Determination of the collision cross-section of hydrogen, deuterium, carbon, and oxygen for fast neutrons

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The total collision cross-section of hydrogen for fast neutrons is of great theoretical and practical interest. Theoretically, it is of fundamental importance for our understanding of nuclear forces and, practically, it is required as an auxiliary quantity in the measurement of neutron fluxes, in the study of the energy distribution in a neutron beam, and for many other purposes. We have therefore performed measurements of the neutron-proton scattering cross-section for a series of neutron energies. Since we used paraffin-wax as the scattering material it was necessary to measure the carbon cross-section as well. We also needed the neutron-deuterium cross-section in connection with the estimation of neutron fluxes in the presence of gamma-rays. We therefore carried out scattering experiments with ordinary and heavy water, thus obtaining the oxygen cross-section as a by-product. The accuracy of the oxygen results was necessarily rather low, since the oxygen cross-section is small compared with twice that of hydrogen; but there were clear indications of a resonance in the scattering. We therefore thought it worth while to investigate this further by making measurements with a compound for which the contribution of oxygen to the cross-section was relatively high. Lead dioxide was chosen for this purpose, measurements being also made with lead scatters.

Outline of experimental method.

The neutrons were obtained from the bombardment of a deuterium or carbon target with deuterons of various energies supplied by the 1 MeV generator at the Cavendish Laboratory. A proportional counter filled with hydrogen gas acted as a neutron detector and the scatterer was interposed between source and counter (see Fig. 1).

A logarithmic plot of the transmitted neutron intensity (after subtraction of the background) against the thickness of the scatterer was made, and from the slope, the composition of the scattering material and the density the cross-section was obtained.

Neutron sources.

We had available for our experiments deuterons of variable energy from the 1 MeV generator. This allowed us to obtain roughly monochromatic neutrons of energy from 0.25 to 0.65 MeV with the help of the reaction $^{12}C + {}^{2}D = {}^{13}N + n$. For neutrons of energy ranging from 2 to 4 MeV we used the reaction $^{2}D + {}^{2}D = {}^{3}He + n$.

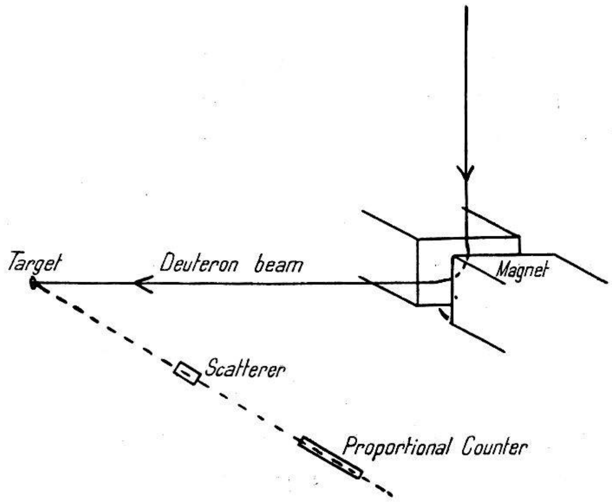

Fig. 1.
Diagram of experimental Set-Up. Scale 1 mm = 3 cm.

The neutron energy was varied by using the neutrons emitted at various angles to the incident deuteron beam, or by changing the deuteron energy.

In the case of the carbon neutrons we used a graphite disc as target. In order to prevent the contamination of the carbon neutrons with D + D neutrons it was necessary to allow the target to get red hot so that the absorption of heavy hydrogen on its surface was prevented. This was achieved by mounting the graphite disc on a thin tungsten rod, thereby reducing the thermal conduction to the metal parts of the target holder.

The deuterium target consisted of sodium deuteroxide, which we found, after comparative tests, to be more efficient than heavy phosphoric acid or aluminium deuteroxide.

In the early experiments we used a vertical ion beam without magnetic analysis. This was permissible since the molecular ion beam contributed only about 10% of the total current. However we preferred a horizontal, magnetically analysed beam, which allowed much easier variation of the direction of observation. In order to reduce the neutron background we led the deflected beam through a soda glass tube away from the magnet box through a distance of 120 cm to the target. The target currents (measured in a Faraday cage) of the deflected beam ranged usually from 70 to 150 microamperes.

Neutron detection and Counting apparatus.

We used proportional counters 2.5 cm in diameter, filled with hydrogen at 30 to 60 cm Hg pressure. Butane was tried as a substitute for the hydrogen in an attempt to improve the counting efficiency by increasing the hydrogen concentration; but it proved not very satisfactory. The potential supply to the counters consisted of dry cell batteries to ensure sufficient stability.

Alignment of Target, Scatterers and Counters.

In view of the large distances (60 to 170 cm.) between counter and target special care was devoted to securing alignment of the system. All parts were adjusted optically in the following manner:— Dummies of the counter tube and the scatterer were made and provided with a small hole through the centre. A telescope placed at 2 to 3 metres from the source was focussed on the centre of the target, and the positions of the cradles which carried the counter tube and the scatterer dummies were adjusted until the centre of the target was in line with the centres of the holes through the dummies. In the experiments with the deflected beam the cradles were suspended with fine steel wires from an iron arm which could be rotated round an axis vertically above the centre of the target. It was possible to adjust the positions of the counter and scatterer so well that they remained in alignment with the centre of the target while the angle between their axis and the ion beam was varied over its full range.

Scatterers.

The scattering cylinders were of diameter 3.8 cm.

For the hydrogen measurements paraffin wax scatterers of various lengths were cast in a vacuum to render them free from air bubbles. Their length was machined accurately and the density was determined from the weight and the dimensions. A batch of the material was analysed in two different laboratories and found to have the composition corresponding to the formula $CH_{2 \cdot 05}$ to $CH_{2 \cdot 08}$.

For the experiments with ordinary and heavy water a number of very thin-walled steel containers were made. Their effect on the scattering was of course taken into account experimentally.

For the carbon measurements graphite scatterers were used, and for the experiments with lead oxide the powdered material was packed tightly into the thin-walled steel containers.

Experimental procedure.

A suitable discriminating bias was chosen, so that a few thousand counts per minute were recorded. Absorption measurements were made with a series of lengths of scatterer and the background determined by interposing sufficient wax so that a further increase did not alter the count. 30 cm of wax was found to be enough for this

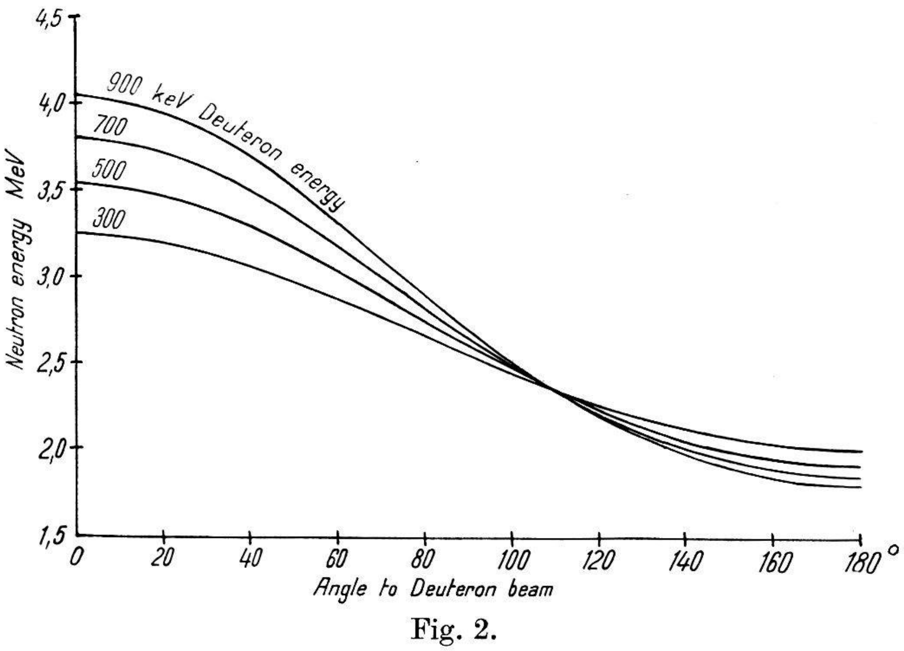

Fig. 2.

D+ D neutron energy as a function of Angle to Deuteron Beam for various Deuteron energies.

purpose. The whole transmission curve was covered several times. The importance of this repetition became evident in a recent observation, where we found that the transmission for a given scatterer thickness diminished with the age of the target when neutrons from the D + D reaction were used. At the same time the log-plot deviated from the straight line usually obtained. We traced this disturbance to the formation on the target of a carbon deposit which increased with time.

The number of recoils obtained with a carbon target was always considerably greater than with a deuterium target. The background in the first case was of the order of 3 to 10 per cent, while it rose in the latter case from 10 per cent in the forward direction to about 30 per cent for large angles to the deuteron beam. Most of this increase in background is due to the diminution of distance between counter and secondary sources of neutrons located along the tube through which the beam passes.

Different neutron energies were obtained either by varying the energy of the deuteron beam or by changing the direction of observation with respect to the incident beam. The energy of the neutrons emitted at an angle α to the beam for a deuteron energy T_0 and heat of reaction Q is

$$T(\alpha) = 3/4\,Q + T_0/4[(1+\cos^2\alpha)+\cos\alpha\,(2+\cos^2\alpha+6\,Q/T_0)^{\frac{1}{2}}]$$

for the D target (where $Q = 3.3$ MeV), and is

$$T(\alpha)=13/14\,Q+T_0[11/14+1/49\cos^2\alpha+\cos\alpha/49(77+\cos^2\alpha+91\,Q/T_0)^{\frac{1}{2}}]$$

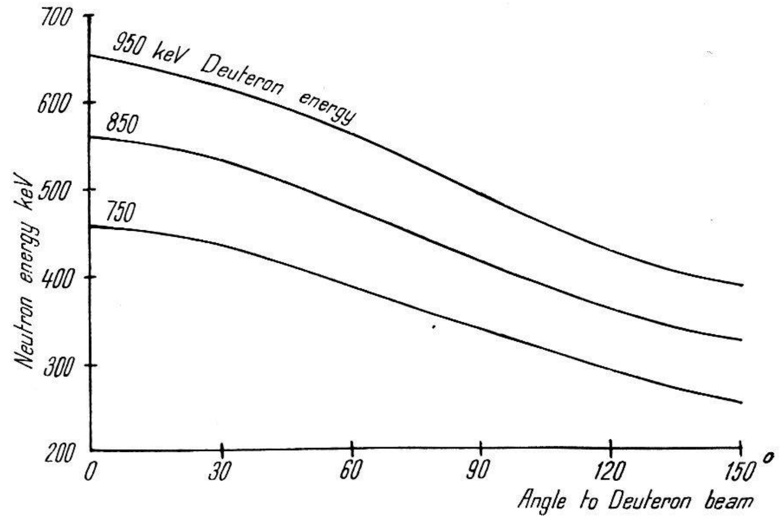

Fig. 3.
C+ D neutron energy as function of Angle to Deuteron Beam for various Deuteron energies.

for the C target (with $Q = -0.27$ MeV). Graphs illustrating these relations are seen in Figs. 2 and 3. Variation of the deuteron energy gives only a small variation of the neutron energy for the D target, and suffers from the disadvantage that the neutron yield decreases if the bombarding potential is diminished. It affords, however, a useful check on results obtained by changing α. The latter method permits of a variation of the D + D reaction neutron energy from about 1.9 MeV in the backwards direction to 4 MeV in the forward direction for the bombarding voltage of 0.9 MeV. An inspection of Fig. 2 will show that for certain angles the neutron energy is nearly independent of the primary energy, and a thick target emits a spectrum nearly as satisfactory as that from a thin one. Thus the slight disadvantage of the lower intensity in the 90^0 position is more than offset by the purity of the neutron spectrum at this and slightly larger angles. The energy spectrum in the forward direction is least satisfactory. The neutron energies given below in the tables of cross-sections correspond always to the bombarding voltage. The influence of the variation of the bombarding potential on the energy of the neutrons from the C + D reaction is much larger (see Fig. 3) but fortunately the excitation function is so steep that by far the largest contribution in a thick target comes from the particle with full bombarding potential. Owing to the good geometry used no corrections for the angular variation of the energy is necessary, since the angle subtended by the scatterer at the source is quite small.

Experiments with carbon neutrons are complicated by the fact that, in addition to the neutrons of a few hundred keV from ^{12}C, there are weak fast neutron groups due to ^{13}C. However, we made sure that our counts comprised a considerable fraction of the total proton recoils by a suitable choice of counter cut-off-bias. Moreover we ascertained that the slope of the log-plot was unaffected by a considerable change of cut-off-bias.

Results.

Hydrogen cross-section		*Carbon cross-section*	
Neutron energy MeV	$\sigma \cdot 10^{24}$ cm²	Neutron energy MeV	$\sigma \cdot 10^{24}$ cm²
0.22	8.30	0.22	3.59
0.30	7.22	0.30	3.38
0.38	6.90	0.38	3.46
0.46	6.24	0.46	3.43
0.60	5.47	0.54	3.25
1.90	2.88	0.60	3.21
2.20	2.78	1.90	1.84
2.70	2.30	2.20	1.89
3.11	2.50	2.70	1.52
4.05	1.97	3.11	1.64
		3.31	1.80
		4.05	1.98

H_2O—D_2O comparison

Neutron energy MeV	σ $H_2O \cdot 10^{24}$ cm^2	σ $D_2O \cdot 10^{24}$ cm^2	σ $D \cdot 10^{24}$ cm^2	σ $O \cdot 10^{24}$ cm^2
0.26	17.04	8.34	3.5	1.4
0.31	16.76	9.00	3.4	2.2
0.36	16.60	9.31	3.3	2.8
0.41	17.52	10.66	3.1	4.5
0.46	18.80	12.83	3.2	6.4
0.46	18.30	12.47	3.3	5.9
0.49	18.97	12.42	2.7	7.0
0.49	17.48	11.17	2.8	5.5
0.49	17.48	11.61	3.1	5.5
0.54	16.80	10.26	2.5	5.2
0.59	14.20	9.29	3.0	3.2
0.66	13.79	9.20	2.9	3.4
2.35	5.58	4.96	2.3	0.4
3.80	6.01	5.73	1.9	2.0

Pb—PbO_2 comparison

Neutron energy MeV	σ $Pb \cdot 10^{24}$ cm^2	σ $PbO_2 \cdot 10^{24}$ cm^2	σ $PbO_2 \cdot 10^{24} cm^2$ (corrected)	σ $O \cdot 10^{24}$ cm^2
0.26	7.19	13.10	12.64	2.7
0.36	6.63	15.30	14.85	4.1
0.39	6.31	15.76	15.30	4.5
0.42	6.10	18.03	17.55	5.7
0.46	6.00	20.20	19.70	6.8
0.48	5.22	19.04	18.55	6.7
0.49	5.08	17.90	17.41	6.2
0.54	4.99	14.94	14.49	4.8
0.60	5.30	14.10	13.72	4.2
0.66	5.17	13.04	12.67	3.8
2.35	6.02	7.37	7.22	0.6

Discussion of results.

The values obtained for the various cross-sections are given in the tables above. Our results for the neutron-proton cross-section are shown on a graph (Fig. 4) together with the more recent results of BAILEY, BENNETT, BERGSTRALH, NUCKOLLS, RICHARDS and WILLIAMS (1946). The agreement between the two sets of results is quite satisfactory.

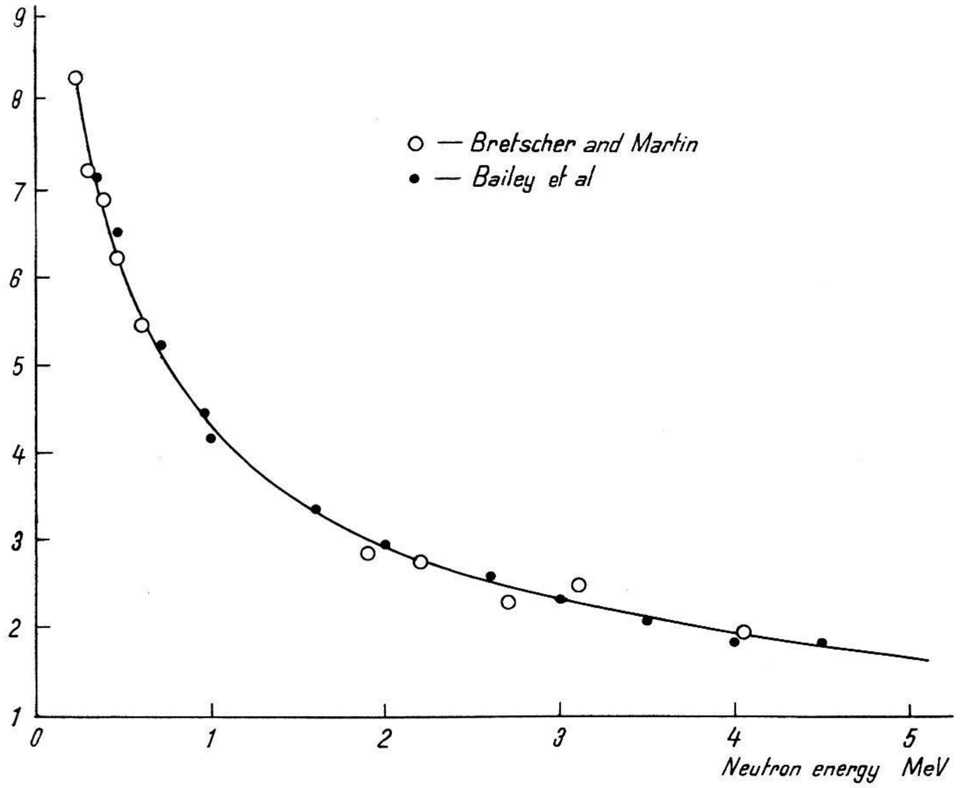

Fig. 4.
Proton-Neutron cross-section.

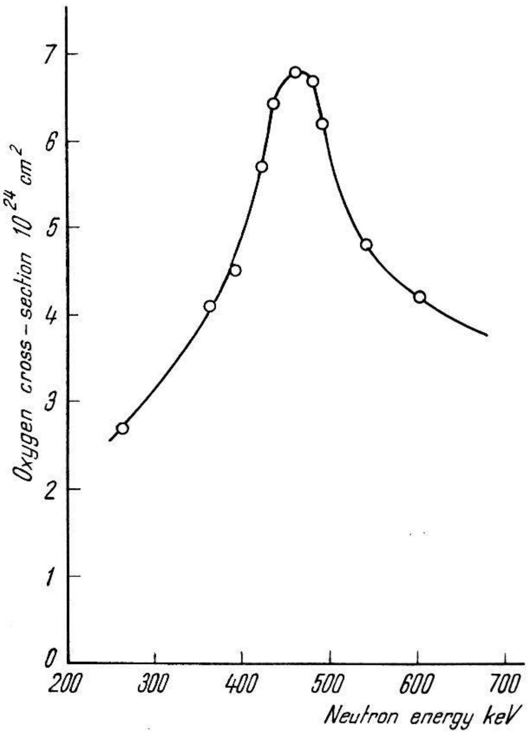

Fig. 5.
Oxygen cross-section.

The values of the carbon and deuteron cross-sections are also in reasonable agreement with those obtained by BAILEY et al. (loc. cit.).

Our values for the oxygen cross-section, obtained from the lead and lead oxide comparison are shown on a graph in Fig. 5. The resonance at 0.46 MeV is clearly shown. This resonance corresponds fairly well to the excited state in ^{17}O found by JAECKEL (1935) at 4.6 MeV above ground level.

Corrections.

No correction has been made for the effect of the finite size of scatterers and counter. With our geometry the necessary correction is very small, except in the case of hydrogen: here it would have the effect of increasing the cross-sections by about 1%.

The PbO_2 was analysed several times in different laboratories and a water content of about 0.2% was found. The oxygen cross-section determined from the lead oxide measurements has been correspondingly corrected.

This work was carried out at the Cavendish Laboratory during the years 1942—1946 as part of the war-time Government research programme under the auspices of the Ministry of Aircraft Production and the Department of Scientific and Industrial Research. We would like to thank these Authorities for permission to publish this part of our work.

Summary.

Measurements have been made of the total cross-sections of H, D, C, and O for neutrons from the reaction C + D and D + D. The results are in good agreement with those of other workers. In the case of oxygen the scattering shows a pronounced resonance for a neutron energy of 0.46 MeV.

References.

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