PHYSICAL REVIEW VOLUME 72, NUMBER 3 AUGUST 1, 1947

A Thermal Neutron Velocity Selector and Its Application to the Measurement of the Cross Section of Boron

E. FERMI, J. MARSHALL, AND L. MARSHALL
Argonne National Laboratory, University of Chicago, Chicago,** Illinois*

(Received April 25, 1947)

A mechanical velocity selector for the study of monochromatic neutrons in the range of energies below 0.3 ev is described.

The instrument has been applied to the measurement of the cross section of boron, which is found to be 703×10^{-24} cm^2 for neutrons of 2200 meters per second velocity.

INTRODUCTION

SLOW neutrons emerging from various moderators with different geometries usually have average velocities comparable, but by no means equal, to the thermal agitation velocity. Large differences, both positive and negative, are observed depending on the nature and the geometry of the moderating substance. This phenomenon has been observed by various experimenters.[1–4]

In this paper we have collected some typical examples of the variations of average velocity of slow neutrons using different moderators as indicated by changes in the apparent cross section of boron. Since boron is often used as a standard substance in slow neutron measurements, its cross section has been determined also by use of monochromatic neutrons obtained with a velocity selector of new design operated in connection with the thermal column of the Argonne graphite pile.

The observed temperatures of the neutrons emitted from the various moderators and arrangements of moderators appear to be in accordance with the individual arrangements employed. Within the experimental errors of the method, the cross section of boron varies as the $1/v$ law, and the measured cross section is 703×10^{-24} cm^2 per atom per neutrons of velocity 2200 meters per second.

TEMPERATURES OF NEUTRONS FROM VARIOUS SOURCES

With the thermal purification column of the graphite pile at the Argonne Laboratory as a primary neutron source, a number of measurements were made of the cross section of boron. In all cases the detector was a proportional counter filled with BF_3 gas. By the use of cadmium diaphragms a neutron beam was obtained with small angular dispersion.

The absorber and detector in these experiments were both boron and consequently both obeyed the $1/v$ law of neutron absorption. It was possible, therefore, to use the correction method given by Bethe[5] to calculate the cross section of boron for mono-energic neutrons of energy kT where T is the absolute temperature of the Maxwellian distribution emitted from the source. Since the cross section of 2200 meters per second neutrons (kT at 293°K) is known, one can then determine the effective temperature of the neutron beam. It must be understood that these effective temperatures are based on the assumption that the neutron beam is Maxwellian in velocity distribution. This is certainly not strictly true for most sources employed.

The results of these experiments are given in Table I. It is quite clear from an inspection of the table that the effective temperature of the neutron beam depends strongly on the source of neutrons. During these experiments the temperature of the thermal column was in the neighborhood of 30°C or 303°K.

* The information contained in this document will appear in Division IV of the MPTS as part of the contribution of the Argonne National Laboratory.

** All three authors now at Institute for Nuclear Studies, University of Chicago.

[1] J. Rainwater and W. W. Havens, Jr., Phys. Rev. **70**, 136 (1946).

[2] W. W. Havens, Jr. and J. Rainwater, Phys. Rev. **70**, 154 (1946).

[3] J. H. Manley, L. J. Haworth, and E. A. Luebke, Phys. Rev. **69**, 405 (1946).

[4] R. F. Bacher, C. P. Baker, and B. D. McDaniel, Phys. Rev. **69**, 443 (1946).

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

TABLE I.

Source of neutrons	Absorber	Cross section for kT neutrons (cm^2)	Effective temp. (°K)
1. Beam from surface of thermal column	Gaseous BF_3	$\sigma_B = 855\times 10^{-24}$	198
2. Beam passed through a 3.7-cm slab of paraffin	Gaseous BF_3	598×10^{-24}	408
3. Beam passed through 7.6c m. of heavy water at 33.7°C in a container 18-in. diam.	Gaseous BF_3	Corrected to 20.4°C $\sigma_B = 710\times 10^{-24}$	288
4. Beam passed through a 22 cm. column of graphite 10 cm square	Pyrex plate calibrated in velocity selector	2800×10^{-24}	18.4
5. Beam from hole in thermal column 125 cm deep, 10 cm square	Gaseous BF_3	701×10^{-24}	293
6. Beam from a "black hole" in thermal column, a hole 10 cm×10 cm×22 cm high connected to surface of thermal column by a 42-cm tube of cadmium of internal diam. 2.5 cm	Gaseous BF_3	755×10^{-24}	255

The source arrangement given under case 1 produces low temperature neutrons because of the filtering action of the graphite in the pile and thermal column.[6] Very slow neutrons whose de Broglie wave-lengths are longer than periodicities encountered in the graphite crystals are scattered very little and can penetrate to the surface of the column more easily than the faster neutrons. In case 2 the slower neutrons are removed preferentially because both the absorption and scattering cross sections of hydrogen are larger and also because scattering in the forward direction is preferred at higher energy. Heavy water (case 3) acts somewhat in the same way because also for deuterium compounds the scattering cross section and the coherence of successive free paths vary with the energy in the same direction as for hydrogen compounds. Therefore, the effective temperature of the neutrons is raised from the initial 198°K to 288°K. The fact that this last temperature is quite close to the actual temperature of the heavy water probably is coincidental. In case 4 the filtering effect of the graphite is shown very strongly. Most neutrons that are scattered are removed from the beam and the graphite column is so long that almost none of the warm neutrons can travel the whole distance without being scattered. Case 5 gives a rather good approximation of the temperature of the source. The neutrons in the beam from the deep hole should be a fair sample of the neutrons present at the bottom of the hole. Essentially it is a case of blackbody radiation from a hole in the wall of a furnace. Case 6 was expected to give a good temperature value, but failed to do so, probably because the hole was not deep enough.

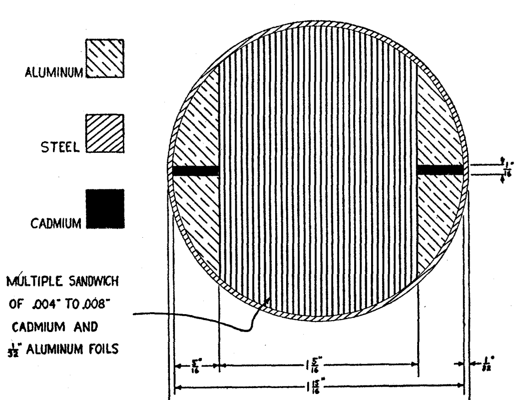

FIG. 1. Cross section of the shutter of the velocity selector.

[6] H. L. Anderson, E. Fermi, and L. Marshall, Phys. Rev. **70**, 815 (1946).

VELOCITY SELECTOR

The velocity selector makes use of a rotating shutter to interrupt the beam of neutrons from the thermal column of the pile. The shutter was constructed by inserting a multiple sandwich of 0.004-inch to 0.008-inch cadmium foils and $\frac{1}{32}$-inch aluminum sheet tightly into a steel cylinder about $1\frac{1}{2}$ inch in diameter with walls $\frac{1}{32}$ inch thick. The shutter was mounted in ball bearings on a heavy steel base plate and was belt and pulley driven by a Dumore grinder motor. Maximum rotational speeds of 15,000 revolutions per minute were possible. It was constructed in the shops of the Metallurgical Laboratory under the direction of Mr. T. J. O'Donnell who is responsible for its mechanical design.

A cross section of the shutter is shown in Fig. 1. From the thickness of the aluminum spacers between the cadmium foils, and from the dimensions of the shutter, one would estimate that no neutrons from a parallel beam would be able to get through when the shutter was more than 1.2° from its full open position. In the experimental arrangement used, it was impossible to use a strictly parallel beam of neutrons. The collimators actually used allowed a maximum divergence of neutron direction in the beam of approximately 3°. Consequently, one would expect the shutter to be completely closed during each 180° of rotation except for an interval of $3°+2\times 1.2°=5.4°$. Actually it was found that the counters indicated background intensity except when the shutter was in a 6° interval.

Through one end of the shutter was inserted a steel rod with its axis perpendicular to the axis of the shutter and with a minor surface ground and polished perpendicular to its axis at each end. Light from a projection lamp and lens system was reflected from these surfaces onto two photo-cells so placed that each photo-cell was illuminated twice during each revolution. One of the photo-cells was used with an amplifier and scaling circuit as a revolution counter. The other, adjustable and calibrated as to angulars position, was connected to an electronic switch circuit which allowed pulses from the proportional counter to be recorded only when the photo-cell was illuminated.

BF_3 filled proportional counters were used as the neutron detector. A nest of four was connected in parallel and mounted at a distance of 146 cm from the shutter. A thick shield of wood, iron, and paraffin was placed between the counters and the pile to compensate somewhat for the fact that the top shield of the graphite pile was not so thick as might be desired. A hole in this shield allowed neutrons from the shutter to reach the counters.

The neutron beam between the shutter and the counters was collimated to make sure that no slow neutrons from sources other than the shutter could enter the counters. Slow neutrons reflected from the walls and roof of the building were eliminated by protecting the sides and back of the counters with a $\frac{1}{2}$-inch thick layer of boron carbide.

The shutter and an improved velocity selector arrangement are to be more fully described in a paper by Brill and Lichtenberger.

DETERMINATION OF BORON CROSS SECTION FOR NEUTRONS OF KNOWN VELOCITY

The cross section of pure BF_3 at several different pressures was measured for neutrons from the thermal velocity selector for velocities ranging from 1700 to 5000 meters per second. Within the experimental accuracy of the method the cross section of boron varied according to the 1/v law. After corrections for scattering were made, the average cross section of boron for neutrons of 2200 meters per second velocity was 699×10^{-24} cm²/atom. 2200 m/sec. is the velocity of a neutron of energy kT where T is 293°K.

In order to verify this value a similar measurement was made with a different boron compound as absorber. $Na_2B_4O_7$ was ignited at about 400° and dissolved in heavy water. The solution was enclosed in a thin-walled aluminum cell, and a second cell of identical wall thickness, which contained an amount of heavy water equal to that in the solution, was prepared. The transmissions of these two absorbers for neutrons from the velocity selector were measured, and the value of the boron cross section for 2200 m/sec. neutrons was found to be 700×10^{-24} cm² corrected for scattering.

In good agreement with these values was the cross section as calculated from measurements at the indium resonance energy.[7] Transmission measurements were made using a collimated beam of neutrons from the interior of the graphite pile of the Argonne Laboratory. The indium foil detectors were protected from thermal neutron activation by thick cadmium covers. Background measurements were made

TABLE II.

	Measurement	$\sigma_{kT}(B)$ at 293°K
$Na_2B_4O_7-D_2O$	Velocity selector	700×10^{-24} cm²
BF_3	Velocity selector	699×10^{-24}
BF_3	In resonance	710×10^{-24}
	Average	703×10^{-24} cm²

[7] J. Marshall, Phys. Rev. **70**, 107 (1946).

by use of an indium filter. Thus the measurements were limited in more than one way to neutrons absorbed strongly by indium.

BF_3 gas in a steel cylinder was interposed in the collimated beam. The BF_3 was highly purified (the same gas as used in the thermal neutron transmission experiments described above). The transmission of the steel container filled with BF_4 at 44 and 68 lb/in.[2] was compared with the transmission of the empty container. The density of gas used was determined by weighing the cylinder. The pressures used and the length of the cylinder (30 cm) were such that the transmissions were in an accurately determinable range (approximately a $\frac{2}{3}$ transmission for the 68-lb sample).

The total cross section of BF_3 for indium resonance neutrons was measured as 107.1×10^{-24} cm²/atom. Assuming

$$\sigma_{\text{scattering}}(F) = 3.7 \times 10^{-24} \text{ cm}^2,$$
$$\sigma_{\text{scattering}}(B) = 2 \times 10^{-24} \text{ cm}^2,$$
$$\text{indium resonance energy} = 1.44 \text{ ev},$$

the boron absorption cross section for neutrons at velocity 2200 m/sec. is 710×10^{-24} cm²/atom.

The results of the three measurements are given in Table II.

This report is based on work done at the Argonne National Laboratory, the University of Chicago, under the auspices of the Manhattan District, U.S. Corps of Engineers, War Department.

PHYSICAL REVIEW VOLUME 72, NUMBER 3 AUGUST 1, 1947

Scattering of Fast Neutrons by Helium*

T. A. HALL† AND P. G. KOONTZ‡
University of California, Los Alamos Scientific Laboratory, Santa Fe, New Mexico
(Received March 28, 1947)

Measurements have been made of the angular distribution of helium recoils for incident neutrons of energies from 0.6 to 1.6 Mev. The distribution curves also permit estimates of the total cross section in this energy range. The results confirm the existence of a cross-section peak of about 6.8×10^{-24} cm² around 1 Mev and indicate, under the assumption of *s*- and *p*-wave scattering only, that the peak is double. But preliminary attempts to fit the data to Bloch's detailed theory of *s*- and *p*-scattering with a split *p*-level have not been successful, and the sign of the postulated splitting is not established.

INTRODUCTION

A SCATTERING theory for helium must satisfy quantitatively two previous sets of data as well as that reported here. Barschall and Kanner[1] obtained recoil distribution curves at neutron energies of 2.5 and 3.1 Mev, and Staub and Tatel[2] obtained the backward scattering cross section as a function of energy around 1 Mev, finding a peak (possibly double). The Barschall-Kanner curves are strongly anisotropic with a preponderance of forward scattering. Wheeler and Barschall[3] have shown that the data at 2.5 Mev can be fitted by the assumption of strong spin-orbit coupling, a *p*-wave resonance around 2.5 Mev, and a weak addition of *d*-wave of a size not unreasonably large for 2.5 Mev. But this data at 2.5 and 3.1 Mev cannot be matched with a simple theory involving only resonances around 1 Mev: an *s*-wave resonance would be isotropic and higher resonances at 1 Mev must fall off to insignificance at 2.5 and 3.1 Mev. Thus the two sets of data provide essentially two different problems, at any rate for analysis in terms of resonances. The Bloch formula for

* This paper will appear in Division V of the Manhattan Project Technical Series as part of the contribution of the Los Alamos Laboratory of the University of California.

† Now at the University of Chicago, Chicago, Illinois.

‡ Now at Iowa State College, Ames, Iowa.

[1] H. H. Barschall and M. H. Kanner, Phys. Rev. 58, 590 (1940).

[2] H. Staub and H. Tatel, Phys. Rev. 58, 820 (1940).

[3] J. A. Wheeler and H. H. Barschall, Phys. Rev. 58, 682 (1940).