PHYSICAL REVIEW VOLUME 69, NUMBERS 9 AND 10 MAY 1 AND 15, 1946

Experiments with a Slow Neutron Velocity Spectrometer II*

R. F. BACHER, C. P. BAKER, AND B. D. MCDANIEL
Cornell University, Ithaca, New York
(Received February 23, 1942)**

The apparatus previously used for the determination of neutron energy by time of flight method has been completely rebuilt with a view to increasing the accuracy of measurement as well as the high energy limit. The repetition frequency is obtained from a series of relaxation oscillators and a 50-kc oscillator and frequencies of 100, 200, 500, 1000, and 2500 c.p.s. are available. Four detector channels have been built so that neutrons in four different time of flight groups can be counted simultaneously. When used with the highest repetition frequency, this decreases the time to obtain data by a factor of 24 and has thus made the present experiments feasible with the small Cornell cyclotron. The study of the transmission of Ag with a 1.35-g/cm² absorber shows a single strong resonance at 5.8 ev. A re-examination of In with considerably higher resolution than was previously used shows a single resonance at about 1.35 ev. The effective mean life of neutrons in several different sources was examined and a thin paraffin source with Cd backing devised for measurements in the thermal region. The absorption of B has been examined and found to be proportional to $1/v$ within the limits of error of the experiment, from 0.028 to 50 ev. An experiment to determine the B cross section of the Cd stopped neutrons gave 540×10^{-24} cm². The B absorption curve shows that the cross section of thermal neutrons (0.025 ev) is 708×10^{-24} cm². It is concluded that the effective energy of the Cd stopped neutrons is not that of kT at thermal energy, for the geometry used, but is 0.041 ev. This conclusion is confirmed by the measured resonances in Ag and In which are higher than the values obtained by the boron absorption method. Correction of these values, as measured by Horvath and Salant (reference 4) for the effective energy of the Cd stopped neutrons, leads to 1.32 ev for In and 5.2 ev for Ag, in agreement with the present results. It is concluded that resonances measured by the boron absorption method are in error by an amount which depends upon the geometry of the experiment, and are probably too low by a factor of $0.041/0.025=1.64$.

In order to extend the range of the equipment[1] previously developed to determine neutron energy from time of flight, the apparatus has been completely rebuilt. Since the previous equipment was able to detect only very low resonances, it appeared that an extension of the energy range and greater resolution were desirable to study neutron transmission characteristics and to obtain more information about resonance absorption.

In addition to higher timing accuracy and the possibility of greater resolution, it appeared necessary to decrease the time required to obtain data. The time required in the region of 1 ev was already excessive, and with higher resolution would be expected to be longer. Accordingly, three new features were incorporated in the equipment: (1) a finer and more accurate subdivision of the cycle of operation, (2) a range of frequencies of the fundamental cycle so that it might be possible to increase the intensity by increasing the frequency to the limit determined by the overlapping of cycles at the detector, and (3) the possibility of recording data in several different time of flight intervals simultaneously.

APPARATUS

A schematic diagram of the measuring equipment is shown in Fig. 1. All frequencies are controlled from a 50-kc oscillator, and the repetition frequencies are obtained from relaxation oscil-

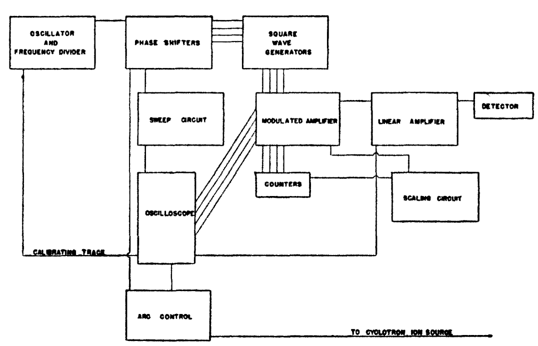

FIG. 1. Schematic diagram of neutron velocity spectrometer.

* Some of the observations reported in this paper have been considerably extended since its preparation. It is hoped that the somewhat more precise and detailed results of these experiments will be reported in the near future.

** This paper was received for publication on the date indicated but was voluntarily withheld from publication until the end of the war.

[1] C. P. Baker and R. F. Bacher, Phys. Rev. 59, 332 (1941).

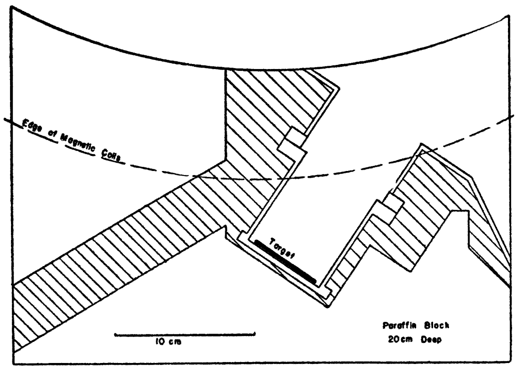

FIG. 2. Central section plan of paraffin block source and cyclotron target.

lators. These feed into a bank of six phase shifters, four of which control the square wave generators which work into the modulated amplifier to govern the "on" time of the detecting channels. Another phase shifter controls a special sweep circuit providing for large expansion, and all time comparisons are made and checked with a 50-kc calibrating trace directly on the oscilloscope face. The last phase shifter adjusts the arc control.

The oscillator and frequency divider was a primary oscillator working at 50 kc and four frequency division stages composed of thyratron relaxation oscillators. By proper tuning of the relaxation oscillators to lock in with the primary oscillator and with each other, a repetition frequency of 100, 200, 500, 1000, or 2500 c.p.s. could be obtained for use as a modulation frequency. The primary oscillator or any of the relaxation oscillators could be used as a calibrating wave and furnished a convenient subdivision of the cycle. A small oscilloscope was provided to observe and check the operation of this system, the saw-tooth wave form of the relaxation oscillators making the patterns very easy to recognize. Since it was possible to obtain any desired frequency with no stage differing by more than a factor of five from its driving stage, very little difficulty with stability was found. The frequency of the primary oscillator was checked and reset from time to time by comparison of one of the lower frequencies with a 1000-cycle fork although it was never found to differ from its previous setting by as much as one percent.

The phase shifter consisted of a filter to provide sinusoidal wave form and a resistance and capacity to produce a 90° phase shift. The two signals 90° out of phase were impressed on the grids of six twin triodes in parallel. The output of each member of the twin was fed into a mixing circuit, and the proper combination of the two signals made it possible to obtain a wave of any desired phase. It was arranged so that the manipulation of two variable resistors gave a smooth continuous 360°-phase shift. The outputs of these mixing circuits were used to control the timing of the production and detection and observation of the neutrons.

The arc control made use of two FG67 thyratrons which controlled the voltage on the arc type ion source in the cyclotron. One tube was placed in series with the arc to turn it on and the other in parallel to turn it off by short circuiting. A considerable amount of redesign on this circuit from that used in the previous work was necessary, both because of the higher frequencies required and because of the low power electronic source of the repetition frequency instead of an a.c. motor generator supply. Tubes with a short de-ionization time were necessary, and type FG67 was found to be most satisfactory from this standpoint but required much more grid power than the FG57's formerly used. Each tube consequently required a power amplifier. Difficulty was also experienced in extinguishing the tubes after their cycle of operation since the power supplied to the arc came from a d.c. motor generator set. Some method of interrupting the current through the tubes for at least 100 μsec. must be provided. After several unsuccessful attempts to do this with other thyratrons, a bank of power tubes was placed in series with the motor generator. At the lower frequencies this method was not necessary, but at 2500 cycles no simpler method was found.

The modulated amplifier was very little changed from the one previously described except for the inclusion of four channels instead of one and for the particular care taken to obtain speed of response. The first tube was a thyratron discriminator which flashed for all neutrons detected, and which was fed into the scaler and into the four modulated channels. A modulated channel consisted of an amplifier tube whose control grid was actuated by the neutron pulse and whose screen grid was actuated by a square wave generator which determined the open time of the tube. Output circuits were provided to drive the counters. The square wave generators were almost identical with that previously described except for a modification in the phasing and grid driving. The waves were quite accurately square, the voltage rising or falling within 0.5 μsec. The square pulse could be varied in width from 1 μsec. at 2500 cycles (a little more at lower frequencies) to a quarter of a cycle.

A new linear amplifier was constructed with special consideration for stability and speed of response. The gain per stage had to be sacrificed on both of these counts so that seven stages were necessary. Small time constants and negative feedback were incorporated, and to reduce the difficulties introduced by the unavoidable shunt capacity of the cable connecting the amplifier proper with the ionization chamber, two stages of amplification preceded this cable.

Tests on resolution were made using two of the square wave generators. With two pulses of 5 μsec. duration and 15 μsec. separation center to center impressed on the grid of the first tube, two completely separated pulses could be observed at the output. With 10 μsec. separation the pulses were not completely resolved, but the voltage fell to half maximum between pulses. The over-all time lag of the apparatus, including lags in production and acceleration of the deuterons in the cyclotron and in collection of ionization in the detector, was measured by the method previously described[1] and found to be 19 μsec. Subsequent improvements have been made during the course of the experiments, the shortest lag so far produced being 8.5 μsec. This compares to a time lag of 35 μsec. in the earlier apparatus.

EXPERIMENTAL PROCEDURE

The general arrangement of the equipment with the cyclotron was essentially the same as that previously shown. The cyclotron chamber has been rotated about 30°, making the target somewhat more centrally located. The geometry of the paraffin block surrounding the B target which is shown in Fig. 2 was also changed to keep the face perpendicular to the line to the ionization chamber. The face dimensions were approximately 20×35 cm^2.

In order to cut down the fast neutron background, about 10 cm of paraffin was placed around the collimating tube holding the ionization chamber. Figure 3 shows the fraction of fast neutrons as a function of time. These measurements were taken with about 10 cm of paraffin, Cd, and a thick B_4C absorber in front of the collimator. For time of flight experiments, carried out at 3 meters, the background is 3 percent or less for energies of 19 ev or below.

A hydrogen-filled ionization chamber was used to determine how accurately the production and detection of neutrons was controlled under actual experimental conditions. This chamber was sensitive only to fast neutrons so that times of flight and scattering difficulties did not enter, and the time distribution of proton recoils gave an accurate indication of the time of production of neutrons. The duration of the neutron burst was measured in the following manner: the square pulse controlling the ion source was adjusted for 10 μsec. width, and the square pulse controlling detection was made very long (120 μsec.) and initially completely overlapping the time of production. The start of the detector "on" time was then made later and later in the cycle so that it overlapped the time of production by smaller and smaller amounts. This procedure is similar to that used for the previously described time lag measurement.[1]

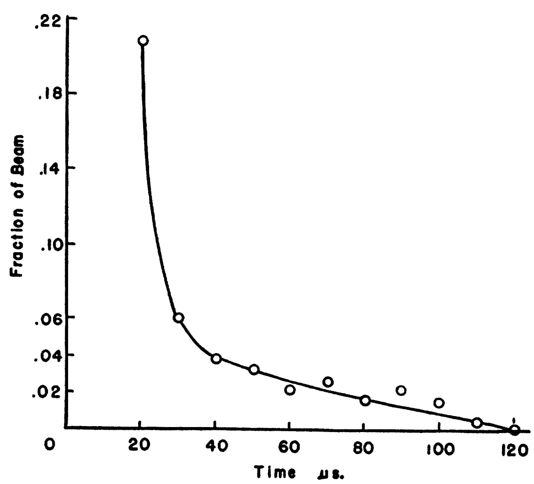

FIG. 3. Fraction of counts due to fast neutrons plotted against time of observation.

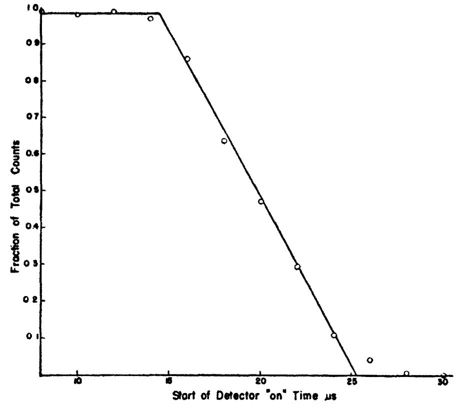

FIG. 4. Relative counts observed with hydrogen-filled ionization chamber plotted against the difference in time setting of the start of the burst and the start of the detector "on" time.

One would expect the counting rate to be constant as long as there is complete overlap and a linear decrease until there is no overlap so that the duration of the linear decrease is a measure of the duration of the burst. Figure 4 shows the counting rate plotted against the difference in time between the settings of the start of the burst and the start of the detector "on" time. The counting rate is seen to be constant until 14.5 μsec. and then to decrease until 25.2 μsec., showing an "on" time of the source of 10.7 μsec. There is evidence for a small tail as a few neutrons were recorded after production had presumably stopped. This amounts to about 4 percent of the maximum intensity about 2 μsec. later, and less than 1 percent 6 μsec. later. The magnitude of this tail was found to be insensitive to changes in gas pressure, filament temperature, or arc voltage. The fact that the start of the decrease occurs at 14.5 μsec. indicates an over-all time lag of this amount.

The detector was measured in a similar way, and the sensitivity was found to be 3 μsec. longer than the duration indicated by the setting of the controlling square wave, although otherwise well behaved, having no observable tailing effects. The extra 3 μsec. was found to be due to the smearing of a pulse in the modulated amplifier which should have been of very short duration. This pulse has now been sharpened, but unfortunately the difficulty was not discovered until after the measurements described here were made. The effect of this broadening is to increase the resolution width by 3 μsec. and to decrease the mean time of flight associated with an observation or the distance between the centers of the "on" times by half this amount. For the data taken at three meters this means a change in resolution of 1 μsec. and a change of 0.5 μsec. in the time of flight in the plots on the one meter time of flight axis and was neglected.

RESULTS

A. Silver

The experiments on Ag were carried out at a repetition frequency of 2500 c.p.s. and with a Cd absorber 0.45 g/cm^2 thick in front of the collimator to absorb the low energy neutrons which would otherwise appear in succeeding cycles. The time of flight spectrum of the source as measured with the chamber and Cd absorber is shown in Fig. 5. The number of counts per unit total is plotted against time of flight and the number of neutrons per time of flight interval is nearly constant except where the Cd begins to cut off.

The results of a series of three separate runs on a 1.35-g/cm^2 thick Ag absorber have been collected and the relative transmission plotted against time of flight for 1 meter in Fig. 6. The circles with a cross in them represent data from a preliminary run taken at 2 m with 20 μsec. "on" time for source and detector. These data were taken with the same amplifier used in the previous work.[1] The open circles represent data taken at 3 m with the same equipment and "on" times. The heavy circles represent data taken at 3 m at the same resolution with the new linear

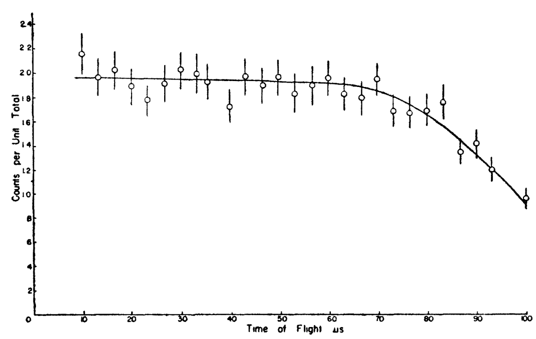

FIG. 5. Time of flight spectrum (in μsec./meter) of paraffin block source measured through a 0.45-g/cm^2 Cd filter.

amplifier described briefly above. While the settings were the same, these points do not have the same abscissae as the open circles because of the different measured time lag with the new amplifier. The vertical lines indicate the probable errors from the number of counts. Measurements of the over-all transmission were made in the 3-m runs, and these two measurements were averaged. This over-all transmission was used in the way previously described[1] to obtain the transmission curve. The preliminary data were adjusted to the same over-all transmission and are included here mainly to show that the data repeat with a different path length. Since the timing errors can hardly depend on the path length, this provides a check.

The datum representing transmission at a given time of flight actually represents a time of flight band due to the resolving power of the apparatus. Since the "on" times of source and detector are each 20 μsec., the data taken at 3 m include for a particular point no neutrons whose velocity is 6.7 μsec./meter different from that indicated for the point. The distribution function is triangular[1] and is such that 0.75 of the neutrons have velocities between those of the two adjacent points.

The most prominent feature of the transmission curve is the strong absorption which appears to be just below the point at 5.8 ev. While there seems to be some evidence for a lower transmission at about 1.5 and 0.78 ev, the interpretation of these dips as resonances is very doubtful, and they are not included in the curve. The data show a transmission of about 0.3 at the resonance minimum. In order to give a transmission of 0.25 at 30 μsec. and 0.5 at the adjacent points, it takes nearly complete absorption between 4.7 and 7.3 ev with the resolution of the apparatus considered. Such strong absorption over a wide band is to be expected with the thick absorber used.

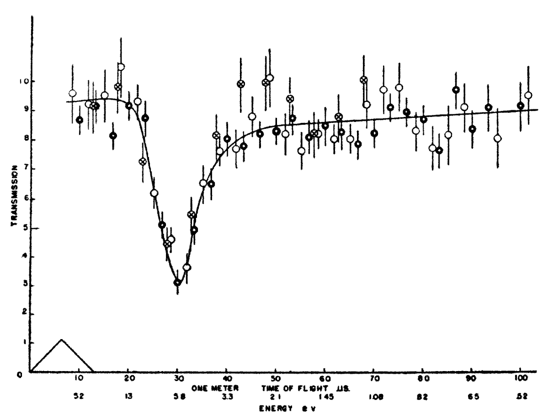

FIG. 6. Transmission of 1.35-g/cm² Ag absorber plotted against time of flight for 1 meter.

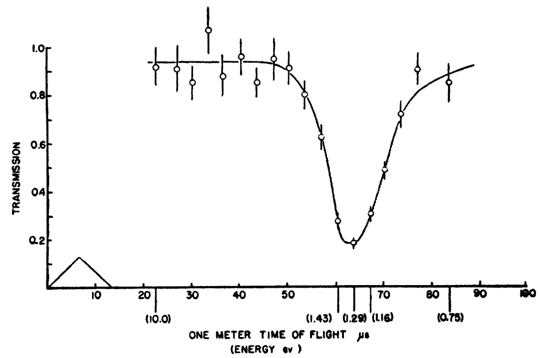

FIG. 7. Transmission of 0.169-g/cm² In absorber plotted against time of flight for 1 meter.

B. Indium

Further experiments were made on indium in order to establish more accurately the energy of the resonance. The previous measurements[1] showed a transmission minimum slightly above 1.0 ev. This measurement was made with much poorer resolution than it has since been found possible to use and serves mainly to demonstrate the effect of this resonance. Because of the considerable effect of resolution, low precision, and background corrections involved it is not considered a reliable measure of the resonance energy.

The present measurements of the transmission of indium were made at a distance of 3 m with "on" times of source and detector of 20 μsec. using an absorber of 0.169 g/cm² and covered the energy region from 10 to 0.75 ev (23 to 84 μsec./m). The results are plotted in Fig. 7. The vertical lines indicate the probable error in the transmission measurements, and the isosceles triangle shows the resolution function, or spread in time of flight to which the apparatus was sensitive. The fast neutron background was not significant in the region studied. It is evident that between 0.75 ev and 10 ev there is only one strong resonance, and it occurs in the neigh-

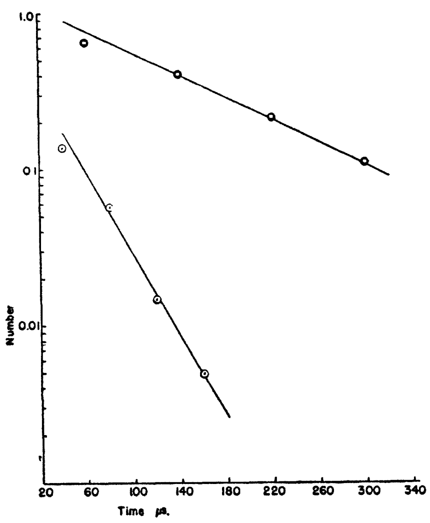

FIG. 8. Relative number of neutrons plotted against time after neutron burst for paraffin block source (upper curve) and tray (lower curve).

borhood of 1.3 ev. This shows a much better resolution of the resonance than the previous measurement even though the thickness of the absorber is less.

While no effort has been made to find the shape of a resonance which could produce the observed curve with the resolution used, it seems probable that there must be a region of negligible transmission of approximately 5 to 10 μsec. in width, or several tenths of a volt, showing that the exact position of the resonance is still masked by the resolution and by the thickness of the absorber. An investigation of the effect of resolution on certain sample transmission curves calculated from the Breit-Wigner one-level formula shows that both of these effects make the resonance appear at a lower energy than its actual value.

A further measurement was made with a thinner absorber (0.051 g/cm^2) and higher resolution which indicated that the energy lies between 1.29 and 1.43 ev probably at or above 1.35 ev. More complete measurements on indium are in progress making use of a wide range of thickness, and until these are complete no attempt will be made to determine the shape of the level.

C. Effective Mean Life

It was known from the previous measurements that the time of arrival of *thermal* neutrons at the detector is not a good measure of their time of flight because of the relatively long mean life in the paraffin. Unless precautions are taken to reduce this effect the results of time of flight measurements are uncertain below 0.2 ev and probably quite untrustworthy below 0.1 ev. A method of controlling the effective mean life was devised which made use of a change in the source geometry.

The face of the paraffin block was covered with a sheet of cadmium 43×43 cm and 0.45 g/cm^2 in thickness. This absorbed all thermal neutrons emitted, but allowed neutrons of somewhat higher energy to penetrate. Thermal neutrons were regenerated in a thin (1.6-cm) layer of paraffin 38×38 cm placed in front of this cadmium. The whole assembly is referred to as the tray. It was anticipated that the effective mean life in this thin layer would be considerably reduced by diffusion out of the paraffin.

The effective mean life was measured by placing the face of the ionization chamber against the source and measuring the time dependence of the emission of neutrons after the burst. The results of the measurements are shown in Fig. 8. The "on" times of both source and detector were 40 μsec., and the relative number of neutrons recorded in the various time intervals are plotted on a logarithmic axis. The upper curve is for the paraffin block shown in Fig. 2, and shows an effective mean life of 123 μsec. The lower curve is for the same block with the tray in front, and shows an effective mean life of 33 μsec. This geometry was used for all work below 0.5 ev.

It was found possible to control the effective mean life by another and possibly more satis-

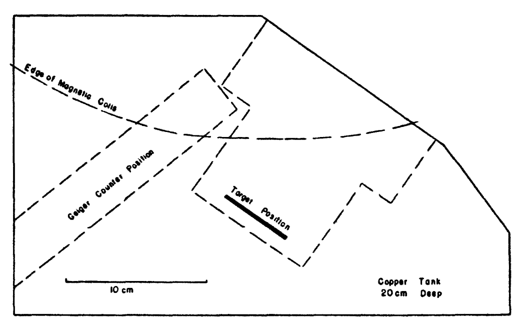

FIG. 9. Central section plan of copper water tank source and cyclotron target.

factory method.[2] The source was surrounded by a copper water tank of a shape similar to the paraffin block and shown in Fig. 9. The effective mean life was measured in the same way with water and with various strengths of B_2O_3 solution. The results showed a life of 107 μsec. for tap water, 70 μsec. for a solution of 1.8 g/liter B_2O_3, and was reduced to 43 μsec. for a solution of 7.3 g/liter B_2O_3. The volume of the tank was 11 liters. It is realized that a measurement of the true mean life could be made with a detector placed in the middle of the source and with a different timing scheme, but the purpose of these measurements was to measure the effective mean life of the neutrons arriving at an external detector in order to evaluate the results of time of flight measurements.

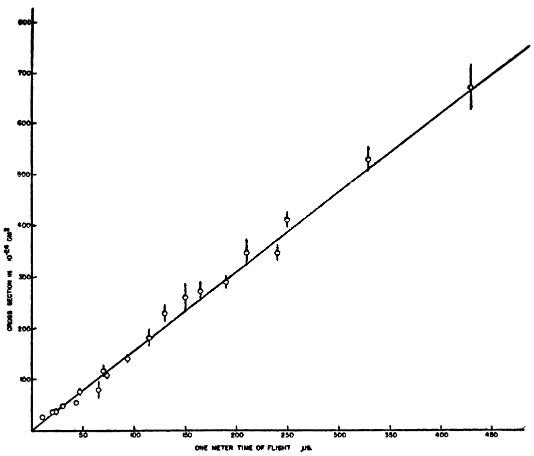

FIG. 10. Boron cross section plotted against time of flight for 1 meter.

D. Boron

The absorption of boron in the form of B_4C absorbers has been investigated from 0.028 ev to about 50 ev (1-m time of flight 430 μsec. to 10 μsec.). The B_4C absorbers[3] were made in flat bottomed Al cups by dusting the powder from a height of about 5 ft. The powder rained into the cup which was filled with ether and a small amount of celluloid dissolved in acetone to act as binder. The amount of celluloid remaining in the absorber after evaporation was obtained for each absorber and varied from about 2 percent by weight for the thinnest absorber to 0.2 percent for the thickest absorber. The thicknesses of B were corrected for this known amount of binder. Since the resulting absorber was a rather compact cake, the thickness was determined by cutting out the material around the edge to give a circular disk which still adhered to the Al, and the thickness in g/cm² was obtained from the size and the known weights before and after making the absorber.

Five B_4C absorbers were used in the experiments containing 0.273, 0.1197, 0.0585, 0.0487, and 0.0318 g/cm² B. Experiments with the two thicker absorbers were carried out using the paraffin block source shown in Fig. 2, and with a distance of 3 m between source and detector. The source and detector were "on" for 20 μsec. each. The repetition frequency was 2,500 c.p.s., and a Cd absorber 0.9 g/cm² was used as a screen.

For the three thinner absorbers the repetition rate was 500 c.p.s. with "on" times of 50 μsec. for the 0.0487-g/cm² absorber, and 80 μsec. for the other two absorbers. The distance of source to detector of 2 m was used for these three absorbers. At the lower recurrence rate used, it was necessary to investigate the effect of neutrons appearing in succeeding cycles (recycling) by some measurements at still lower frequency. With the usual source it was found that there was a very considerable effect. This was decreased by the use of the tray previously described to cut down the mean life in the source and by the introduction of a thin B_4C screen containing 0.0205 g/cm² of B. Without the screen there was still an appreciable recycling, but with the screen the effect was indistinguishable from background.

The collected results of the absorption measurements on B are shown in Fig. 10 where the B cross section is plotted against $1/v$ in μsec./meter. Within the accuracy of the data the points fit a straight line. The straight line shown was fitted by least squares methods, the vertical lines representing probable errors from the number of counts taken. The slope of the straight line is $(1.55\pm0.035)\times10^{-24}$ cm²/μsec., and the intercept is $(-0.5\pm2.1)\times10^{-24}$ cm². The one point at 43 μsec. is rather far off the curve, and in fact makes half the contribution of the sum

[2] This was suggested by E. Fermi.

[3] The B_4C was obtained from the Norton Company and is reported to be sufficiently pure B_4C that the percentage of boron was computed from the atomic weights giving 78.3 percent B by weight.

of the squares of the residuals. Omitting this point the slope remains unchanged, and the intercept is increased to $(+4.4\pm 1.4)\times 10^{-24}$ cm². A negative intercept has no physical significance, and indeed a small positive intercept is to be expected due to the scattering cross section.

A further experiment with boron was carried out to determine the cross section in boron of the neutrons emitted from the paraffin block source stopped in thick Cd. No timing arrangements were used for this experiment, and the experiments are subject to errors in stability of the source which do not appear for the time of flight experiments. The geometry of the experiment was essentially that described above for the B measurements at 2 m except for the removal of the tray in front of the source and of the B_4C screen. In addition to the brass face of the ionization chamber there was a 20-mil piece of copper for electrical shielding in the beam path. An examination of a piece of brass of the same thickness as the ionization chamber face and a piece of 20-mil Cu showed that its transmission for the Cd stopped and transmitted neutrons was within the accuracy of the experiment the same. The Cd absorber used was 0.90 g/cm². Further experiments were also carried out with the tray source described previously, but with the geometry otherwise the same.

The results are summarized in Table I for the three different B absorbers which were used. The third column gives the absorber thickness, the fourth the observed transmission, and the fifth the cross section of the Cd stopped neutrons obtained. The cross sections have been used with the curve of Fig. 10 to obtain the corresponding time of flight, from which the effective energy given in the last column can be obtained.

The effective energy of the Cd stopped neutrons is nearly twice that expected on the basis of thermal equilibrium. With the large paraffin block this seemed so unusual that the measurements were scrutinized very carefully but repeated experiments gave essentially the same results. This difference will be discussed later. It will also be noticed that there is a gradual increase in σ for the thinner absorbers, which might be expected if there were a filtering or "hardening" action of the absorber. The experiments with the thinner source show a higher effective energy which might be expected from the thinner paraffin. They also show a much greater dependence of the effective energy on absorber thickness, associated possibly with a more inhomogeneous source.

TABLE I. Summary of B absorption measurements of the Cd stopped neutrons emitted by two different sources.

Source	Measurements	Absorber thickness g/cm²	Transmission	$\sigma(B)$ Cd stopped neutrons cm²$\times 10^{-24}$	τ time of flight μsec.	E effective energy ev
Paraffin block	3	0.0487	0.242	519	334	0.047
Paraffin block	3	0.0318	0.388	531	342	0.045
Paraffin block	1	0.0205	0.539	540	348	0.043
1.6-cm paraf-	1	0.0487	0.319	418	270	0.072
fin over Cd	1	0.0318	0.435	466	301	0.058
	1	0.0205	0.550	522	337	0.046

DISCUSSION OF RESULTS

The results in boron show that within the accuracy of the experiments, the cross section is proportional to $1/v$ from 0.028 to 50 ev. The cross section attributed to neutrons of thermal energy (0.025 ev) is 708×10^{-24} cm², which is considerably greater than the values usually quoted for the so-called C group neutrons (those absorbed in thick Cd) which are usually referred to as thermal neutrons. The measurements of Horvath and Salant[4] give an absorption coefficient for the C group neutrons of $K=30.2\pm 0.03$, which gives a cross section $\sigma=539\times 10^{-24}$ cm². The strong difference in the measured cross sections suggests that the neutrons emitted with the relatively small amount of paraffin usually used may not have the expected thermal distribution. This may be due to the effect of the leaking out of neutrons at the sides of the slowing down material.

The measurement of the cross section of the C neutrons in B was made in the untimed experiments previously described using various B absorbers. The paraffin block source which was used was designed to be as nearly as practicable like a Fermi cylinder[4] with the source located near the top. If the cross sections obtained from the measurements with the three different absorbers are plotted against absorber thickness, a straight line is obtained, and if extrapolated to zero absorber thickness this line gives a cross section of 552×10^{-24} cm² or an absorption co-

[4] W. J. Horvath and E. O. Salant, Phys. Rev. 59, 154 (1941).

efficient of 31.0 cm^2/g. The thinnest absorber used gave 54 percent transmission, and this leads to a cross section of 540×10^{-24} cm^2 (Table I). This is in close agreement with the measurements of Horvath and Salant[4] with somewhat the same geometrical arrangement. There appears, therefore, to be no disagreement on these absorption measurements.

The cross section of 552×10^{-24} cm^2 above gives from the plot of Fig. 10 an effective energy of the Cd stopped neutrons of 0.041 ev. In the determination of resonance energies by the boron absorption method,[5] this energy is assumed to be that of thermal neutrons and the ratio of the boron absorption coefficient of the C group neutrons to that of the resonance group used to multiply the assumed thermal energy to obtain the desired resonance energy. The conclusions arrived at here indicate that the resonance energies thus obtained by the boron method are in error by an amount which depends upon the geometry of the experiment. For the Fermi geometry the energies so obtained should be raised by a factor $0.041/(kT)=0.041/0.025=1.64$. It should be pointed out that the determination of this factor depends upon the untimed experiments and may, therefore, be subject to certain small errors arising from the steadiness of the source.

The measurements of the Ag and In resonances provide a strong check on the above conclusions. In Ag the most prominent feature of the observed neutron absorption spectrum (Fig. 6) is the resonance at 5.8 ev. This resonance shows very strong absorption and must be correlated with the A group in Ag. The careful boron absorption measurements of Horvath and Salant[4] using a Fermi cylinder give a resonance energy for the A group of 3.3 ev. This value is in violent disagreement with the resonance energy observed by these time of flight experiments, but if the value obtained by the boron absorption method is multiplied by the correction factor,[6] the resonance energy as obtained is 5.2 ev which agrees fairly well.

For In the measurements of Horvath and Salant yield a resonance energy of 0.84 ev for the 54-min. period. The present measurements show only one resonance and that at 1.35 ev. With the same correction factor the value of Horvath and Salant becomes 1.32, which agrees very well. This agreement must depend to a considerable extent on the rough similarity of geometry.

These results lead to the inescapable conclusion that with the geometrical arrangements used in the past, the C group neutrons are not of thermal energy. Resonance energies determined by the boron absorption method which assume that the C group neutrons have thermal energy are incorrect. The correction factor for the geometry used here is 1.64, but this factor will depend on the experimental arrangements.

Early experiments[7] with a mechanical velocity selector indicated that the velocity distribution of the C group neutrons observed from a paraffin block or howitzer source was such that agreement between the expected and observed distribution was obtained if it is assumed that the emitted neutrons have a Maxwell distribution at room temperature. This result now appears to be in disagreement with the present work. The disagreement is possibly caused by the fact that the mechanical velocity selector experiments were of necessity carried out with very poor resolution. It seems difficult, therefore, to consider the disagreement serious.

The earlier experiments also showed that when the source was cooled, the emitted distribution shifted toward lower velocity. Furthermore it was shown in experiments by Fink[7] that the cross section of various elements except Cd increase when the source is cooled, in agreement with the increased activity also observed. This definitely shows the presence of some neutrons in thermal equilibrium, and this qualitative conclusion does not disagree with the present results.

The authors are indebted to the Research Corporation for a grant which made this work possible.

[5] H. Bethe, Rev. Mod. Phys. 9, 134 (1937).

[6] Here 1.57 since Horvath and Salant use $kT=0.026$ ev.

[7] J. R. Dunning, G. B. Pegram, G. A. Fink, D. P. Mitchell, and E. Segrè, Phys. Rev. **48**, 704 (1935); G. A. Fink, Phys. Rev. **50**, 738 (1936).