Interaction of Neutrons with Matter

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The interaction of fast neutrons with matter has been studied through their transmission out of spheres of various materials. Of the order of 90 percent or more of the collisions with atomic nuclei were found to be approximately elastic, probably around 10 percent of the neutrons which make collisions with nuclei being captured or suffering energy losses which make them undetectable through projected protons. The interaction of "slow" neutrons with matter has been studied largely through the ionizing particles ejected with high efficiency from Li (or B) by slow neutrons, with very sensitive ionization chambers whose inner surfaces are entirely of Li metal, the ionization being detected through amplifier systems using thyratron or photographic oscillograph recorders. The anomalous effects characteristic of slow neutrons, such as high absorption in Cd, are not observable with the lowest energy neutrons detectable through projected protons. The use of a Cd shutter with the Li ion chamber permits separation of fast and slow neutrons effects. Cd is used as shielding against slow neutrons, and serves as effective material for slits to define beams of slow neutrons. The production of slow neutrons through collisions of fast neutrons with H nuclei has been studied by using paraffin, H_2O and D_2O. The slow neutron production curve with paraffin and H_2O shows a maximum with spheres of about 10 cm radius and the decrease in the number of slow neutrons emerging from larger spheres is attributed largely to absorption processes such as combination with H to form deuterium. The presence of large numbers of neutrons with energies already below 100,000 e.v. in Rn-Be neutron sources appears necessary to account for this and other effects. Li also detects neutrons having energies intermediate between fast and slow. H_2O is about 5.5 times as effective as D_2O in producing slow neutrons, as determined through the relative enhancement of the artificial radioactivity produced in Ag. The question of thermal equilibrium of slow neutrons was investigated, and in the range from about 95° to 373°K, the change in the number of disintegrations of Li was found to be very small and the change in the absorption of Cd was found to be of the order of 5 percent, the results probably indicating that many of the neutrons approach thermal equilibrium but that these effects are not sensitive functions of the neutron energy in this region. The absorption of Cd for slow neutrons has been found to be very nearly exponential when measured with a reasonably parallel beam of slow neutrons. The neutron-nucleus collision cross sections for fast neutrons lie on a fairly smooth curve, indicating increasing nuclear radii with atomic weight in fair accord with other data, although all the lower atomic weights have about the same cross section for fast neutrons. The neutron-nucleus collision cross section for slow neutrons has been investigated over a wide range of elements with an approximately parallel slow neutron beam, and varies from values which may be slightly smaller than the comparison values for fast neutrons in such cases as Al and S, to values several thousand times larger, in the case of Gd, Sm and Cd, the first two having the largest absorption coefficients for slow neutrons yet measured. Studies of the amount of elastic scattering of slow neutrons from Cd show that, compared to Cu, less than 1 percent of the slow neutrons are elastically scattered, indicating that the large neutron-nucleus cross sections for slow neutrons are due to neutron capture and not elastic scattering. The same appears to be true for other elements of high absorbing power.

HIGH ENERGY NEUTRONS

THE interaction of fast neutrons, having energy of the order of 1 MEV, with matter has now been studied from a number of standpoints[1, 2, 3, 4, 5, 6, 7] and it appears that most of the phenomena associated with the passage of such neutrons through matter arise from the scattering of the neutrons by elastic collisions with atomic nuclei, rather than from the less frequent capture of neutrons by nuclei. The interaction of fast neutrons with nuclei, expressed in terms of neutron-nucleus collision cross section, gives values for nuclear radii which vary quite smoothly over the range of elements[4, 8] and which agree well with nuclear radii inferred from other types of measurements[9] and from theoretical considerations. The disintegration of various nuclei by neutrons,[10, 11, 12, 13] the dis-

[1] Chadwick, Proc. Roy. Soc. **A136**, 702 (1932); **A142**, 1 (1933), London Conf., Solvay Conf.
[2] Curie-Joliot, J. de phys. et rad. **4**, 21 (1933); **4**, 278 (1933).
[3] Dunning and Pegram, Phys. Rev. **43**, 497 (1933); **43**, 775 (1933).
[4] Dunning, Phys. Rev. **45**, 586 (1934).
[5] Meitner and Phillip, Naturwiss. **21**, 286 (1933).
[6] Bonner, Phys. Rev. **44**, 235 (1933); **45**, 601 (1934).
[7] Dee, Proc. Roy. Soc. **A135**, 727 (1932).
[8] Rabi, Phys. Rev. **43**, 838 (1933).
[9] Pollard, Phys. Rev. **47**, 611 (1935).
[10] Feather, Proc. Roy. Soc. **A141**, 194 (1933); **A142**, 3 (1933); **A142**, 689 (1933).
[11] Harkins, Gans and Newson, Phys. Rev. **43**, 208 (1933); **44**, 945 (1933); Harkins, Phys. Rev. **47**, 702 (1935); **44**, 529 (1933); **46**, 397 (1934).
[12] Kurie, Phys. Rev. **43**, 771 (1933); **47**, 97 (1935); **45**, 904 (1934); **46**, 324 (1934).
[13] Meitner and Phillip, Zeits. f. Physik **87**, 484 (1934).

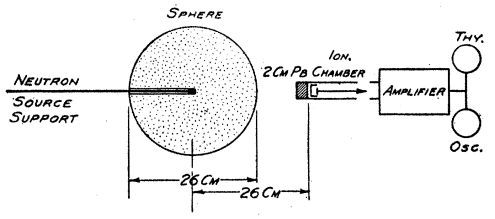

FIG. 1. Apparatus for the measurement of the absorption of fast neutrons in spheres of various materials.

covery by Fermi and his colleagues[14] of artificial radioactivity produced by neutrons, which is well explained as due to the capture of the neutron by the struck nucleus, and the suggestion of possible energy losses by neutrons through noncapture processes,[15, 16, 15a, 15b, 15c] make it desirable to have measurements of the absorption of neutrons as contrasted with scattering.

ABSORPTION OF FAST NEUTRONS

The amount of actual absorption of high energy neutrons, i.e., capture or large reduction in energy, has been studied[16] by observing the number of detectable neutrons emerging through spheres, surrounding the neutron source, of various materials and graded sizes.

Fig. 1 shows the general experimental arrangement. A Rn-Be neutron source of about 500 mc strength, encased in a platinum container of the form shown, with about 5 mm wall thickness, was placed in the position shown, and surrounded successively by spheres of 3.8, 6.3, 10.2 cm radius, of H_2O, C (coal), Al, SiO_2 (sand), Cu (shot) and Pb (shot). Spherical shells of about 1 mm thick Cu were used as containers for all except the Al which was solid. The number of neutrons emerging from the various spheres was measured through the number of projected protons (from paraffin front), plus projected nitrogen and oxygen nuclei (from chamber gas), detected in an ionization chamber connected to an amplifier system with thyratron and photographic oscillograph recorders.[16a]

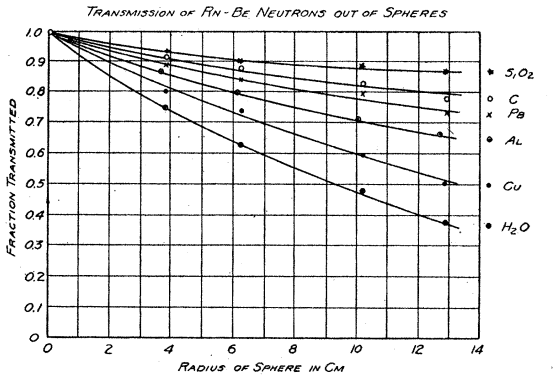

FIG. 2. Transmission of fast neutrons out of spheres of various materials and sizes.

Fig. 2 shows the decreasing number of neutrons detected as the sphere size was increased. If there were no absorption, or some process making the neutrons undetectable through projected nuclei, every neutron would emerge and the number observed with increasing sphere size should be practically constant. The obliquity of neutron paths in the case of larger spheres was not a factor since the chamber was shown in a test experiment to decrease in sensitivity by only a few percent at most when neutrons entered it from the largest angles that are possible in this arrangement.

Two general processes can account for these results: (1) capture of the neutron, and therefore removal from the beam, or (2) loss of energy by the neutrons so that some no longer have sufficient energy to project H, N or O nuclei with detectable ionization. The first process would appear to apply in the case of Al or Si, the neutron capture giving rise to artificial radioactive elements, and this undoubtedly accounts for at least part of the decrease. Capture may also play some part in the case of all the other materials tested, if the production of stable nuclei by fast neutron capture occurs (or perhaps radioactive nuclei of period so long or so short that it has not been observed), or if the reaction ${}_0n^1+{}_1H^1\rightarrow{}_1D^2+\gamma$ occurs, as has been suggested by Lea.[15] Only rather crude estimates can be made of the number of neutrons and the number of radioactive atoms produced in such cases as Al and Si but on the basis of such estimates, to account for the amount of artificial radioactivity observed, the ratio of the probability of capture

[14] Fermi, Amaldi, D'Agostino, Rasetti, Segrè, La Ricerca, Proc. Roy. Soc. **A146**, 483, 34 (1934).
[15] Lea, Nature **133**, 24 (1934); London Conference.
[15a] Fleischmann, Naturwiss. **22**, 839 (1934).
[15b] Auger, Comptes rendus **198**, 365 (1934).
[15c] Kurtchatov, Kurtchatov, Myssowsky, Roussinow, Comptes rendus **200**, 1201 (1935).
[16] J. R. Dunning, G. B. Pegram, G. A. Fink, Phys. Rev. **47**, 325 (1935).
[16a] J. R. Dunning, Rev. Sci. Inst. **5**, 387 (1934).

to the probability of elastic scattering need certainly not be greater than 1 to 10, while theory[16, 17] indicates that the ratio is very much smaller than this.

In regard to the second process, neutrons becoming undetectable through loss of energy, it is obvious that in the case of H particularly, large energy losses will occur in purely elastic collisions, and this undoubtedly accounts for the major part of the reduction with H_2O. The loss of energy in elastic collisions must be an appreciable factor even in the cases of C, O and Al. In addition, it may well be that there is some loss of energy through non-elastic nuclear collisions that result in excitation and subsequent gamma-radiation or nuclear rearrangement without neutron capture.[15a] Such evidence as there is[7, 5, 18, 19] indicates that neutron-electron interaction is too small to give a measurable part of the absorption observed in these experiments. A similar statement may be made as to more speculative processes such as neutron disintegration or neutron-neutrino interaction.

From our previous work,[4] we know the approximate mean free path of fast neutrons in the materials of these spheres (for collisions resulting in about 15° mean scattering of the neutrons) and it should be possible to arrive at some value for at least the maximum probability of capture (or large energy loss) per collision. An exact calculation of the probable number of collisions has not been attempted but the tabulation in Table I indicates the minimum possible number of collisions (for neutrons coming nearly straight out) and hence the maximum fraction of the neutrons lost per collision. The figures in the adjacent columns indicate more probable numbers of collisions (perhaps still too low) and hence a more probable value for the ratio of the fractional loss of neutrons to the probable number of collisions made by a single neutron in getting out of the sphere. The estimate of this ratio is if anything too high. This probability of neutron loss per collision is of about the same order of magnitude for each of these materials, around 10 percent and it seems quite certain that at least 90 percent of the collisions of high energy neutrons with these nuclei are approximately elastic.

TABLE I. *Transmission of fast neutrons out of spheres.*

MATERIAL	FRACTION TRANS.	FRACTION ABS.	RADIUS SPHERE	EXPER. M.F.P.	EST. MIN. NUMBER COLLIS.	EST. NUMBER COLLIS.	MAXIMUM FRACTION ABS./COLL.	ESTIMATED FRACTION ABS./COLL.
H_2O	.38	.62	12.85	5.9 cm	2.2	3.3–4.	0.28	0.19–0.15
C (coal)	.74	.26	12.85	14.0 cm	1.0	1.4–1.9	.26	.17– .13
SiO_2	.852	.148	12.85	30 cm	.43	.65–1.0	.32	.23– .14
Al	.662	.338	12.65	6.5 cm	1.95	2.9–4.	.17	.117–.085
Cu	.55	.45	12.85	7.05	1.82	2.8–3.6	.22	.16–.125
Pb	.731	.269	12.85	8.85	1.46	2.2–2.9	.18	.12–.092

SLOW NEUTRONS

Fermi and his co-workers[14] observed that neutrons from an ordinary source, such as radon-beryllium, when surrounded by a substance containing hydrogen, such as paraffin or water, show much increased interaction with atomic nuclei, including enhanced production of radioactive atoms, great variation in absorption from element to element, and the immediate disintegration of certain light elements. Since the effect on neutrons of passing through hydrogen is certainly to slow them down, the term slow neutrons is applied to neutrons showing these enhanced interactions with nuclei. The stopping power of cadmium for these slow neutrons is so great that we may approximately describe the slow neutrons as those that do not go through a sheet of cadmium, say half a mm thick. It may be remarked here that the question of whether or not the range of neutron velocity in which cadmium absorption is very high coincides with the velocity range of neutrons showing the other characteristic slow neutron effects will be touched upon later in this paper.

A fundamental question regarding slow neutrons is that of the range of velocities involved. It was readily found that no measurable fraction of the neutrons detected through projected protons showed any anomalous effects characteristic of slow neutrons, such as the increased absorption in Cd, although the sensitivity of the apparatus for slow projected protons was increased to the limit. This would indicate that slow neutrons have much lower energies than could be detected by the projected proton method, i.e., probably well below 100,000 e.v.

[17] (*a*) Wigner, Phys. Rev. **43**, 252 (1933); (*b*) Bethe, Proc. Roy. Soc. **A149**, 176 (1935).

[18] Massey, Proc. Roy. Soc. **A138**, 460 (1932).

[19] N. F. Mott, *Handbuch der Physik*, Vol. **24**, p. 834.

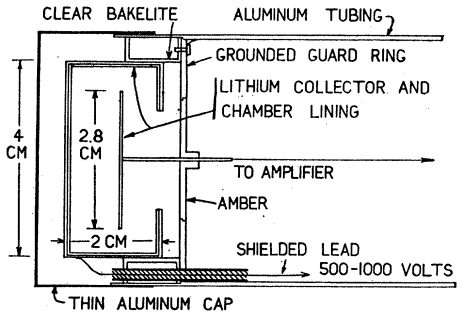

FIG. 3. Lithium ionization chamber for the detection of slow neutrons.

The nuclear transformations produced by slow neutrons resulting in the immediate ejection of heavy particles, as with boron[21] or lithium,[22, 23] which particles can be detected with an ionization chamber and amplifier system, afford for many purposes a more direct and convenient method of studying slow neutrons than the production of artificial radioactivity. We have used chiefly the lithium disintegration, for which the reaction is probably:

$$_3Li^6 + _0n^1 \rightarrow _2He^4 + _1H^3 + K.E.,$$

resulting in two groups of particles of about 1.5 and 5–6 cm range in air, which have the characteristic ionization of alpha-particles and hydrogen nuclei, respectively. This nuclear transformation seems to take place with such high efficiency that practically every slow neutron in traversing a distance of not more than about a mm in Li is captured by a Li nucleus with the formation of a helium and a hydrogen (isotope) nucleus and with an energy liberation of about 2 or 3 MEV.

The earlier experiments discussed in this paper were performed with ionization chambers having a Li front only. In the later work, chambers of the type shown in Fig. 3 have been used, which make use of nearly the full possibilities of Li as a detector, since nearly all the internal surfaces are Li. The external parts of the chamber, with the thin clear Bakelite support, amber insulation, guard ring and thin aluminum shell, are assembled and sealed at the joints with picein or glyptal. The walls and the collector, made of Li metal rolled out to about 0.015 cm thickness (just sufficient to absorb the longest range particles ejected in the reaction) are then put in place, being securely held by a conducting cement, and chamber front sealed up under a N_2 or A atmosphere. Since the two particles are ejected in opposite directions,[24, 24b] one particle will usually get into the chamber, if it has enough energy to emerge from the thin Li. Hence practically the whole chamber is effective and the detection efficiency is high. A chamber lined with powdered boron is about equally effective.

A 500 mc, Rn-Be source in a 6 cm radius paraffin sphere 30 cm from the chamber gives about 1600 counts a minute. In contrast as to detection efficiency, a similar paraffin front chamber for detecting fast neutrons from the same source at the same distance gives about 20 counts a minute. Most of the work was done with counting at a much lower rate, such as 200 per minute. The Li walls, of low atomic weight, also reduce gamma-radiation disturbance to a minimum. We estimate that the lithium chamber may detect $\frac{1}{4}$ or more of the slow neutrons falling on it.

Although a Li lined chamber responds most effectively to slow neutrons, it is also affected by higher energy neutrons. Detection with Li makes it comparatively easy to separate out high and low energy neutron effects, by making use of the anomalous absorption of slow neutrons by Cd. As will be seen from the absorption curve of Cd in a later section, the introduction of 0.030 to 0.075 cm of Cd as a shutter in front of the chamber is sufficient to absorb practically all of the slow neutrons which lie within the absorption band of Cd and within the efficient disintegration region of Li. From such a chamber there is always a residual number of counts (about 10 percent) due to higher energy neutrons that have not been entirely slowed down, so that they still have sufficient energy to project nitrogen nuclei from the chamber gas, to project occluded H from the Li, to project Li nuclei directly and, in addition, they may also disintegrate Li nuclei. The residual count left when Cd is interposed is

[21] Amaldi, D'Agostino, Fermi, Pontecorvo, Rosetti, Segrè, Ricerca Scient. V, vol. 1 (1935).
[22] Chadwick and Goldhaber, Nature **135**, 65 (1935).
[23] J. R. Dunning and G. B. Pegram, Phys. Rev. **47**, 640 (1935).
[24] Taylor and Goldhaber, Nature **135**, 341 (1935).
[24b] Kurtchatov, Kurtchatov, Latychev, Comptes rendus **200**, 1199 (1935).

then called the high energy neutron residual component (although it might possibly be that a few of these counts are due to neutrons lying below the Cd absorption region) but in any case the use of Cd permits studying the effects of slow neutrons lying within a fairly definite region. There is some evidence to be noted later that the lithium detection region extends to higher velocities than the Cd absorption region.

As will be shown later, Cd really absorbs practically all the slow neutrons incident, for the number of slow neutrons elastically scattered from it is almost undetectable. Cd thus offers unusual possibilities for defining beams of slow neutrons, since very thin sheets may serve to define slits etc., and it may also be used as shielding against slow neutrons, as is indicated in the accompanying figures of apparatus for the various experiments. A combination of a hydrogen containing material, such as paraffin or water, and a material having a high absorption coefficient for slow neutrons, such as Cd, B, Hg, etc. serves as an effective shield for both high and low energy neutrons. The combination of a paraffin sphere with a canal and defining diaphragms of Cd serves fairly well to collimate a beam of slow neutrons and has been used in a few experiments.

Production of Slow Neutrons

A number of problems, concerning the initial and final energies of the neutrons, the number of collisions necessary and the combination of slow neutrons with H, C or O arise in considering the production of slow neutrons through the process of allowing fast neutrons to lose energy in collisions with hydrogen nuclei in such substances as water or paraffin.

Fig. 4 shows the experimental arrangement used to investigate some of these questions. A 500 mc Rn-Be source bulb, about 4 mm in diameter with about 0.75 mm lead foil around it, was suspended as far from floor, ceiling, walls or other objects as possible, at 64 cm from the Li lined ionization chamber. This source was then successively surrounded by a series of ten paraffin spheres of sizes up to 23 cm radius, and the number of slow neutrons emerging was measured for each sphere. With a sphere surrounding the

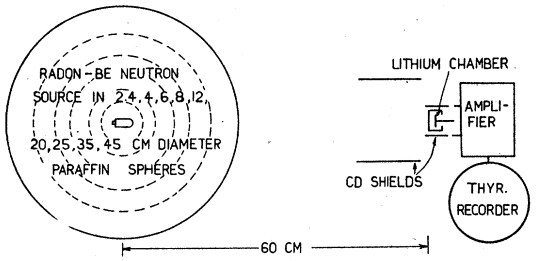

FIG. 4. Arrangement of apparatus to investigate the production of slow neutrons.

source, the number of neutrons detected should be a constant fraction of the number emerging from the sphere, regardless of the size of the sphere. The ionization chamber in the earlier experiments had a Li front only[25] but in the later work an all Li chamber was used.[26] Sheet Cd cylinders 0.040 cm thick were suitably placed to protect the detecting chamber from slow neutrons scattered back from the floor, etc., and from high speed neutrons, which have been scattered back into the chamber as slow neutrons, after being slowed down due to impacts with H in the floors, walls, etc. This latter effect is quite appreciable and may account for some of the artificial radioactivity ascribed to fast neutrons if the experiments are done near wooden table tops, etc. Readings were taken with and without Cd interposed to block the beam of slow neutrons out of the chamber, so as to follow both the change in the number of slow neutrons diffusing out of the spheres and the change in the number of higher energy neutrons emerging which were outside of the Cd effective absorption region.

Fig. 5 shows the observed results. The upper solid curve shows the results without Cd and the lower curve the results with Cd shutter interposed, the intermediate dashed curve being the difference between them, or the "slow" neutron component. For comparison, the lower dashed curve shows the data from Fig. 2, for high energy neutrons emerging from spheres of water, when detected through projected protons.

The number of slow neutrons present in the original beam is apparently zero and until a fairly considerable amount of paraffin surrounds

[25] J. R. Dunning, G. B. Pegram, Phys. Rev. **47**, 640 (1935).
[26] J. R. Dunning, G. B. Pegram, G. A. Fink, D. P. Mitchell, Phys. Rev. **48**, 970 (1935).

the source, the number of slow neutrons produced is still practically zero. After adding a thickness of paraffin sufficient to cause enough neutron-proton collisions to bring the lowest velocity neutrons present in the original source down to the "slow" region, the number of slow neutrons climbs rapidly, reaches a maximum at around 10 cm radius and then drops off quite rapidly as the amount of paraffin is still further increased. Water in thin Cu spherical shells of 10, 12.8 and 17.5 cm radii gave about the same results as paraffin.[25a]

Previous experiments with paraffin samples, using fast neutrons detected through projected protons,[4] show mean free paths in paraffin of the order of 4–5 cm, for collisions with H (or C) which result in scattering of the neutrons through about 15° mean angle. Attempts to measure changes of the neutron MFP in paraffin with lower energy neutrons, by making the detection system favor the lower velocity projected protons, in order to provide some comparison of neutrons above 2 MEV with neutrons of the order of 500,000 e.v. down to the limit of detection (possibly 100,000 e.v.) have failed to show a significant change of MFP in that region. On the other hand, the MFP of slow neutrons in paraffin is of the order of 2 to 3 mm, as shown later. Thus there seems to be a large difference in the neutron-proton interaction at the lowest "fast" neutron energy we can measure with one method, perhaps around 100,000 e.v. and in the "slow" neutron region which may be near thermal energies. Since the lower solid curve in Fig. 5 with the Cd shutter interposed actually shows a slight rise with Li detection for the smaller paraffin spheres, whereas when projected proton detection is used, the number of "fast" neutrons steadily decreases, Li must be detecting some of the neutrons in the intermediate range between fast and slow which are not highly absorbed by Cd. This appears to explain the small angle observed between the tracks of the ejected particles in the experiments of Taylor and Goldhaber.[24] Experiments with these intermediate energy neutrons have been performed by absorbing the slow neutrons in the beam with Cd and then measuring the proton cross section with the high and intermediate energy neutrons remaining. These results indicate a neutron-proton cross section of the order of 7×10^{-24} cm^2, and a MFP in paraffin of the order of 8 to 15 mm. The transition to higher neutron-proton cross sections and shorter MFP thus takes place above the Cd absorption range and this factor should considerably increase the slowing down of the neutrons, once they are down in this region.

It hardly seems likely that high energy neutrons, of the order of 2 to 5 MEV with MFP of about 4–5 cm in paraffin could make enough impacts in a sphere of 3 cm radius to become slowed down to thermal velocities, even though the factor mentioned above is operative. However, there seems to be good evidence that in this type of Rn-Be source there are already a large number of neutrons which have energies so low that they can no longer be detected through projected protons.[4] The simplest way to explain the 2 to 1 difference in the number of fast neutrons detected with "forward" and "backward" neutrons in the work mentioned is that half or more of the backward neutrons have energies already too small to detect with this method. The continued rise at the low energy end of the curve in the same paper showing number of projected protons *versus* range also lends point to this view. From this standpoint, the presence

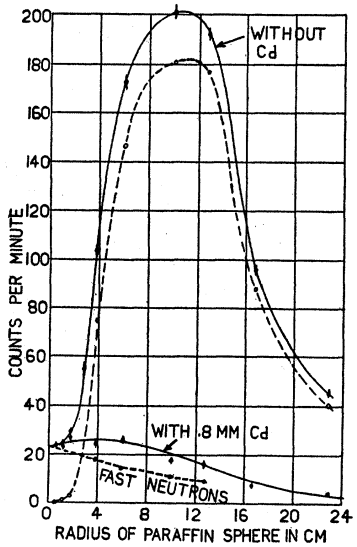

FIG. 5. Production of slow neutrons.

[25a] Westcott and Bjerge, Proc. Camb. Phil. Soc. 145 (1935).

of a considerable number of quite low energy neutrons in the source, whose MFP may already have decreased appreciably, makes it seem reasonable that some of these neutrons can make a sufficient number of collisions in a sphere of 3 cm radius to be brought down into the near thermal region, for Fermi has shown,[14] that the neutrons lose $1/e$ of their energy per collision, on the average. As the sphere size is further increased, more and more of the fast neutrons are of course slowed down and, with a sphere of 12–15 cm radius, most of the higher energy neutrons might be slowed down and the growth curve might simply flatten out, if there were no absorption.

As to the decrease in observed number with the largest spheres, since the chamber showed practically no difference in sensitivity with neutrons coming at it from the largest angles possible with the big sphere, the obliquity of entrance from the sides of the larger spheres is proved unimportant. To account for this decrease two postulates are available; (1) either the neutrons have been dropped in energy below the Li detection region or (2) some process is removing neutrons from the beam. There is no evidence that suggestion (1) is reasonable; from the viewpoint of Bethe's theory this should not be possible. The evidence for (2), however, is not entirely conclusive either. Reactions involving capture of the neutrons such as:

$$_1H^1+{}_0n^1\rightarrow{}_1D^2+\gamma$$

or similar reactions involving O^{16} or C^{12} or their isotopes, might occur.[15] There seems to be no reason for excluding these reactions at present but, since the MFP of the neutron with respect to the H in the paraffin is so small, the number of collisions with H has increased enormously for the two largest spheres and the experiment proves that the probability of capture per collision with protons must be very small. However, it might well account for the decrease. The number of collisions with C or O, from the neutron-nucleus cross section measurements in a following section, is much smaller than with protons and it is not considered likely that these play much part but here, also, the experiment shows that probability of capture cannot be very large, certainly less than 10 percent per collision and, furthermore, O cannot be very much different from C. It may well be that the slowest neutrons are being continually removed from the beam through combination with H, C or O, which might prevent the emerging neutrons from ever reaching a near thermal equilibrium. The more speculative possibilities of the disintegration of the neutron or combination with neutrinos may also deserve some consideration.

Production of Slow Neutrons by Deuterium

The relative efficiency of H_2O and D_2O in enhancing artificial radioactivity produced by neutrons was studied with the experimental arrangement shown in Fig. 6.[26a]

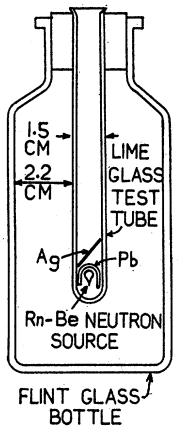

FIG. 6. Apparatus for studying the relative enhancement of artificial radioactivity by H_2O and D_2O.

A piece of silver 1.5×2.5 cm by 0.025 cm thick was activated by suspending it above a 200 mc Rn-Be neutron source encased in about 2 mm of lead at the bottom of a thin soft glass test tube, first in an empty 200 cc bottle, next with the bottle filled with 200 cc of H_2O and then with 200 cc of D_2O (99.8 percent), kindly supplied by Professor H. C. Urey. The radioactivity of the silver was tested by placing it under a thin-walled tube counter of Dow metal (Mg alloy), 0.025 mm thick. The data are summarized in Table II. The number per minute in the table is the average number for the first 4 minutes after placing the silver under the counter. Subtracting for the effects of the naturals and the number from the direct beam with nothing but air

[26a] J. R. Dunning, G. B. Pegram, G. A. Fink, D. P. Mitchell, Phys. Rev. **47**, 416 (1935).

TABLE II. *Enhancement of artificial radioactivity by D_2O and H_2O.*

	H_2O	D_2O	Air	Naturals
Runs	5	8	7	21
Number per minute	107	35.2	19.3	3.7
Net	103.3	31.5	15.7	
Enhancement	87.6	15.8		
Relative effect	6.5 : 2 : 1			
Relative enchancement	5.5 : 1			

surrounding the material, the results indicate that H_2O is about 5.5 times as effective as D_2O in enhancing the artificial radioactivity from Ag under these conditions.[27, 28] This enhancement by D_2O is little more than might be expected from the back-scattering of high energy neutrons from any material placed around the source and sample.[29] Since the average energy lost by a neutron in an elastic collision with the deuteron is only slightly (1/8 in the case of direct impact) less than in a proton collison, the comparatively small production of slow neutrons by D_2O must be ascribed to a lower probability of collision, that is a much smaller interaction between neutron and deuteron than between neutron and proton. This accords with absorption results discussed in another section.

ENERGIES OF SLOW NEUTRONS

The question of whether or not the "slow" neutrons do have approximately thermal velocities is of fundamental importance. Fermi[30] and his colleagues first attacked this problem using hydrocarbon mixtures to slow the neutrons down, and studying the artificial radioactivity produced first at room temperatures, then with the hydrocarbon mixture raised to about 200°C. No significant effects on the properties of the neutrons were observed.

In our experiments[31, 32] we have used the temperature range from liquid air to boiling water in order to get a greater change in energy of the neutrons, if the neutrons are in thermal equilibrium with the hydrogenic materials used to slow them down and we have used the Li chamber detection system.

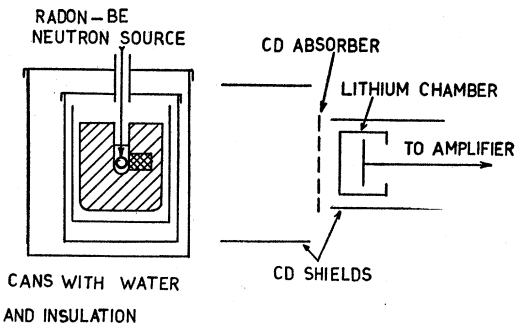

FIG. 7. Apparatus for investigation of the effect of temperature on the properties of slow neutrons.

Fig. 7 shows the general arrangement of the apparatus. The Rn-Be neutron source encased in a platinum container was placed in a cylindrical vessel of water, which was in turn placed inside of several thin concentric polished cans. This permitted cooling the H_2O down to liquid air temperatures, by pouring liquid air over the inner container, and with the insertion of a small electric heater, allowed heating to the boiling point. The temperature was measured with thermocouples. The neutrons, after being slowed down in the water or ice by impacts with the H nuclei, were detected in the usual manner, with a Li lined ionization chamber. Two major groups of runs were made. In the first series, the chamber had a Li front only; in the second group, runs 4 and 5, the chamber walls were entirely of Li, increasing the counting efficiency and reducing the high energy neutron background from 35 to 11 percent. In the first group, runs 1, 2 and 3, the Rn-Be bulb was at the same temperature as the H_2O. It was subsequently found, in a separate test listed at the bottom of Table III, that when the bulb alone was cooled, the radon could condense on or near the Be so as to increase the recorded number of neutrons by 3 to 8.6 percent. To eliminate this effect, in runs 4 and 5 the platinum source container was placed inside a small soft glass Dewar with a heater coil and thermocouple attached to it, by which the bulb was held at about room temperature. The inner vessel was of thin Cu with 1100 g of H_2O in

[27] Libby, Long, Latimer, Phys. Rev. **46**, 424 (1935).
[28] Herszfinkill, Rotblat, Zyw, Nature **135**, 654 (1935).
[29] Danyz, Rotblat, Wertenstein, Zyw, Nature **134**, 970 (1934).
[30] Amaldi, D'Agostino, Fermi, Pontecorvo, Rasetti, Segrè, Proc. Roy. Soc. **A149**, 522 (1935).
[31] Dunning, Pegram, Fink and Mitchell, Phys. Rev. **47**, 796 (1935).
[32] Dunning, Pegram, Fink and Mitchell, Phys. Rev. **48**, 888 (1935).

runs 1 and 2. In runs 3, 4 and 5, a larger thin Al vessel containing 3400 g of H_2O was used, in order to bring the number of slow neutrons produced up to about the maximum value. Cd shields were used to reduce room scattering to the detection chamber in the last two runs. In most cases, the H_2O was first frozen and a series of readings taken at about 273°K. The temperature was then lowered to the liquid air point, about 95°K, and the series of readings taken only after the liquid air had almost completely evaporated, small amounts of liquid air being added between readings. Readings were taken at the 273°K point again and the temperature was then raised to near 373°K for a series of readings where loss by evaporation was replaced when necessary.

Table III shows the results of the 5 runs in terms of the percentage change in the observed number of counts (about 65 percent from Li disintegrations in the first group, about 90 percent from Li in the second group) and in the last column, the percentage change in the absorption of Cd as the temperature was lowered from 373°K in the first group and 273°K to about 95°K in the second group. Runs 1 and 2 consisted of about 5000 to 7000 counts on each point; run 3 of about 10,000 to 12,000 counts on each point and runs 4 and 5 of about 12,000 to 20,000 counts on each point. The last two runs are considered the most reliable from all standpoints and the accuracy from the point of view of statistical fluctuations should be better than ±1.5 percent.

In regard to the change in the total number of counts observed at the various temperatures, as shown in column 2, a number of factors must be taken into consideration. The condensation of the radon mentioned previously, which may cause increases of the order of 3 to 8.6 percent, is probably sufficient to explain the increase in the counts, due largely to Li disintegrations, in the first series of 3 runs. As to the apparent decrease in runs 4 and 5, the possibility of a slight amount of frost absorbing some of the neutrons, the possibility of increased absorption of slower neutrons within the walls of the all Li chamber, the possibility of a small amount of liquid air not having evaporated before the beginning of the run or the possibility of increased combination with H in the H_2O at low temperature may be sufficient to explain the apparent decrease. In view of this, we cannot conclude that the emission from Li is definitely increased by the decrease in temperature of the water.

TABLE III. *Change in the number of observed counts (chiefly Li disintegrations) and in the absorption of Cd as the temperature was lowered to about 95°K.*

RUN	CHANGE IN LI DISINTEGRATIONS	CHANGE IN CD ABSORPTION
Source at H_2O temperature, 95°–373°K		
1	+7.8 percent	+ 2.6 percent
2	+4.1	+10.7
3	+8.9	+ 2.7
Source at constant temperature, H_2O at 95°–273°K		
4	−1.46 percent	+ 3.8 percent
5	−2.8	+ 2.4
H_2O at constant temperature, source at 95°–273°K		
	+3 to 8.6 percent	

The change in the absorption of Cd, as measured by introducing a sheet of about 0.005 cm of Cd (sufficient to absorb about 50 percent of the slow neutrons) is a test of the properties of the neutrons which should be little affected by factors that may change the total number. The results in column 3 of Table IV indicate that "cold" neutrons are slightly more easily absorbed by Cd. While the effect is small, of the order of 5 percent, it is considerably larger than the probable error, and the probability that the apparent consistency of the 5 runs is fortuitous should be very small.

There are a number of interpretations which can be made of these results. (1) No large fraction of these slow neutrons is actually in thermal equilibrium. (2) A considerable fraction of these neutrons may be in thermal equilibrium but the absorption of Cd, and the disintegration of Li, are not sensitive functions of the neutron energy in this region. (3) The removal of the slowest neutrons from the beam by combinations with H or O as suggested before, may keep any large number from emerging with thermal energies. There is likewise the possibility that the Li detection region may not extend down to near zero energy or that the small differences between the Li and Cd regions suggested by the data on the production of slow neutrons may be influencing the results. The fact that the absorption curve of Cd, when measured with a reasonably parallel beam of slow neutrons, is very nearly exponential seems to show that the absorption of

Cd is not a sensitive function of the neutron energy. In experiments such as these, in which a wide range of neutron energies must be present, if the Cd curve is singly exponential, then once the neutrons are below the threshold where abnormal absorption effects set in, the absorption of the slow neutrons will not be a sensitive function of the neutron energy and the temperature effects will be small. If the high absorption by Cd extends up to neutrons well above thermal velocities, say above 0.1 e.v., the shift in the thermal velocities caused by changing the temperature of the water would make little change in the effect of the neutrons.

Interaction of Slow Neutrons with Matter

The interaction of high energy neutrons, i.e. neutrons which have energies above 100,000 e.v., with atomic nuclei has already been investigated by various methods and as shown previously, most of the phenomena associated with their passage through matter are accounted for by more or less elastic scattering in about 90 percent or more of the nuclear impacts. The variation in neutron-nucleus collision cross section with atomic weight, investigated under fairly good geometrical conditions as discussed in one of our earlier papers[4] is shown in Fig. 8. The variation in cross section for the elements of lower atomic weights, has been studied more carefully and, as the curve shows, H, D, Li, Be and C, all appear to have very nearly the same cross section but beyond this point the heavier elements show cross sections which increase about as the (atomic weight)$^{2/3}$. The nuclear radii, as calculated by Professor Rabi and Mr. Clark from these data, agree quite well with nuclear radii inferred from other types of measurements, if the neutron radius is taken as about 1.2×10^{-13} cm.

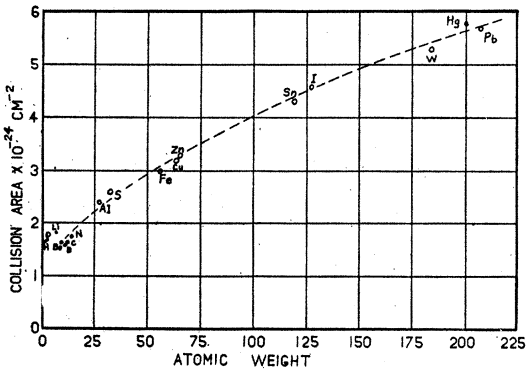

FIG. 8. Neutron-nucleus collision cross sections of the various elements for fast neutrons.

As neutrons are slowed down by impacts with H nuclei, no great differences have been observed as yet in their properties as long as they have sufficient energy to be detected through projected protons, although there may be resonance phenomena which are not observed because of the wide range of energies present. The borderline region where neutrons can no longer be detected through projected protons is not very well defined, being dependent on amplifier sensitivity and disturbances, and the nature of the interaction in this region, but it is probably somewhere in the neighborhood of 100,000 e.v. We have not succeeded in detecting in this energy range any of the effects peculiar to slow neutrons. The region where the effects characteristic of slow neutrons set in is probably far below this region, possibly down to near thermal energies.

It is possible to make some measurements in the intermediate region between fast and slow with Li as a detector but the fast neutron residual component is difficult to allow for.

Absorption of Cadmium

The remarkably high absorption of slow neutrons in cadmium makes its absorption curve of especial interest. It requires only about 0.005 cm thickness of Cd to absorb 50 percent of the slow neutrons, which is of the order of α-particle absorption, although it still requires about 2.5 cm of lead to absorb one-half of the slow neutrons. In earlier experiments,[33] the absorption curve was shown to be very nearly exponential but in those experiments the chamber had a Li front only and the large high energy neutron background made accurate measurements difficult. There was also some question as to the effect of room scattering.

Fig. 11 in the next section shows the general arrangement for a more recent series of measurements. The all Li chamber, with Cd shields to protect against room scattering, was used. Fig. 9 shows the absorption curve for the slow neutrons. As the amount of cadmium interposed is in-

[33] Dunning, Pegram, Fink and Mitchell, Phys. Rev. **47**, 796 (1935).

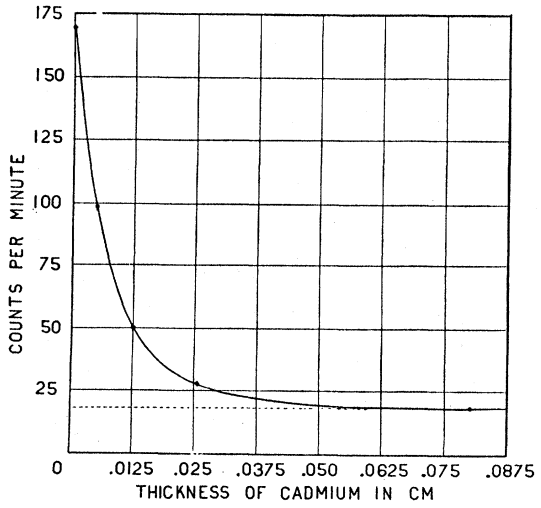

FIG. 9. Absorption of slow neutrons by cadmium.

creased, the number of counts drops off rapidly and the curve flattens out until with about 0.04 cm of Cd it is almost asymptotic, the slope from there on being about what one would expect for high energy neutrons, practically all of the slow neutrons having been absorbed.

Fig. 10 shows the absorption curve plotted on logarithmic scale, with the high energy neutron component subtracted, in order to obtain the absorption of the slow neutrons only. The deviation from a straight line is only a few percent. If the neutron beam were more nearly parallel, the curve should more nearly approach a straight line. Fermi and his collaborators obtained an absorption curve for Cd by using artificial radioactivity as a detector but it was necessary to

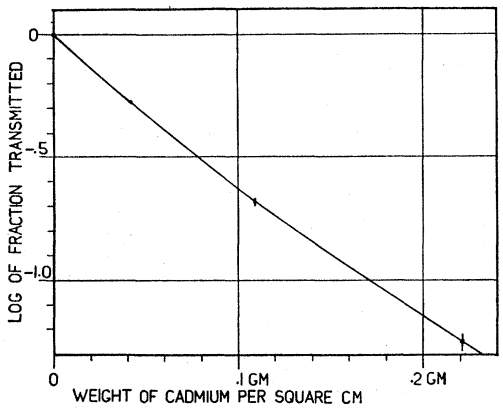

FIG. 10. Absorption of slow neutrons by cadmium-logarithmic plot.

place the Cd and the detector close to the paraffin blocks used to slow down the neutrons.[30] The large number of slow neutrons entering the Cd at oblique angles would naturally show a higher absorption than those entering near the normal and would give a different absorption curve from that obtained with a nearly parallel beam. Fig. 10 indicates that the absorption of Cd for the slow neutrons which disintegrate Li can be closely expressed by a single exponential curve. Considering the wide range of neutron energies undoubtedly present, this must mean that the absorption of Cd is not a sensitive function of the neutron energy in this region. It is not clear how Bethe's theory[34, 35, 36] of the interaction of slow neutrons with nuclei can adequately explain this exponential absorption curve for Cd. There must be some compensating factors not taken into account in the theory which make the absorption more independent of energy than the theory indicates. This absorption curve may also suggest that if these neutrons do have approximately thermal energies, either this abnormal absorption sets in at a quite sharp threshold and does not come in gradually over a wide velocity region, or else that abnormal absorption extends above the main group of slow neutrons so that no large number of the slow neutrons lie within the region where the absorption coefficient varies. Any of these interpretations would indicate that the temperature effect should not be large. One might expect the change in temperature to affect only those neutrons which are responsible for the departure from exponential absorption, or those near the threshold of the abnormal cross section change, if that threshold is quite low. There is always some question as to whether some peculiar characteristic of the Li detection region may not be influencing these results but, except for the indication in Fig. 5 that Li is slightly affected by neutrons which are above the Cd absorption region, Li seems to be entirely satisfactory.

ABSORPTION OF SLOW NEUTRONS BY VARIOUS ELEMENTS

In order to investigate the neutron-nucleus interaction for slow neutrons over a wide range of

[34] Bethe, Phys. Rev. **47**, 747 (1935).
[35] Perrin and Elsasser, Comptes rendus **200**, 450 (1935).
[36] Beck and Horsley, Phys. Rev. **47**, 510 (1935).

elements, we have made several series of absorption measurements by interposing test samples between source and detector, using the experimental arrangement shown in Fig. 11, for the later measurements. In the earlier measurements[23, 26] the chamber had a Li front only and the source and chamber were unshielded. The necessity for subtracting a large high energy neutron background and the uncertain scattering from the room made these earlier measurements only approximate. The arrangement in Fig. 11 greatly improves the situation. The source and 12 cm diameter paraffin ball are contained in a cylindrical box of Cd, so that slow neutrons emerge in the forward direction only, so as to minimize room scattering, and Cd shields protect the chamber. A Cd diaphragm with a 4 cm hole further defines the beam to the size of the test sample. The neutron beam striking the sample is only approximately parallel but it is much better than can conveniently be used with artificial radioactivity as a detector, with this type of source. Geometrical conditions are very important in determining the cross section values obtained from experiment, as noted in the preceding section. Apparently for this reason our cross section estimates are lower than those of Professor Fermi and his group.

The test samples were cylinders 4 cm in diameter, with the thickness adjusted to give about a 40 percent decrease in the slow neutrons, when interposed. Pure elements were used if available, and in solid form where possible. The powders, finely divided metals, etc. were held in very thin Dow metal (Mg alloy) containers, which have practically no absorption. Where pure elements were not available, the oxides were in general used, since the absorption of O is small and its effect can be allowed for. Since many elements exhibit high cross sections, their presence in small amounts as impurities might seriously affect the results. Practically all the elements tested showed analyses that indicated very little impurity of high cross section elements but analyses were not available for some of the elements tested. Particularly in the case of the rare earths the purity was in most cases uncertain, and since a small admixture of samarium or gadolinium would give a large increase in the absorption a number of the results must be considered rather rough estimates. Where the amount of absorbing material in powdered form necessary to absorb 40 percent is very small, as with gadolinium or samarium, it is difficult to get a very uniform thin layer, and some uncertainty in their large cross sections results from this. The water content of the slightly hygroscopic substances may possibly influence the results somewhat in those cases.

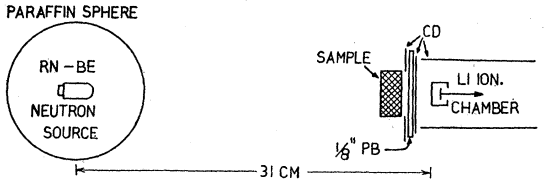

FIG. 11. Experimental arrangement for slow neutron absorption measurements.

A new sample of uranium oxide has given a much lower absorption than a sample previously reported.[32]

In computing these results, it is convenient to express them in terms of neutron-nucleus collision cross section. If N_0 is the original number of counts per minute with no absorber and N the number with absorber interposed, then for the fraction transmitted, we have

$$p=N/N_0=e^{-\lambda/d} \qquad \text{where} \qquad \lambda=1/N\pi\sigma^2$$

is the mean free path of the neutrons, d is the thickness of the sample, N the number of nuclei per cm^3, and $\pi\sigma^2$ is the neutron-nucleus collision cross section, σ being the sum of the "radii" of the neutron and of the nucleus. In order to determine the cross section for slow neutrons only, all readings were taken with and without cadmium, in order to eliminate the high energy neutron component. The readings for the high energy neutron components were subtracted to make N and N_0 refer to the slow neutrons only. These cross sections have been computed without taking into account the thermal velocities of the neutrons, which would be of significance only if there were a considerable number of neutrons near thermal equilibrium with one of the lighter elements.

Table 4 shows the various elements tested, their atomic weights, the compound used if the element was not feasible, the g/cm^2 used, the fraction transmitted, P computed for slow

TABLE IV. *Neutron-nucleus collision cross sections.*

ELEMENT	ATOMIC NO.	ATOMIC WT.	COMPOUND USED	G/CM²	FRACTION TRANSMITTED P	CROSS SECTION ×10²⁴ CM⁻² SLOW NEUTRONS	CROSS SECTION ×10²⁴ CM⁻² FAST NEUTRONS
H	1	1.008	$(CH_2)_n$	0.131	0.673	35	1.68
D	1	2.014	D_2O	1.36	.631	4.0	1.71
Li	3	6.94	LiF	.24	.765	45	1.84
Be	4	9.02	Be	.703	.780	5.3	1.65
B	5	10.82	B_4C	.0557	.418	360	1.60
C	6	12.00	C	2.86	.549	4.1	1.65
N	7	14.01	NaN_3	1.30	.630	11.3	1.76
O	8	16.00	SiO_2	3.78	.709	3.3	
F	9	19.00	NaF	1.94	.827	2.5	
Na	11	23.00	Na	1.48	.847	4.2	
Mg	12	24.32	Mg	4.67	.669	3.5	
Al	13	26.97	Al	7.24	.788	1.5	2.4
Si	14	28.06	Si	2.23	.867	2.5	
P	15	31.03	P	1.69	.615	14.7	
S	16	32.06	S	6.6	.840	1.4	2.6
Cl	17	35.46	NaCl	1.35	.541	39	
K	19	39.10	K	1.60	.816	8.2	
Ca	20	40.07	CaO	1.87	.751	11.0	
Ti	22	48.1	TiO_2	1.97	.760	11.9	
V	23	50.96	V_2O_5	2.41	.751	10	
Cr	24	52.01	Cr	5.82	.718	4.9	
Mn	25	54.93	Mn	3.69	.558	14.3	
Fe	26	55.84	Fe	3.87	.605	12.0	3.0
Co	27	58.94	Co	1.41	.602	35	
Ni	28	58.69	Ni	3.03	.637	15.4	
Cu	29	63.57	Cu	6.22	.642	7.5	3.2
Zn	30	65.38	Zn	10.7	.627	4.7	3.3
Ge	32	72.60	GeO_2	.08	.93	*est.* 75	
As	33	74.96	As	5.28	.692	8.6	
Se	34	79.2	Se	3.47	.606	19	
Br	35	79.92	KBr	3.43	.705	11.8	
Sr	38	87.63	$SrCrO_4$	2.21	.832	*est.* 9	
Y	39	88.9	Y_2O_3	.18	.463	800	
Zr	40	91	ZrO_2	1.87	.807	16.7	
Cb	41	93.1	Cb_2O_5	1.01	.90	*est.* 14	
Mo	42	96.0	Mo	1.70	.926	7.1	
Ru	44	101.7	Ru	6.1	.647	12.5	
Rh	45	102.9	Rh	0.62	.664	115	
Pd	46	106.7	Pd	6.2	.715	10–	
Ag	47	107.88	Ag	1.88	.557	55	
Cd	48	112.41	Cd	.0416	.524	3300	
Sn	50	118.70	Sn	18.8	.678	4.0	4.3
Sb	51	121.77	Sb	7.26	.745	8.1	
Te	52	127.5	Te	5.52	.790	8.2	
I	53	126.93	I	6.78	.738	9.4	4.6
Ba	56	137.37	BaO	.662	.680	140	
La	57	138.90	La_2O_3	.214	.933	80	
Ce	58	140.25	CeO_2	.98	.896	*est.* 25	
Pr	59	140.9	Pr_2O_3	2.43	.77	25	
Nd	60	144.27	Nd_2O_3	.72	.559	220	
Sm(Sa)	62	150.43	Sa_2O_3	.04	.525	4700	
Eu	63	152	Eu-Gd-Al	.02	.647	*est.* <1000	
Gd	64	157.6	Gd_2O_3	.0068	.590	30,000	
Tb	65	159.2	Tb-Al	.06	.919	*est.* <1000	
Dy	66	162.5	Dy-Al	.27	.685	700	
Ho	67	163.4	Ho-Al	.144	.877	*est.* 400	
Er	68	167.7	Er_2O_3	.666	.780	120	
Tm	69	169.4	Tm-Al	.07	.987	*est.* 500	
Yb	70	173.6	Yb_2O_3	.315	.912	90	
Lu	71	175.0	Lu-Al	.045	.93	*est.* 400	
Ta	73	181.5	Ta	4.56	.663	27	
W	74	184.0	W	7.05	.592	23	5.3
Re	75	186.31	Re	2.39	.501	89	
Os	76	190.8	Os	5.35	.643	27	
Ir	77	193.1	Ir	.785	.509	285	
Pt	78	195.2	Pt	4.30	.769	25	
Au	79	197.2	Au	2.52	.508	88	
Hg	80	200.61	HgO	.545	.556	380	5.8
Tl	81	204.39	Tl	10.5	.710	11	
Pb	82	207.20	Pb	22.7	.568	8.6	5.7
Bi	83	209.00	Bi	9.07	.805	8.2	
Th	90	232.15	ThO_2	2.75	.772	32	
Ur	92	238.17	UrO_2	2.52	.83	43	

neutrons only, and the values for the slow neutron-nucleus cross section. The slow neutron cross sections vary all the way from values apparently below those for fast neutrons to enormous values in such cases as Cd, Sm and Gd. The samarium and gadolinium samples are probably quite pure. Previous measurements on a sample of terbium, known to contain possibly 40 percent impurities, indicated a cross section of about 6000×10^{-24} cm², but measurements on a terbium-aluminum alloy show a cross section probably less than 1000×10^{-24} cm. Gadolinium as an impurity was doubtless the cause of the high absorption by the earlier sample of terbium. We estimate that in most cases the values given are accurate to within ±10 percent for the smaller cross sections and probably within ±25 percent for the larger values, except in the Cd case, where it should be within ±10 percent. In some cases where only a small amount of material was available or other factors made the result only approximate, the estimated cross sections are labelled "est." A number of the rare earths tested were in the form of alloys with aluminum of which the composition was known to be between 40 and 60 percent aluminum. In the final column, the comparison values for high energy neutrons from the curve in Fig. 8 are included.[33b]

The geometrical conditions were much better for the high energy neutron measurements and the ratio of fast neutron to slow neutron cross section is modified somewhat by this and by the fact that what is measured here is a combination of elastic-scattering cross section, and capture cross section. Either elastic scattering of the neutron by the struck nucleus through a sufficient angle, or capture of the neutron by the struck nucleus, would remove it from the beam. In the high energy neutron case, the cross section computed is almost entirely due to elastic scattering of the neutrons through angles of about 15° or more. In the slow neutron case, however, both elastic scattering and capture play a part. From the evidence in the following section on scattering of slow neutrons, it appears that in cases in which the slow neutron cross section is about the same as that for fast neutrons, elastic scattering plays the major part. For intermediate

[33b] Preiswerk, Comptes rendus **200**, 827 (1935).

cross sections, both elastic scattering and capture are involved, while for the large cross sections, capture seems to be the major factor. Since the neutron must be scattered as much as 30° to be scattered out of the chamber with the geometrical arrangement as in Fig. 11, the small cross section values for slow neutrons, where elastic scattering is the main factor, are a little too small in comparison with the fast neutron values. Some measurements with fast neutrons, using copper spheres and detection through projected protons, indicate that this geometrical factor may be of the order of 1.25; i.e., the smaller cross sections for slow neutrons such as Al and S should be multiplied by about 1.25. Even so, this factor is not sufficient to bring the slow neutron cross section of Al and S up to the value for fast neutrons and, while these correction factors are not certain, it seems that the slow neutron interaction with such nuclei as Al and S is probably less than with fast neutrons. This may be reasonable from Bethe's theory.

The nuclear cross section values for slow neutrons from our earlier data have been tabulated by Bethe.[34] At that time it seemed that, in terms of his theory, a random distribution of phase angles among the various elements might account for the distribution in observed cross section values. Since samarium and gadolinium as well as Cd have now been shown to have enormous cross sections, the point may need to be examined again. The question of whether all or only one of the isotopes of these elements is responsible for the large interaction is not quite clear as yet. Cd has 6 to 9 isotopes, the most abundant of which is 35 percent; Sm has about 7 isotopes, with the most abundant about 25 percent; and gadolinium has probably five isotopes, the most abundant being around 23 percent. If only one of the isotopes in Gd or Sm is responsible, then the cross section of that isotope must be very much larger yet, approximating the size of the K shell of electrons or even larger.

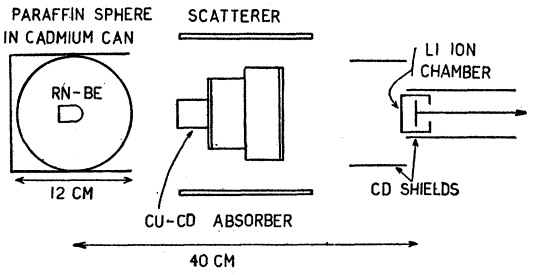

FIG. 12. Experimental arrangement for the measurement of the scattering of slow neutrons.

CAPTURE AND SCATTERING OF SLOW NEUTRONS

The question of what is actually happening to the neutron in the cases where large neutron-nucleus collision cross sections indicate large interaction between nucleus and neutron is not entirely clear as yet. The work of Fermi has shown that in a number of cases where the cross sections are large, the amount of artificial radioactivity is greatly increased, indicating capture of the neutron, but in other cases such as cadmium where capture is quite certain, the radioactivity is small or absent. The elastic scattering cross section, from Bethe's theory, should be at least as large or larger than the capture cross section. If the neutron is captured, we may expect the production of an immediately unstable combination, such as in the Li or Al cases, resulting in the emission of heavy particles with or without subsequent radioactivity; or we may expect the production of an unstable radioactive isotope of the struck nucleus, with subsequent beta-emission and gamma-emission; or the production of a stable isotope, with gamma-ray emission, as has been indicated in a number of cases.

In order to obtain experimentally an estimate of the ratio of scattering to capture of slow neutrons in the case of cadmium we have made some experiments using the arrangement in Fig. 12. The Rn-Be source with paraffin sphere and chamber are enclosed in Cd to reduce the room scattering, while the direct beam to the chamber of the order of 500 per minute is reduced to about 15 per minute by a Cd disk to eliminate the slow neutrons and by a Cu or paraffin cylinder to reduce the high energy neutrons. The scattering of various materials was then observed by placing them, in cylindrical form in most cases, in the position shown, so that the neutrons could be scattered back into the chamber. The results in Table V show the approximate relative scattering of the various materials. The results are not very

TABLE V. *Scattering of slow neutrons from various materials.*

Material	No. per min.
Background	16.7
Cu cylinder	45
Cd cylinder	14.1
NaCl	22.3
MgO brick	43.4

exact since the Mg was in brick form, while the NaCl and $CaCO_3$ were in flat form, but these were taken largely as a rough comparison to Cd.

Cd shows so little elastic scattering of slow neutrons that introducing a cylinder of it does not increase the number of neutrons recorded but actually decreases it, since it screens out some of the neutrons scattered back from the floor, etc., into the chamber. It is certain from this experiment that, even though practically every slow neutron incident on the Cd is stopped, only a few percent could possibly be scattered, but the limit is hard to set and the experiment described in the following section was designed to measure this more accurately. NaCl does show some scattering but the scattering is little more than might be expected from the low cross section Na, the high cross section Cl probably absorbing most of the neutrons that fall on it. Cu, $CaCO_3$ and MgO, all of which show rather ordinary cross sections, show quite large elastic scattering. Apparently the large cross sections of various elements are due to capture then, rather than scattering, although from these experiments we cannot express the ratio of scattering to capture very quantitatively.[37]

Fig. 13 shows the arrangement designed to determine the residual elastic scattering of slow neutrons by Cd more accurately. In effect, the

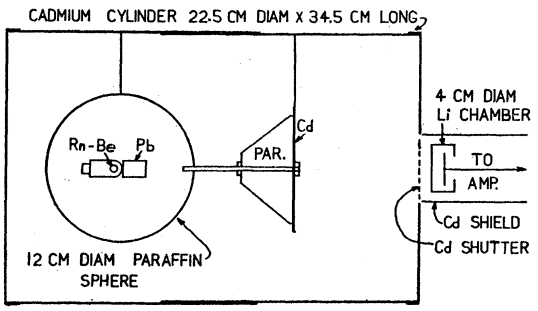

FIG. 13. Arrangement for the measurement of the residual scattering of slow neutrons from cadmium.

[37] Mitchell and Murphy, Phys. Rev. **47**, 812 (1935).

experiment is done inside of a cylindrical Cd box to eliminate room scattering and the experiment measures the scattering from the interior walls of the Cd cylinder itself. The direct beam of slow neutrons to the chamber is cut out by a disk of Cd 0.1 cm thick, and the direct fast neutron beam is greatly reduced by some paraffin directly behind the Cd disk. The only slow neutrons that can enter the chamber, then, are those scattered from the walls of the Cd cylindrical box or from the air itself in the box. By interposing a Cd shutter in front of the chamber opening, the slow neutrons scattered from the walls or air are stopped and the decrease measures the number of scattered slow neutrons. A series of measurements (2000 counts total) gave 13.4 per minute as the number of neutrons detected with the shutter removed and 12.7 per minute with the Cd shutter interposed, the difference, 0.7 per minute, representing the number of scattered slow neutrons. This is not much more than the probable error from statistical fluctuations. Had the cylindrical box been made of copper, the number scattered to the detecting chamber would have been about 100 a minute. The elastic scattering of slow neutrons from a sheet of cadmium is then very small, certainly less than 1 percent of the number captured. The neutron-nucleus cross section of Cd as usually computed is therefore to be regarded as a capture cross section and not an elastic collision cross section. Rough experiments with other highly absorbing elements also indicate small scattering.

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Band Spectra of AgO and CuO

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Band spectra of AgO and CuO, obtained by arcing between metal electrodes in oxygen at reduced pressure, have been photographed in the first order of a 21-foot grating. An ultraviolet and a blue system of AgO are subjected to vibrational analysis and are attributed respectively to $^2\Sigma \rightarrow {}^2\Sigma$ and $^2\Pi \rightarrow {}^2\Sigma$ transitions, with a common lower state. A third system in the far red was too faint for measurement. It is found that the red system of CuO is due to something more complicated than the $^2\Sigma \rightarrow {}^2\Sigma$ transition attributed to it by Mahanti.

THE arc source previously used[1] for the study of the spectrum of SnO has here been applied to AgO and CuO. It is simply an arc between metal electrodes operating in a stream of oxygen at some 5 cm pressure and has proved to be a rather intense and stable source for oxide spectra.

SILVER OXIDE BANDS

Hulthén and Zumstein,[2] while studying the spectrum of AgH observed a group of bands near 2600A which they attributed to the AgO molecule. These bands were not found in the present investigation, although three other systems were observed. One of these is in the ultraviolet between 3400 and 3700A and degrades to higher frequencies, a second is in the blue and degrades toward the red, and the third is in the red and degrades in the direction of decreasing frequencies. The bands in the red are of very low intensity and have not been photographed with sufficient dispersion to permit a vibrational assignment. The other two systems have been photographed in the first order of a 21-foot grating with an average dispersion of 1.3A/mm. A vibrational analysis of these two systems has been made and it is found that the frequencies of their heads can be represented by the following expressions:

$$\nu = 28{,}074.6 + \{534.7(v'+\tfrac{1}{2}) - 6.10(v'+\tfrac{1}{2})^2\} - \{493.2(v''+\tfrac{1}{2}) - 4.10(v''+\tfrac{1}{2})^2\}, \quad (1)$$

$$\nu = \left.\begin{matrix}24{,}139.9\\ 24{,}310.9\end{matrix}\right\} + 233.0(v'+\tfrac{1}{2}) - \{493.2(v''+\tfrac{1}{2}) - 4.10(v''+\tfrac{1}{2})^2\}. \quad (2)$$

These indicate, of course, that the two systems have a common lower state.

The frequencies and roughly estimated intensities of these bands, together with vibrational quantum assignments and deviations of observed frequencies from those calculated from Eqs. (1) and (2) are given in Tables I and II.

Since the vibrational spacings in the upper and lower states of the ultraviolet system are nearly equal, the bands are grouped into non-overlapping sequences and are comparatively easy to assign.

[1] Loomis and Watson, Phys. Rev. **45**, 805 (1934).
[2] Hulthén and Zumstein, Phys. Rev. **28**, 13 (1926).