The Neutron Absorption Limit in Cadmium

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In order to find the high energy absorption limit in Cd the absorption in boron of the transmitted neutrons was measured. The slow neutron absorption coefficient in boron is found to be 38 cm²/g in agreement with Amaldi and Fermi. The Cd penetrating neutrons are inhomogeneous in energy and therefore are not absorbed exponentially but according to the law $(1-e^{-x})/x$, where $x=\kappa\delta$, κ is the absorption coefficient for neutrons just penetrating Cd and δ is the thickness of boron traversed. κ is found to be 9.5 cm²/g B. A sheet of Cd 0.5 mm thick reduces the neutron counts to 8.4 percent of the total; 5.7 percent are absorbable in heavy layers of boron. Assuming the $1/v$ law for the absorption of neutrons in boron the absorption limit in Cd is found to be 0.41 ev. With the aid of data from the wheel experiment of Rasetti and collaborators the resonance energy and the half-width are calculated and are $E_r=0.18$ ev and $\Gamma=0.15$ ev, respectively. An estimate is made of the neutron width which turns out to be $\Gamma_n=1.3\times10^{-3}$ ev.

INTRODUCTION

THE Wigner-Breit formula for the absorption cross section, σ, for neutrons in a given element,

$$\sigma=\frac{1}{E^{\frac{1}{2}}[(E-E_r)^2+\Gamma_{\frac{1}{2}}{}^2]} \tag{1}$$

indicates that the absorption of neutrons should take place as $1/E^{\frac{1}{2}}$, or $1/v$, in an energy interval far removed from the region of the resonance energy, E_r. Experimental results obtained from the mechanical velocity selector of Rasetti and collaborators[1] indicate that the absorption of slow neutrons in Cd does not follow the $1/v$ law but remains constant in an interval of neutron energies of approximately 20 percent about $\frac{3}{2}kT$. On the other hand, Moon and Tillman[2] and Powers and collaborators[3] have shown that neutrons cooled down to 95°K have a greater absorption coefficient in Cd than neutrons in thermal equilibrium at 300°K, the difference amounting to 7 percent. Thus, if it is assumed that neutrons are in thermal equilibrium with the paraffin at these temperatures, it appears that the absorption of slow neutrons in Cd is governed by no simple law. The Wigner-Breit formula suggests a resonance level lying in or just above the region of thermal energies.

The method for determining the high energy limit has been described by Bethe.[4] The absorption coefficient for neutrons transmitted by Cd was measured in boron, it being assumed that the absorption in boron follows the $1/v$ law.

EXPERIMENTAL PROCEDURE

The Rn-Be source of neutrons was placed inside a lead sphere of 3.65 cm radius around which was fastened a paraffin shell 7.1 cm thick as shown in Fig. 1. The distance from the center of the Rn-Be source to the outer surface of the paraffin shell was 10.75 cm. The outer wall of the BF_3 gas chamber for the detection of the neutrons was placed 6.4 cm from the paraffin surface. This chamber had a shielding jacket of B_4C of thickness equivalent to 0.391 g B/cm² the end of which lapped over the end of the chamber in order to define accurately the aperture, 2.6 cm diameter, over which the absorbers were placed. A shield of 20 mil Cd equivalent to 0.582 g Cd/cm² covered the boron shield. The chamber was operated at 500 volts. The pulses due to the disintegration of B were fed directly to the first tube of a linear amplifier of the type described by Dunning,[5] and recorded by a scale-of-eight counter.[6] The sphere was suspended by a $\frac{1}{8}''$ brass rod from the ceiling into the center of the room so that the nearest scattering surface was 150 cm away. Similarly, in order to reduce scattering effects, the chamber was mounted on

[1] Rasetti, Segrè, Fink, Dunning and Pegram, Phys. Rev. **49**, 104 (1936).
[2] Moon and Tillman, Nature **136**, 66 (1935).
[3] Powers, Fink, and Pegram, Phys. Rev. **49**, 650 (1936).
[4] H. Bethe, Rev. Mod. Phys. **9**, 148 (1937).
[5] J. R. Dunning, R. S. I. **5**, 387 (1934).
[6] Wynn-Williams, Proc. Roy. Soc. **A136**, 312 (1932).

an iron pipe framework. It was found that with no absorber before the aperture a Rn-Be source of 462 mC gave 700 counts per minute. The number of counts produced by neutrons penetrating 20 mil thick layer of Cd was 8.4 percent of the total; 5.7 percent are absorbable in thick layers of boron. The remaining 2.7 percent of counts is probably due to fast neutrons disintegrating B or F, gas atoms recoiling from fast neutrons, or stray neutrons entering the chamber through the shields.

Experimental Results and Discussion

Boron absorption curves were taken with and without a 20 mil Cd filter. Pyrex plates gave thin boron layers, there being 0.0294 g B/cm^2 in a $\frac{1}{8}''$ plate. Fig. 2 shows the trend of the absorption. Since neutrons enter the chamber from a spherical surface, an obliquity correction is necessary. This was calculated assuming that the distribution of neutrons emerging from the surface is given by the Fermi law, $\cos\theta+\sqrt{3}\cos^2\theta$, where θ is the angle from the normal to the surface. It must also be taken into account that the neutrons entering along the axis of the chamber traverse more BF_3 than those entering obliquely and therefore have a greater probability of being counted. Mainly for this reason, the obliquity correction turns out to be very small, *viz.* about 10 percent. With this correction applied the absorption coefficient of the neutrons emerging from the sphere is 36 cm^2/g B. This figure was obtained in an absorber which reduced the intensity of thermal neutrons by a factor $e^{-1.16}$; according to reference 4, Fig. 15, this

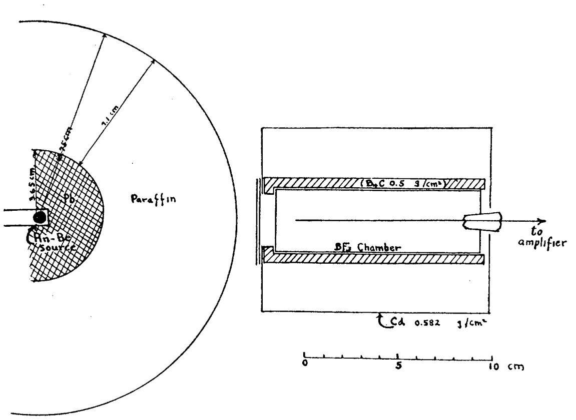

Fig. 1. Arrangement of source and ionization chamber.

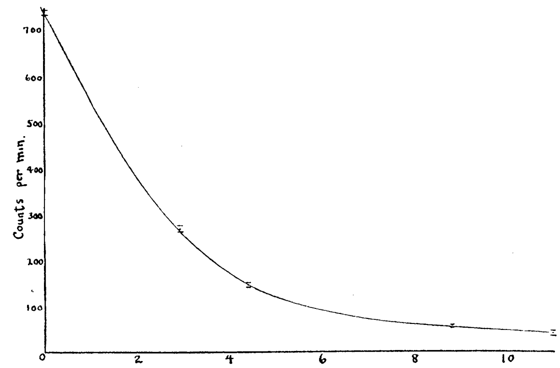

Fig. 2. Absorption of neutrons in Pyrex plates.

corresponds to neutrons having an average energy of 1.12 kT. Therefore, the boron absorption coefficient determined from the $1/v$ law for an energy kT would be $36(1.12)^{\frac{1}{2}}\approx 38$ cm^2/g B. This is in exact agreement with the result of Amaldi and Fermi[7] who give 38 cm^2/g B for the "C" group (exact energy not stated). Goldsmith and Rasetti[8] give 28 cm^2/g B for neutron energies $E=kT$.

The absorption curve for neutrons in Cd is given in Fig. 3; its essential feature is that the 20 mil Cd filter (0.582 g Cd/cm^2) reduces the counts per minute to 8.4 percent of the initial rate. The ratio of the number of transmitted neutrons to the number with no Cd present was determined by taking 10,024 counts over a period of 60 minutes with no Cd and 841 counts in 60 minutes with the 20 mil Cd. The ratio was found to be 0.084 ± 0.002.

Absorption curves in thick layers of boron were taken with neutrons filtered through 20 mil Cd, Fig. 4. These layers were made of B_4C of various thicknesses up to 2.44 g B_4C/cm^2. It can be shown that this absorption curve is given by the expression:

$$I/I_0=1-e^{-x}/x, \tag{2}$$

where $x=\kappa\delta$, κ is the absorption coefficient of neutrons just penetrating Cd, and δ is the thickness of the absorbing layer of boron. This expression follows from the Fermi distribution law according to which the number of neutrons per cm^2 and second in the energy interval dE is

[7] Amaldi and Fermi, Phys. Rev. **50**, 899 (1936).
[8] Goldsmith and Rasetti, Phys. Rev. **50**, 328 (1936).

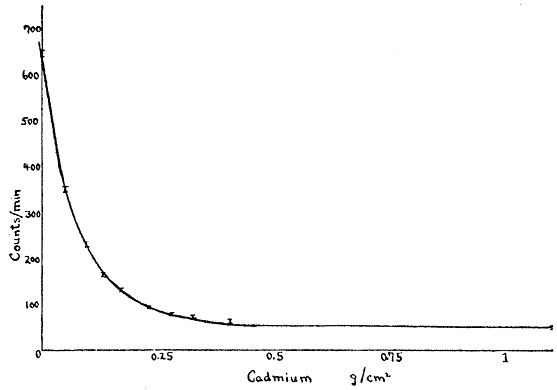

FIG. 3. Absorption of neutrons in cadmium.

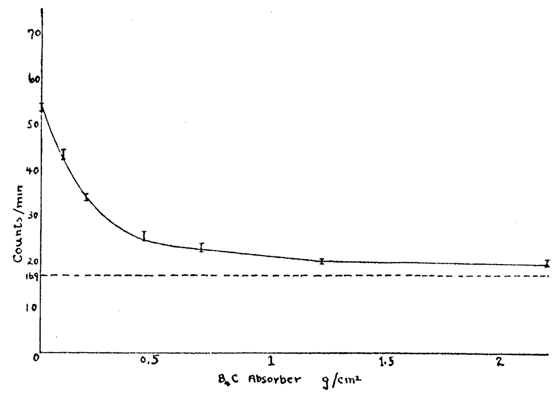

FIG. 4. Absorption of neutrons in B_4C filtered through 0.582 g/cm² Cd.

$N(E)\sim dE/E$. The BF_3 chamber sensitivity is a function of neutron energy given by $1/E^{\frac{1}{2}}$. The boron layer absorbs as $\exp\left[-\kappa\delta(E_L/E)^{\frac{1}{2}}\right]$ according to the $1/E^{\frac{1}{2}}$ law of absorption, where E_L is the upper energy limit for neutrons absorbed in Cd. Thus the total number of neutrons detected will be:

$$C\int_{E_L}^{\infty}(1/E^{\frac{1}{2}})\exp\left[-\kappa\delta(E_L/E)^{\frac{1}{2}}\right]dE/E$$
$$=2C(E_L)^{-\frac{1}{2}}(1-e^{-\kappa\delta})/\kappa\delta.$$

The proportionality constant, C, is determined by the condition $I=I_0$ for $\delta=0$ which immediately gives the expression (2). The dotted line in Fig. 4 is a background line determined by calculating the number of neutrons which would penetrate the 20 mil Cd and an infinitely thick layer of boron. With this background taken into account the value of κ is 9.5 cm²/g B.

Since the absorption of neutrons in boron is taken as proportional to $1/E^{\frac{1}{2}}$, the energy of the upper absorption limit in Cd may be calculated from $E_L=E_{\text{th}}(\mu/\kappa)^2$ where $\mu=38$g/cm and $E=kT=0.026$ v. The result is[9] that $E_L=0.026\ (38/9.5)^2=0.41$ ev from which it appears that Cd absorbs neutrons having energies considerably higher than the thermal. Frisch and Plazcek[10] found in a preliminary measurement that $E_L\leq 1$ ev.

The absorption limit, E_L, in Cd combined with the results of the wheel experiment by Rasetti *et al.* permits a calculation of the resonance energy, E_r, and the half-width of the resonance band, Γ. The calculation which is given in detail by Bethe (reference 4, p. 149) gives:

$$E_r=\frac{E_L{}^2+2\lambda kT-(kT)^2}{2(E_L+\lambda-kT)},\qquad (3)$$

$$\epsilon=\frac{(E_r-kT)^2+(\Gamma/2)^2}{2(E_r-kT)},\qquad (4)$$

where $$\lambda=\epsilon(p_{\text{th}}-p_L)/p_L.\qquad (5)$$

Here p_{th} and p_L are the capture probabilities in Cd for thermal neutrons and neutrons just penetrating 20 mils Cd, respectively, the capture probability being defined by $p=\kappa E^{\frac{1}{2}}$. The absorption coefficient for thermal neutrons in Cd was taken as 15 cm²/g according to Amaldi and Fermi and to our own experiments, Fig. 3. The absorption coefficient, κ_{th}, of neutrons penetrating 20 mils (0.582 g/cm²) of Cd was assumed to be about $1/0.58\approx 2$ cm²/g. Therefore:

$$p_{\text{th}}/p_L=15/2\ (kT/E_L)^{\frac{1}{2}}$$
$$=15/2\ (0.026/0.37)^{\frac{1}{2}}=1.99.\qquad (6)$$

The quantity ϵ in (3) and (5) is obtained from Rasetti's wheel experiment. If $\Delta p/p$ is the relative change in the absorption coefficient in that experiment, then

$$\epsilon=2muv_a(p/\Delta p)\sin\theta,\qquad (7)$$

where u is the velocity of rotation of the edge of the wheel and $v_a=(2kT/M)^{\frac{1}{2}}$ is the average Maxwell velocity of thermal neutrons. In

[9] This result is independent of the obliquity correction of 10 percent because this correction applies equally to the absorption coefficients for thermal and Cd penetrating neutrons.
[10] Frisch and Placzek, Nature **137**, 357 (1936).

Rasetti's experiment, $v_a=2200$ meters/sec., $u=140$ m/sec., and $\Delta p/p=6.3$ percent. From (7):

$$\epsilon=0.09_5 \text{ ev.} \tag{8}$$

Inserting (6) and (8) in (3), (4), we obtain:

$$E_r=0.18 \text{ ev}, \quad \Gamma=0.15 \text{ ev.} \tag{9}$$

This result is, unfortunately, very sensitive to small errors in $\Delta p/p$ as can be seen from an inspection of (7). If ϵ is changed to 0.11 ev, the result is that $E_r=0.17$ ev and $\Gamma=0.19$ ev. With the present measurements it seems that E_r and Γ are of the same order of magnitude and are both about 0.15 ev. Bethe and Placzek[11] have made calculations using Amaldi and Fermi's data[7] on the absorption of "D" neutrons in Cd and find $E_r=0.14$ ev and $\Gamma=0.20$ ev. According to Eq. (9) the experimental ratio $\Gamma/E_r=0.80$, which would correspond to the case of a fairly pronounced resonance hump in the curve of cross section plotted against E/E_r as given by Bethe and Placzek. The figures calculated by Bethe and Placzek give $\Gamma/E_r=1.42$ approximating the case $\Gamma/E_r=\sqrt{2}$ which has a less pronounced resonance hump and a region of almost constant cross section as the energy varies from 0.05 to 0.12 ev.

From the values given in (9) an estimate may be made of the neutron width according to the calculations of Bethe and Placzek[11]

$$\Gamma_N=\frac{E_r\kappa_r\Gamma_{\text{eff}}}{1.23\times10^3}, \tag{10}$$

where κ_r is the absorption coefficient at resonance and Γ_{eff} is the effective cross section which may be replaced by $\pi\Gamma$ if the natural width, Γ, is large compared with the Doppler width. κ_r is about 1.3 times the absorption coefficient at thermal energies. Thus $\Gamma_N=(1.3E_r\kappa_r\pi\Gamma)/1.23\times10^3$ and $\Gamma_N=1.3\times10^{-3}$ ev.

The authors are indebted to Professor H. A. Bethe for major assistance in the calculations and interpretations of the experimental data, and to the Committee on Radiation of the National Research Council for financial support.

[11] Bethe and Placzek, Phys. Rev. 51, 450 (1937).

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Production, Characteristics, and Reliability of Geiger-Müller Counters*

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A technique for the production of reliable Geiger-Müller counters is described. By the use of pure hydrogen gas and by cleaning the electrodes by sputtering in a glow discharge in hydrogen previous to filling the tubes with hydrogen gas, tubes with plateaus of 400 volts are produced. Copper, nickel, and tungsten have been found suitable for cathode cylinders while aluminum was not. Tubes filled with pure argon, pure oxygen, or air were found to give many spurious counts. An extensive series of reliability tests is described which shows that carefully made counter tubes used in properly designed circuits give completely reliable quantitative data.

THE use of Geiger counters for quantitative measurements on natural and artificial radioactivity has been practically abandoned because they have been found to be unreliable. However, their many advantages made it seem desirable to investigate the characteristics of the tubes and the circuits in an effort to develop reliable counting apparatus. Consequently, a systematic study has been made of the electric discharges in the tubes and of the characteristics of the electric circuits. The variations in the constants and the characteristics of the discharges produced by changing the electrode materials and the gas were investigated. Observations were made on the effects of impurities on the surface of the cathode and in the gas. After a

* Reported at the Washington Meeting of the American Physical Society. Phys. Rev. 51, 1027, 1937.