On the Scattering of Neutrons from the C+D Reaction

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The scattering cross section for neutrons emitted by bombarding carbon with 600-kev deuterons was measured for 39 elements.

I. INTRODUCTION

IN recent years in measurements of the scattering and absorption of fast neutrons the neutron source has usually been either the D+D reaction[1] (neutron energy between 2.5 and 3 Mev) or photoelectric neutrons[2,3] (neutron energy between 0.14 and 0.2 Mev).

As the properties of neutrons of energy of the order of 10^5 ev seem very interesting, we have undertaken to perform scattering experiments on the neutrons obtained by bombarding carbon with deuterons, as carried out by Tuve and Hafstad[4] for the case of hydrogen. Bonner and Brubaker[5] have shown that the neutrons from carbon bombarded with 0.9-Mev deuterons, consist of three groups of maximum energies 5.6, 1.8, and 0.35 Mev, whose intensities are in the ratio 1 : 3 : 300. On account of the weak intensity of the high energy groups, in most cases it is sufficient to consider only the group of lowest energy. This, according to the above authors, arises from the reaction

$$_6C^{12}+D=_7N^{13}+n+Q, \tag{1}$$

where

$$Q=-0.37 \text{ Mev}. \tag{2}$$

However, Livingston and Bethe,[6] on the evidence of the measurements of Cockcroft and Lewis,[7] consider as more probable the lower value

$$Q=-0.28 \text{ Mev}. \tag{2'}$$

II. EXPERIMENTAL ARRANGEMENT AND METHOD

Our neutrons were produced by bombarding a target of Acheson graphite with deuterons accelerated in the high voltage tube of the Istituto di Sanità Pubblica.[8] The unanalyzed ion current was of the order of 50μa, as deduced by comparing the power dissipated in the target (measured calorimetrically) with the accelerating voltage. The latter quantity was measured by means of a 4×10^9-ohm resistor connected in series with a microammeter. The voltage calibration has been often checked during the measurements by comparison, up to 200 kv, with the readings on a Schroeder electrostatic voltmeter.

During the measurements, the voltage was kept constant at 600 kv. The voltage fluctuation due to the load was of the order of one-tenth of one percent, and therefore negligible.

From the applied voltage and the value of the reaction energy, it follows that the neutrons emitted at 90° to the direction of the incident deuterons, as used in our experiments, had a maximum energy of 0.13 or 0.21 Mev, according to whether one assumes for Q the value (2) or (2'). From the steepness of the excitation curve[9] of reaction (1), we may conclude that most neutrons have energies only slightly lower than either of these values. In the following, we shall assume the average effective energy of the neutrons to be either 0.10 or 0.18 Mev.

[1] E. T. Booth and C. Hurst, Proc. Roy. Soc. **161**, 248 (1937); R. Ladenburg and M. H. Kanner, Phys. Rev. **52**, 911 (1937); W. H. Zinn, S. Seely and V. W. Cohen, Phys. Rev. **53**, 921 (1938); **55**, 679 (1939); **56**, 260 (1939); S. Kikuchi and H. Aoki, Phys. Rev. **55**, 108 (1939); Scient. Papers of the I.P.C.R. **34**, 864 (1938).

[2] M. Goldhaber, Nature **137**, 824 (1936).

[3] A. Leipunski, L. Rosenkewitsch and D. Timoshuk, Physik. Zeits. Sowjetunion **10**, 625 (1936); **10**, 751 (1936); E. Fedorow and N. Perfilieva, Physik. Zeits. Sowjetunion **11**, 660 (1937); G. I. Satkoverzky, Physik. Zeits. Sowjetunion **11**, 664 (1937).

[4] M. A. Tuve and L. R. Hafstad, Phys. Rev. **50**, 308 (1936).

[5] J. W. Bonner and W. M. Brubaker, Phys. Rev. **50**, 308 (1936).

[6] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 334 (1937).

[7] J. D. Cockcroft and W. B. Lewis, Proc. Roy. Soc. **154**, 261 (1936).

[8] G. C. Trabacchi, E. Amaldi, D. Bocciarelli and F. Rasetti, Ric. Scient., in press.

[9] E. Amaldi, L. R. Hafstad and M. A. Tuve, Phys. Rev. **51**, 896 (1937).

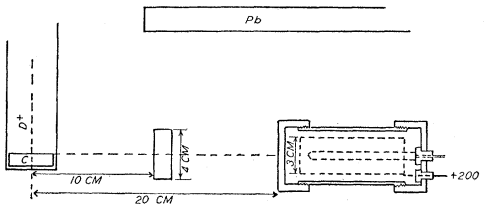

FIG. 1. Experimental arrangement.

The neutrons emitted at 90° were recorded by means of an ionization chamber filled with hydrogen at 20 atmospheres, and an Edelmann electrometer; the sensitivity of the latter instrument being 20 divisions per volt.

The effective diameter of the cylindrical ionization chamber was 3 cm, while the average distance between the target and the chamber was 26 cm. The geometry of the experiment is clearly apparent from Fig. 1.

By taking into account the solid angle subtended by the scatterers and by the ionization chamber, we estimated that in the case of isotropic scattering (which applies to all elements except hydrogen) the error due to the imperfect geometry was of the order of five percent. We therefore corrected by that amount the experimental values, assuming that for neutrons of energy of the order of 10^5 ev, scattering prevails over true absorption. In the case of hydrogen (paraffin), the correction for the geometry is larger, as the scattering takes place mostly in the forward direction. A rough evaluation indicates that the true mean free path should be about 15 percent shorter than the one directly measured.

Under our conditions, the ionization chamber recorded, besides the neutrons coming directly from the target, a background of neutrons scattered by the walls and also x-rays coming from the upper part of the tube. The intensity of the latter was reduced as much as possible by means of lead screens. In order to determine the residual background to be subtracted from our measurements, we placed a paraffin cylinder 4 cm in diameter and 15 cm in length between the neutron source and the ionization chamber. This scatterer was estimated to reduce the direct neutron intensity to about one percent. The residual ionization, measured under such conditions, amounted to one-third of the total one. A check of this value of the background ionization is provided by the fact that the scattering curves obtained with different thicknesses of all substances investigated are exponential to a fairly high degree of accuracy.

The neutron intensity remained constant, within a few percent, over a period of several hours. Nevertheless, we recorded each scattering curve at least six times, changing the order of succession of the different thicknesses.

The scatterers were shaped in the form of cylinders 4 cm in diameter and of convenient thickness. Powders were sufficiently compressed to form compact cylinders. Liquids were placed in convenient containers, the scattering effect of the walls being taken into account.

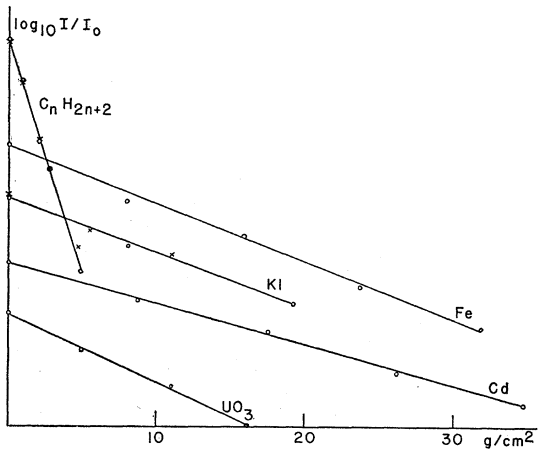

FIG. 2. Scattering curves of selected substances. Crosses and dots refer to two series of measurements.

III. EXPERIMENTAL RESULTS

Figure 2 shows, for a few selected substances, the scattering curves on a logarithmic scale. Table I gives the values of the reciprocal scattering coefficient in g/cm² and of the atomic cross section. Both these values have been corrected for the imperfect geometry as explained above. In the last column we give for comparison the values of the scattering cross section as found by the Russian experimenters[3] using photoelectric neutrons of 0.15 Mev energy.

Where elements were not available, the atomic cross section was deduced by subtraction from that of a convenient compound. Such values are, of course, subject to a larger error than the

others. A question mark indicates those cross sections which appear to be particularly uncertain, either because only two points of the scattering curve could be measured, or because their values were deduced by subtraction from more than two measured cross sections of compounds.

As appears from Fig. 3, there is no simple relation between the cross section for neutron scattering and the atomic number, although a generally increasing trend of the cross section towards the heavy elements is apparent. This result is similar to that found by other experimenters using homogeneous neutrons.[1, 2] As we see from Table I, there is poor agreement between our values and those found by Leipunski and others.[3] Probably the disagreement can be

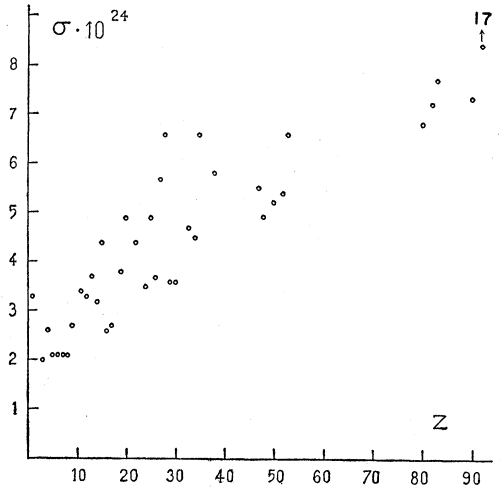

FIG. 3. Scattering cross section plotted against atomic number.

TABLE I. *Cross sections for neutron scattering.*

ELEMENT		SUBSTANCE USED	THICKNESS FOR REDUCTION TO 1/e IN G/CM²	CROSS SECTION IN CM² ×10²⁴	CROSS SECTION IN CM² ×10²⁴ BY LEIPUNSKI AND OTHERS
1	H	CH_2	2.7	3.3	8
3	Li	Li	5.9	2.0	1
4	Be	Be	5.7	2.6	2.9
5	B	B	8.2	2.1	3.8
6	C	C	9.5	2.1	1.5
7	N	NaN_3	8.6	2.1	1.6
8	O	MgO	12.4	2.1	1.8
9	F	NaF	11.6	2.7	6.3
11	Na	Na	11.4	3.4	3.6
12	Mg	Mg	12.4	3.3	8.4
13	Al	Al	12.4	3.7	4.0
14	Si	Si	14.6	3.2	1.4
15	P	P	11.7	4.4	
16	S	S	20	2.6	1
17	Cl	NaCl	16	2.7	3.6
19	K	KCl	19	3.8?	
20	Ca	CaF_2	12.6	4.9?	
22	Ti	TiO_2	15	4.4	
24	Cr	Cr_2O_3	19	3.5	
25	Mn	MnO_2	16	4.9	
26	Fe	Fe	26	3.7	2.7
27	Co	CoO	17	5.2?	
28	Ni	NiO	14.3	6.6	
29	Cu	Cu	29	3.6	4.2
30	Zn	Zn	30	3.6	4.0
33	As	As	27	4.7	
34	Se	Se	29	4.5	
35	Br	NaBr	17	6.6	
38	Sr	SrO	22	5.8	
47	Ag	Ag	33	5.5	
48	Cd	Cd	38	4.9	
50	Sn	Sn	37	5.2	5.2
51	Sb	Sb	37	5.4	
53	I	KI	27	6.6?	
80	Hg	Hg	50	6.8	
82	Pb	Pb	48	7.2	7.3
83	Bi	Bi	46	7.7	
90	Th	ThO_2	38	7.3?	
92	U	UO_3	22	17	

at least partly explained by taking into account the much higher homogeneity of photoneutrons as compared with neutrons of reaction (1).

The largest cross section was found for uranium ($\sigma = 17 \times 10^{-24}$ cm²), and it may be interesting to notice that it is practically equal to the scattering cross section found for neutrons of thermal energies.[10]

The cross section found for hydrogen from paraffin ($\sigma = 3.3 \times 10^{-24}$ cm² after applying the correction for geometry and subtracting the cross section of carbon) may throw some doubt on the correctness of the whole experiment, since there appears to be a considerable disagreement with the theoretically expected value. If our neutrons were really homogeneous of either 0.10 or 0.18 Mev energy, the cross section calculated according to the formula of Bethe and Peierls[11] (assuming 0.12 Mev as the energy of the singlet S state of the deuteron) should be either 9.4×10^{-24} or 7.9×10^{-24} cm². It seems impossible to explain such a large difference as due to insufficient correction for the geometry. On the other hand, the neutron groups of 1.8 and 5.6 Mev (in our case, 1.5 and 5.3) are so weak that, even taking into account the larger ionization produced by their recoil protons, they must contribute only 2.5 percent and 5 percent, respectively, to the total ioniza-

[10] H. H. Goldsmith, V. W. Cohen and J. R. Dunning, Phys. Rev. **55**, 1124 (1939).

[11] See, for instance, H. A. Bethe and R. F. Bacher, Rev. Mod. Phys. **8**, 117 (1936).

tion. The evaluation of the efficiency of the chamber for these groups was calculated by means of the formula of Bethe and Peierls.

We must also keep in mind the possibility of an emission of D+D neutrons due to a deuterium contamination of the target surface. This objection seems to be ruled out by our conditions being similar to those of Bonner and Brubaker, who observed only a negligible number of neutrons corresponding to the D+D reaction. It appears moreover, unlikely that a red hot graphite target, under a pressure of 7×10^{-5} mm, as in the tube during our experiments, could adsorb an amount of deuterium (of the order of one-tenth of one percent within the effective thickness of the target) sufficient to give an average cross section of the order of the one observed by us.

Finally, the possible explanation that our small value of the cross section is due to an admixture of neutrons of higher energies does not appear to be consistent with the exponential form of the scattering curve.

A similar result was found by Goldhaber[2] using photoneutrons. The value (from 3.7 to 4.7×10^{24}) found by Tuve and Hafstad[4] for the neutrons from the C+D reaction appears to be also somewhat lower than theoretically expected. Instead, Leipunski, Rosenkewitsch and Timoshuk,[3] using photoelectric neutrons of 0.15 Mev energy, found the theoretically expected value.

We intend to investigate further this point in order to understand why the scattering cross section in hydrogen in our experiments was much smaller than we expected.

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Effects of Shape of Potential Energy Wells Detectable by Experiments on Proton-Proton Scattering

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The shapes of several types of potential wells giving approximate agreement with proton-proton scattering experiments are discussed. The somewhat poor agreement of the K_0, E curve for the exponential well with experimental data is shown to be due to the "tail" of the well at large radii. In the case of the meson potential well the effect of very large values of the potential at small distances counteracts the effect of the tail. The experimental dependence of phase shift on energy is not reproduced by the inverse square potential well. The maximum theoretically admissible depth of this potential fits experiment at about 1 Mev. A series expansion is developed which gives the change of the phase shift caused by a given change in the potential well, and an example of the use of the formula is given. The approximate equality of the proton-proton and proton-neutron interactions is discussed, and the close agreement in the case of the meson potential is shown to be due to the large attraction at small distances.

THE first experiments[1] on the scattering of protons by protons determined the s-wave anomaly in the energy range 600–900 kev and have indicated the rather close equality of the proton-proton and proton-neutron interactions on the assumption of the same shape of potential well.[2] The energy range covered was insufficient, however, to determine the range of force except very qualitatively and the shape of the nuclear potential curve was also left quite undetermined. The newer experiments[3] have increased the energy region in which the s anomaly is known

[1] W. H. Wells, Phys. Rev. **47**, 591 (1935); M. G. White, Phys. Rev. **47**, 573 (1935); M. A. Tuve, N. P. Heydenburg and L. R. Hafstad, Phys. Rev. **49**, 402 (1936); **50**, 806 (1936); L. R. Hafstad, N. P. Heydenburg and M. A. Tuve, Phys. Rev. **51**, 1023 (1937); **53**, 239 (1938).

[2] G. Breit, E. U. Condon and R. D. Present, Phys. Rev. **50**, 842 (1936).

[3] R. G. Herb, D. W. Kerst, D. B. Parkinson and G. J. Plain, Phys. Rev. **55**, 998 (1939); N. P. Heydenburg, L. R. Hafstad and M. A. Tuve, Phys. Rev. **55**, 603(A) (1939). For analysis of data see BTE, pp. 1035–36.