extensive data in the Department of Physics of the University of California, Berkeley.

Professor R. T. Birge's generous hospitality in extending the facilities of the Department of Physics was of the greatest assistance. Professor R. B. Brode did everything possible to forward the work. Professor J. R. Oppenheimer reviewed much of the data and made many valuable suggestions in its interpretation. Professor Bayes M. Norton of the department of Chemistry at Kenyon College took many of the first photographs made on the mountain.

Two Kenyon students, Richard W. Penn and Henry Meyers, each gave a summer of work on Mt. Evans. Their help was essential to the many things necessary to the success of the expeditions on the mountain. Professor J. C. Stearns, at that time in charge of the laboratory on Mt. Evans, was of great assistance to us while we were on the mountain.

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The Velocity Dependence of the Absorption of Boron for Slow Neutrons

J. H. Manley, L. J. Haworth, and E. A. Luebke
Department of Physics, University of Illinois, Urbana, Illinois

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Measurements of the slow neutron velocity distribution between 1 and 10 km/sec. from a 14-cm cube of paraffin, with a source of 2.5-Mev neutrons in the center, show the distribution to be approximately Maxwellian with $T=400°K$, but with an excess of fast neutrons for $V>3.5$ km/sec. Similar measurements of the distribution of neutrons transmitted through a boron absorber verify the assumed $1/v$ absorption law in this velocity range.

INTRODUCTION

Apparently a number of physicists[1–4] realized, about 1937, that the development of artificial neutron sources would lead to a method of measuring neutron velocities through modulation of the ion beam producing the neutrons. Previous to these electrical methods a mechanical velocity selector had been used to investigate the neutron distribution from paraffin[5] and the rotating wheel method for checking a $1/v$ absorption law had been applied to boron, cadmium, and silver.[6]

The velocity distribution of slow neutrons has been examined only by the mechanical method and by the electrical method of Fertel, Gibbs, Moon, Thomson, and Wynn-Williams[3] (FGMTW). In neither case was the resolution available particularly high. With a method available for determining velocity distributions, the distribution before and after passing through an absorber or scatterer may be measured and the cross section as a function of neutron velocity found. Only FGMTW have published results on both the distribution and absorption laws, the absorption being in boron. Their results on boron are in disagreement with a $1/v$ variation of cross section which has been assumed for slow neutrons producing an (n, α) reaction in such a light element. The validity of this assumption is of importance since many measurements of neutron energies depend upon it. In addition to the experiment of FGMTW, the rotating disk method has been applied to boron[6] as has been the electrical method of Alvarez.[1] Both indicate a $1/v$ dependence of cross section, but the disk method is not capable of large changes in relative speed and Alvarez assumed thermal equilibrium of the

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

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[2] J. M. W. Milatz and D. Th. J. ter Horst, Physica **5**, 796 (1938).

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

[5] G. A. Fink, Phys. Rev. **50**, 738 (1936).

[6] Rasetti, Segre, Fink, Dunning, and Pegram, Phys. Rev. **49**, 104 (1936); Rasetti, Mitchell, Fink, and Pegram, Phys. Rev. **49**, 777 (1936).

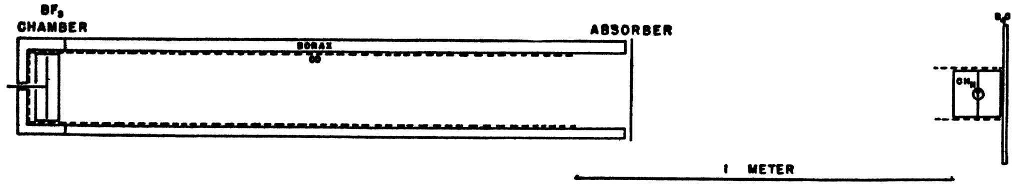

FIG. 1. Arrangement of source, detector, absorbers, and shielding.

neutrons at room temperature which is not justifiable for the small amount of paraffin used.

APPARATUS AND METHOD

The neutron source and circuits for obtaining a sharp neutron burst and the record of time of neutron arrival at a distant detector have been described previously.[7] The detector for these measurements was a parallel plate ionization chamber filled with BF_3 at atmospheric pressure. The chamber was circular, 19 cm in diameter. Positive ions were driven to the collecting electrode by a field of 1000 volts/cm. The sensitive volume of approximately 1100 cm^3 absorbed about 6 percent of the incident neutrons. The arrangement of the chamber, shielding, absorbers, and source is shown in Fig. 1.

In this type of work, it is essential to know of any time delays in the recording of the neutrons. The amplifier itself was first tested by impressing a pulse approximately one microsecond wide on the first grid. This pulse and that from the discriminator output of the amplifier were observed simultaneously on the oscilloscope. No appreciable (much smaller than 5 microseconds) delay was observed. There may be, however, a considerable delay with actual pulses due to possible delays in other parts of the circuit, or in the chamber, as, for example, the finite time of rise of output pulse before the discriminator tube becomes conducting since it must be biased to eliminate amplifier noise. Such delays, together with any involved in the processes inside the paraffin, were studied by determining the number-time distribution when the chamber was placed next to a paraffin block. From these results an over-all delay of about 50 μsec. was observed, an analysis of which is given by the authors.[7]

The shape of the slow neutron burst from the paraffin surface must be known in order to make an accurate velocity analysis. This shape depends on the amount of paraffin present and may be expressed in terms of a half-life for the change of intensity of the emergent neutrons. Measurements of this "source time distribution" were made with a small BF_3 proportional counter very close to the surface of the paraffin block. Figure 2 shows the results, an exponential rise and decay as would be expected from the effects of capture and diffusion in the paraffin. The measured half-life in this case (for a block used in velocity experiments at 250-cm distance) was 50 μsec. As is seen, the delay using the counter is much smaller, amounting to about 8 μsec., attributable to a lag between initiation of the sweep and the incidence of the ion current on the target.[7]

In order to increase the slow neutron intensity for measurements at greater distances a different arrangement was used. The 14-cm cube was surrounded by a large amount of paraffin built up in the form of a howitzer. A large increase in the half-life caused by the much greater amount of

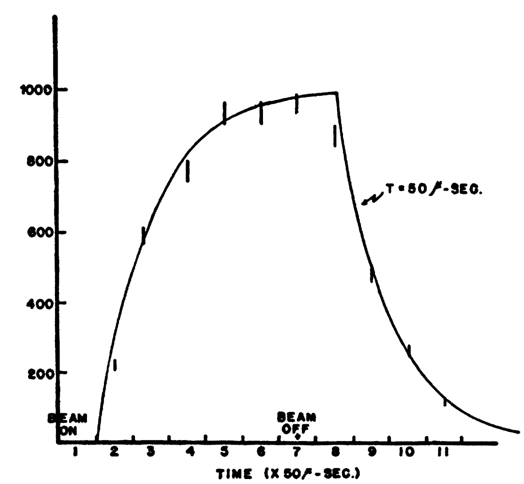

FIG. 2. The slow neutron time distribution from paraffin irradiated by a 325 μsec. fast neutron burst. The half-life for growth or decay is 50 μsec.

[7] L. J. Howorth, J. H. Manley, and E. A. Luebke, Rev. Sci. Inst. **12**, 591 (1941).

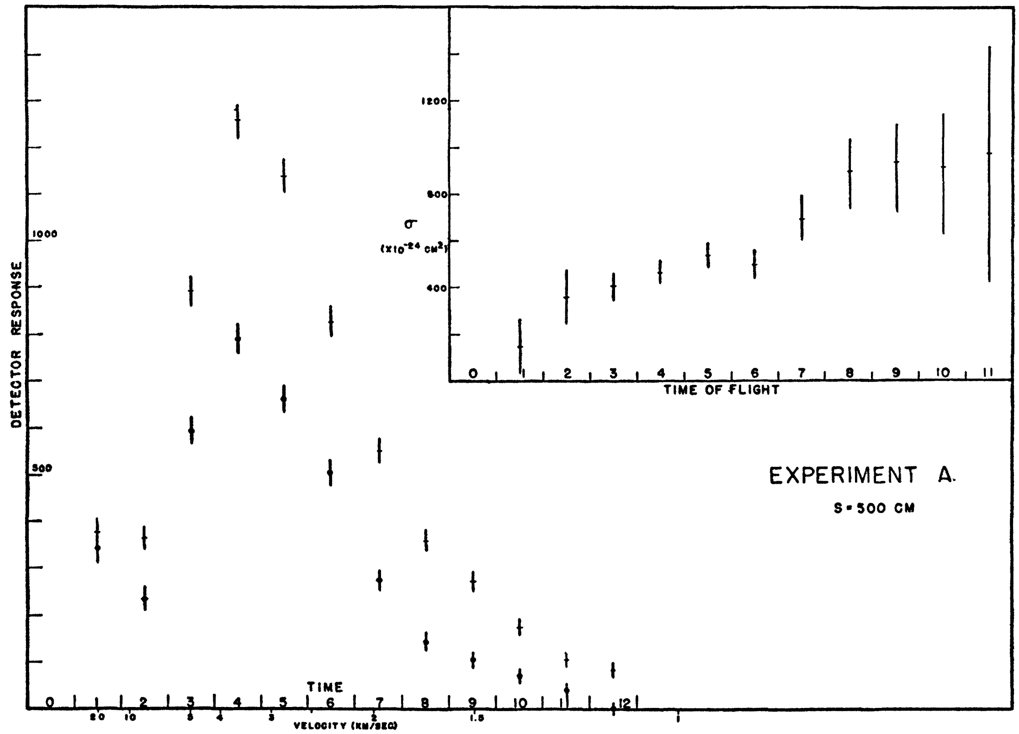

FIG. 3. Neutron time distribution curves, experiment *A*. Bars—without boron absorber; dots—with boron absorber; insert—boron cross section as a function of time of flight.

paraffin was prevented by cadmium sheet so arranged that neutrons slowed to thermal energies in the additional paraffin would be prevented from reaching the inner block. Slightly faster neutrons passing back through the cadmium and subsequently slowed in the small cube contributed to the intensity, but did not greatly increase the half-life since their time spent in the outside paraffin was as fast neutrons. The measured half-life for this arrangement was 90 μsec.

To measure the absorption coefficient of an element for slow neutron absorption, an absorber is required large enough to cover the entrance of the borax tube (Fig. 1) and of a thickness which absorbs about half the neutrons incident on it. The thickness of boron required is the order of 0.02 g/cm^2. Unfortunately it is difficult to produce a uniform, pure boron absorber of this thickness having the necessary mechanical strength. Additional materials must be used and it is desirable that they have a small interaction with slow neutrons. The materials chosen were carbon and aluminum. A space of $\frac{1}{32}''$ between two aluminum sheets each $\frac{1}{32}''$ thick was filled with a mixture of carbon (Dixon's No. 635 dry graphite) and B_4C (Norton Company.) The mixture was dried by heating in a vacuum and the edges of the absorber were sealed immediately after filling. Based on an analysis of 78.22 percent boron in B_4C (by engineers of the Norton Company) the absorber presented a thickness of 1.03×10^{21} boron atoms per cm^2 to the slow neutron beam.

To eliminate any effect the presence of carbon and aluminum might have on the measured cross section, a "blank" was prepared with the same thickness of carbon and aluminum as in the thin boron absorber. Comparison of measurements with this "blank" and the thin absorber should give an effect due only to the boron. The absorption in the "blank" was found to be less than 5 percent.

The shielding used was not sufficient to eliminate completely the fast neutrons which were scattered from the room. Consequently, in order to be certain that the neutrons measured came directly from the target a thick (0.5 g/cm^2) B_4C and Cd (0.45 g/cm^2) absorber was used to de-

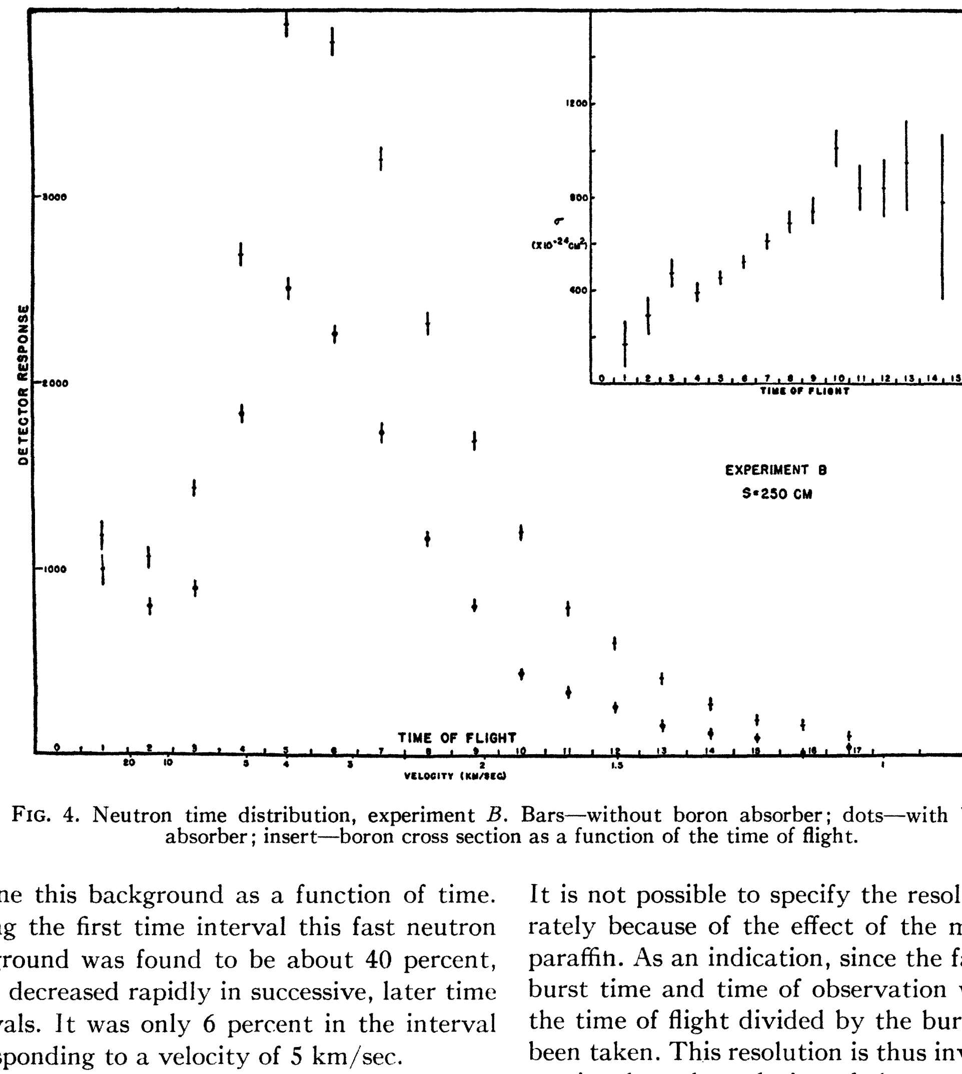

FIG. 4. Neutron time distribution, experiment B. Bars—without boron absorber; dots—with boron absorber; insert—boron cross section as a function of the time of flight.

termine this background as a function of time. During the first time interval this fast neutron background was found to be about 40 percent, but it decreased rapidly in successive, later time intervals. It was only 6 percent in the interval corresponding to a velocity of 5 km/sec.

Two complete experiments A and B were performed. In each case the neutron burst width Δt_1 and the time interval of observation Δt_2 were equal and adjusted to the time of flight, t, so as to give approximately the same resolution, $v/\Delta v$. The time of flight of the slowest neutrons determines the time, τ, between neutron bursts necessary to prevent carry-over of slow neutrons into the fast neutron part of the next cycle. The experiments were performed with the following arrangements in which t and $v/\Delta v$ refer to the slowest neutrons measured, those of approximately 1 km/sec.

	S	$\Delta t_1 = \Delta t_2$	t	$v/\Delta v$	τ
A	500 cm	380 μsec.	6000 μsec.	15	6,700 μsec.
B	250 cm	150 μsec.	3000 μsec.	20	4,000 μsec.

It is not possible to specify the resolution accurately because of the effect of the mean life in paraffin. As an indication, since the fast neutron burst time and time of observation were equal, the time of flight divided by the burst time has been taken. This resolution is thus inversely proportional to the velocity of the neutrons being measured.

RESULTS

Figure 3, upper curve, shows the distribution of neutron counts with "blank" absorber N_0 (net) as a function of time interval; lower curve, the distribution with a thin boron absorber N_b (net) as a function of time interval, for experiment A. The vertical bars represent standard statistical deviations. The inset is a plot of cross section σ as a function of time interval. Figure 4 is a similar plot for experiment B. The velocity scales of the insets were obtained using the average $t=0$ from the center of area of the proper slow neutron time distribution at the source for each experiment. The observations and results for intervals 1 and 2 in both experiments are not very reliable because of a comparatively low resolution and a large correction for scattered neutrons.

Remembering that the time scale is proportional to $1/v$ it is seen from the insets that, to the approximation involved in using the data directly, the $1/v$ absorption law is verified. Since, however, the method of measurement involved finite time intervals in both the emission and detection processes, more detailed calculations seemed advisable.

Let $M(t)$ be the true time distribution of neutrons arriving at the detector, the spread in time being due only to their velocity. There will also be a time distribution $f(t')$ of the emission of neutrons from the source due to delays in the slowing and escape processes. At a time T, all neutrons emitted at a time t', with a velocity v, such that $T-t'=t=S/v$ will reach the detector and be recorded as a number of counts,

$$R(T)=\int_0^T dt' f(t') M(T-t') D(T-t'), \quad (1)$$

in which $D(T-t')$ is the detector response function. However, the number of counts at the detector is observed during an interval ΔT so the points on the histograms of Figs. 3 and 4 are

$$H(T)=\int_{T-\Delta T/2}^{T+\Delta T/2} dt \int_0^T dt' f(t') M(T-t') D(T-t').$$

It is evident that $M(T-t')$ can be satisfactorily determined only if $f(t')$ is appreciable only at values of $t' \ll T$.

In order to obtain a true representation of the neutron velocity distribution, a curve has been fitted to the experimental points of N_0 (net), Fig. 4, so that the area under the curve over an interval equals the number of counts observed, thus giving $R(T)$. With the observed $f(t')$, a curve $M(t)D(t)$ has been found that satisfies (1). This curve is just the reciprocal velocity distribution seen by the detector as a function of $1/v$. It is replotted in the more usual form in Fig. 5. By anticipating that the thin boron detector obeys the $1/v$ law, we see that $D(t)$ provides just the factor necessary to change from a beam to a density so that Fig. 5 represents the distribution inside a container from which particles are escaping according to the usual kinetic theory picture. It must be recalled that this distribution pertains to neutrons passing through the carbon-aluminum blank. Since the average transmission of this blank over the entire region is more than 95 percent, and it is unlikely that any velocity-dependent interactions confined to a very narrow range exist for these elements, it is assumed that the blank has no effect on the form of the distribution.

Similar analyses were carried out for the distribution transmitted through the thin boron absorber. When the results were applied to the calculation of the cross section, however, no appreciable change was noticeable from the values plotted in the insets of Fig. 4, which indicates that resolution corrections do not affect appreciably the ratio of N_b to N_0. The data of the two experiments are combined in Fig. 6 and shown with the statistical error. This error is largest in the fast neutron end of the observed range due to high background and in the very slow neutron end because of the small number of neutrons of low velocity in the distribution. The results are consistent with the $1/v$ law for boron in this velocity range. From these data the value of K in the law $\sigma_B=K/v$ was found to be approximately 16×10^{-22} cm^2-km/sec.

It has been assumed for some time that neutrons slowed by collision in hydrogenous material reach an approximate thermal equilibrium with the material. Indirect measurements of temperature effect and more direct measure-

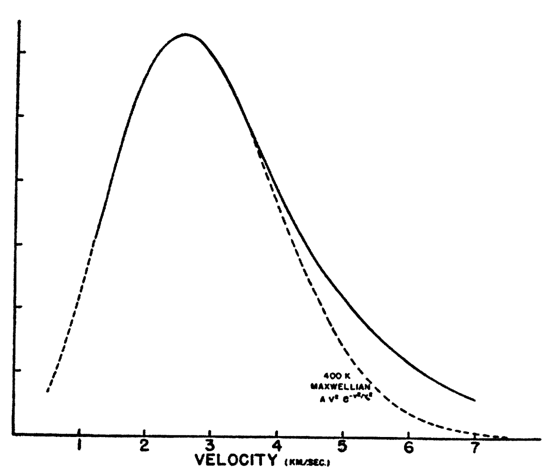

FIG. 5. Neutron velocity distribution.

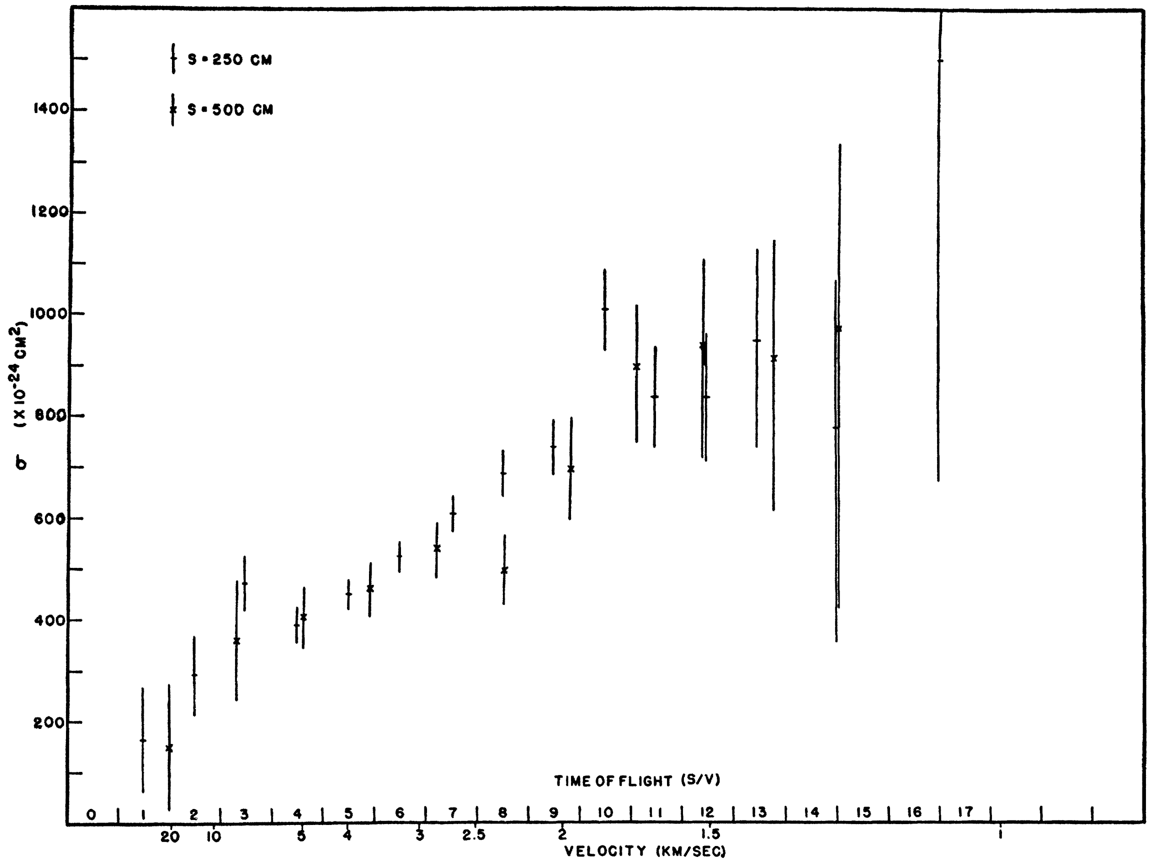

FIG. 6. Composite curve. Boron cross section as a function of time of flight.

ments[3, 5] support this assumption. Although the linear velocity plot of Fig. 5 and variable resolution make portions of the curve less reliable than others, it may still be considered as a fairly good representation of the neutron distribution obtaining to this case. The low velocity portion is most reliable and this was used in determining the temperature of a Maxwellian distribution which would provide the best fit. This is shown by the dotted line of Fig. 5 which is for a temperature of 400°K. The difference between this indicated temperature and that of the paraffin ($\sim$300°K) seems to be real, for in experiment A with a larger amount of paraffin the indicated temperature was 340°K.

DISCUSSION

Several checks on the results are possible. First of all, the velocity range covered in these experiments includes practically all of the C neutrons as may be seen from the cadmium transmission measurements of Baker and Bacher.[4] A check of the results may be obtained, therefore, by measurement of the C neutron transmission of the absorber used. This was found to be 58 percent in excellent agreement with the ratio $\sum N_b/\sum N_0 = 57.6$ percent obtained from the observations in each time interval. This corresponds to a C neutron cross section for boron of 540×10^{-24} cm^2. If $\sigma = K/v$ with $K = 16\times 10^{-22}$ cm^2-km/sec. adequately represents the cross section in this velocity range, the above sum may also be written as $\sum N_0 \exp(-nKx/v)/\sum N_0$. This also has the value 58 percent.

An additional check on K can be obtained from the boron absorption for resonance neutrons, rhodium for example. The data of Goldsmith and Rasetti[8] for the boron absorption coefficient and

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

the energy of the rhodium resonance, the latter checked by direct velocity measurements,[4] yield $K=10\times10^{-22}$ cm²-km/sec. Other data[9] indicate an even higher value, but all such measurements are subject to corrections which may introduce uncertainties in the absorption coefficient. It is therefore not possible to state the discrepancy is real and that a deviation from the $1/v$ law exists at larger velocities.

The effective thermal energy as would be obtained by the boron method is directly determined from the observed dependence of cross section on velocity. The C neutron transmission of 58 percent would be obtained if all the neutrons had a velocity of approximately 3 km/sec. or an energy of 0.047 ev (1.37 kT for $T=400°K$). This is considerably higher than the usual value from considering the distribution to be Maxwellian.[10]

Our experiments have given direct evidence that the slow neutron distribution from paraffin approximates a Maxwellian distribution with an excess at high velocities. Assignment of a temperature to these neutrons has no very precise meaning, not only because of the departure from an equilibrium distribution, but also because the distribution and "temperature" depend on the amount of slowing material present. Absorption measurements on boron at different neutron velocities have demonstrated the $1/v$ absorption law for this element in the velocity range from 1 to 10 km/sec.

The assistance of Mr. F. B. Berger in part of this work, and a grant from the Graduate School Research Board for equipment, are gratefully acknowledged.

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

[10] H. A. Bethe, Rev. Mod. Phys. **9**, 136 (1937), Fig. 15.

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Capture Cross Sections for Slow Neutrons

J. W. COLTMAN† AND M. GOLDHABER
Department of Physics, University of Illinois, Urbana, Illinois
(Received June 12, 1941)*

A method for measuring capture cross section for slow neutrons has been developed. Neutrons from a Ra-α-Be source are slowed down in a paraffin block containing a cylindrical cavity. A BF_3 detector in the center of the cavity measures the reduction in neutron intensity which results when an element or compound under investigation "suspended" in graphite powder is introduced into the cavity. The arrangement is calibrated with boron. The method has been used to measure the capture cross section of 19 elements. The results are tabulated at the end of the paper.

THERE have been reported recently several investigations of the capture cross sections of various elements for slow neutrons.[1–3] For a considerable number of elements, however, the capture cross sections are still unknown, and in some cases this is due to the fact that they have not been readily measurable by previous methods.

Lapointe and Rasetti have measured the capture cross sections of several elements relative to that of boron by dissolving the substances under investigation in a vessel filled with water in which neutrons were being slowed down, and noting the effect of the solute on the neutron intensity. This method is limited in sensitivity

† Now at the Westinghouse Research Laboratories, Pittsburgh, Pennsylvania.

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

[1] C. Lapointe and F. Rasetti, Phys. Rev. **58**, 554 (1940).

[2] R. D. O'Neal and M. Goldhaber, Phys. Rev. **59**, 102 (1941).

[3] F. Rasetti, Phys. Rev. **58**, 869 (1940).