daughter activities was obtained. Allocation of the 130-min. activity to mass 177 is made on the basis of recognition of the 53-hour Ta^{177} daughter activity and also from considerations of yield in bombardments at various energies which agree with formation by a p, $5n$ reaction.

80±5-min. W^{176}

This activity was formed in bombardments of tantalum with protons of energy greater than about 50 Mev, and was obtained in a relatively pure yield in short bombardments of 0.2-mil tantalum foil with 70 Mev protons. The radiation characteristics were obtained from absorption measurements carried out immediately after chemical separation. The approximate ratios of the various radiations were ~0.1 Mev e^-: ~0.2 Mev e^-: ~2 Mev β^+: L x-ray: K x-ray: γ-ray = ~0.1: ~0.02: ~0.005: ~1: ~1: ~0.1.

The activity was shown to be the parent of the 8.0-hour Ta^{176} activity by chemical separations at successive time intervals. The half-life of the wolfram activity was obtained by measurement of the activity of aliquots of a stock solution taken at fifteen minute intervals and counted immediately after removal of the tantalum daughter activity. The decay through five half-lives was obtained after correction from the 130-min. W^{177} activity initially present to the extent of about five percent. The 53-hour Ta^{177} activity was found in small yield in the decays of the 8-hour daughter of the 80-min. wolfram as would be expected.

Thanks are due Dr. H. G. Hicks for assistance in part of the experimental work, T. Putnam, B. Rossi and the crew of the 60-inch Crocker Laboratory cyclotron, R. Watt and the crew of the linear accelerator, and J. Vale and the crew of the 184-inch cyclotron for their cooperation in bombardments. The advice and interest of Professors G. T. Seaborg and I. Perlman are gratefully acknowledged.

PHYSICAL REVIEW VOLUME 80, NUMBER 4 NOVEMBER 15, 1950

Resonance Capture of Neutrons by Uranium*

HERBERT L. ANDERSON†
Columbia University, New York, New York
(Received April 27, 1940)

The resonance capture of slow neutrons by U^{238} has been studied by absorption methods with "good" geometry and thin detectors using the cyclotron as an intense source of neutrons. The experimental cross section for self-absorption for slow neutrons transmitted by cadmium was measured with thin absorbers and found to be 4600×10^{-24} cm²/atom±40 percent. Evidence is given for the existence of more than one level. The predominant level has an energy somewhat under 11 ev, a total natural width somewhat less than 0.20 ev and a neutron width somewhat less than 0.0086 ev. The value $\int\sigma dE/E$ in the resonance region was found to be 290×10^{-24} cm²/atom±40 percent.

I. INTRODUCTION

IT is known that when neutrons are captured by uranium, either a fission of the uranium nucleus may take place, or the neutron may be captured in a typical resonance process, resulting in a radioactive isotope of uranium, U^{239}, which decays by β-emission of 24-minute half-life.[1] Since the latter process absorbs but does not produce neutrons, its investigation is of interest in relation to the problem of obtaining a self-propagating fission process with uranium.[2]

The process of resonance capture is characterized by a large capture cross section for neutrons of energy close to a certain value. According to the theory as given by Breit and Wigner[3] and extended by Bethe and Placzek,[4] the possibility of resonance arises whenever the compound nucleus, which is formed when a neutron falls upon a nucleus, has an energy level corresponding to positive kinetic energy of the neutron. A neutron of energy close to this value may be captured in the level and the subsequent emission of a γ-ray will leave the neutron bound in the nucleus. The width of the level is determined by the probability of γ-ray emission and by the probability of neutron re-emission.

If only one level predominates, the variation of the capture cross section with energy is given by the dispersion formula of Breit and Wigner,[3]

$$\sigma(E)=\pi\lambda^2\frac{2J+1}{(2s+1)(2i+1)}\frac{\Gamma_n\Gamma_\gamma}{(E-E_R)^2+(\Gamma/2)^2}=\left(\frac{E_R}{E}\right)^{\frac{1}{2}}\frac{\sigma_R(\Gamma/2)^2}{(E-E_R)^2+(\Gamma/2)^2},\quad(1)$$

* This article was originally received for publication on April 27, 1940, but was withheld voluntarily for reasons of national security. It was declassified by the Atomic Energy Commission on June 22, 1950, and submitted for publication in revised form on July 12, 1950. Publication assisted by the Ernest Kempton Adams Fund for Physical Research of Columbia University.

† University Fellow, Columbia University. Present address: Institute for Nuclear Studies, The University of Chicago, Chicago, Illinois.

[1] Meitner, Hahn, and Strassmann, Zeits. f. Physik **106**, 249 (1937). These authors give 23 min. as the half-life.

[2] Anderson, Fermi, and Szilard, Phys. Rev. **56**, 284 (1939).

[3] G. Breit and E. Wigner, Phys. Rev. **49**, 519 (1936).

[4] H. A. Bethe and G. Placzek, Phys. Rev. **51**, 450 (1937).

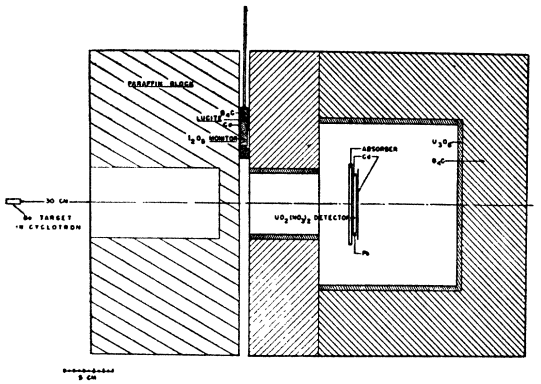

FIG. 1. Arrangement for investigating the resonance capture of neutrons by uranium.

where E is the energy of the neutron; E_R is the energy of the resonance level; σ_R is the capture cross section at exact resonance; $2\pi\lambda$ is the neutron wave-length; i and J are the nuclear spins of the original and compound nucleus, respectively; s is the neutron spin and has the value $\frac{1}{2}$; Γ_n and Γ_r are the neutron and radiation widths, respectively; while $\Gamma=\Gamma_n+\Gamma_r$ is the total natural width of the resonance level at half-maximum. It is to be observed that Γ_n is proportional to the neutron velocity.

Measurements have been carried out on (1) self-absorption, (2) boron absorption, and (3) resonance activation. The first gives information on the capture cross section at resonance; the second, on the resonance energy; and the third, on the area under the resonance curve above the thermal region. These measurements are sufficient to describe completely the resonance process, insofar as the Breit-Wigner formula applies. The capture cross section for thermal neutrons which has already been measured[5] may be used as a test of the assumption that only one level predominates. A unique interpretation of the present experiments is no longer possible when more than one level is effective. The values which result for the resonance energy and the cross section at resonance must then be interpreted as a sort of average over the several levels. Bethe and Placzek[4] have shown that interference effects among the levels may arise as a further complication. However, as they point out, the activation of a given level by neutrons which have been slowed down by paraffin may be expected to have an average dependence on the position of the level as $E_R^{-\frac{3}{2}}$. For this reason, levels which lie low in energy are favored in experiments of this kind. In addition, a boron filter technique has been employed which permits the activity due to the activation of levels above about 100 ev to be deducted.

[5] H. L. Anderson and E. Fermi, Phys. Rev. **55**, 1106 (1939); Halban, Kowarski, and Savitch, Comptes rendus **208**, 1396 (1939); L. Meitner, Nature **145**, 422 (1940).

II. ABSORPTION EXPERIMENTS

Absorption experiments were performed on boron and and uranium by measuring the activity induced in a uranium detector with and without the absorber in the path of the neutrons. A uranium detector, which is covered by cadmium to remove thermal neutrons, is sensitive mainly to what will be termed uranium resonance neutrons.[6] Hence, any measurement made with such a detector will be a measurement on uranium resonance neutrons. A small part of the activity induced in a uranium detector covered with cadmium is due to the fission process, but can be accounted for. Ideally, in such experiments, a parallel beam of neutrons should be used and the detectors should be thin enough to avoid the effects of self-absorption. In the previous work[1] on the uranium resonance process, measurements were made under geometrical conditions for which a large correction for obliquity had to be made. In the present experiments a cyclotron was available as an intense source of neutrons. Accordingly, a geometrical arrangement was used for which the correction for obliquity was only 1.5 percent. This arrangement is shown in Fig. 1.

III. EXPERIMENTAL ARRANGEMENT

Neutrons were produced in the cyclotron by bombarding beryllium with 6-Mev protons and were slowed down by means of a paraffin block. The detector was a thin layer of uranyl nitrate deposited on a lead dish and enclosed in cadmium. Lead was used because it is not made radioactive by neutrons from the cyclotron. The detector was surrounded by a thick cylinder of boron carbide which served to shield the detector from stray slow neutrons and to collimate the neutron beam emerging from the paraffin block. The interior of the cylinder was lined with uranium oxide to improve the shielding and to reduce the scattering of those neutrons which are most effective in activating the detector. To monitor the neutron beam, three disks of iodine pentoxide were placed between the paraffin and the boron shield and symmetrically disposed around the opening. They were covered with cadmium so that they would respond to epithermal[6] rather than to thermal neutrons. The radioactivity induced in iodine by slow neutrons has a half-life of 25 minutes. The difference between the half-lives of the detector and monitor is not sufficient to produce an appreciable error in monitoring due to possible variations in neutron intensity which may occur during irradiation.

[6] Cadmium is known to absorb strongly all neutrons below about 0.3-ev energy. In this paper neutrons strongly absorbed by cadmium will be referred to as thermal neutrons. Slow neutrons transmitted by cadmium but absorbed by thick boron will be termed epi-thermal; epi-thermal neutrons strongly captured by uranium, resonance neutrons; while all others will be called fast neutrons. On an energy scale, thermal neutrons are below about 0.3 ev, epi-thermal neutrons are between 0.3 and about 100 ev, while in the present case, fast neutrons have an energy not exceeding 3×10^6 ev.

IV. DETECTORS

The use of uranium as a detector is complicated by the fact that uranium itself is naturally radioactive. The β-activity of one of its daughter products, uranium X_2, was sufficiently intense partially to obscure a measurement of the induced activity. For this reason it was necessary to prepare, for each experiment, a new detector from which the uranium X had been removed. In order to compare the detectors with one another, the UX activity which builds up after the U^{239} activity has decayed was taken as an index. This is preferable to the use of the weight as an index since it minimizes errors due to non-uniformity of the uranium layer. The difference between the absorption coefficients of the β-rays must, however, be taken into account. The mass absorption coefficients in aluminum were measured and found to be 5.8 cm^2/g and 13.5 cm^2/g for UX_2 and U^{239}, respectively, for the particular geometry used in the measurement of the activity. Furthermore, the absorption was found to follow an exponential law for not too large absorber thicknesses. For $UO_2(NO_3)_2$, these values should be multiplied by a factor 1.5, obtained by assuming that the absorption increases as the cube-root of the atomic number. Since the detectors were quite thin (about 7 mg/cm^2) the correction for the difference in the β-ray absorptions in the detector amounted only to about 5 percent.

V. ABSORBERS

Uranium absorbers were prepared by thoroughly mixing U_3O_8 powder with sulphur flowers. The mixture was then uniformly packed in an aluminum dish over which a second aluminum dish was crimped by means of a press, to form a sealed disk 8 cm in diameter and 0.3 cm thick. The U_3O_8 was prepared by ignition of a solution of uranyl nitrate. Boron absorbers were prepared in the same way with 800-mesh B_4C obtained from the Norton Company. I am indebted to Dr. R. R. Ridgeway of that company for an analysis of this boron carbide. He found that it contained 78.13 percent boron, 21.23 percent carbon, 0.14 percent iron, and 0.50 percent oxygen. Data on the absorbers are given in Table I.

VI. PROCEDURE

The experimental procedure was as follows: (1) Purification of uranium from uranium X. Uranyl nitrate was dissolved in ether, a little water added and after shaking removed again with the aid of a separating funnel. UX and other impurities are removed with the water while most of the uranium remains in ether solution. By repeating this several times the activity due to UX_2 can be reduced by a factor of 1000. The detector was prepared by evaporating, out of ether solution, from 150 to 250 milligrams of $UO_2(NO_3)_2$ on a lead dish of 28 cm^2 area. (2) Measurement of the residual UX activity. All measurements of uranium activities were made by means of a Geiger-Müller counter connected to a scale-of-four recorder. The counter was of the thin-walled silvered glass type[7] filled with a 9-cm argon, 1-cm alcohol mixture. Such a counter has a plateau of several hundred volts and in the several months during which these experiments were being carried out, natural background and sensitivity were frequently checked and found to vary inappreciably. (3) Irradiation by means of the cyclotron for 30 minutes. (4) Measurement of the ment of the U^{239} activity for 27 minutes starting three minutes after the end of the irradiation. (5) Measurement of the monitor activity against a uranium standard by means of an ionization chamber connected to an FP-54 amplifier. The combined activity of the three I_2O_5 disks was measured. (6) Measurement of the build-up of the UX activity for four days after the end of the irradiation. Care was taken to reproduce the disposition of the detector with respect to the counter in all measurements. From these data the initial slope of the UX build-up could be computed in counts per minute per hour.

TABLE I. Scattering data for the absorbers. The amount of each substance contained in the absorber is expressed in g/cm^2. The assumed cross sections for scattering are expressed in units of 10^{-24} cm^2. The scattering correction is estimated on the assumption that $\frac{1}{2}$ of the neutrons which are scattered reach the detector.

Substance	Al	B	C	O	S	U	
Scattering cross section[a]	2.0	2.5	4.8	3.0	2.5	13.0	Scattering correction %
Absorber	g/cm^2						
0.0191 U	0.12				0.19	0.0191	0.7
0.0342 U	0.12			0.01	0.21	0.0342	0.7
0.123 U	0.13			0.02	0.24	0.123	0.8
0.203 U	0.13			0.04	0.24	0.203	1.5
0.0312 B	0.12	0.0312	0.01		0.21		1.0
0.078 B	0.12	0.078	0.03		0.12		1.6
0.235 B	0.12	0.235	0.08				2.8
0.470 B	0.12	0.470	0.16				5.8
1.96 B	0.24	1.96	0.56				24.3
2.20 B	0.36	2.20	0.64				29.6

[a] The scattering cross sections for C and U are those for indium resonance neutrons reported by H. B. Hanstein and J. R. Dunning, Phys. Rev. **57**, 565 (1940). The others were estimated by comparing the cross sections for fast neutrons reported by Zinn, Seely, and Cohen, Phys. Rev. **56**, 260 (1939), with those for thermal neutrons reported by Dunning, Pegram, Fink, and Mitchell, Phys. Rev. **48**, 265 (1935).

VII. RESULTS

In a typical experiment, a detector with 203 mg of UX-free $UO_2(NO_3)_2$ was irradiated with cadmium only as absorber. The total number of counts in 27 minutes was 39,500, from which was subtracted 2870 counts due to natural background (18 counts per minute) and UX activity. From this, the initial activity immediately after the end of the irradiation was computed to be 2130 counts per minute. The initial slope of the UX build-up was found to be 16.8 counts per minute per hour while the monitor activity was 0.744 referred to a 5-gram uranium standard. Thus, the initial activity, A, of U^{239} per unit monitor and per unit UX slope was 170. The fraction f of uranium atoms activated per second

[7] Made by Eck and Krebs, New York City.

TABLE II. Fraction f of uranium atoms activated per second by a neutron beam having unit intensity, in terms of the iodine monitor, f is given in units of 10^{-18} sec.$^{-1}$.

Absorber thickness g/cm²	Observed	Background	Scattering correction %	Fission	Corrected
0	3.26	0.21	0	1.06	1.99
Cd (0.45 g/cm²)	2.39	0.21	0	0.22	1.96
Cd+0.0191 U	2.02	0.21	0.7	0.22	1.60
Cd+0.0342 U	1.81	0.21	0.7	0.22	1.39
Cd+0.123 U	1.19	0.21	0.8	0.22	0.71
Cd+0.203 U	1.03	0.21	1.5	0.22	0.61
Cd+0.078 B	2.14	0.21	1.6	0.21	1.75
Cd+0.235 B	1.71	0.21	2.8	0.19	1.35
Cd+0.470 B	1.27	0.21	5.8	0.19	0.93
Cd+1.96 B	0.52	0.21	24.3	0.17	0.21
Cd+2.20 B	0.48	0.21	29.6	0.17	0.18
Cd+0.235 B+0.203 U	0.88	0.21	4.3	0.19	0.51
Cd+0.470 B+0.203 U	0.74	0.21	7.4	0.19	0.38
Cd+1.96 B+0.0342 U	0.48	0.21	25.0	0.17	0.17
Cd+1.96 B+0.123 U	0.45	0.21	25.1	0.17	0.13
Cd+1.96 B+0.203 U	0.44	0.21	26.1	0.17	0.12

by a neutron beam of intensity corresponding to unit monitor activity may be calculated from this result by means of the formula,

$$f = A\lambda\eta/\tau_1(1-e^{-t/\tau_2}), \qquad (2)$$

where, $\lambda = 4.87\times10^{-18}$ sec.$^{-1}$ is the disintegration constant of uranium, $\tau_1 = 852$ hours is the average life of UX, η is the factor which takes into account corrections for the absorptions of the neutrons and the β-rays, while $t = 30$ minutes is the irradiation time and $\tau_2 = 34.7$ minutes is the average life of U^{239}. The contribution to η due to the β-ray absorption in the walls of the counter was determined by slipping over the counter a cylinder of aluminum having about the same thickness as the counter wall (0.029 g/cm²). Its transmission for the β-rays of U^{239} was found to be 67.7 percent and for UX, 85.0 percent; this yields a factor 1.25. The correction for the absorption of the β-rays in the detector itself was estimated from the observed value of the UX slope and the measured values of the absorption coefficients, the average weight of uranyl nitrate per unit of UX slope being 48 mg/28 cm². In the present example, this correction raised the result by 4.2 percent. The correction for the self-absorption of neutrons in the detector was estimated from the experimental self-absorption curve and in this case increased the result by 3.0 percent to a final value of 2.31×10^{-18} sec.$^{-1}$; possible differences in the *scattering* of the β-rays were neglected. Individual results obtained in this way had an average deviation from their mean of less than 4 percent. The values of f for different absorbers listed in Table II depend on at least two measurements of this kind and the precision measure of a result stated there may be taken to be 3 percent. On the other hand, the absolute measure of f is subject to considerable error due principally to the uncertainty in estimating η. The *relative* values, which are used in determining the transmissions of absorbers, are not subject to this limitation.

A considerable uncertainty in measurements of this type is due to the scattering in the absorbers and to the activities produced by fast neutrons. If there were no scattering, the residual activity with a thick boron absorber placed in front of the detector could be deducted and the difference properly ascribed to neutrons absorbed by thick boron. However, this is not the case; scattering does take place, and moreover, scattering cross sections, especially for boron, are not well known. In Table I data on the absorbers have been compiled, together with values of the scattering cross sections which were assumed. In computing the scattering correction it was assumed that the scattering was spherically symmetrical and that, therefore, $\frac{1}{2}$ of the scattered neutrons did not reach the detector.

The background due to neutrons striking the detector from behind was estimated to be 0.19 (in units of f) and the scattering correction was not applied to this part of the activity. A part of the observed activity was due to fission of uranium nuclei. To estimate the contribution due to fission, experiments were performed in which uranyl nitrate was irradiated with and without a cadmium absorber, and the U^{239} activity separated from all other activities *after* the irradiation, by a second ether separation. The activity with no absorber was only slightly larger than the activity with a cadmium absorber, wherefore, almost all the activity due to thermal neutrons could be ascribed to the fission process. The ratio of the number of fissions due to thermal neutrons, to the number due to epi-thermal and fast neutrons, was determined by placing, in the detector position, a uranium-lined ionization chamber connected to a linear amplifier. The number of fissions was then recorded with the different absorbers in place. A small boron-trifluoride counter was used as a monitor in these experiments. The activity which remained with the thickest absorber after this fission activity had been subtracted was probably due to the fast neutrons.

VIII. FILTER TECHNIQUE

In studying the resonance process, several filters have been employed in order to distinguish the effects of different neutron groups. A cadmium filter was placed in front of the detector to remove thermal neutrons. A second filter, sometimes of boron and sometimes of uranium, could be interposed or taken out of the beam. Differences of activities observed with and without this second filter represent the action of a neutron band that does not contain the thermal neutrons and is absorbed by the second filter. Thus, whenever the second filter is a thick boron layer the corresponding band includes only the epi-thermal neutrons. With a uranium layer of moderate absorption as second filter, the effect is that of neutrons strongly absorbed by uranium near the center of resonance band.

The columns of Table III give the transmission observed with several second filters. They are calculated

from the data of Table II with the formula,

$$T=(f_A-f_{A+F})/(f_0+f_F), \quad (3)$$

where the subscripts A and F refer to the absorber and the filter, respectively, it being understood that the detector is always covered with cadmium. The transmission value computed in this way is that fraction of the resonance neutrons which is absorbed in the filter but transmitted by the absorber.

IX. SELF-ABSORPTION

If the resonance curve were rectangular in shape the transmission of uranium resonance neutrons by uranium absorbers would decrease, with increasing thickness, according to an exponential law. Usually, the curve has a well-defined maximum and neutrons of energy corresponding to this maximum are absorbed more strongly than the others, giving rise to the phenomenon of self-reversal.[8]

When the resonance curve is sharp enough so that the number of neutrons per unit energy interval does not vary appreciably over the resonance region, then for a parallel beam of neutrons the transmission for self-absorption may be written,

$$T=\int \sigma(E)e^{-\sigma(E)N}dE \Big/ \int \sigma(E)dE, \quad (4)$$

where $\sigma(E)$ is the capture cross section for neutrons of energy E, N is the number of atoms per cm^2 and the integrals are extended over the resonance region. With the single level formula (1) and neglecting the Doppler effect, the integrals may be evaluated provided that the resonance maximum is very sharp. The expression for the transmission which results is,[9]

$$T=e^{-\sigma_R N/2}I_0(\sigma_R N/2), \quad (5)$$

where I_0 is the Bessel function of zero order and imaginary argument and σ_R is the capture cross section at exact resonance. For very thin absorbers (5) is equivalent to an exponential law with an effective cross section $\sigma_0=\sigma_R/2$, termed the experimental cross section for self-absorption.

The experimental points for the self-absorption of resonance neutrons, obtained with a 1.96-g/cm^2 boron filter, fit fairly well the theoretical curve (5) plotted in Fig. 2 with $\sigma_0=4600\times10^{-24}$ cm^2. The result, $\sigma_0=4600\times10^{-24}$ cm^2/atom$\pm$15 percent, is considerably higher than the value $\sigma_0=1200\times10^{-24}$ cm^2, obtained by Meitner, Hahn, and Strassmann.[1] It is in good agreement with the result $\sigma_0=5000\times10^{-24}$ cm^2/atom reported more recently by Sauerwein.[10]

[8] H. von Halban and P. Preiswerk, Nature **138**, 163 (1936); J. de phys. et rad. **8**, 29 (1937).

[9] Tables for this function are to be found in Watson, *Theory of Bessel Functions* (Cambridge University Press, 1922), p. 698.

[10] K. Sauerwein, Zeits. f. Naturforshg. **2a**, 73 (1947).

TABLE III. Absorber transmissions for uranium resonance neutrons. Transmission values refer to those neutrons which are absorbed by the filter noted. Cadmium (0.45 g/cm^2) always covers the detector to remove thermal neutrons.

Absorber	Transmissions for neutrons absorbed by filter 1.96 B	0.470 B	0.203 U
0	1.000	1.000	1.000
0.0191 U	0.806		
0.0342 U	0.697		
0.123 U	0.365		
0.203 U	0.280	0.224	
0.078 B	0.881		
0.235 B	0.660		0.622
0.470 B	0.440		0.407

If there were just one level the transmission values would not be altered by using a thinner boron filter. The existence of higher resonance levels is indicated by the fact that, with a thinner boron filter, the 0.203-g/cm^2 uranium absorber has a lower transmission.

X. BORON ABSORPTION

The data of Table III for the boron absorbers are plotted on a logarithmic scale in Fig. 3. The experimental points for uranium resonance neutrons absorbed by a 1.96-g/cm^2 boron filter lie along a curve corresponding to an absorption coefficient in boron $\mu_B=1.68$ cm^2/g. The resonance energy may be obtained from this result and a knowledge of the absorption coefficient μ_T of boron for thermal neutrons, by making use of the $1/v$ (v is the neutron velocity) law for the absorption of slow neutrons by boron. Thus, the resonance energy is given by the formula,

$$E_R=E_T(\mu_T/\mu_B)^2. \quad (6)$$

The slow neutron absorption coefficient of boron has been measured in a reliable way with neutron velocity

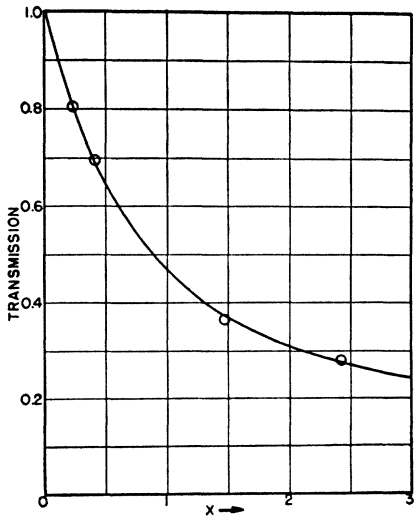

FIG. 2. Self-absorption curve for uranium: The curve is the function $e^{-x}I_0(x)$; the experimental points for various absorber thicknesses N, in atoms/cm^2, are plotted assuming $x=4600\times10^{-24}N$.

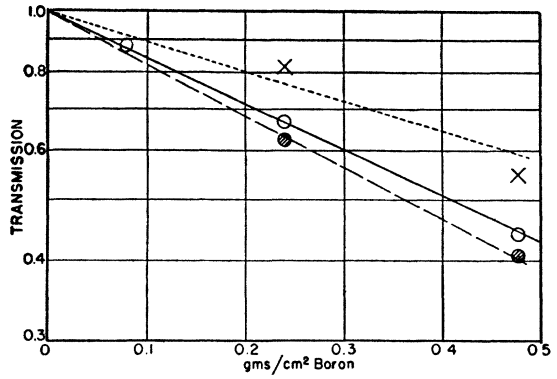

FIG. 3. Boron absorption of uranium resonance neutrons. The empty circles refer to the experimental transmissions for neutrons absorbed by a 1.96 g/cm² boron filter, while the shaded circles and the crosses refer to the transmissions for neutrons absorbed by and transmitted through a 0.203 g/cm² uranium filter, respectively. The three straight lines are drawn to fit as well as possible the three sets of points.

selectors[11] with the result $\mu_T=39.4$ cm²/g at $E_T=0.025$ ev.

The value of E_R which is obtained from these data is 13.7 ev. Measurements were also made with a uranium filter. The data given in Table III indicates a somewhat higher boron absorption coefficient, 1.85 cm²/g, which corresponds to a resonance energy of 11.3 ev. If there are several resonance levels, μ_B and E_R represent average properties of these levels. When a uranium filter is used the strongest levels are emphasized, which may account for the difference between this result and that obtained with the boron filter. A more sensitive test for the existence of higher levels is a measurement of the boron absorption coefficient for those resonance neutrons *transmitted* by a uranium filter. The uranium filter removes a large fraction of the low energy resonance neutrons, thereby augmenting the percentage of those which may be captured in the higher energy levels. Transmission values for this case, calculated from the data of Table II, are plotted in Fig. 3. The experimental accuracy of these points is quite poor, but the low value for the absorption coefficient to which they correspond clearly indicates the existence of the higher levels in the compound nucleus U^{239} which are responsible for neutron capture.

XI. RESONANCE ACTIVATION

In this paper the activity of the detector has been expressed as the fraction of atoms activated per second, by a neutron beam of intensity corresponding to one unit of iodine monitor activity. The activity f_R due to epi-thermal neutrons only, obtained directly from Table I as the difference between the f values with a cadmium absorber and with a cadmium plus thick (2.20 g/cm²) boron absorber, has the value 1.78×10^{-18} sec.$^{-1}$. A probable error of about 30 percent might reasonably be assigned to this result due principally to the uncertainty in the value for the correction factor which takes into account the differences between the β-rays of U^{239} and of UX.

It is possible to obtain an estimate of the area of the resonance curve from a knowledge of f_R and the intensity and energy distribution, $N(E)dE$, of the neutron beam corresponding to unit monitor activity. For energies above 1 ev the energy distribution of neutrons emerging from paraffin may be approximately represented by the law,[12]

$$N(E)dE=QdE/E. \tag{7}$$

Below one ev deviations from this law arise due to the thermal motion and the binding of the protons in the paraffin. The lower limit of the energy distribution is determined by the cut-off energy of the cadmium absorber used to shield the detector. Recent experiments by Baker and Bacher[13] using the modulated beam technique for obtaining mono-energic neutrons, indicate that a cadmium absorber of 0.45 g/cm² thickness transmits about 5 percent at 0.2 ev and 50 percent at 0.5 ev. For this reason, it is difficult to speak of a sharp cut-off energy for cadmium.

A measure of a "practical" cut-off energy for cadmium, which will be consistent with the assumptions which have been made, may be obtained by determining, with a boron-lined ionization chamber connected to a linear amplifier as detector, the boron absorption of neutrons transmitted by the cadmium absorber. Under the assumption that boron absorbs according to the $1/v$ law and that (7) holds for the energy distribution of neutrons emerging from paraffin, the transmission of a boron absorber of thickness x g/cm², in terms of the boron absorption coefficient μ_c at the "practical" cut-off energy of cadmium, may be written,

$$T=(1/\mu_c x)(1-e^{-\mu_c x}). \tag{8}$$

An experiment was performed with the arrangement of Fig. 1 with a boron-lined ionization chamber in place of the detector. The results, corrected for scattering and obliquity in the manner previously described, are plotted in Fig. 4. They are compared with the theoretical transmission curves (8) plotted for several values of the cut-off energy. μ_c is obtained from the cut-off energy E_c by applying the $1/v$ law,

$$\mu_c=\mu_T(E_T/E_c)^{\frac{1}{2}}, \tag{9}$$

and using the values $\mu_T=39.4$ cm²/g and $E_T=0.025$ ev. It is seen that the data fit quite well the curve for $E_c=0.34$ ev. The main uncertainty arises in estimating the magnitude of the background. This result is in good agreement with the value 0.4 ev obtained by Hoffman and Livingston[14] in a similar experiment.

[11] Bacher, Baker, and McDaniel, Phys. Rev. **69**, 443 (1946); Manley, Haworth, and Luebke, Phys. Rev. **69**, 504 (1946); Fermi, Marshall, and Marshall, Phys. Rev. **72**, 193 (1947).

[12] E. Fermi, Ricerca Scient. **7**, 13 (1936); see also Bethe, reference 4, p. 122.

[13] C. P. Baker and R. F. Bacher, Phys. Rev. **57**, 1076A (1940).

[14] J. E. Hoffman and M. S. Livingston, Phys. Rev. **52**, 1228 (1937).

The coefficient Q was determined by depositing a small amount of boron (0.47 milligram of the same boron carbide as was used in the absorbers) on one electrode of an argon-filled ionization chamber connected to a linear amplifier. The ionization chamber was placed in the detector position of Fig. 1. The gain of the linear amplifier was set so as to record all of the α-particles but none of the Li ions from the boron reaction.[15] Account was taken of the fact that one-half of the α-particles entered the electrode on which the boron carbide was deposited, and hence were not recorded.

By monitoring the output of the cyclotron simultaneously with both a BF_3 counter and the iodine monitors it was possible to obtain the number of boron disintegrations per unit iodine monitor activity corresponding to a 30-minute irradiation of constant intensity. The number of boron disintegrations per second, per unit iodine activity and per gram of boron, after subtracting the background, due mostly to gas recoils in the ionization chamber, was found to be 18.78×10^5. Of these, 17.47×10^5 were due to thermal neutrons while 1.31×10^5 were due to epi-thermal neutrons. The number of boron disintegrations per second and per gram due to epithermal neutrons may be obtained by applying (7) and the $1/v$ law, to be,

$$A_B=\int_{E_c}^{\infty}Q\frac{dE}{E}\mu_c\left(\frac{E_c}{E}\right)^{\frac{1}{2}}=2Q\mu_c, \tag{10}$$

in which a negligible error is incurred by extending the limit of integration to infinity. Thus, taking $\mu_c=10.7$ cm^2/g (corresponding to $E_c=0.34$ ev), the result for Q is 6120 per cm^2-second. The activity f_R is given by the expression,

$$f_R=Q\int\sigma(E)dE/E. \tag{11}$$

The integral, which has to be taken over the resonance region, will be called the *resonance activation*. It is

$$\alpha_R=\int\sigma(E)dE/E=f_R/Q=290\times10^{-24}\text{ cm}^2/\text{atom}. \tag{12}$$

If an error of about 30 percent be assigned to the value for Q, due principally to the uncertainty in the value of μ_c, then the error to be assigned to α_R should be about 40 percent.

[15] It is assumed that the boron absorption process always leads to the emission of α-particles which would be detected in the present experiment. Some doubt on this point may be thrown by the work of W. Maurer and J. B. Fisk, Zeits. f. Physik **112**, 436 (1939), who reported a group of low energy protons which would escape detection. However, a cloud chamber study by C. W. Gilbert, Proc. Camb. Phil. Soc. **44**, 447 (1948) is in support of the view adopted here. A low energy proton group is made improbable by the smallness of the Gamow factor.

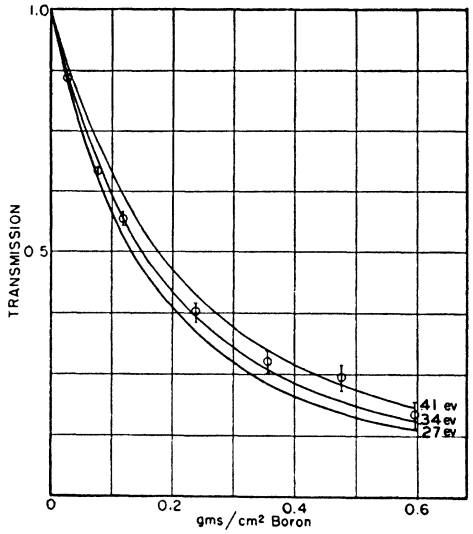

FIG. 4. Determination of the cut-off energy of cadmium. Experimental points for the self-absorption in boron of neutrons transmitted by cadmium, are compared with theoretical curves for several values of the cut-off energy of cadmium.

XII. ANALYSIS OF THE RESONANCE PROCESS

In the experiments described above, the errors were due more to the effects of scattering of the neutrons and the β-rays involved and to the presence of stray neutrons, than to any lack of self-consistency in the individual measurements themselves. The interpretation of the experiments is hampered not only by the somewhat uncertain validity of the theoretical assumptions which have been used, but also by the existence of more than one level which is responsible for neutron capture. The difficulty is fundamental in the method itself because of the lack of the necessary selective elements. In what follows the analysis of the resonance process will be carried through as though only one level were effective and no attempt will be made to correct the results so obtained for the effect of other levels.

For convenience, the experimental results which have bearing on the following analysis are collected below, together with an approximate estimate of the error. $\sigma_0=4600\times10^{-24}$ cm^2/atom$\pm$15 percent. $E_R=11$ ev$\pm$30 percent. $\alpha_R=290\times10^{-24}$ cm^2/atom$\pm$40 percent.

In the case where the resonance curve is not broadened to the Doppler effect, its shape is given by the Breit-Wigner formula (1). If the resonance is very sharp

$$\alpha_R=\frac{\sigma_R\Gamma}{2E_R}\int_{-\infty}^{\infty}\frac{dx}{1+x^2}=\frac{\pi}{2}\frac{\sigma_R\Gamma}{E_R}, \tag{13}$$

where $\sigma_R=2\sigma_0$ is the cross section at exact resonance and Γ is the total natural width of the curve at half-maximum. From this relation and the above data Γ may be computed to be 0.22 ev and the cross section at exact resonance σ_R, to be 9200×10^{24} cm^2.

The above value for the total width indicates that the effect of Doppler broadening is not negligible. Fol-

owing Bethe and Placzek,[4] who neglected the zero-point motion,[16] the Doppler width is defined by the expression,

$$\Delta=4(mE_Rk T/M)^{\frac{1}{2}}, \tag{14}$$

where m and M are the masses of the neutron and capturing nucleus, respectively. For the case of a very small natural width, Δ is the width of the resonance curve at the point where the cross section is $1/e$ of its maximum value. In the case of uranium, with $kT=0.026$ ev, Δ is found to be 0.14 ev. The cross section at exact resonance of the natural line is now given by

$$\sigma_R=\sigma_0/\chi(\xi), \tag{15}$$

where ξ the ratio of the natural to the Doppler width, and the function $\chi(\xi)$ has been calculated by Bethe and Placzek.[4] For $\Gamma\gg\Delta$, $\chi=\frac{1}{2}$. The relation (13) holds for all values of ξ, from which it follows that

$$\xi=\frac{2}{\pi}\frac{E_R\alpha_R}{\sigma_0\Delta}\chi(\xi). \tag{16}$$

From (13), (14), (15), (16) and the graph of the function $\chi(\xi)$ given by Bethe and Placzek,[4] may be found the values: $\xi=1.4$, $\sigma_R=10{,}000\times10^{-24}$ cm^2, and $\Gamma=0.20$ ev.

Wayland and Placzek have kindly communicated to me the results of some calculations of the self-absorption curves with different values of ξ. However, the experimental accuracy is not sufficient to distinguish between the slight differences in shape of the curve of Fig. 2 ($\xi=\infty$) and that corresponding to $\xi=1.4$.

The neutron width at resonance may be calculated by applying Eqs. (1) and (13). Assuming that the spin change in the process $U^{238}\rightarrow U^{239}$ is from $i=0$ to $J=\frac{1}{2}$, it follows that

$$\Gamma_n=\frac{\alpha_RE_R}{2\pi^2\lambda\!\!\!^{-}_R{}^2}=0.0086 \text{ ev}. \tag{17}$$

[16] The effect of chemical binding on the Doppler width has been studied by W. E. Lamb, Phys. Rev. **55**, 190 (1939).

If the above values are inserted in the Breit-Wigner formula (1), the capture cross section at thermal energies turns out to be about ten times higher than that obtained[5] by direct measurement. This indicates the presence of more than one level, possibly even of negative energy levels, which, by interference, may give rise to the low thermal cross section observed. It is to be pointed out that in the preceding paragraphs the Breit-Wigner formula was made use of only in the immediate vicinity of resonance, in which use the influence of the other levels is not as marked as when the formula is extrapolated to the thermal energy region.

The neutron and total widths obtained above must be regarded as upper limits for the lowest level for U^{238} above the cadmium cut-off. This is because the value obtained for E_R is certainly higher than the resonance energy of this level, while α_R contains contributions from all the levels above the cadmium cut-off. The indications are, however, that the higher levels contribute in only a minor way to the values obtained here.

Recently, Sauerwein[10] has reported some measurements on the resonance capture of neutrons by uranium, and has given evidence for the existence of an absorption band in the region of several hundred ev. The value $\Gamma=0.0075$ ev given by him is very much smaller than that given here. His method of deducing Γ from the shape of the self-absorption curve is questionable, however, in view of the existence of higher levels.

In conclusion I wish to express my indebtedness to Professors E. Fermi and J. R. Dunning who followed the course of the work with constant interest and much helpful guidance, and to Mr. H. Glassford of the cyclotron staff for his aid in carrying out the experiments. The aid of the Research Corporation has been very helpful. Acknowledgment is made to the United States Work Projects Administration of New York City for assistance rendered under project No. 24.