Interaction Experiments with Resonance Neutrons*

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A slow neutron collimator of good geometrical proportions with multiple shielding has been constructed especially for use with the cyclotron, and transmission measurements of high precision have been made with neutrons in well-defined regions of the energy spectrum. With the resonance filter method for defining the energy of the neutron beam, cross sections of selected elements were determined for the resonance neutrons of indium (~0.9 ev energy) and iodine (25–100 ev energy) as well as the cadmium absorption group (thermal energy). Measurements were made by following the induced resonance activities of very thin detectors with an ionization chamber—electrometer system. The experimental work consisted of (1) cross section measurements of selected elements for indium resonance neutrons; (2) investigation of interference effects; (3) measurement of the neutron-proton and neutron-deuteron interactions for indium resonance neutrons and comparison measurements with thermal neutrons; (4) measurement of the neutron-proton interaction for iodine resonance neutrons. The neutron-proton cross section was investigated in some detail to establish definitely the free neutron-proton interaction. The effects of molecular binding should be practically negligible at about 1-ev energy and this is indicated by the fact that the same value of the neutron-proton interaction was obtained for the indium and iodine resonance neutrons; *viz.*, 21×10^{-24} cm^2. From these measurements it would appear that the free neutron-proton cross section commonly accepted for theoretical calculations; *viz.*, 14×10^{-24} cm^2 should be revised upward. The comparison measurements with cadmium absorption neutrons agreed well with values obtained by several other investigators using different methods for neutron detection, and the general results show that the method of working inside a collimating enclosure in the immediate vicinity of the cyclotron operates satisfactorily.

INTRODUCTION

THE need for accurate investigation of the interaction of neutrons having well-defined energies in the low energy region (less than 1000 ev) has long been recognized. The resonance capture by certain elements of neutrons which have the proper energies provides a method for such energy selection through the use of these elements both as selective detectors and selective filters. The experiments described in this paper utilize this method together with the high intensities available from the cyclotron to obtain, in effect, a parallel beam of essentially "monochromatic" neutrons.

In a study of nuclear interactions involving these slow neutrons it becomes important for many considerations to distinguish between the various regions of the neutron energy spectrum. Recent experiments[1,2] have indicated the importance of investigations for neutron energies which are well above the thermal region and free from the uncertain effects of molecular interactions. This is particularly true for such cases as the neutron-proton and neutron-deuteron interactions. Theoretically, the results of such measurements should be much simpler to interpret, especially when the neutrons have a well-defined narrow energy range.

The selective resonance capture of neutrons in well-defined regions of the energy spectrum by various elements has been studied by many investigators.[3–8] Experiments with the cadmium mechanical velocity selector[9] showed that the neutrons emerging from paraffin, and which were strongly absorbed by cadmium, largely possessed thermal velocities and had a velocity distribution approximately Maxwellian in form, with a maximum at about 0.03 ev. The strong capture by elements such as rhodium, silver, indium, iodine, bromine and others, was shown by super-

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[1] H. G. Beyer and M. D. Whitaker, Phys. Rev. **57**, 976 (1940).

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[4] E. Amaldi and E. Fermi, Phys. Rev. **50**, 899 (1936).

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[6] H. H. Goldsmith and F. Rasetti, Phys. Rev. **50**, 328 (1936).

[7] Manley, Goldsmith and Schwinger, Phys. Rev. **55**, 39 (1939).

[8] Hornbostel, Goldsmith and Manley, Phys. Rev. **58**, 18 (1940).

[9] Dunning, Pegram, Mitchell, Fink and Segrè, Phys. Rev. **48**, 704 (1935).

position experiments to occur selectively for neutrons of particular velocities which differed for the various elements. The theoretical deduction and experimental proof that the strong neutron absorption in certain light elements, such as boron, varied inversely with the neutron velocity, provided a method for estimating approximately the velocity and thus the energy of these resonance neutron groups.

The process of selective absorption or resonance capture of certain neutrons by certain elements is accounted for in terms of a resonance phenomenon[10, 11] of the neutrons associated with an energy level of the compound nucleus formed by the capture of the neutron by the nucleus. When the energy of the neutron is nearly that of one of these resonance levels, there is a large probability of capture generally followed by the emission of radiation which leaves the neutron bound in the nucleus. The energy width of the resonance capture level is related to the probability of re-emission of a neutron, and the probability of the emission of radiation or other particles.

While more exact measurements of the spectral position of such resonance levels should be carried out with more refined methods of neutron spectroscopy as they are being developed, the boron absorption method together with experiments on the self-absorption of neutrons in the same element has now yielded sufficient information to give at least a rough estimate of the position, width and height of the more prominent levels in the few nuclei thus far studied. The neutron velocity selection obtained by the modulated beam technique[12, 13] has verified these results for cadmium and rhodium, and further development of this and other neutron spectroscopy methods will undoubtedly reveal more information.

The experiments described in this paper involve measurements made with the cadmium absorption neutrons, and the resonance neutrons of indium and iodine. As indicated above, the mechanical velocity selector showed that most of the cadmium absorption neutrons have energies corresponding to thermal velocities, although the cut-off for cadmium is beyond this energy at about 0.2 ev.[13] Indium shows a pronounced selective capture for neutrons characterized by having a relatively sharply defined energy in the region of 0.9 ev.[8] Another region of the neutron spectrum is that associated with the resonance capture in iodine, although here it seems likely that the energy (25–100 ev) is distributed among several levels.[14, 15]

There are several factors associated with the indium-resonance neutrons which make them particularly desirable for interaction experiments. The energy of these neutrons is sufficiently beyond the thermal energy region to minimize the uncertain effects inherent in thermal neutron interactions, and yet the energy is sufficiently near the thermal region so that there is little extrapolation of the $1/v$ law for boron, thus allowing the energy to be determined with a fair degree of accuracy. The absorption of indium-resonance neutrons in boron exhibits a well-defined exponential decrease with thickness which strongly indicates that only one level or one narrowly defined region of the energy spectrum is responsible for most of the activation when thin samples are used. Furthermore the data from self-absorption experiments are consistent with a sharp narrow line (less than 0.1 ev wide) with a very high cross section[8] (approximately $20{,}000\times 10^{-24}$ cm^2) at resonance, so that these neutrons are ideally suited for monochromatic beam measurements. Indium is also readily malleable and available in thin sheets—a convenience when the experimental arrangement is considered.

The interaction of slow neutrons with atomic nuclei can be appreciably influenced by interference effects when the neutrons have such energies that their de Broglie wave-lengths are of the order of magnitude of the interatomic spacing, as reported recently.[1, 2] Thus thermal neutrons with a most probable wave-length of 1.7 angstrom units exhibit interference effects which in several cases should be absent when the measurements are repeated with indium-resonance neutrons of higher energy and shorter wave-length of approximately 0.3 angstrom unit.

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[10] N. Bohr, Nature **137**, 344 (1936).

[11] G. Breit and E. Wigner, Phys. Rev. **49**, 519 (1936).

[12] L. W. Alvarez, Phys. Rev. **54**, 609 (1938).

[13] C. P. Baker and R. F. Bacher, Phys. Rev. **57**, 351 (1940).

[14] H. A. Bethe, Rev. Mod. Phys. **9**, 144 (1937).

[15] J. Hornbostel and F. A. Valente, Phys. Rev. **55**, 108 (1939).

In the case of compounds containing hydrogen the interaction of neutron and proton depends upon the relative values of the neutron energy and the energy of the lowest vibrational level of the hydrogen compound molecule.[16] Calculations indicate that these effects of molecular binding on the free neutron-proton interaction should be very small for neutrons of about 1-ev energy, so that indium-resonance neutrons with energy of about 0.9 ev should show very small effects due to molecular binding. However, in order to eliminate completely any such slight residual effects, measurements can be repeated with iodine-resonance neutrons having energies definitely beyond the binding range.

The desirability of investigating neutron interaction with neutrons having well-defined energies above the thermal region has resulted in several experiments using silver, rhodium, indium and iodine resonance neutrons for measuring the neutron-proton cross section.[17–19] Due to the low intensity of resonance neutrons obtainable with the natural radioactive sources used in these experiments, the results of some of these measurements are necessarily associated with poor geometrical arrangements and low statistical accuracy.

In the experiments described in this paper the cyclotron was used as a source of neutrons and the intensities available permitted measurements with large intensities as well as good geometry. The experimental work consisted of several rather separate parts; (1) Cross-section measurements of selected elements for indium-resonance neutrons; (2) investigation of interference effects; (3) measurement of the neutron-proton and neutron-deuteron interactions for indium-resonance neutrons and check measurements with thermal neutrons; (4) measurement of the neutron-proton interaction for iodine-resonance neutrons.

Apparatus

In carrying out any transmission experiments with a beam of neutrons it is extremely important that good geometrical conditions prevail. Experiments under other conditions employing non-parallel neutron beams with both source and detector close to the sample have been shown to be unreliable, especially for samples containing hydrogen. The uncertain angular distribution of neutrons, together with large corrections for multiple scattering, slowing down processes, back scattering and obliquity make such experiments difficult to interpret. The design of the collimating device used in these experiments was such as to make errors introduced by geometrical factors almost negligible.

Indium neutron collimator

Figure 1 shows the neutron collimator consisting of a boron-cadmium-indium lined enclosure with diaphragms located so that the incident and scattered portions of the beam are accurately defined. The double lines indicate cadmium sheet of 0.05 cm (43 mg/cm^2) and the triple lines represent 0.0013 cm (9 mg/cm^2) of indium between two sheets of cadmium. The housing surrounding the detector is of indium and cadmium, and serves to limit the "angle of vision" of the detector to the actual effective neutron beam. The monitor is so located that it "sees" only the incident beam and does not record any appreciable back scattering. Both detector and monitor are backed by 0.2 cm thickness of cadmium and 0.025 cm thickness of indium, and their front faces are covered with 0.15 cm of cadmium to exclude any activation due to residual thermal neutrons in the beam. The paraffin block serves to slow down the fast neutrons produced by the proton-beryllium reaction in the cyclotron and cadmium covers the front window to exclude thermal neutrons. Investigation showed that a thin paraffin layer of 1 to 2 cm thickness gave the maximum yield of slow neutrons under the conditions of the experiment. For the final neutron-proton measurements the cross section of the beam was divided into four quadrants (shown in dashed outline) by means of cadmium-indium partitions, so that the geometrical arrangement was materially improved. Actually the same measurements of the proton cross section were made with and without this cross collimation.

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[16] E. Fermi, Ricerca Scient. **7**, 13 (1936).

[17] Cohen, Goldsmith and Schwinger, Phys. Rev. **55**, 106 (1939).

[18] Cohen, Goldsmith and Hornbostel, Phys. Rev. **57**, 352 (1940).

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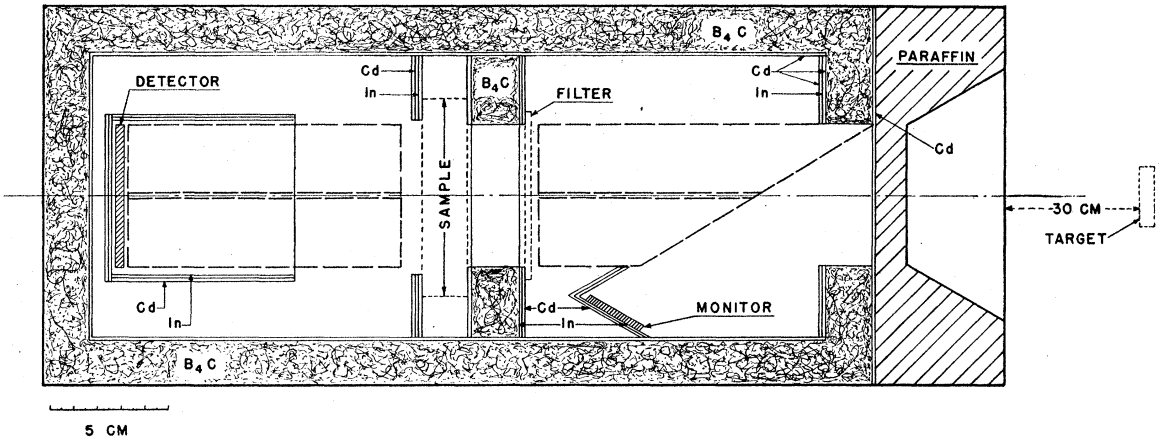

Fig. 1. Arrangement of indium resonance neutron collimator for transmission measurements.

Detectors, monitors and selective filters

It is essential in precision experiments of this kind, that the detector and monitor have "parallel" characteristics, and that both "see" only neutrons from the same effective source. The detectors and monitors used consisted of thin indium foil (27 mg/cm^2) mounted on 0.013 cm thick sheet nickel holders, the detectors being circular of 6 cm diameter and monitors 2×4 cm. With such thin indium most of the induced activity is due to those neutrons near resonance where the cross section is a maximum. The nickel holders showed no observable activity for any of the radiation conditions encountered during the experiments. The selective filter employed to define further the neutron beam consisted of 33 mg/cm^2 of indium foil mounted on 0.013 cm thick aluminum sheet. This thickness reduced the open beam intensity by some 35 percent and represented a compromise which in effect absorbed only the "center" of the absorption line, thus removing a good fraction of the resonance neutrons from the beam without absorbing the "tails" of the line appreciably or the nonresonance neutrons comprising the background of the beam.

Thermal neutron technique

The same collimator was also used for making transmission measurements with thermal neutrons. For these experiments much thicker indium detectors and monitors were used and their faces covered with thick indium foil to minimize resonance activation. The front window of the collimator was covered with thick indium instead of the cadmium and the selective filter was a sheet of cadmium 43 mg/cm^2 (0.05 cm) thick. The same cross collimation was used.

Iodine neutron technique

In adapting the collimator for iodine-resonance neutron measurements the indium shielding was replaced with shield of tightly packed lead iodide. However, because of the much smaller capture cross section of the boron shielding for the higher energy neutrons, some fast neutrons could reach the detector from all directions, and activate the higher energy iodine levels appreciably. To make the boron and iodine more effective it was found necessary to shield the entire collimator by enclosing it in a paraffin house with walls some 20 cm thick. With this arrangement the neutrons exterior to the collimator were either removed or slowed down so effectively that the boron again showed a large capture cross section. The iodine filter finally adopted consisted of approximately 200 mg/cm^2 of iodine in the form of fused lead iodide deposited on 0.013 cm thick nickel sheet and reduced the open beam intensity by some 30 percent. Detectors and monitors were prepared in the same way by fusing lead iodide on the nickel. Four different detectors were used interchangeably, their thickness varying from 60 to 120 mg/cm^2. No cross collimation was used for the iodine measurements.

Measuring system

The measuring system for following all the detector and monitor activities consisted of an ionization chamber connected to an Edelman string electrometer. The chamber with its 5-mil duralumin window was filled with Freon (difluorodichloromethane) to a gauge pressure of 60 lb./in.^{2}, and completely shielded with 3 cm of lead. With this arrangement the natural leak or background for the entire system was such that the ratio of time of drift due to natural leakage, to the time of drift resulting from the beta-radiation of a 100-mg standard of uranium oxide (wrapped in 1-mil aluminum foil) was better than 50 to 1.

Samples

In most cases the samples used for neutron interaction measurements consisted of the particular elements of carefully determined purity and were of such thickness that 30 to 40 percent of the resonance neutrons traversing the sample were removed from the detected beam. With such transmissions the effect of double scattering was very small. For the measurements of the neutron-proton cross section, a carefully prepared sample of cetane ($C_{16}H_{34}$) was further purified by recrystallizing, melting, drying and filtering, and used in accurately machined, chromium-plated, thin brass cells with glass windows. Cetane was chosen because it is a paraffin which can be readily obtained in very pure form.

PROCEDURE

In using the resonance filter method for transmission measurements, the activities of detector (and monitor) had to be measured for each of the four conditions: (1) open beam; (2) filter in the beam; (3) sample in the beam; (4) both sample and filter in the beam. For a constant source of neutrons, the difference between (1) and (2) is proportional to the number of resonance neutrons passing down the beam; and the difference between (3) and (4) is proportional to the number of resonance neutrons passing through the sample without being scattered out of the beam. The transmission, P, is calculated from the relation

$$P=[(3)-(4)]/[(1)-(2)]$$

and the cross section found from the formula

$$P=e^{-\sigma N x}$$

where σ is the total cross section (scattering plus capture), N is the number of nuclei per cm^3, and x the thickness in cm.

Since the output of the cyclotron during successive runs was not always the same, each detector activity was normalized to its respective monitor activity in terms of the uranium standard, so that any transmission value had to be found as the quotient of two quantities each of which was itself the difference of two quotients. Fifteen-minute radiation intervals generally gave sufficient activation of the 54-minute indium period so that detector activities were some thirty times the electrometer background, and monitor activities forty times this background.

Insofar as the measuring system was involved, any normalized detector activity could readily be determined with a precision measure of less than one percent with the usual nine readings to check detector and monitor activities. Over a long period it was found that repeated measurements of such normalized detector activity would never fluctuate by more than several times this precision measure, due to factors beyond reasonable control at the time. For example, complete data taken with one detector and its monitor over a period of several months showed that readings did not fluctuate more than a few percent and that the averaged values had a precision of 0.5 percent. During this interval the collimator and its paraffin front were separately removed and replaced numerous times. These results are of further interest in that they indicate the feasibility of working inside a collimating enclosure located in the immediate vicinity of the cyclotron. Generally the transmission could be readily measured with a precision appreciably better than 2 percent, so that cross section results are considered known to better than 5 percent. Better precision could be obtained when required by increasing the number of observations.

Corrections

Because of the good geometry of the collimated beam, the corrections of the observed transmission were small. Obliquity corrections were so small (<0.25 percent) that they were neglected.

However, all observed transmissions were corrected slightly to account for the increased detector activity caused by the neutrons which, although scattered by the sample, did reach the detector. It was assumed, except for the proton measurements, that this scattering was spherical and that all neutrons scattered into the detector were still in the resonance region, thus resulting in the maximum possible geometrical correction which could be applied, since some of the neutrons scattered into the detector will have lost enough energy to reduce their probability of detection. For a transmission of 60 percent this correction amounted to about 0.5 percent with the cross collimated beam and about 3 percent for the earlier beam arrangement.

Results

In Table I are given the results of measurements of the total cross sections of various elements for indium-resonance neutrons as well as several thermal neutron values. For further comparison the other corresponding thermal neutron cross sections have been included with appropriate references. In the cases of D, C, Fe, Ni, Cu, Pb, and Bi the same specimens were available for both sets of measurements, so that the results should be directly comparable. The scattering cross sections for thermal neutrons shown in the last column are those given by Goldhaber and Briggs.[20]

Interference effects

A brief investigation of the interference effects mentioned previously was made by measuring the cross sections of several compounds in different crystalline states. Table II shows the results of measurements on single crystal quartz and finely divided sand for both indium-resonance and thermal neutrons. The value shown for sand with thermal neutrons was taken from the work of Beyer and Whitaker,[1] and is the result for the same sand as that for which the indium-resonance measurement was made.

Table I. *Cross sections of elements* $\times 10^{24}$ *cm*$^{-2}$.

Element and Form	σ for In Neutrons $E\approx0.9$ ev	Thermal Neutrons $E\approx0.03$ ev	
		Total	Scat
H Cetane	21.0±1.0	49.0	
D D_2O	3.3	5.7	
C Graphite	4.9±0.2	4.9	4.8
Al Metal	1.5±0.1	1.5[1]	1.6
Fe Armco	11.1±0.3	12.0[2]	10.3
Ni Rolled	16.1±0.8	19.8[2]	12.4
Cu Rolled	8.3±0.3	10.5[2]	8.6
Zn Metal	4.2±0.2	4.5[2]	5.2
Sn Metal	5.7±0.3		4.9
Pb Metal	9.6±0.8	12.5[2]	12.9
Bi Metal	8.7±0.5	8.9[2]	8.9

[1] Dunning, Pegram, Fink and Mitchell, Phys. Rev. **48**, 265 (1935).
[2] H. G. Beyer and M. D. Whitaker, Phys. Rev. **57**, 976 (1940).

Table II. *Cross sections* $\times 10^{24}$ *cm*$^{-2}$.

	In-Resonance Neutrons	Thermal Neutrons
Quartz Crystal (4.5 g/cm^2)	7.5±0.5	4.3±0.3
SiO_2 sand (3.3 g/cm^2)	8.8±0.8	8.8±1.0

Measurements were also made with indium-resonance neutrons to determine whether there would be a change in the transmission for a physical mixture of the constituents of an alloy and the alloy itself. In the case of permalloy it was found that there was no difference in the transmission (within the precision of measurements) of a given thickness of Permalloy and an equivalent thickness of its nickel and iron components.

Neutron-proton and deuteron measurements

Measurements of the neutron-proton cross section were made with a carefully prepared sample of cetane, $C_{16}H_{34}$, a standard hydrocarbon of known composition. The results for three thicknesses of cetane are shown by the logarithmic plot in Fig. 2 with the calculated precision of each point indicated. The two plots for indium-resonance neutrons are those corresponding to (*a*) transmission corrected for spherical scattering, (*b*) corrected for total forward scattering, assuming in both cases that all scattered neutrons reaching the detector remain within the energy region. Correction (*b*) represents the maximum possible geometrical correction which could be applied since some of the neutrons scattered into the detector will have lost enough energy to eliminate their detection. For these data the corresponding corrected neutron-proton cross sections for indium-resonance neutrons are (*a*) 20.3 and (*b*) 21.6×10^{-24} cm^2, with the value 4.9×10^{-24} cm^2 previously determined for the cross section of carbon. A more probable value would be between these two extremes, and for

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[20] M. Goldhaber and G. H. Briggs, Proc. Roy. Soc. **A162**, 127 (1938).

the purpose of this paper it is given as $21\pm1\times10^{-24}$ cm^2.

In order to verify the entire method of experiment, measurements were also made with the same cetane for thermal neutrons absorbed in cadmium. Thick indium detectors covered with indium to minimize resonance activation were used. The plot in Fig. 2 also shows the transmission for thermal neutrons absorbed in cadmium, corrected for spherical scattering and gives a value for the neutron-proton cross section of 49.0×10^{-24} cm^2. If there is a small amount of forward scattering this value would be increased slightly. This result is in good agreement with the values previously obtained with the boron or lithium $1/v$ law detectors and ion-chamber-linear amplifier systems and shows that this method operates satisfactorily.

The results for the deuteron cross section were obtained from transmission measurements on two thicknesses of deuterium oxide, and the logarithmic plot in Fig. 3 gives these data corrected for spherical scattering both for indium-resonance neutrons and thermal neutrons. The cross section for indium-resonance neutrons is found to be 3.3×10^{-24} cm^2, taking the cross section for oxygen to be 4×10^{-24} cm^2.[21] The corresponding thermal neutron value from these data was found to be 5.7×10^{-24} cm^2. The D_2O used in these experiments was kindly supplied by Professor Urey and the original analysis indicated a purity of 99.8^+ percent, so the correction for presence of ordinary hydrogen should be small.

Iodine measurements

The measurements with iodine-resonance neutrons were made with the same cetane specimens used earlier and Fig. 4 gives the logarithmic plot of the transmission corrected for spherical scattering. For comparison the corresponding transmission for indium neutrons (found before cross collimation was added) is shown by the second set of points, indicating that there is no appreciable difference between the two values. From this plot the iodine-resonance neutron-proton cross section becomes 20×10^{-24} cm^2 (with the value of 4.9×10^{-24} cm^2 previously determined for the cross section of carbon for these same neutrons). As mentioned earlier, these iodine neutron readings were taken without the cross collimation used for the final indium neutron experiments, so that the absolute values of the neutron-proton cross section for iodine neutrons could not be determined with the same accuracy. The experiment does show that there is no experimentally observable difference between the neutron-proton cross sections for neutrons of approximately 1-ev energy and those with an energy of the order of 25 to 100 ev.

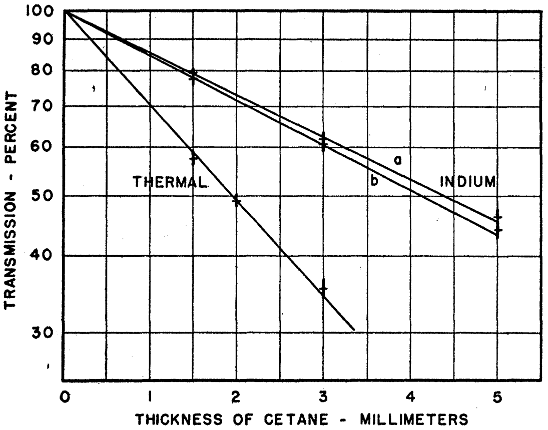

FIG. 2. Transmission of slow neutrons in cetane.

DISCUSSION

The theory of scattering and capture interaction of slow neutrons with atomic nuclei has been developed by Breit and Wigner.[10] If it is assumed that there is only one nuclear resonance level involved; and that the neutron width Γ_n is small compared with the sum of all the other partial widths Γ, (i.e., if the probability of re-emission of a neutron is small compared with that for radiation) then the expressions for consideration are

$$\sigma_{\text{capture}}=\frac{h^2}{8\pi M(EE_r)^{\frac{1}{2}}}\frac{\Gamma_n\Gamma}{(E-E_r)^2+\frac{1}{4}\Gamma^2},$$

$$\sigma_{\text{scattering}}=\frac{h^2}{8\pi ME_r}\frac{\Gamma_n{}^2}{(E-E_r)^2+\frac{1}{4}\Gamma^2}.$$

Here E denotes the kinetic energy of the neutron, M its mass, and E_r the resonance energy. The energy widths Γ and Γ_n represent the energy

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[21] H. Carroll and J. R. Dunning, Phys. Rev. **54**, 541 (1938).

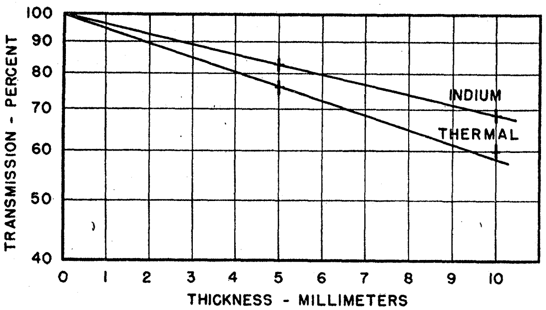

Fig. 3. Transmission of slow neutrons in deuterium oxide (D_2O).

range over which the cross section is greater than half of its maximum value. In the case of the capture cross section there is not only the resonance factor $(E-E_r)^2$ but also the factor $E^{-\frac{1}{2}}$ representing the $1/v$ variation of the absorption cross section. For E very small compared with the resonance energy and the total width Γ, this $1/v$ factor will be dominant.

An inspection of the cross sections shown in Table I indicates that there is in general a decrease in the total (scattering plus capture) interaction for the indium-resonance neutrons as compared with the thermal neutron value. Such a difference is consistent with the lower probability of nuclear capture of the indium-resonance neutrons since the capture process is a more critical function of neutron energy than the scattering interaction due to the factor $E^{-\frac{1}{2}}$ mentioned above. A further comparison of these same indium-resonance values with the scattering results for thermal neutrons found by Goldhaber and Briggs does not show the same consistency, especially for the element Pb. However, in this case the total cross sections for both indium and thermal neutrons were measured on the same Pb sample, with the same order of precision, so that these two values are directly comparable. Even if there should be no contribution of the capture process to the total cross section of Pb for thermal neutrons, it does not seem likely that the scattering interaction should vary as rapidly with energy as would be required by the scattering data and the data for the indium-resonance neutrons. As a general rule, the scattering cross section for slow neutrons is considered independent of neutron energy, since the neutron width Γ_n is very small compared with Γ.

The data in Table I would also indicate that for the elements C, Al, Fe and Bi, the interaction of neutron and nucleus in this energy region is almost entirely a scattering process. In the case of carbon this is further verified by the data obtained for iodine-resonance neutrons which is identical with the data found for the other two neutron energies.

The measurements on single crystal and polycrystalline quartz are only of interest in that they agree with the results of a similar experiment performed by Whitaker, Bright and Murphy,[22] using a different method of neutron detection.

The neutron-proton cross section found for indium-resonance neutrons agrees well with the value of $20\pm2\times10^{-24}$ cm^2 found by Cohen, Goldsmith and Schwinger[17, 18] for the resonance neutrons of rhodium, indium and silver. It is considerably higher than the value of 10 to 12×10^{-24} cm^2 originally obtained by Amaldi and Fermi.[23] In the case of the neutron-proton value for the cadmium absorption neutrons the value of 49×10^{-24} cm^2 is in very good agreement with recent determinations; *viz.*, 50.0,[24] 49.0,[25] and 47.5[26] where different methods of neutron

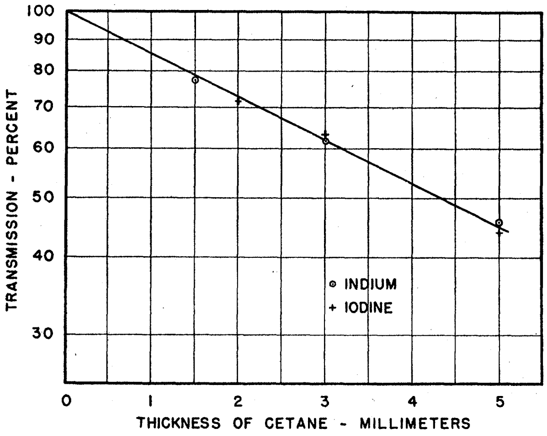

Fig. 4. Transmission of slow neutrons in cetane ($C_{16}H_{34}$).

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[22] Whitaker, Bright and Murphy, Phys. Rev. **57**, 551 (1940).

[23] E. Amaldi and E. Fermi, Ricerca Scient. **7**, 310 (1936).

[24] H. Carroll and J. R. Dunning, Phys. Rev. **54**, 541 (1938).

[25] Frisch, v. Halban, and Koch, Kgl. Danske Vid. Sels. Math.-fys. Medd. **15**, 10 (1938).

[26] M. Goldhaber and G. H. Briggs, Proc. Roy. Soc. **A162**, 127 (1937).

detection were used, and shows that the method of working inside such a collimating enclosure with the cyclotron yields results consistent with other techniques.

A consideration of the results obtained for the deuteron interaction indicates that the cadmium absorption value is in good agreement with the value of 5.7×10^{-24} cm^2 obtained by Carroll and Dunning.[27] The indium-resonance value for the deuteron interaction was found to be 3.3×10^{-24} cm^2, and it is of interest to investigate the effect of molecular binding on this interaction. If the capture contribution in this interaction be assumed very small, the scattering cross section would vary as the square of the reduced mass of the system, associating the indium neutron value with the free deuteron interaction, and the thermal neutron result with the bound deuteron cross section. This molecular binding effect would reduce the thermal neutron value of 5.7×10^{-24} cm^2 to a minimum of 2.8×10^{-24} cm^2, which is in fair agreement with the experimental value of 3.3×10^{-24} cm^2, especially since this correction assumes infinite molecular binding for the deuteron. The theoretical calculations of Motz and Schwinger[28] give appreciably higher values for the deuteron-neutron interaction but their results are subject to approximations which would be expected to give a higher value.

The results for the neutron-proton interaction for iodine-resonance neutrons are of particular interest, since the minimum value of the cross section was found to be 20×10^{-24} cm^2. This is considerably higher than the value of 14.8×10^{-24} cm^2 recently reported by Simons[19] for the same energy neutrons but with poor geometry. The author also reports the same value for this cross section when the measurements were repeated with silver resonance neutrons (energy 3 ev) and this result is at variance with the value of 20×10^{-24} cm^2 reported by Cohen, Goldsmith and Hornbostel[18] for these same neutrons. Since the data taken in these experiments on the cetane samples for cadmium and indium neutrons agree well with the results found by several other investigators, the values of the neutron-proton cross section for the three different neutron energy groups should be directly comparable. It is difficult to account for the value of 14.4×10^{-24} cm^2 for the neutron-proton interaction recently reported by Amaldi, Bocciarelli and Trabacchi[29] using rhodium neutrons. However, the rhodium filter used was exceedingly thick and may partially account for such a low value.

The effects of molecular binding on the neutron-proton interaction have been extensively investigated and lead to the conclusion that these effects should already be very small for neutrons of about 1-ev energy. This prediction is verified by the results of these experiments in view of the agreement between the iodine and indium resonance neutron interactions for the proton. If this is the case then it appears that the free neutron-proton cross section commonly accepted for theoretical calculations; *viz.*, 14×10^{-24} cm^2 should be revised upward to approximately $21\pm1\times10^{-24}$ cm^2.

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