K'=0.014(1-T) \tag{12'}$$

in the case of neutrons of 4 Mev, and

$$K'=0.018(1-T) \tag{12''}$$

in the case of neutrons of 12.5–13.5 Mev as suggested by our preceding results.[10]

K'' was calculated numerically in the case of a scatterer of 30×30 mm^2 section and $z=\Lambda=90$ mm thick. We found, for nuclei of atomic weight larger than 1,

$$K''=0.008; \tag{13}$$

for hydrogen

$$K''=0.002. \tag{14}$$

The low value of K'' in this case is caused by the energy-loss that a neutron undergoes in collisions against hydrogen. As we must expect that K'' varies roughly proportionally to $(z/\Lambda)^2$ we used

$$K''=0.008(z/\Lambda)^2 \tag{13'}$$

in the case of D and C, and

$$K''=0.002(z/\Lambda)^2 \tag{14'}$$

in the case of hydrogen.

Of course in the case of paraffin we used the average of the corrections due to carbon and hydrogen.

Table III contains the cross sections calculated by means of (9) and (10); we give also the values of K', K'', and $T-(K'+K'')$ in order to show that the corrections represent always only a few percent of the transmitted fraction T of neutrons. The mean free path given in column 1 is obtained from a semilogarithmic graph of the uncorrected transmitted percentage of neutrons; therefore it is only an approximate value. In the first column we have also indicated the detector: recoil-protons or Cu-activity. In this last case, according to Salant and Ramsay,[7] we assume for the mean energy of the detected neutrons $\bar{E}=14$ Mev. Such a high value is justified by the presumably rapid increase of the cross section of process (4) with the energy of the impinging neutrons.

Column 6 contains the cross section per molecule whose weighted averages are given in column 7. The atomic cross sections are given in the following column. Finally for D+Li neutrons we have averaged the values obtained with two different detection methods although the corresponding mean energies are slightly different.

Such a procedure appears justified considering that the two averaged values are equal to one another within the experimental errors, and that, under all known reasonable assumptions about the proton-neutron interaction, the scattering cross section does not change appreciably in a narrow energy interval.

6. COMPARISON OF THE NEUTRON-PROTON AND NEUTRON-DEUTERON COLLISION

Although the results contained in the last column of Table III are to be discussed in Section 7, we will now compare the neutron-proton and neutron-deuteron cross sections. From Table III we see that they are equal, within the experimental errors, at 4.1 Mev, while at higher energies the deuteron cross section is slightly larger than the proton cross section. From the data of Table III we have, at 14 Mev,

$$\sigma_D/\sigma_H=1.22\pm0.05. \qquad (15)$$

For such a high energy the neutron-proton cross section is caused only by the scattering, while in the case of deuterons we must consider also the $(n, 2n)$ process

$$_0n^1+{}_1D^2\rightarrow{}_1H^1+2{}_0n^1+Q, \qquad (16)$$

where Q is equal to the mass-defect of the deuteron, i.e., $Q=-2.17$ Mev. Therefore we can write

$$\sigma_D=\sigma_e+\sigma_d, \qquad (17)$$

where σ_e is the cross section for elastic scattering and σ_d the cross section of process (16).

To investigate reaction (16) and to evaluate the corresponding cross section, we have performed the following experiments:

(1) We replaced the light paraffin P with a heavy paraffin layer and measured the absorption curve of the recoiling particles. This curve is reproduced, as a function of the range in cm of air, in Fig. 2 (curve D); in the same figure we give also the absorption curve of protons recoiling from light-paraffin (curve H).

As we have shown in an earlier paper,[10] the ordinate $N(E_0)$ of the two curves of Fig. 2, are given by the equation

$$N(E_0)=\frac{N_0g}{F}\int_{E_0}^{\infty}\int_{E}^{\infty}f(E)\sigma(E)dE, \qquad (18)$$

where $F=dE/dR$ is the energy loss of the recoiling particles in light or heavy paraffin, N_0 the number of protons or deuterons per cm^3, $f(E)dE$ the number of neutrons emitted by the source with energy between E and $E+dE$, $\sigma(E)$ the corresponding cross section, and g a pure geometrical factor. Under the reasonable assumption that $\sigma(E)$ varies only slowly in the energy interval involved, and considering that N_0 was about the same in the light (7.44×10^{22}) and heavy paraffin (7.35×10^{22}), we can write

$$N(E_0)\cong\frac{1}{F}\bar{\sigma}\Phi(E_0), \qquad (19)$$

where

$$\Phi(E_0)=\int_{E_0}^{\infty}\int_{E}^{\infty}f(E)dE \qquad (20)$$

is the twice integrated spectrum of the emitted neutrons and $\bar{\sigma}$ the cross section averaged over the energy interval extending from E_0 to the maximum energy $E_{\max}$ of the neutron spectrum.

(2) The energy of a deuteron recoiling in a head-on collision with a 15-Mev neutron is

8/9 of 15 or 13.3 Mev corresponding to a range in air $R_D=112$ cm. Considering that $E_{\max}$ for the D+Li neutrons is certainly lower than 15 Mev, curve D of Fig. 2 gives evidence that the paraffin also emits a few protons. In order to settle this point, we took the paraffin layer away from its position P in Fig. 1 and arranged on the two opposite faces of a brass plate 2 mm thick two layers of light and heavy paraffin each 1 mm thick. The brass plate was secured to the pivot G so that we could change very rapidly the light and heavy paraffin and compare the numbers of recoiling particles. Using an Al absorber A so thick that the registered particles had a range equal or larger to 116 cm of air, we found

$$N_l(116)/N_w(116)=14\pm 2.2, \tag{21}$$

i.e., the heavy paraffin bombarded with D+Li neutrons emits protons of energy larger than 10 Mev whose number is equal to about 7 percent of the number of protons of the same energy recoiling from light paraffin. In Fig. 2 the two circles plotted at $R=116$ cm represent the result of this measurement.

(3) The number of protons emitted from the heavy paraffin we used is so small that it could be caused completely or in part by light hydrogen impurity. Assuming again that the maximum energy of the D+Li neutrons is 15 Mev, the maximum energy of protons emitted in the forward direction in reaction (16) is equal to 12.5 Mev corresponding to 171 cm of air. Therefore we repeated a measurement similar to that described in (2) for this higher value of the range. We found

$$N_l(171)/N_w(171)=11\pm 6. \tag{22}$$

The two circles marked in Fig. 2 at $R=171$ cm represent this result.

Although the experimental error is very high, we can conclude that the observed protons are due at least in part to hydrogen impurity.

The heavy paraffin is supposed to contain no more than five percent of light paraffin,* which is consistent with our preceding results.

In any case, from the above results it is impossible to form any conclusion about the existence of process (16) except that its cross section must be very small for neutrons of 13–14 Mev.

(4) Finally instead of comparing the numbers of particles, emitted from light and heavy paraffin, having the same range, we have compared the numbers of recoiling particles due to neutrons of the same energy. The experiment was performed for neutrons of energy equal or larger to 13 Mev which give rise to recoiling protons and deuterons of, respectively, 13 and 11.15 Mev.

The corresponding ranges in air ($R_p=183$, $R_D=88$ cm) were obtained by using two convenient Al absorbers in the two cases (223 and 87.6 mg/cm^2). We remember that in this experiment the distance from paraffin to the first wall of the third counter was 20 cm (of argon). We found, in 72 measurements,

$$N_w=5765\pm 134 \qquad N_l=N_H=2724\pm 122$$
$$N_w/N_l=2.12\pm 0.11.$$

These data, represented in Fig. 2 by two crosses, were used to adjust the two absorption curves on the same scale.

Now we must consider that the particles emitted from the heavy paraffin are of three types: recoil deuterons, disintegration protons, and recoil-protons due to light paraffin impurity. The number of these last can be deduced by curve H of Fig. 2 once we know the percentage (five or seven percent) of the impurity: for instance the lower curve of Fig. 2 was obtained by multiplying curve H by 0.05.

In the following we shall show some simple calculations in both cases of five and seven percent impurity.

We have

$$5\% \quad N_D=N_w-\frac{5}{100}N_H=3665, \tag{23}$$

$$7\% \quad N_D=N_w-\frac{7}{100}N_H=2865. \tag{23'}$$

Neglecting a constant factor and applying (19) to our case, we have

$$\begin{aligned} N_D&=\frac{1}{F_D}\sigma_e\Phi(13)+\frac{1}{F_H}\sigma_d\Phi(10.9),\\ N_H&=\frac{1}{F_H}\sigma_H\Phi(13). \end{aligned} \tag{24}$$

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* The Norsk Hydro-Elektrisk Kvoelstofaktieselskab, from which we bought the heavy paraffin, kindly communicated these data to us.

The energy of the neutrons which gives rise to disintegration protons in the forward direction fast enough to be registered (8.6 Mev corresponding to $R_p=88$ cm) is 10.9 Mev. From (24) we deduce

$$\frac{N_D}{N_H}=\frac{F_H}{F_D}\frac{\sigma_e(13)}{\sigma_H(13)}+\frac{\sigma_d(10.9)}{\sigma_H(13)}\frac{\Phi(10.9)}{\Phi(13)}. \tag{25}$$

From the range-energy curve[11] we have: for protons of energy between 13 and 14 Mev, $F_H=3.84\ 10^{-2}$ Mev/cm of air; for deuterons of energy between 11.55 and 12.5 Mev, $F_D=7.5\ 10^{-2}$ Mev/cm of air:

$$F_H/F_D=0.5. \tag{26}$$

The factor $\Phi(10.9)/\Phi(13)$ can be obtained from curve H of Fig. 2

$$\frac{\Phi(10.9\text{ Mev})}{\Phi(13\text{ Mev})}=\frac{\Phi(134\text{ cm})}{\Phi(183\text{ cm})}=6. \tag{27}$$

Introducing the numerical values (23), (23′), (26), and (27) in (25) we find

$$5\%\quad 1.35=0.5\frac{\sigma_e(13)}{\sigma_H(13)}+6\frac{\sigma_d(10.9)}{\sigma_H(13)}, \tag{28}$$

$$7\%\quad 1.05=0.5\frac{\sigma_e(13)}{\sigma_H(13)}+6\frac{\sigma_d(10.9)}{\sigma_H(13)}. \tag{28′}$$

We remember that the cross sections appearing in these relations are averaged from the given values of the energy up to the maximum energy of the neutrons of D+Li reaction (14.5 Mev). Recalling (15) and (16) we can write

$$\sigma_e/\sigma_H=1.22x,\qquad \sigma_D/\sigma_H=1.22(1-x) \tag{29}$$

where

$$x=\sigma_e/(\sigma_e+\sigma_d) \tag{30}$$

is the percentage of neutron-deuteron collisions which gives rise to recoil deuterons.

Under the reasonable assumption that σ_d does not vary very much when the energy of the impinging neutrons changes from 11 to 14.5 Mev, we can introduce the relations (29) in (28) and (28′) and calculate the value of x. We find

$$5\%\quad x=(6-1.1)/(6-0.5)=0.89, \tag{31}$$

$$7\%\quad x=(6-0.9)/(6-0.5)=0.93. \tag{31′}$$

The result is not very sensitive to errors of the ratio $\Phi(10.9)/\Phi(13)$ or to the percentage of light paraffin. In order to have $x=1$ it would be necessary to have $N_D/N_H=1.22\times 0.5=0.6$, i.e., a percentage of light paraffin equal to 13–14 percent, which seems definitively too high.

7. DISCUSSION

Excepting for the results of the measurements at 12.5 Mev (D+B), which are not very accurate for the reasons explained in Section 4, all other values of the cross sections are affected by errors of the order of a few percent. As we have already pointed out in Section 5, the good agreement between the results obtained at 14 Mev using two detectors of quite different type, can be considered as a satisfactory reciprocal check of the applied methods. By averaging these two groups of results, the experimental errors were correspondingly lowered. We can now compare our results with that of other authors and with the theoretical predictions.

As far as we know the neutron-proton and the neutron-deuteron cross sections were not yet measured for neutrons of about 4 Mev. Going to the theoretical predictions, we can use, for the neutron-proton collision, the formula deduced by Kittel and Breit,[14] considering the scattering of the S wave by a square potential-well of the Heisenberg-Majorana type. It differs from preceding simpler formula only because the finite value of the radius of nuclear forces was considered and assumed equal to the electronic radius, as suggested by the proton-proton scattering experiments.

The scattering of the P wave seems to be negligible at such a low neutron energy under all usual assumptions about the nuclear forces. From that formula we find, at 4.1 Mev,

$$\sigma=1.95\times 10^{-24}\text{ cm}^2,$$

i.e., a value appreciably higher than our experimental result ($1.73\pm 0.06\times 10^{-24}$ cm^2); we cannot, however, exclude the possibility that such a difference is mostly caused by experimental errors.

The neutron-deuteron collision was investigated theoretically by Höcker[15] who has calcu-

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[14] C. Kittel and G. Breit, Phys. Rev. **56**, 744 (1939).

[15] H. Höcker, Physik. Zeits. **43**, 236 (1942).

lated the cross sections for elastic scattering, disintegration according to reaction (16), and radiative capture.

He used, for the interaction between the three particles, the Voltz-potential, i.e., a linear combination of Majorana, Heisenberg, Bartlett, and Wigner forces decreasing with the distance according to a gaussian curve.[16] The relative values of these four terms were adjusted by Voltz to obtain the well-known saturation effect of the forces and the experimental values of the deuteron constants.

At 4.1 Mev we need to consider only the elastic scattering whose cross section was, unfortunately, calculated by Höcker only up to about 3 Mev where it is equal to 1.5×10^{-24} cm². However, considering the regularly decreasing shape of the Höcker curve, we can conclude that our experimental value is appreciably higher than the theoretical one.

The same conclusion can be drawn from the experimental results of other authors: at 2.4 Mev Kikuchi and Aoki[17] found 1.98×10^{-24} cm² where the Höcker value is 1.60×10^{-24} cm²; Zinn, Seely, and Cohen[18] found $2.17\pm0.08\times10^{-24}$ cm² at 2.88 Mev; the value given by Höcker is 1.55×10^{-24} cm².

Also for thermal energy the experimental values obtained by various authors, and particularly by Dunning and Carroll,[19] are higher than the theoretical one.

Considering that in neutron transmission experiments all systematical errors tend to give cross sections lower than the right values, it seems to us reasonable to attribute the above stated discrepancy to defects of the theory. It is however to be noticed that the above mentioned experimental data differ even more from preceding calculations of other authors.[20]

The results obtained at 12.5 Mev (D+B) although in agreement with our other measurements, are not accurate enough for a strict comparison with theoretical predictions.

For neutron energies of about 14 Mev the neutron-carbon and neutron-proton cross sections have been measured by Salant and Ramsay[7] by detecting the D+Li neutrons by means of the copper activity produced according to reaction (4). These authors performed measurements both at 90° ($\bar{E}=14$ Mev) and 0° ($\bar{E}=15$ Mev) with respect to the direction of the impinging deuterons on lithium. The results obtained in the first group of measurements can be compared with our results: they found

$$\sigma_c=(1.27\pm0.04)\times10^{-24},\quad \sigma_H=(0.70\pm0.06)\times10^{-24}\ \mathrm{cm}^2$$

in very good agreement with our results

$$\sigma_c=(1.23\pm0.015)\times10^{-24},\quad \sigma_H=(0.694\pm0.019)\times10^{-24}\ \mathrm{cm}^2.$$

According to the Kittel-Briet formula the proton cross section at 14 Mev is 0.66×10^{-24} cm².

The contribution to the total cross section due to the scattering of the P wave wascalculated by Kittel and Breit[14] and by Ferretti[21] for neutrons of 16 Mev, under the assumption that the nuclear forces are of the neutral type studied by Bethe.[22] According to these authors the P wave contribution represents nine percent of the cross section deduced by the scattering of the S wave. With the neutral meson forces studied by Rarita, Schwinger, and Nye[23] the P-wave contribution would represent 46 percent of the cross section deduced by the S-wave scattering.

As we have already pointed out in an earlier paper,[10] the small difference between the experimental value and the scattering cross section deduced by the Kittel-Breit formula is in better agreement with the neutral meson theory of Bethe than with the neutral meson theory of Rarita and others.

Finally we consider the neutron-deuteron collision experiments at 14 Mev. As we have shown in section 6, for neutron energy of 13–15 Mev, the cross section of the $(n, 2n)$ deuteron disintegration process is equal to about 10 percent of the total collision cross section.

In this connection it is to be noticed that,

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[16] H. Voltz, Zeits. f. Physik **105**, 537 (1937).

[17] S. Kikuchi and H. Aoki, Proc. Phys. Mat. Soc. Japan **21**, 75 (1939).

[18] W. H. Zinn, S. Seely, and V. W. Cohen, Phys. Rev. **56**, 260 (1939).

[19] See L. Motz and J. Schwinger, Phys. Rev. **58**, 26 (1940).

[20] L. I. Schiff, Phys. Rev. **52**, 242 (1937); S. Flügge, Zeits. f. Physik **108**, 545 (1938).

[21] B. Ferretti, Ricerca Scient. **12**, 843, 993 (1941).

[22] H. A. Bethe, Phys. Rev. **57**, 260, 390 (1940).

[23] W. Rarita, J. Schwinger, and H. A. Nye, Phys. Rev. **49**, 209 (1941).

according to the numerical values of the coefficients appearing in (26) and (29), our method of observation is 12 times more sensitive to disintegration-protons than to recoil-deuterons. The value we found for the disintegration cross section has to be considered an upper limit because it would decrease by increasing the assumed percentage of light-paraffin impurity. For this reason we consider it impossible to state with certainty, from our experimental results, the existence of process (16) for neutrons of 14 Mev. If it takes place as one would conclude by assuming a reasonable value for the light paraffin impurity, the corresponding cross section can be calculated from the total cross section given in Table III and the values (31), (31′) of x:

$$\begin{aligned}\sigma_d &= (0.1\times 0.86 - 0.05\times 0.86)\times 10^{-24}\\ &= (0.09-0.04)10^{-24}\text{ cm}^2. \qquad (32)\end{aligned}$$

Process (16) was investigated by Bagge[24] who observed in a Wilson-chamber filled with heavy hydrogen the spectrum of recoil particles of the Rn+Be neutrons. From an irregularity observed in the spectrum at about 11.0 mm of hydrogen, this author draws the conclusion that process (16) takes place for neutrons of energy higher than $E_{th}=3.45$ Mev (threshold of the process) with a cross section of about

$$\sigma_d = 0.3\times 10^{-24}\text{ cm}^2.$$

Such a value is between three and seven times larger than that we found at 13–15 Mev.

If we do not assume an irregular dependence of the cross section of process (16) from the energy of the impinging neutrons, we must conclude that the irregularity observed by Bagge is not due to the (n–$2n$) disintegration of deuteron.

Barkas and White[25] have investigated the disintegration process of deuterons under proton bombardment. With protons of 5.1 Mev they found a cross section equal to

$$0.014\times 10^{-24}\text{ cm}^2.$$

The influence of the electrostatic repulsion on the value of the cross section has been calculated by Höcker who deduced from the Barkas and White result the following value of the cross section of process (16) for neutrons of 5.1 Mev

$$\sigma_d = 0.02\times 10^{-24}\text{ cm}^2.$$

This value seems to be in reasonable agreement with our result as the cross section would increase by a factor 2–5 on increasing the energy of the impinging neutrons by a factor 3.

The cross section of process (16) has been calculated by Höcker who found an increase with the energy E of the impinging neutron, roughly proportional to the square of the difference $E-E_{th}(E_{th}=3.45$ Mev threshold of the process): at 14 Mev the absolute value would be

$$\sigma_d = 2.5\times 10^{-24}\text{ cm}^2, \qquad (33)$$

that is, at least 30 times larger than our experimental value (32).

Such a high difference between the experimental and the theoretical value can be recognized also independently from the experiments of section 6, by simple comparison of the total cross section at 14 Mev given in Table III $(0.864\pm 0.028)10^{-24}$, with the theoretical value that can be deduced by adding to (33) the theoretical elastic scattering cross section: this can be roughly evaluated to about 0.5–1.0×10^{-24} cm^2 by extrapolation of the Höcker corresponding curve.

We can conclude that, in contradiction with theoretical predictions at 14 Mev, and probably also at lower energy, the disintegration process (16) has a cross section very small with respect to the elastic scattering cross section.

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[24] E. Bagge, Physik. Zeits. **43**, 226 (1942).

[25] W. H. Barkas and M. G. White, Phys. Rev. **56**, 288 (1939).