writers found that long baking alone was not sufficient to remove such contamination. In fact, without the induction heating it was possible to get a positive ion current leaving the outside of the collector and guard ring which was comparable with the metallic ion current which was to be measured. Some such effect may account for the lower values found by Smith and Moon.

While the accuracy in the determination of φ_{0+} is not as great as is desired, it is questionable whether due to the variable emissivity discussed above greater precision would have much significance.

Discussion of Results

Eq. (1) establishes a relation between the quantities determined in the foregoing sections and the ionization potential. If we take Russell's value for this quantity, the left side of the equation equals 16.54, and if a value of 4.6 ev be taken for φ_{0-} the right side is 16.53 ev. The writers feel however that the possible error is so large that such a close check is of no significance. The value of 4.6 ev for φ_{0-} is chosen as the weighted mean of 4.55 and 4.63. Either of the values would of course close the cycle well within the limits of error.

It is questionable furthermore if the cycle should close when observations are made on a polycrystalline surface. If one assumes, for example, that the thermionic surface is made up of two crystal faces of equal area but with a difference in the work function of 0.2 ev, the low work function surface would contribute 80 percent of the electron emission at a temperature of 1500°K. This is on the assumption that the A of Richardson's equation is the same for both surfaces. While this is probably not true, it still seems probable that the measured φ_{0-} will be closer to the value for the low work function face than to that of the other.

If the positive ion equation is written in the form

$$i_+ = Bf(T) \exp(-11{,}600)(I+H-\varphi_{0-})/T$$

one sees immediately that the greater positive ion emission comes from the surface with the high value of φ_{0-} assuming that the rate of evaporation of neutral atoms from the two surfaces is the same. The cycle should accordingly fail to close by an amount somewhat less than the difference in the work functions of the two surfaces. The failure of the cycle to close in the work on Mo mentioned above is probably partly due to such an effect.

In conclusion, the writers wish to express their appreciation to Mr. George Sears for his assistance in the emissivity determinations, and to the Wisconsin Alumni Research Foundation whose support made the above work possible.

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The Production and Absorption of Thermal Energy Neutrons

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From measurements of the number of neutrons reduced to thermal energies in successive cylindrical layers of water the rate of absorption of the thermal energy neutrons in the water, corrected for the rate of production, was calculated. The total number of neutrons emitted from a Rn–Be source was estimated to be of the order of 15,000/sec./mc. Similar experiments with C, Al, Cu, Fe and SiO_2 were performed, in each case some slowing down of the neutrons from the source being observed. The angular distribution of slow neutrons emerging from the surface of paraffin spheres was found to be more concentrated along the normal than a cosine law distribution. A description is given of the construction of a source arrangement concentrating the slow neutrons coming from it into a roughly collimated beam. Measurement of the absorption of neutrons having slightly greater than thermal energy proved that Hg is nearly transparent while Rh and Ag showed less absorption than for thermal neutrons. Experiments with a neutron source cooled to liquid-air temperature show increased absorption for H, Li, B, Rh, Ag, I, Gd and Hg and practically no change for Sm and Cd. The construction and operation of mechanical velocity selectors for slow neutrons is discussed and results are given showing that the neutrons from the source used were in thermal equilibrium with it.

Introduction

FERMI and his collaborators[1] found that the radioactivity induced in some elements such as Ag and Rh was enormously increased when a source of neutrons was surrounded by a hydrogen-containing material. The nuclear reactions thus enhanced were found to be those in which the active product is an isotope of the irradiated element formed by radiative capture. They observed that the "slow" neutrons producing the intense activity were not only strongly absorbed in the activated elements but also in others such as Cd and Hg which do not become active. Fermi explains this effect by assuming that the neutrons were slowed down by elastic collisions with protons and then because of their slower motion past the nuclei in the absorber were more likely to be captured. Since the proton mass is approximately the same as the neutron mass, a neutron can lose nearly all of its energy in a single central impact, and on the average will lose about half its energy in one impact.[1, 2] A neutron with an energy of some millions of electron volts can be brought into the thermal energy region by about 25 collisions.

Westcott and Bjerge,[3] using the radioactivity induced in Ag, and Dunning and his colleagues,[4] using an ionization chamber as the detector, have experimented with Rn–Be neutron sources in spheres of water and paraffin. While the number of "fast" neutrons detected by proton recoil decreases steadily with increase in radius, about 50 percent in a sphere of 10 cm radius, the "slow" neutrons which produce the activity of Ag and the disintegration of Li in a Li-lined chamber increase to a maximum for a paraffin sphere of about 10 cm radius and for larger spheres decrease at a rate about equal to that of the fast neutrons. The number of slow neutrons obtained with only 3 to 4 cm of paraffin around the source is too great to be ascribed to the slowing down to thermal energies of neutrons that started with energy of the order of 1 Mev or higher because the radius of the paraffin sphere is of the order of magnitude of a single mean free path of such neutrons. This is in agreement with the experiments of Dunning[5] and Auger[6] which indicate that a Rn–Be source emits many neutrons having energies less than the maximum, perhaps less than 0.1 Mev. Bonner and Brubaker[7] showed that the neutrons producing increased activity in indium had energies of less than 0.03 Mev.

Attempts to demonstrate that these "slow" neutrons actually had thermal energies by finding an effect of the temperature of the material through which they passed on the properties of the neutrons were at first unsuccessful,[1, 8] but later definite effects were found.[9–11] That some neutrons have thermal velocities was definitely shown by experiments with rotating disks by Fermi and his associates[12] and by Frisch and Sorenson.[13] In this laboratory a direct measurement with a mechanical velocity selector proved that those neutrons coming from a block of paraffin that can be absorbed by $\frac{1}{2}$ mm of Cd are in approximate thermal equilibrium with the paraffin.[14] Rasetti and his collaborators have also done another type of rotating disk experiment further confirming thermal velocities.[15] These thermal energy neutrons form the "*C*" group of selectively absorbed neutrons of Fermi and Amaldi.[16]

Experimental

(A) Production and absorption of thermal energy neutrons in water and paraffin

When spheres or cylinders of hydrogenous materials are used to slow down neutrons emitted from centrally placed Rn–Be sources, the number of slow neutrons emerging depends on two factors,

[1] Amaldi, d'Agostino, Fermi, Pontecorvo, Rasetti and Segrè, Ricerca Scient. **2**, 282, 380 (1934); Proc. Roy. Soc. **A149**, 522 (1935).
[2] Condon and Breit, Phys. Rev. **49**, 229 (1936).
[3] Westcott and Bjerge, Proc. Camb. Phil. Soc. **31**, 145 (1935).
[4] Dunning, Pegram, Fink and Mitchell, Phys. Rev. **48**, 265 (1935).
[5] Dunning, Phys. Rev. **45**, 586 (1934).
[6] Auger, Comptes rendus **196**, 170 (1933).
[7] Brubaker and Bonner, Phys. Rev. **48**, 470 (1935).
[8] Dunning, Pegram, Fink and Mitchell, Phys. Rev. **47**, 796 (1935).
[9] Moon and Tillman, Proc. Roy. Soc. **A153**, 476 (1936).
[10] Lukirski and Zareva, C. R. de l'acad. sc. U.R.S.S. **3**, 393 (1935).
[11] Westcott and Niewodniczanski, Proc. Camb. Phil. Soc. **31**, 617 (1935).
[12] Amaldi, d'Agostino, Fermi, Pontecorvo, Segrè, Ricerca Scient. **6**, No. 1 (1935).
[13] Frisch and Sorenson, Nature **136**, 258 (1935).
[14] Rasetti, Segrè, Fink, Dunning and Pegram, Phys. Rev. **49**, 104 (1936).
[15] Dunning, Pegram, Fink, Mitchell and Segrè, Phys. Rev. **48**, 704 (1935).
[16] Amaldi and Fermi, Ricerca Scient. **6**, No. 2 (1935).

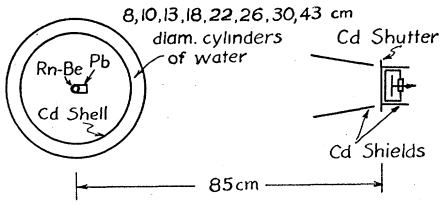

FIG. 1. Experimental arrangement for measurement of production of "slow" neutrons in cylindrical layers of water.

(1) the conversion of faster neutrons into "slow" neutrons, by which we mean those that disintegrate Li and B and are strongly absorbed in Cd, and (2) the absorption of the slow neutrons by the material. In order to separate these two factors and find the true rate of absorption by capture we have observed the numbers of slow neutrons coming from successive cylindrical layers of water surrounding Cd cylinders filled with water.[17] The experimental arrangement is shown in Fig. 1 and the results in Fig. 2 reduced to a source strength of about 325 mc. Both the inside Cd shell and the outer vessel containing the water were cylinders with heights equal to their diameters. The detector used was an 8-cm diameter Li-lined ionization chamber and the linear amplifier-Thyratron recorder system described previously.[4] The upper curve in Fig. 2 gives the numbers when no Cd was inside the water cylinder, while the others are for inner Cd shells of radii 3.8, 6.5, 9, 11 and 15 cm as given by the abscissas of their endpoints on the lower curve which represents the numbers of neutrons counted when the ionization chamber was covered by a screen of $\frac{1}{2}$ mm Cd.

The curves show that the rate of production of slow neutrons per cm increase of radius at 12 cm from the source is still about half of what it was at 6 cm. The fast neutrons from which the slow ones are produced decrease at about the same rate, indicating that approximate equilibrium between fast and slow neutrons has been reached, as is also shown by the fact that the ratio of fast to slow neutrons remains nearly constant as both decrease beyond 10 cm radius. It is estimated that in the layers used the actual rate of production of slow neutrons is twice the observed rate since about half of the slow neutrons "produced" (brought into the energy range where they are strongly absorbed by Cd) will diffuse inward and be captured by the Cd inside the water layer. On this basis the rate of production of slow neutrons per cm increase in radius was calculated from the data shown in Fig. 2 and the results are given in Fig. 3, curve number 1.

At 12 cm radius the number of slow neutrons emerging from a sphere or cylinder has begun to decrease although slow neutrons are still being produced. This must mean that the slow neutrons are being absorbed in the paraffin or water, presumably by the hydrogen with the formation of deuterium. Lea[18] and others have observed gamma-rays attributed to this capture process. To calculate the true absorption per cm increase of radius of the paraffin we must correct the apparent absorption coefficient that would be obtained from the measured rate of decrease of emergent slow neutrons by subtracting the rate at which slow neutrons are being produced from the fast neutrons present. The mean corrected rate of absorption is 0.35 per cm increase in radius, giving a half-value thickness of 2 cm. The corrected rates of absorption at different radii are in fair agreement, the probable error being estimated at about 25 percent. From this half-value thickness for absorption and the half-value thickness of 2.8 mm and cross section of 35×10^{-24} cm^2 found for scattering in paraffin[4] we calculate that a slow neutron makes on the average about 150 elastic impacts before being captured and the absorption cross section of the proton is about 20×10^{-26} cm^2. This cross section is larger than the value of 3.0 to 8.3×10^{-26} cm^2 found by

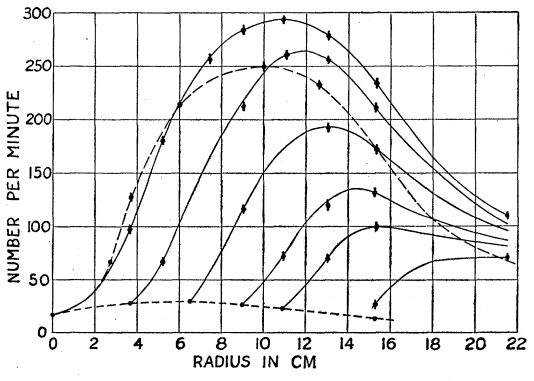

FIG. 2. Curves showing the production of slow neutrons in cylindrical layers of water.

[17] Fink, Dunning, Pegram and Segrè, Phys. Rev. **49**, 199 (1936).

[18] Lea, Nature **133**, 24 (1934).

Kikuchi, Husimi and Aoki[19] who compared the intensities of gamma-radiation produced by neutrons absorbed in water and in a solution of Cd but smaller than the latest value given by Amaldi and Fermi, 31×10^{-26} cm^2.[20] Our distance for half-absorption is between that found by Westcott and Bjerge[3] (1.5 cm H_2O) and that found by Preiswerk and von Halban[21] (2.5 cm paraffin).

Knowing the rate of production of slow neutrons per cm as a function of the radius, one can calculate the total number produced out to a given radius, or the number that would come from a sphere of that radius if there were no absorption. The results of such a calculation are shown in Fig. 3 where curve 1 gives the number produced per cm increase in radius, curve 2 the number observed from spheres, and curve 3 the total produced out to a given radius. Curve 3 extrapolated goes to nearly 8000 neutrons counted per minute per millicurie of radon using the whole solid angle around the source, or 140/sec./mc. Now the only neutrons which can be detected by a B or Li-lined ion chamber are those which are captured in the lining near enough to the surface for one of the ionizing particles produced by the resulting disintegration to emerge from the chamber lining into the air in the chamber. From the ranges of the particles and the absorption coefficient of Li for slow neutrons we estimate an upper limit for the sensitivity of the chamber used in this work to be 1.6 percent with 1 percent more probable since the ionizing particles must emerge from the chamber lining with a considerable fraction of their initial range if they are to be detected above the background of gamma-ray ionization and tube noise. With the detection efficiency taken as one percent a count of 140/sec./mc means that approximately 14,000 neutrons are emitted per second by a one millicurie radon plus Be source, in rough agreement with Jaeckel[22] who found ~10,000/sec./mc, Paneth and Loleit[23] who found >3000/sec./mc and Amaldi and Fermi[20] who found 30,000/sec./mc.

[19] Kikuchi, Husimi and Aoki, Nature **137**, 30 (1936).
[20] E. Amaldi and E. Fermi, Ricerca Scient. **1**, No. 11–12 (1936).
[21] Preiswerk and von Halban, Nature **136**, 951 (1935).
[22] Jaeckel, Zeits. f. Physik **91**, 493 (1934).
[23] Paneth and Loleit, Nature **136**, 950 (1935).

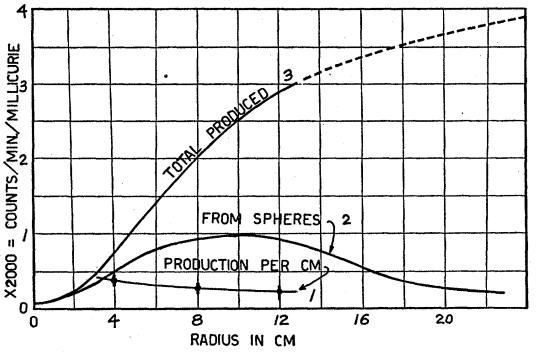

FIG. 3. Total number of slow neutrons produced in spheres of paraffin, number emerging from spheres, and rate of production per cm increase of radius.

(B) Production and absorption of slow neutrons in other materials

Similar experiments have been performed on the absorption and production of thermal energy neutrons in other materials: C,[24] Al, Pb, Fe, SiO_2, Cu. Counts were taken with each material in a set of standard arrangements as follows: 1, no absorber around a paraffin cylinder 8.8 cm diam., and 10 cm long, no Cd in front of ionization chamber; 2, same as 1 with Cd in front of chamber; 3, Cd around paraffin and absorbing material around it in a 22 cm diameter can filled to a height equal to its diameter, no Cd on chamber; 4, same as 3 with Cd on chamber; 5, absorbing material around paraffin without Cd between them, no Cd on chamber; 6, same as 5 with Cd on chamber. The results are plotted in Fig. 4 in a manner similar to Fig. 2 along with a curve for paraffin cylinders from Fig. 2. The data for arrangements 3, 4, 6 are replotted in Fig. 5 on a larger scale so that the small differences can be seen. In every case there seems to be a small number of slow neutrons produced in the material surrounding the paraffin and Cd, indicated by the count for set-up 3 being higher than that for set-up 4. A comparison of the counts in arrangement 5 with that in 1 shows that in Al, SiO_2, C and Pb slowing down overbalances absorption. Even for the relatively light nuclei Al, Si, O and C, and certainly in the case of Pb which is much heavier and yet produces more slow neutrons, the results indicate the high probability of inelastic collisions with nuclei and the necessity for introducing a nuclear model

[24] Fink, Dunning and Pegram, Phys. Rev. **49**, 340 (1936).

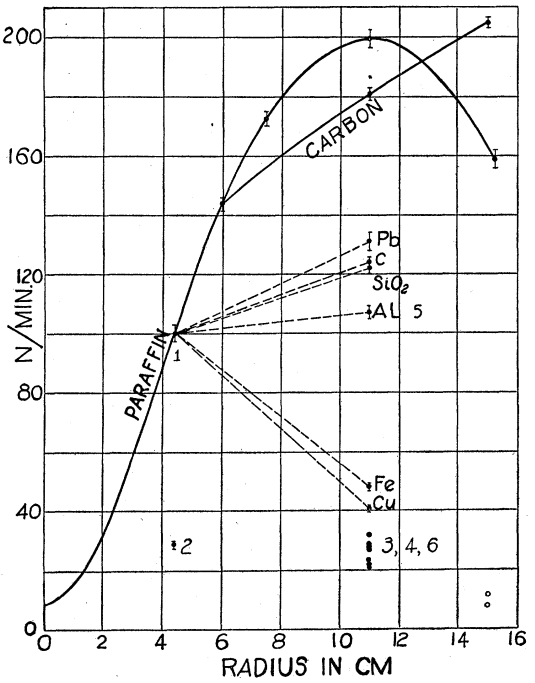

FIG. 4. Production and absorption of slow neutrons in Pb, C, SiO_2, Al, Fe and Cu.

such as that of Bohr such that the neutron remains in the nucleus a relatively long time and hence may lose considerable amounts of energy before emerging. Fleischmann[25] and Fermi and others have also observed phenomena indicating inelastic collisions in Pb.

The upper curve marked carbon shows that by surrounding a 6 cm radius paraffin cylinder with carbon more slow neutrons may be obtained than from any size of paraffin sphere.

(C) Angular distribution of neutrons from the surface of a sphere

To measure the number of neutrons coming from the surface of a paraffin sphere at a chosen angle, the following method was used. Sheet Cd disks and rings were placed between the sphere and ionization chamber so that slow neutrons could reach the chamber from only one zone of the sphere at a time. The fast neutron count with Cd in front of the chamber was subtracted from the count from each zone. The relative numbers of slow neutrons from the zones divided by the areas of the zones are plotted against the angles of the zones to get the arcs in Fig. 6. Smooth angular distribution curves are drawn through points on these arcs dividing the zones into two approximately equal areas. On each diagram is drawn a circle representing for comparison the cosine law distribution expected if the neutrons are emitted from the *surface* uniformly in all directions. The neutron distribution is seen to be more concentrated along the normal to the surface. This may be explained by a filtering process in the surface layers of the sphere. A slow neutron starting out from a point inside the surface of a sphere a distance of the order of a mean free path will have a better chance of emerging without collision if it starts out in the direction of the normal than if it started out in any other direction where it must penetrate a greater thickness of material to escape. The experimental angular distributions here given are quite similar to the theoretical angular distribution derived by Fermi,[26] especially in the case of the 12.5 cm sphere where the number of zones and other experimental conditions were better.

(D) Design and test of a source arrangement to produce a beam of neutrons concentrated in one direction.

To produce an intense collimated beam of slow neutrons a special arrangement of scattering material around the source was developed. Its cross section is shown to the left in Fig. 8. Growth curves such as those in Fig. 2 show a maximum (number of neutrons per unit solid angle) from a sphere or cylinder of approximately 10 cm radius

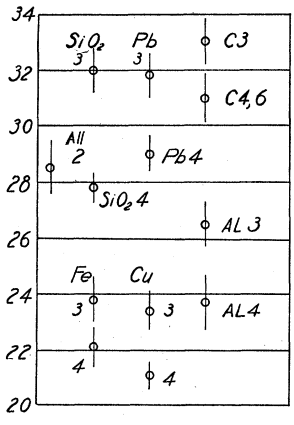

FIG. 5. Points in lower right hand corner of Fig. 4 replotted on larger scale.

[25] Fleischmann, Zeits. f. Physik **97**, 242, 265 (1935).

[26] Amaldi and Fermi, Ricerca Scient. May 1936.

but the number emitted per unit area at the surface of the sphere is a maximum at about 4 cm. This high density of slow neutrons near the source is also shown by the curves in Fig. 7 which give the numbers of neutrons counted from a 22 cm diameter cylinder of water with the source in different positions along a diameter of the cylinder through its center. The number emerging is seen to be a maximum when the source is about 3 cm from the side of the cylinder toward the ionization chamber. The density per unit area of the surface of the cylinder when the source is 3 cm from it is greater than the density at the surface of a 4 cm radius sphere because the added material behind the source scatters back many of the neutrons that leave the small sphere with high velocity. A further increase is obtained by putting paraffin around the beam from the source to the chamber which is similar to the effect of the paraffin tubes used for "canalization" of neutrons by Szilard and Chalmers.[27] Neutrons coming from the paraffin surface near the source in directions that do not go through the opening of the tube are partly scattered back and the density near the source is increased. Some of the neutrons thus scattered back will after a few more impacts emerge down the tube in a useful direction. The direct beam of fast neutrons that have made few collisions since leaving the source is scattered away from the chamber by a plug of copper and paraffin which also serves to reduce the intensity of the gamma-ray ionization in the chamber.

The intensity of the slow neutron beam from this device, commonly known in this laboratory as a "howitzer," is more than six times as great as that from a sphere of the same diameter

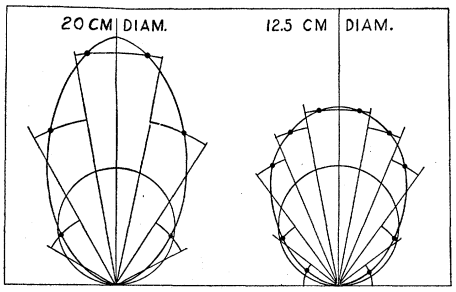

FIG. 6. Angular distribution of neutrons from surface of paraffin spheres.

[27] Hopwood and Chalmers, Nature **135**, 341 (1935).

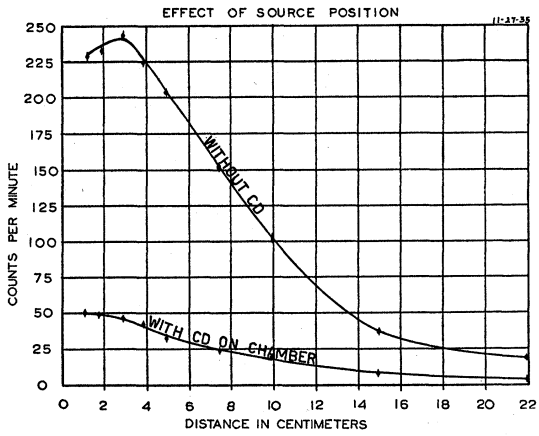

FIG. 7. Effect of change of position of source in cylinder of water on number of neutrons coming out on one side.

as the opening of the howitzer with the source at the same distance from the detector. This slow neutron intensity is 5 times that from the optimum size of sphere although the total intensity is only 4.5 times as great because of a smaller fraction of fast neutrons. The fraction of the neutrons from the howitzer that are not absorbed by Cd is about six percent while 11 to 19 percent of those from spheres are not absorbed. This lower background is an advantage for many purposes, especially for the velocity selector described below. The degree of collimation obtained is indicated by the fact that the intensity 20° off the axis is only 60 percent of that on the axis.

(E) Absorption of neutrons of slightly more than thermal energy

The absorption of several materials for those neutrons that pass through Cd but after a few impacts in a layer of paraffin are absorbable in Cd was measured with the experimental arrangement shown in Fig. 8. A sheet of Cd was placed over the opening of the howitzer source placed near an 8 cm diameter ionization chamber. A disk of paraffin 6 mm thick and 14.5 cm diameter was placed between the source and chamber. Counts were then taken; 1, without a Cd screen in front of the chamber, 2, with a Cd screen in front of the chamber, 3 and 4, same as 1 and 2, respectively, but with an absorber between the howitzer and paraffin. The difference 1–2 is the number of slow neutrons produced in the paraffin from the neutrons that passed through the Cd on

the source and 3–4 is the number produced from neutrons passing through both Cd and the other absorber. The ratio 3–4/1–2 is the fraction transmitted through the absorber, of those Cd-penetrating neutrons which after passing through the paraffin are absorbable by Cd. The results are given in Table I. It will be noticed that the transmission of Ag+Rh is less than the product of the transmissions of Ag and Rh, indicating selective absorption by these elements of certain energy regions slightly above the thermal range although the difference is barely larger than the experimental error. Recently Ag and Rh[28] have been shown to exhibit the phenomenon of resonance capture for neutrons having energies of 2 to 3 and 1 to 1.2 ev. The Ag and Rh absorbers show absorption cross sections for these higher energy neutrons. That Rh shows a greater fraction of its thermal energy cross section than does Ag agrees with the fact since found that Rh has a broader resonance at lower energy as mentioned above. More striking is the almost complete transparency of the HgO sample which absorbed 51 percent of thermal energy neutrons.

This in connection with the temperature effect which is about the same as that for Ag, Rh, Li and B, indicated that if mercury has any resonance it must be in the thermal region and broad enough so that the slope of the cross-section-velocity curve in that region is not much different from that for Ag.

(F) The effect of temperature on neutron absorption

As mentioned in the introduction the concept of neutrons coming into thermal equilibrium with matter led to attempts to demonstrate an effect of the temperature of the scattering material on the properties of the scattered neutrons. Fermi and his associates[1] found no difference, to within two percent, of the activity of Rh placed near a source in cylinders of hydrocarbons having at 20° and 200°C the same density and atomic composition. Using a more favorable arrangement with a thinner layer of material cooled to liquid air temperature, Moon and Tillman[9] observed a definite increase of the activity induced in Ag at the lower temperature. Lukirsky and Zareva[10] tried various thicknesses

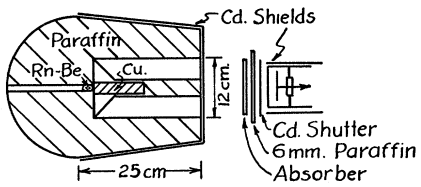

FIG. 8. Arrangement for absorption measurements with neutrons of slightly greater than thermal energy.

of cooled paraffin and showed that with large thicknesses absorption in the paraffin masked the effect of lowering the neutron velocity range. The change in number of neutrons was separated from the change in their effectiveness in producing activation by Westcott and Niewodniczanski[11] who measured the absorption of several materials including the detecting substance at each temperature and also went down to liquid hydrogen temperature with increased effects.

The first experiments in this laboratory[8] performed to show an effect of the temperature of the material through which neutrons passed on their absorption in Cd gave a negative result which is now understandable since a rotating disk experiment[14] has shown that the absorption of Cd is nearly constant throughout the thermal region. Further experiments on the absorption of Cd and other elements have now been performed.[29] In these experiments the "cold" neutron beam was taken out of the top of a small "howitzer" weighing 2400 grams cooled to liquid air temperature in a wide-mouthed Dewar flask covered with only a single thickness of paper. Table II gives the results in terms of nuclear absorption cross sections for neutrons coming from the source at room temperature and liquid air temperature. Large changes in absorption are found in every case except those of Cd and Sm. The results for Cu and Ag are in substantial agreement with other observers using artificial radioactivity as the detector of slow neutrons.

TABLE I. *Data on absorption of neutrons.*

Absorber	Ag	Rh	HgO	Rh+Ag
Fraction transmitted	0.791	0.686	0.981	0.483
Stan. dev.	0.037	0.035	0.051	0.028
Cross section	20±4	86±12	12±33	$\times 10^{-24}$ cm²
C neutron transmission	0.519	0.596	0.487	
C neutron cross section	56	128	450	$\times 10^{-24}$ cm²

[28] Goldsmith and Rasetti, Phys. Rev. **50**, 328 (1936).

[29] Powers, Fink and Pegram, Phys. Rev. **49**, 650 (1936).

(G) Mechanical velocity selectors for slow neutrons

Previous work in this laboratory with a mechanical velocity selector[15] had shown that the distribution of velocities of neutrons coming from a block of paraffin is approximately Maxwellian. An improved velocity selector with higher resolution and higher velocity range has now been built and tested. The principal features of its construction are illustrated in Fig. 9 which is diagrammatic and not drawn to scale. It is mounted with vertical shaft so that the velocity distribution curve may be determined for a cold source of the type described in the previous section as well as for a source at room temperature. The shaft is made shorter to regain some of the intensity lost by going to higher resolution. To cover the same velocity range with the short shaft a larger number of sectors was put on each disk, 90 in place of 50. Higher disk speeds were made possible by using steel sectors plated with Cd in place of pure Cd which is mechanically weak and flows under a small stress, less than one thousand pounds per square inch. The phase of the fixed sectors at one end may be varied with respect to that of the other by rotating the casing which carries the fixed Cd sectors at the upper end. The ratio of closed to open space on the rotating Cd sector disks of the old velocity selector is 1 to 1 while on the new one the ratio is 3 to 1. The open space is then one-quarter of the total in place of one-half. The relative resolving power of the two selectors may best be judged from their velocity transmission curves, calculated as follows from the geometry of the fixed and moving sector systems.

TABLE II. *Absorption of neutrons at room temperature and liquid-air temperature.*

Absorber	Capture cross section ($\times 10^{-24}$ cm^2) Room temperature source	Liquid-air temperature source	% Increase
H (paraffin)	38±3	48±3	26
Li (LiF)	72±3	86±3	20
B (Pyrex)	540±20	715±20	32
Rh	130±5	175±6	35
Ag	56±2	77±3	20
Cd	2900±100	3100±200	7
I	14±1	17±2	21
Sm (Sm_2O_3)	4600±100	4400±100	−4
Gd ($Gd_2(C_2O_4)_3$ 10 H_2O)	22000±1000	31000±1000	41
Hg (HgO)	445±25	605±25	36

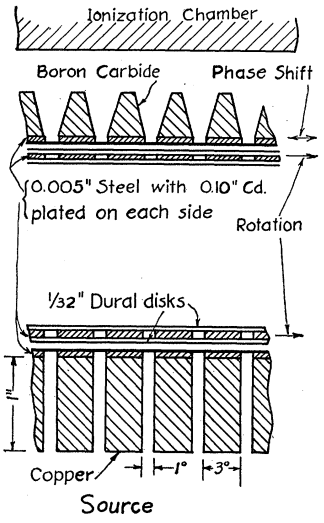

FIG. 9. Diagram of shutter systems of new velocity selector.

The probability of a neutron getting through the selector is the product of the fractions of the area that are open at each end of the velocity selector. These fractions are equal in the case of what may be called the "in phase" adjustment in which the shutter system at one end reaches its maximum opening at the same time as the system at the other end. As the shaft of the velocity selector is rotated the fraction open at each end F, and its square, which is the instantaneous probability W of a neutron getting through, vary as shown in Figs. 10A, E and B, F for the 1 to 1 and 3 to 1 ratio. The average probability $\overline{W}$ of a neutron passing through when the shaft is revolving slowly and uniformly is of course the average ordinate of the instantaneous probability curve.

Now consider a beam of neutrons of a single velocity V incident upon the selector when the disk is revolving at a speed of the order of 1000 r.p.m. The probability W is now the product of the fractional area open at the source end at the time of incidence and the fraction open at the detector end at a time d/V later where d is the distance between the ends of the selector. In this time the disks have turned through an angle $d/V \times$r.p.m./$60 \times 360°$. If this angle is 3.6° in the case of the selector with 50 sectors or 2° in the case of the one with 90 sectors the disks turn from the open to the closed position in the time taken for a neutron to travel the length of the shaft, 54 cm in the first case and 25.7 cm in the second. We then have maximum cut-off and the

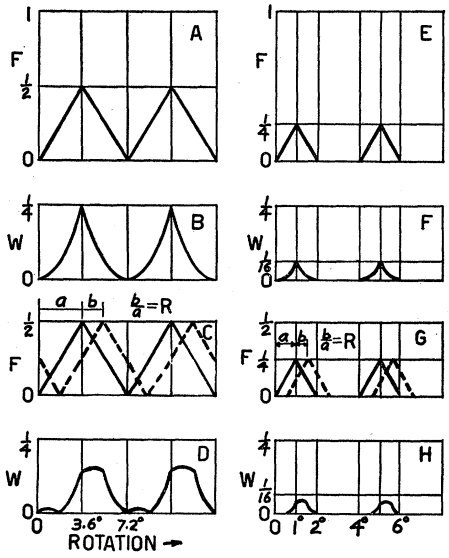

FIG. 10. Diagrams illustrating operation of velocity selectors.

necessary rotational speeds are: r.p.m. $= V/54 \times 60/100 = V$(cm/sec.)$/90$ and r.p.m. $= V/25.7 \times 60/180 = V/79$. The linear velocity thus related to the rotational speed of the shaft and disks we may call the "velocity" of the selector. The transmission of the selector may then be calculated as a function of the ratio R=selector velocity/neutron velocity. This ratio determines the shift of one curve with respect to the other in Figs. 10C and 10G. The product of corresponding ordinates of the curves in 10C and 10G is plotted in Figs. 10D and 10H to get the instantaneous transmission curves for a particular value of R. The average ordinates of such curves for various values of R are plotted against R in Figs. 11A and 11E. It will be noted that the 1 to 1 selector at most only cuts off half of the neutrons of a fixed velocity while the 3 to 1 selector cuts off completely neutrons of one velocity. The transmission may also be plotted as a function of $1/R$=neutron velocity/selector velocity as in Figs. 11B and 11F marked "in phase." Figs. 11C and 11G are the corresponding curves for the "out of phase" condition. The two sets of curves are complementary in that one shows a maximum of transmission where the other shows a maximum of absorption. With a fixed selector speed these curves represent the transmission as a function of neutron velocity measured in terms of the selector velocity as a unit. Now we may take the Maxwellian velocity distribution curves

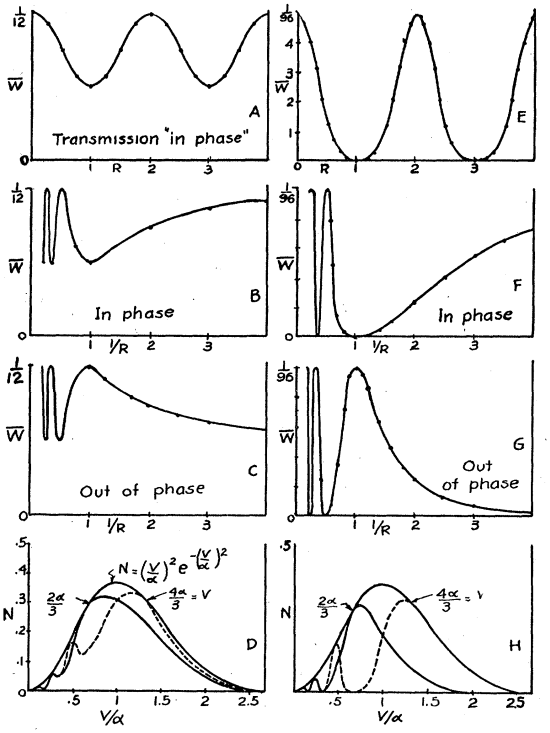

FIG. 11. Velocity-transmission curves for velocity selectors.

in Figs. 11D and 11H and multiply each ordinate by the corresponding ordinate of the transmission curve to get points of the transmitted velocity distribution curves. Such transmitted velocity curves are drawn in Figs. 11D and 11H for selector speeds of $2\alpha/3$ and $4\alpha/3$ where $\alpha = \sqrt{2kT/M}$, the most probable velocity of the Maxwellian distribution. Curves like these have been plotted for a number of selector speeds and the relative areas under the curves found by use of a planimeter. The areas are proportional to the numbers transmitted at the corresponding speeds out of a Maxwellian distribution of velocities. (If the detector efficiency did not vary with neutron velocity the appropriate velocity distribution curve would be $(V/\alpha)^3 e^{-(V/\alpha)^2}$ because the higher velocities are more likely to come out of the source where the density function is $(V/\alpha)^2 e^{-(V/\alpha)^2}$, but since the detecting elements Li and B show absorptions varying approximately as $1/V$ the V^2 distribution was used.)

If these areas multiplied by an appropriate constant are plotted against the selector speed we get the experimental curve to be expected if the velocity selector is operated at various speeds

with a $1/v$ detector on a neutron beam having the Maxwellian V^3 velocity distribution. Such expected curves for 300°K with the 1 to 1 ratio velocity selector running "in phase" and "out of phase" are given in Fig. 12. Two curves are shown for operation in phase, one using the V^3 velocity distribution and the other the V^2 distribution. In a Letter to the Editor of the *Physical Review*[30] the "in phase" data were given with an expected curve calculated from the V^3 distribution since at that time it was not known that the Li detector had an absorption varying as $1/v$. Much better agreement is now seen to be obtained with the V^2 velocity distribution.

The expected curves for both the in phase and out of phase conditions with the 3 to 1 ratio velocity selector and the V^2 velocity distribution are given in Fig. 13 with the experimental points obtained with the new velocity selector. The deviations of the points from the curves are within the statistical fluctuation limits except at 5000 r.p.m. At this speed the count is too high, presumably because the noise made by the velocity selector was being picked up by the slightly microphonic ionization chamber and was thus causing spurious counts.

Figs. 10 and 11 show clearly that intensity is rapidly lost as resolution is gained. The loss of intensity of the slow neutrons transmitted is especially troublesome because of the background of fast neutrons which are not absorbed by Cd. Two devices were used to help in this matter of background. A grid of copper bars 2.5 cm deep radiating from the axis with spacings like those

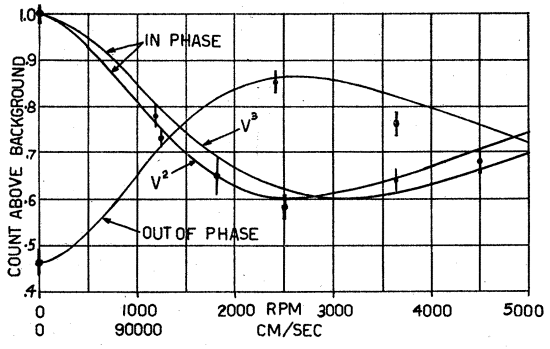

FIG. 12. Expected curves and observed points for 1 to 1 ratio velocity selector.

[30] Fink, Dunning, Pegram and Mitchell, Phys. Rev. **49**, 103(1936).

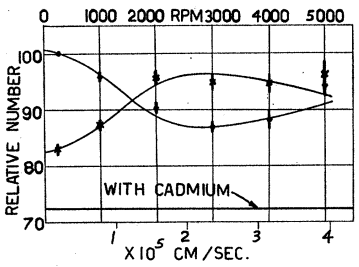

FIG. 13. Expected curves and observed points for 3 to 1 ratio velocity selector.

between the fixed Cd sectors was placed in contact with them to scatter away from the chamber the fast neutrons that would otherwise go through the fixed sectors and cause background counts. In addition this copper absorbs gamma-radiation and scatters back some of the slow neutrons that would otherwise be absorbed in the Cd, thereby increasing the intensity through the openings. At the upper end an absorbing grid is wanted in place of a scatterer and boron carbide is used in sheet copper forms. However, even with these devices the number of slow neutrons transmitted when running slowly in phase is only about 40 percent above the background. As a detector to be used with this selector an ionization chamber constructed and filled with BF_3 gas by Dr. Mitchell and Professor Rasetti of this laboratory has proved very useful. Its sensitivity to slow neutrons is about five times that of a chamber having only a lining of Li or B. Its sensitivity for neutrons which penetrate Cd is also greater so that its background ratio is about the same as that of Li and B-lined chambers. To obtain precision in absorption measurements therefore considerable time will be required. Out of phase operation, in which one end of the velocity selector is open when the other end is closed, can be used to select neutrons of known velocities for absorption measurements. Preliminary tests with Ag and Pyrex sheets can be relied on only to show that the absorption is greater with lower velocities.

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