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MEASUREMENTS OF THE NEUTRON-PROTON SCATTERING CROSS-SECTION

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INTRODUCTION

The cross-section for scattering of thermal neutrons by protons in paraffin wax has been determined rather accurately, the most probable value for neutrons of room temperature being 48×10^{-24} cm² (see 1 and 2). Taking into account the chemical binding forces acting on the protons in paraffin, one can calculate from these measurements the scattering cross-section of free protons relative to slow neutrons, i. e. neutrons of energies less than about 10.000 volts; in this way, a value of 14×10^{-24} cm² has been obtained (3 and 4). The cross-section for protons in paraffin for neutron energies well above the binding energy of the protons has also been measured directly by using, as a detector for such neutrons, the activity produced in various elements when activated through a shield of cadmium. For the mean free path in paraffin of the "resonance" neutrons of these elements, a value of 1,1 cm was found, which corresponds to a value of about $11{,}5 \times 10^{-24}$ cm² for the scattering cross-section of the proton (5). The poor agreement between the calculated and the experimental value and the importance of an accurate knowledge of the neutron-proton cross-section for a number of nuclear problems made a new and more accurate determination seem highly desirable. In the following a description of such measurements is given. A preliminary report of this work has already appeared (6).

Principle and Experimental Arrangement.

The cross-section σ is calculated from the mean free path, using the equation $I/I_0 = e^{-\frac{x}{\lambda}} = e^{-x\sigma k}$, where I_0 and I are the neutron numbers before and after traversal of the scatterer of thickness x, and k is the number of protons per cm^3. The existence of resonance levels in the region above the chemical bonds gives a convenient method of selecting neutrons with suitable energy from the spectrum of a $Ra + Be$-source in paraffin wax. The method of determining the attenuation of the resonance neutrons by the scatterer was in principle the usual one of placing a detector at some distance from the source of neutrons and measuring the activities produced both with and without interposed scatterers. With such an arrangement, however, an appreciable number of neutrons would be recorded by the detector in spite of having been deflected by the scatterer. Because of the necessity for using large solid angles to obtain reasonable intensities, an accurate estimate of the correction thus involved would present some difficulty.

The need for this correction can, however, be avoided by the use of "resonance filters" (as described independently, while the present work was under way, by Cohen, Goldsmith and Schwinger (7)). The method consists in introducing between the source and the scatterer a filter of the same material as the detector in order to select from the neutron beam the neutrons of resonance energy, and taking advantage of the fact that the scattered neutrons have suffered energy loss and are therefore not detected. The difference in activity obtained with and without the filter represents the number of neutrons, with energy equal to the resonance energy E_R of the filter, which have not been scattered. Since a neutron in a collision with a free proton suffers an energy loss $E_0 \cdot \sin^2 \varphi$ (E_0 original energy, φ deflec-

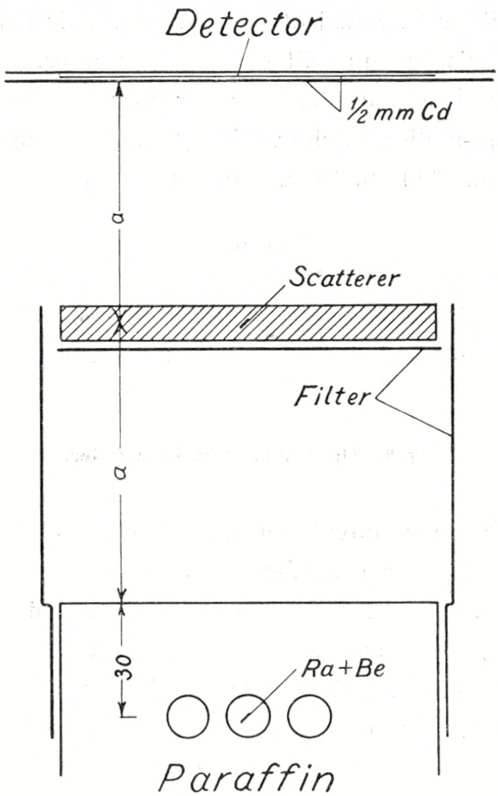

Fig. 1. Arrangement for neutron-proton scattering cross-section experiments.

tion angle) all those neutrons which are deflected enough to lose an energy larger than the energy width ΔE_R of the element used as filter and detector will not be recorded. Neutrons deflected by a smaller angle will be recorded as "not deflected", but their relative number will be about $\Delta E_R / 4\, E_R$, which is, in the case of silver, only about one per cent. The correction for scattering from the walls is also negligible with this method. The only correction to be made is that for the effective increase of the thickness x in the case of oblique traversal of the scatterer. This correction is quite appreciable and will be discussed later.

The arrangement used for measuring the neutron-proton cross-section is shown in fig. 1. The neutron source consisting of 300—600 mg. radium in the form $RaSO_4$,

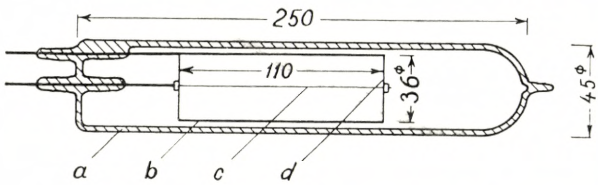

Fig. 2. The Geiger-Müller counter.

mixed with finely powdered beryllium, was placed three cm below the upper surface of a cube of paraffin wax with sides of 10 cm. The detector, in a pocket of Cd-sheet (0,4 g/cm^2), was placed 5 to 14 cm above the upper surface of the paraffin cube, the scatterer midway between source and detector, and the resonance filter immediately below the scatterer. The areas of detector, scatterer, and filter were 10×10 cm^2.

Immediately after the exposure the activity of the detector was measured by means of a large Geiger-Müller counter, the construction of which is shown by the scale drawing fig. 2. This counter consists of a thin-walled glass tube a of 25 cm length and 4,5 cm diameter, in which a 0,1 mm steel wire c serves as collecting electrode, a 0,1 mm thick copper sheet b with mica insulation d as high tension electrode. The chamber is filled with alcohol and argon gas, with partial pressures of 10 mm and 90 mm, respectively, as recommended by Trost (8). The counter was connected to a scale-of-eight counting system.

Measurements.

The measurements were carried out with water as scatterer in a glass container. The experimental procedure was the usual one. Runs (of equal duration) were made 1) with only the empty water trough between paraffin and detector, 2) with the filter, 3) with the water scatterer, 4) with filter and water scatterer. If the recorded numbers of particles are called N_1, N_2, N_3, N_4, respectively, the ratio $(N_3 - N_4)/(N_1 - N_2)$ gives the transmission, in the water layer, of those resonance neutrons which have suffered no energy change of more than the order of the resonance width.

a) Measurements with *Ag*-detector.

The half-value period of *Ag* (resonance energy 2,5 e. v.) is only 22 sec, so one has only a few seconds in which to transfer the *Ag*-detector from the position near the neutron source to the counter. By surrounding the counter entirely with 4 cm of lead and placing an additional 20 cm of lead between counter and source, it was possible to activate and measure in the same room, the distance between the counter and the activating arrangement being about 5 m. The detector and the resonance filter were *Ag*-foils of 0,1 mm thickness. By means of an electromagnetic relay system which was actuated by a contact pendulum the time intervals for activating, transport and counting could be kept very constant. The relay system operated a signal lamp,

Ag-detector.

Distance between detector and neutron source 14 cm.

x = scatterer thickness....	5 mm	10 mm	15 mm
Number of activations ..	40	65	30
N_1	11744	18624	9296
N_2	8800	13432	6752
N_3	10432	16136	8192
N_4	8824	14414	7712
$N_1 - N_2$	2944 ± 143	5192 ± 179	2544 ± 127
$N_3 - N_4$	1608 ± 139	1722 ± 175	480 ± 125
λ_μ	0,86 cm ± 0,15 cm	0,90 cm ± 0,09 cm	0,90 cm ± 0,14 cm
Mean of λ_μ...		0,89 cm ± 0,065 cm	
λ corr.		0,92 cm ± 0,065 cm	

Distance between detector and neutron source 5 cm.
x = 10 mm.

Number of activations...	20
N_1	6840
N_2	4392
N_3	6800
N_4	6120
$N_1 - N_2$	2448 ± 106
$N_3 - N_4$	680 ± 113
Mean of λ_μ	0,78 cm ± 0,12 cm
λ corr.	0,91 cm ± 0,12 cm

I-detector.

Distance between detector and neutron source 14 cm.
x = 10 mm.

Number of activations...	2
N_1	19656
N_2	14160
N_3	17440
N_4	15688
$N_1 - N_2$	5496 ± 184
$N_3 - N_4$	1752 ± 182
Mean of λ_μ	0,87 cm ± 0,09 cm
λ corr.	0,90 cm ± 0,09 cm

which indicated the moment $t = 0$ for putting the detector in its place near the neutron source, and the moment $t = 23$ sec. for taking it away and placing it around the counter. At the moment $t = 38$ sec. the high tension was automatically connected to the GEIGER-MÜLLER counter, counting being carried out during 28 sec., after which the high tension was automatically switched off again.

The neutron source was in this case 300 mgm. $Ra + Be$. Measurements were made with different water layers in the container (5, 10 and 15 mm) and two different distances of the detector from the paraffin block, 5 and 14 cm.

b) Measurements with *I*-detector.

The half-value period of *I* (resonance energy about 50 e. v.) is 25 min. Finely powdered PbI_2 in an envelope (0,2 g/cm² iodine) pressed with binding material was used as detector and a layer pressed without binding material (0.7 g/cm² iodine) as filter. Alternatively, a set of 42 plates of *Na I* of 15 mm diameter, each containing 0,5 g *Na I*, was used as detector. The plates were placed side by side on a piece of medical gauze 10×10 cm² in size. Both the envelope with the thin PbI_2-layer and the "carpet" with the *Na I*-mosaics could be bent around the counter. In the experiments with iodine detectors irradiation always lasted 40 min., the time for transport to the counter was 2 min. and counting was continued for 40 min. The rate of decay was always checked. The neutron source was 600 mgm. $Ra + Be$.

Results.

With the experimental arrangement described in the preceding paragraphs we have determined the cross-section for scattering of slow neutrons by free protons. In the table the results of the measurements are reproduced. The first

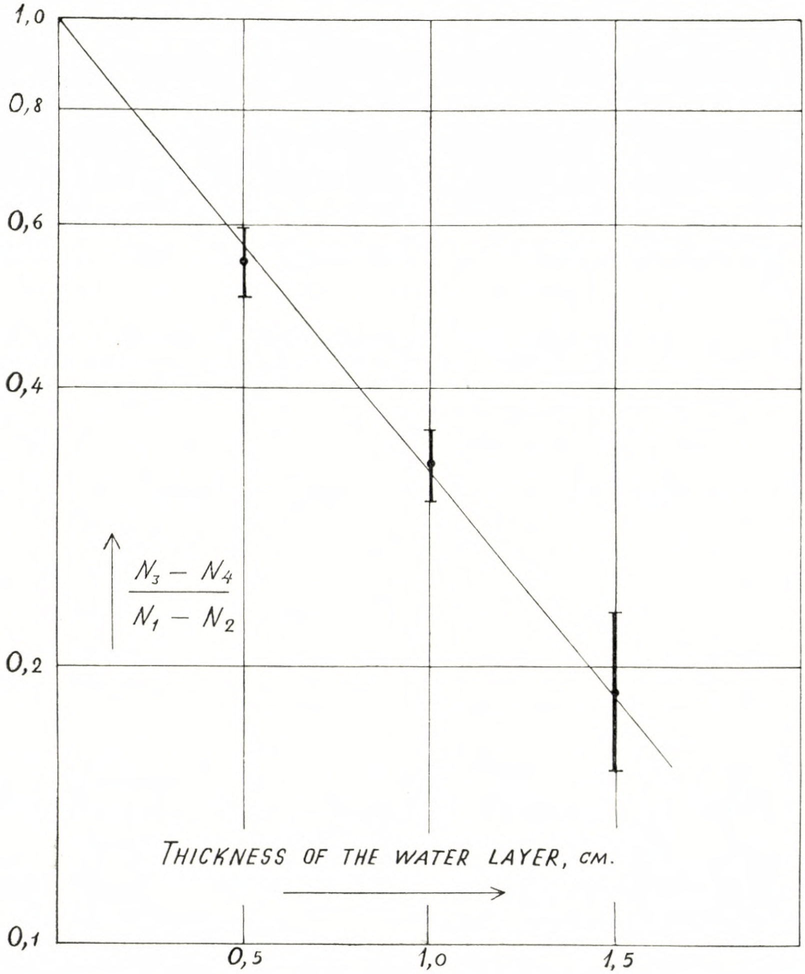

Fig. 3. Absorption curve for water.

part shows the results with corresponding statistical errors for three different thicknesses, 0,5 cm, 1,0 cm and 1,5 cm, of the water scatterer, the distance between the *Ag*-detector and the neutron source being 14 cm. In fig. 3 the ratio $(N_3 - N_4)/(N_1 - N_2)$ of transmitted to initial intensity of the neutrons is plotted on a logarithmic scale as a function of the thickness of the absorber. The vertical lines indicate the statistical errors. The absorption follows practically an exponential law, as is to be expected. The second part of the table shows results with *Ag* detector at a distance from the paraffin block equal to 5 cm, the thickness of the water scatterer being 10 mm, which, from the first experiment, is the most suitable of the three thicknesses employed. The last part of the table contains the results with *I* detector reduced to one scatterer thickness 10 mm and one detector-source distance 14 cm. The quantities λ_μ indicated in the table are defined by the relation

$$\frac{N_3 - N_4}{N_1 - N_2} = e^{\frac{x}{\lambda_\mu}}.$$

To obtain the true mean free paths from these uncorrected values it is necessary to evaluate the obliquity correction.

On the assumption that the angular distribution law of neutrons emerging from paraffin, $f(\theta) = \cos\theta + \sqrt{3}\cos^2\theta$ (where θ is the angle of the neutron path to the normal to the paraffin surface), is valid for $\theta < \theta_0$, while for $\theta > \theta_0$ no neutrons are detected at all, Frisch (9) has calculated the correction factor for various values of θ_0. For $\theta_0 < 45°$, the correction factor f, by which one has to multiply the uncorrected mean free path λ_μ in order to obtain the true one, is approximately equal to $2/(1 + \cos\theta_0)$. In our case, θ_0 may be taken equal to the angle which a line from the centre of the surface of the paraffin to the edge of the detector forms with the normal to the paraffin. For the distance 14 cm of the detector from the paraffin block, a value of $\theta_0 = 19°$ has been adopted and for the distance 5 cm a value of 45°. Consequently, the value of the uncorrected mean free path has to be multiplied by 1,03 in the case of 14 cm distance and by 1,16 in the case of 5 cm distance. Applying these obliquity corrections, the values of $\lambda_{corr.}$ in the table are obtained. The agreement between the values obtained for different distances exhibits strikingly the effectiveness of the resonance filter method in eliminating scattering corrections.

Results obtained with different detectors, different water layers and different distances of the detector from the paraffin block thus agree within the statistical errors, and the most probable value of the mean free path of the resonance neutrons in water is found to be 0,91 cm. From the equation $1/k\sigma = \lambda_{corr.}$ we obtain with this value of $\lambda_{corr.}$ and the number k of hydrogen atoms per cubic centimeter, which is $6{,}73 \times 10^{22}$ for H_2O,

$$\sigma_{HO_{1/2}} = 16{,}4 \times 10^{-24} \text{ cm}^2.$$

This corresponds to a neutron-proton cross-section of

$$\sigma = 14{,}8 \times 10^{-24} \text{ cm}^2,$$

if the cross-section of oxygen is taken as $3{,}3 \times 10^{-24}$ cm^2 (10). The standard error of this figure is about five per cent.

Discussion.

Using essentially the same method, Cohen, Goldsmith and Schwinger found a considerably larger value (20×10^{-24} cm^2) with rhodium as detector. It should be remembered, however, that the resonance energy of rhodium is about

1 e. v. only, which is not much larger than the quantum energy of some of the proton oscillation frequencies, and that one must therefore expect the rhodium resonance neutrons to be scattered more than slightly faster ones. Even the silver resonance neutrons, however, were found, in the present experiment, to be scattered practically in the same way as the considerably faster neutrons of iodine. The value of the cross-section for scattering of slow neutrons by free protons obtained in our measurements agrees well with the value of 14×10^{-24} cm² deduced from the thermal neutron cross-section.

As pointed out by Wigner (11), the large value of the neutron-proton cross-section may be accounted for by the assumption of the existence of a singlet state of the deuteron with a proper energy of very low absolute value. In fact, the formula he obtained for the neutron-proton cross-section is

$$\sigma_H = 4\pi\hbar/M\left[{}^1/_4\left(|E_s| + {}^1/_2 E\right) + {}^3/_4\left(|E_t| + {}^1/_2 E\right)\right],$$

where M is the mass of the proton, E is the energy of the incident neutron, E_t is the binding energy of the triplet state of the deuteron (2,18 Mev), and E_s is the proper energy of the singlet state of the deuteron. Inserting our experimental value of the cross-section in the Wigner formula we obtain for the absolute value $|E_s| = 99360$ e. v. In fig. 4 a graphic representation of Wigner's formula based on this value is given. The results of other investigators, using different neutron energies, are also indicated, and the agreement between theory and experiment is seen to be satisfactory.

Recently Kittel and Breit (12) have made an expansion of Wigner's approximate formula and computed the scattering of the neutrons by protons in the energy range 0—16 Mev. Using $\sigma = 14{,}8 \times 10^{-24}\,\mathrm{cm}^2$ they found that the calculated values are in very good agreement with the new experimental values in the above energy region.

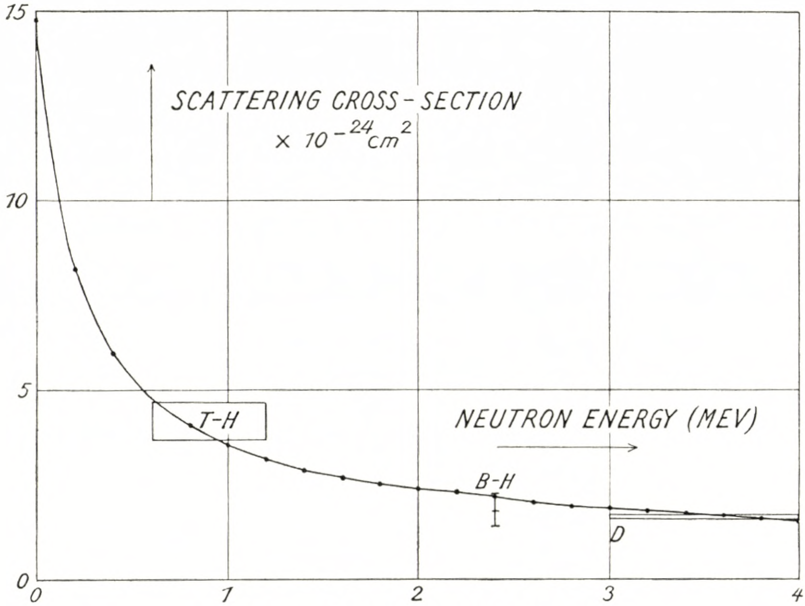

Fig. 4. Graph of Wigner's formula.
T-H = Tuve-Hafstad; *B-H* = Booth-Hurst; *D* = Dunning.

From the scattering cross-section the sign of the term E_s cannot be inferred, i. e. it cannot be decided whether the singlet state of the deuteron is stable or virtual. A number of other effects indicate, however, a virtual singlet state. Thus from the formula of Bethe (13) for the mean life of neutrons in water we obtain, using our experimental value, $2{,}8 \times 10^{-4}$ sec. and $6{,}8 \times 10^{-4}$ sec. for a virtual and a stable state respectively. The value for an unstable state is in good agreement with the experimental value of $2{,}7 \times 10^{-4}$ sec. obtained by Frisch, Halban and Koch (2). The scattering of thermal neutrons by ortho- and para-hydrogen indicates also an unstable singlet state (14).

The new experimental value of the scattering cross-section of slow neutrons and protons would also seem to provide more precise information in the problem of the determination of the interactions between neutrons and protons from scattering experiments. Thus Breit, Hoisington, Share and Thaxton (15) have recently shown that this value points to a close equality of the proton-proton and proton-neutron interactions in the singlet states.

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