between 0.50 and 0.75 to reduce effects of high energy beam components. The experimental results are best fitted with a curve of the Breit-Wigner function having the constants: $E_0=0.180$ ev, $\sigma_0=7800\times10^{-24}$ cm^2/atom, $\Gamma=0.122$ ev, and $\sigma_s=6.0\times10^{-24}$ cm^2/atom.

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Measurement of Neutron Cross Sections with a Crystal Spectrometer*†

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By use of the monoenergetic beams of neutrons diffracted from the (100) planes of lithium fluoride, survey measurements of the total neutron cross section of a series of elements have been made. The strong diffracted beams were obtained by placing a single crystal in the high flux of neutrons emitted by the heavy water moderated pile at the Argonne Laboratory. Observations on this group of elements, which includes several strongly absorbing rare earths, and elements commonly used as neutron filters and detectors, have been made in the range of energy between 0.04 and 65.0 electron volts. The method permits energy dependent cross-section measurement by activation or by transmission. However, all values reported were obtained by calculation from observed transmission data because the range of available intensities in the diffracted beam was best measured with a boron counter. Correction methods for resolution and order effects have been developed which are valid for low neutron energies. The following absorption levels have been observed: Rh, 1.28 ev; Au, 5.4 ev; Ir, 0.635, 1.35, and 6.0 ev; Gd, 0.031 ev; Sm, 0.096, 10.0, and 33.0 ev; Eu, 0.465, 3.3, 9.2, and 22.0 ev. Resonance levels at energies less than zero were found in Dy at −1.01 ev and in Eu at −0.011 ev.

I. INTRODUCTION

EARLY experiments of Szilard,[1] of Amaldi and Fermi,[2] and of Tillman and Moon[3] on the energy variation of neutron absorption cross section, indicated that not all elements showed a simple dependence of cross section upon the energy of the reacting neutron. Several techniques have subsequently been applied in an effort to study the nature of this function, because of its relation to the energy levels of the compound nucleus, in the limited region of low neutron energy. By employing filters and detectors of substances containing single strong resonance levels[1–4] it is possible to obtain an idea of the cross section of an element at the energy of the absorbing or detecting resonance. The obvious limitations of this method include the uncertainty in the knowledge of the position of the absorbing resonance level and the random nature of the distribution of the resulting data on the energy scale.

A method for determining the region of selective absorption for slow neutrons, based on the assumption that the capture cross section for boron and lithium is inversely proportional to the neutron velocity, has been suggested by Weeks, Livingston, and Bethe and by Frisch and

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* Some of these results have been reported previously: Sturm and Turkel, Phys. Rev. **70**, 103 (A) (1946).

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** Now at the University of Wisconsin.

[1] Szilard, Nature **136**, 150 (1935).

[2] Amaldi and Fermi, Ricerca Scient. **1**, 310 (1936).

[3] Tillman and Moon, Proc. Roy. Soc. **A153**, 476 (1936); Nature **135**, 904 (1935).

[4] Bjerge and Wescott, Proc. Roy. Soc. **A150**, 709 (1935); Pontecorvo, Ricerca Scient. **6–7**, 145 (1935); Bethe, Rev. Mod. Phys. **9**, 113 et seq. (1937); Hanstein, Phys. Rev. **59**, 489 (1941); Horvath and Salant, Phys. Rev. **59**, 154 (1941); Feeny, Lapointe, and Rasetti, Phys. Rev. **61**, 469 (1942); Yalow and Goldhaber, Phys. Rev. **68**, 99 (1945).

Placzek.[5] According to this method, the quantitative measure of the absorption of neutrons in boron is taken as a measure of the energy of the captured neutron. Using this procedure, Goldsmith and Rasetti[6] have been able to locate with fair accuracy the position of the predominant levels in a series of strong absorbers.

A third indirect technique for observing the energy dependence of capture cross section has been employed by Powers, Fink, and Pegram[7] and others. By varying the temperature of their neutron moderator they were able to demonstrate an increase in cross section with decreasing neutron velocity for all elements tested. Since the method depends on evaluation of average cross section over a Maxwellian distribution of neutron energies having differing peak values, it cannot be expected that this type of measurement should do more than exhibit small variations in cross section due to the $1/v$ absorption in this region.

The earliest direct and continuous measurements of cross section as a function of neutron energy over a small range of energies was made possible by the rotating shutter velocity selector of Dunning, Pegram, Fink, Mitchell, and Segrè.[8] The range of this type of apparatus is limited to neutrons having energies less than 0.30 ev because of the nature of the cadmium cross section, yet with a sufficiently strong neutron source instruments of this type can be used for quite adequate measurements in this energy range.

With the modulation of the cyclotron beam by Alvarez[9] it was possible to observe the energy dependence of neutron cross section in still another manner. This technique, improved and extended by many observers,[10] has most recently been applied to the problem by Rainwater and Havens[11] who calculated the energy of the reacting neutron by measuring its time of flight over a fixed distance and evaluated many cross-section functions in this manner for energies up to 1000 ev.

The present method, utilizing the wave properties of the neutron, brings techniques analogous to those of x-ray diffraction into practice for these measurements. Using the high neutron flux made possible by the heavy water moderated uranium chain reactor, Zinn[12] has been able to demonstrate the diffraction of neutrons from a single crystal and to show the application of the phenomenon to cross section measurements. The crystal spectrometer for neutrons, unique in that it produces monoenergetic beams of low energy neutrons, provides a relatively simple tool for continuous cross-section measurement by activation or transmission for energies up to 65 ev with present collimators.

II. DESCRIPTION OF APPARATUS

The instrument used for the measurements was the heavy duty analog of an optical spectrometer described by Zinn,[12] permanently mounted in the concrete floor of the pile room in line with port number 4 of the Argonne heavy water pile. In its final, accurately centered and leveled position, tests of the angular reproducibility of the arm showed that its extreme end reproduced within 0.0005 inch repeated settings made on the dial plates of the instrument. For measurement of spectra and of cross section the table and arm could be coupled together by means of a friction clutch to drive the two elements in the two-to-one angular ratio required by these experiments.

A 61-cm long boron trifluoride counter filled to a pressure of 40 cm of mercury, operated in the proportional region and mounted with its axis parallel to the direction of the diffracted beam, served as the neutron detector in the apparatus. Use of enriched boron, consisting of the single isotope B^{10}, increased the detection efficiency for high energy neutrons approximately by a factor

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[5] Weeks, Livingston, and Bethe, Phys. Rev. **49**, 471 (1936); Frisch and Placzek, Nature **137**, 357 (1936).

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[9] Alvarez, Phys. Rev. **54**, 235 (A) (1938); Alvarez, Phys. Rev. **54**, 609 (1938).

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[11] Rainwater and Havens, Phys. Rev. **70**, 136 (1946) and Havens and Rainwater, Phys. Rev. **70**, 154 (1946); Rainwater, Havens, Wu, and Dunning, Phys. Rev. **71**, 65 (1947); Havens, Wu, Rainwater, and Meaker, Phys. Rev. **71**, 165 (1947); Wu, Rainwater, and Havens, Phys. Rev. **71**, 174 (1947).

[12] Zinn, Phys. Rev. **70**, 102 (A) (1946); Zinn, preceding paper.

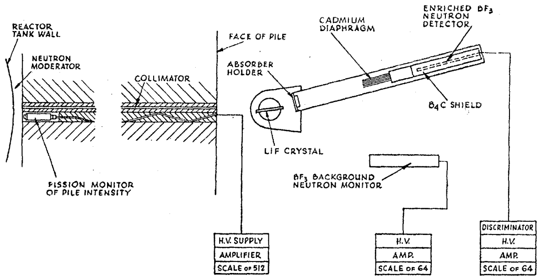

FIG. 1. Schematic diagram of apparatus for total neutron cross-section measurements.

of 5. Operated at 1500 volts above ground with electron collection on the central wire, the efficiency of detection of low energy neutrons approached 100 percent. One stage of preamplification, together with a cathode follower was mounted on the boron-cadmium shield of the counter, from which point the signal was carried by means of an 18-foot cable to an amplifier and scaler on an electronic instrument panel near the apparatus. The normal neutron background counting rate with the pile running was about 15 counts per minute, a small fraction of the 6400 counts per minute of Bragg reflected neutrons from the (100) planes of LiF in the region of the Maxwellian maximum. Counting rates in the energy region above the Maxwellian portion were considerably lower, since here the number of neutrons in the spectrum as well as the detection efficiency decreased.

As is shown in Fig. 1, collimation of the primary neutron beam from the tank wall was achieved by inserting a 9-foot channel into the shielding of the reactor. This channel, a steel-bounded orifice with a 1.27×2.54-cm aperture, was surrounded by a mixture of paraffin, iron shot, and boric oxide to confine the path of neutrons and gamma-rays. The resultant primary neutron beam had a divergence of 32 minutes, and the diffracted beam a base width of 114 minutes. A cadmium diaphragm, consisting of a series of 12 long cadmium metal sheets spaced 3 mm apart, mounted on the spectrometer arm before the detector, served as a means of varying the divergence of the diffracted beam and the resolving power of the instrument. For the cross-section measurements, the half-width of the Bragg reflected beam of neutrons was standardized at 22 minutes.

Crystals and Absorber Mounts

Since the diffracted neutron beam for this series of experiments was obtained by reflection from the flat surface of a crystal rather than by transmission, the crystals employed were generally mounted in a long array in order to increase the strength of the diffracted beam at small glancing angles. Aside from minor variations necessitated by the differing shapes of available crystals, mounts consisted simply of a metal frame supported vertically on the spectrometer table. With this standardized type of mounting, transfer from crystal to crystal was simplified by use of a guide bar on the crystal table, since the planes of the crystal were aligned parallel to the metal frame. The mounts were usually made of aluminum with no metal in the path of the primary beam to minimize the incoherent scattering from the holder itself.

It was possible to measure the transmission, and consequently the total cross section of an element, by introducing it into the primary beam of neutrons, or by placing it in the Bragg reflected monoenergetic beam. Because the diffracted beam was considerably less intense, samples were mounted in the path of this beam to avoid irradiating them excessively. In this position also, the number of neutrons scattered by the sample was lower than if it were in the primary beam.

Except for elements available in foil form, it was necessary to add a second substance, usually sulfur or a solvent, as a support for the sample while its transmission was being measured. This, however, made it necessary to consider the effect of the binder or solvent on the transmission measured. To do this, a second sample containing the binder alone was prepared, and the number of neutrons passed through this sample was measured. The ratio of the counting rate with the bound sample in place to that with the binder alone in the beam was taken as an uncorrected measure of the transmission of the sample. A sliding holder with several apertures was used to support the two samples successively in the beam. Three apertures were provided in the holder to make possible measurement of two samples with identical supporting materials concurrently.

Monitors and Electronic Circuits

Two monitors were regularly employed with the spectrometer in the measurement of neutron cross section. The first, a monitor of the neutron intensity in the primary beam, was a fission chamber mounted near the reactor tank wall, in a removable channel adjacent to that used as a primary source for the spectrometer. The position of the monitor with respect to the tank wall could be varied so that varying pile intensities yielded the same reading on the monitor. Although the pile was automatically controlled, and did not in general fluctuate by more than 3 percent, the monitor was useful in averaging any short term fluctuations and in taking into account any long term drift of the pile. The monitor was an aluminum fission counter containing a thin foil of uranium oxide, U_3O_8, enriched some ten times in the isotope 235. This monitor, operated at 1000 volts above ground, was used as a measure of integrated incident neutron flux in timing the measurements.

A second monitor measured the variations in the intensity of neutron background which were caused by changes in neutron leakage from other points of the pile. This monitor, an unshielded boron trifluoride counter operated in the proportional region, was identical with the main detector described above, except that it was filled with normal boron trifluoride gas to a pressure of 40 cm of mercury. Since this monitor was 100 times more sensitive to change in background neutron intensity than the main detector, it increased the reliability of cross-section measurements by decreasing the uncertainty in background variation. In general the background neutron intensity in the pile room was quite small, and this monitor was used to detect only great variations in background. However, rather than correct the data for these background variations, the reading which was indicated by this monitor to be disturbed was generally repeated under more favorable conditions.

Each of the three counters, the main detector, the fission monitor, and the background counter, had associated with it a preamplifier, cathode follower, amplifier, scaler, and high voltage supply. The preamplifiers and cathode followers were mounted as near as possible to the counter, while all high voltage supplies, amplifiers, and scalers were mounted together on a control panel on a work bench near the instrument. The detector and background monitor signals were recorded on two scales of 64, while the fission signal was recorded on a scale of 512.

Between the amplifier and the scaler of the main detector circuits an additional limiting circuit has been provided,* the function of which was to eliminate large negative or positive pulses, and any small pulses with sign opposite to that of the neutron pulse. This circuit has proved useful in eliminating pulses caused by an electromagnetic disturbance in the vicinity of the spectrometer. For facility, and to assure simultaneous stopping and starting, all of the circuits were operated from a single switch. An oscilloscope was provided to watch the signal at various stages of amplification and scaling, and regular checks were made to assure the perfect functioning of the instrument. During measurements of cross section the oscilloscope constantly registered the output of the main detector.

III. ALIGNMENT

The condition for a maximum in the diffraction pattern of a space lattice is given by the familiar Bragg law,

$$n\lambda = 2d\sin\theta, \tag{1}$$

where d is the interplanar distance, n and λ the order and wave-length respectively, and θ is the glancing angle. Expressed in terms of energy, the relation becomes

$$\mathrm{ev} = kn^2/\sin^2\theta \tag{2}$$

where k is a constant for each interplanar spacing. The problem of alignment, then, was one of determining the glancing angle θ, and thus involved centering the instrument and crystal table with respect to the primary beam, aligning the detector, and finally aligning the crystal.

Alignment of the Table, Detector, and Crystal

Two methods have been used to center the crystal spectrometer and its table with respect to the center of the primary beam. In the first, a long, snug-fitting steel bar was inserted

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* This circuit was designed by Mr. Thomas Brill of this laboratory.

into the primary beam collimator and extended over the spectrometer table. With this method, by inversion of the bar to cancel out any lack of parallelism, the center line of the slot could be located within $\frac{1}{4}$ mm.

The second method used for preliminary determination of the center of the beam involved the use of photographic film. In this method a sheet of orthochromatic film was placed between two layers of cadmium metal, and this sandwich exposed to the beam of neutrons. A small hole drilled through the cadmium sheets was used to orient the film with respect to the crystal table, and the subsequent blackening of the emulsion indicated the shape and position of the neutron beam. The clear spot in the darkened area, representing the hole in the cadmium layers, served then to relate the position of the crystal table to that of the beam. This method, although less accurate than the foregoing because of the associated flux of gamma-rays which caused about 15 percent of the blackening, was useful because it showed both shape and rough position of the primary beam at any point on the arm.

After the detector had been carefully aligned parallel to the arm of the spectrometer and the table centered with respect to the beam, it was necessary to locate the angular position of the arm at which the arm was parallel with and centered in the primary beam. In order to center the detector with respect to the primary beam a curve of neutron intensity as a function of angular position of the detector was plotted. Since the primary beam consisted of a very intense flux of neutrons and gamma-rays, it was necessary to reduce its intensity so that this measurement could be made. In order to reduce the neutron intensity, a thin slab of paraffin was introduced directly into the beam, and, to eliminate entirely the effect of the gamma-rays, the gain of the amplifier was changed so that only the higher neutron pulses were counted. The zero position of the detector was then determined to be the point of intersection of two lines which represent the slopes of the two sides of the curve taken in this manner. This position could easily be determined within 2 minutes of arc, and thus contributed an uncertainty of but 1 minute of arc in the glacing angle θ.

Having determined the position at which the detector was in the center of and parallel with the direct beam, the detector was turned off this zero position by a known amount, usually 40 degrees, and the cadmium diaphragm and crystal carefully placed in position on the instrument. As the crystal approached an angle of 20 degrees with the primary beam, the diffracted maximum could be detected. Leaving the arm in its fixed position, the crystal was rotated for several degrees on either side of this maximum, and a plot of the measurement of the intensity of diffracted neutrons as function of glancing angle made. A lack of symmetry about the maximum of the observed diffraction curve arose from the fact that it was taken with a boron detector, since boron follows the well-known $1/v$ law for absorption of neutrons and is not uniformly sensitive over the entire spectrum range. These data, corrected for the $1/v$ effect, determined the peak of the diffraction maximum within two minutes of arc.

The uncertainty in the glancing angle θ, caused by uncertainties in centering of the crystal table, could be taken as negligible because the width of the beam and the width of the counter were very nearly alike and because of the precision with which this position was ascertained. Because the index of refraction of the crystal used for neutrons is not equal to unity, as has been shown for many substances, one might expect this to introduce an additional error in the measurement of the energy of the diffracted beam. However, since the value of the index of refraction is very likely of the order of 1×10^{-6}, this effect too was completely negligible. Thus the total errors were introduced in aligning the detector, and in aligning the crystal, and resulted in an uncertainty of three minutes of the glancing angle throughout the range of the instrument.

IV. CRYSTALS

Although many crystals, including mica, copper, calcium fluoride, calcite, and lithium fluo-

TABLE I. Relative reflectivity from several crystals.

Crystal	$k\times10^3$	Maximum energy (ev)	Relative reflectivity
LiF (100)	5.08	65.0	6.4
Calcite (100)	2.22	28.0	2.5
Mica (001)	0.20	2.5	9.2
Cu (100)	1.56	20.0	~5.0

ride have been used and tested for crystal spectrometry, all of the measurements of cross section as a function of energy were made with the lithium fluoride crystals. The spectrum from the side hole of the heavy water pile has been measured with several crystals, and the relative peak intensities observed with each of these crystals have been tabulated in column 4 of Table I.

As in the case of x-rays, the reflectivity of a crystal for neutrons can be increased by increasing the mosaic structure of the surface. A single crystal of LiF(100) has been carried through several steps, each involving a change in the surface of the crystal. The relative reflectivity from these surfaces is shown in Table II. In each case the rocking curve was 22 ± 1 minutes in half-width, and since this value was determined by the collimating geometry, no quantitative conclusion with regard the change in mosaic structure could be made from these data. However, obviously the roughened crystal, with its higher reflectivity, is best for use in spectrometer measurements with this type of collimation. Since the range of energies covered by the spectrometer is a function of the interplanar spacing of the crystal used, a consideration which must be weighed in selecting a crystal for spectrometer use is the value of d. As is obvious from Eqs. (1) and (2), the highest energy which can be reached by any crystal as a function of its lattice spacing varies as the square of the reciprocal of the lattice spacing. Column 3 of Table I shows the maximum energy which can be reached using these crystals, assuming that the collimation is such as to permit the utilization of diffracted beams whose incident glancing angle is 30 min.

Calcite and Lithium Fluoride

All early measurements on the thermal column, and some of the first measurements at the side port of the Argonne heavy water pile, were made with a calcite crystal. This crystal, however, because of its lattice perfection, showed a lower reflectivity than many of the other crystals tried. Since, in addition, it is quite a hard crystal and increased mosaic structure cannot easily be introduced, this crystal was used only for preliminary work.

TABLE II. Variation of reflectivity with crystal surface. LiF (100).

Surface	Reflectivity
Smooth cleavage face	1.00
Surface ground	1.65
Surface polished	2.34
Surface roughened with coarse abrasive	2.36

The simple cubic crystal, lithium fluoride, was the crystal selected for most of the work reported in this paper. Because of the small size of the unit cell, and because of the consequent small interplanar spacing in this crystal, the range of energies available for this series of neutron spectrometer studies extended up to 65 ev. These crystals, quite easily available, had the additional advantage that their mosaic structure could be increased simply by the various techniques discussed above.

The 100 planes of this crystal were used for all of the measurements of cross sections reported here. The unit cell dimension for LiF is 4.01 angstroms, and the interplanar spacing is 2.005 angstroms. With this crystal, the range of useful energy lay between 0.04 ev and 65.0 ev, a factor of 1.6×10^3 in energy. The low energy limit was set by choosing that energy characterized by the presence of less than 5 percent second and higher order components in the Bragg-reflected beam, as determined by a series of experiments of the type to be described; in the case of the high energy extreme, the limit was fixed by the smallest useful glancing angle which could be achieved with reasonable collimation, in this case 30 minutes. The LiF crystals used, a bank of small individual crystals mounted in an aluminum holder to form a long array, consisted of 5 small crystals whose individual dimensions were $3.7\times2.7\times.2$ cm. The planes of each of the individual crystals were aligned within 1 minute of arc.

V. SPECTRUM OF THE SOURCE

Two ports of the Argonne heavy water chain reacting pile were used for all of the measurements. The first, the thermal column, interposed a thickness of carbon between the source and the spectrometer rendering the greater part of the neutrons thermal. Their distribution, roughly Maxwellian, was such as to provide a useful source of neutrons in the energy range below 0.2 ev. The second port, a side hole of the same reactor, interposed little moderator between the source and the spectrometer, and while a strong Maxwellian component was present in this beam because of the moderator inside the reactor, this beam contained, in addition, a fairly strong component of higher energy neutrons which rendered the extension of the range of the instrument to 65.0 ev possible.

The Maxwellian Region

Attempts to explain the results observed in the measurements of spectra from the thermal column and side hole of the reactor, have been made by Seitz and Goldberger.** The form of the equation relating the crystal reflectivity R with the glancing angle θ, for detection by a $1/v$ absorber as developed by them is

$$R_n = C|a_n| nK_1 \csc^3\theta \exp\left[-\alpha_n^2 \csc^2\theta\right]. \quad (3)$$

In this equation n is the order of the reflection, C is an arbitrary constant, and

$$K_1 = 2\pi/d_h$$

$$a_n = \sum_j \pm [\sigma_s^j(b)]^{\frac{1}{2}} \exp\left[2\pi i(h_1x_j + h_2y_j + h_3z_j)n\right]$$

$$\alpha_n^2 = \frac{h(2\pi/d_h)^2}{8mk_0T} n^2,$$

in which d_h is the interplanar distance, m is mass of the neutron, $\sigma_s^j(b)$ is the scattering cross section of the j'th atom in the unit cell, k_0 is Boltzmann's constant, and T is the average neutron temperature.

The fit of this expression for $T = 400°\mathrm{K}$ to the experimental points in the Maxwellian region is shown plotted as a solid line in the curve of Fig. 2. The distribution at higher energies, when corrected for detector efficiency, resolution, and amount of beam intercepted, corresponds to the expected $1/E$ function.

VI. ORDER EFFECTS

A study of the intensities of neutron diffraction in the various orders by a series of crystals has recently been made by Fermi and Marshall.[13] Their results show that the relative amounts of first and higher order Bragg reflection varies greatly from crystal to crystal and from plane to plane, depending on the scattering cross sections and the phase of neutron scattering by the target nuclei. Thus the choice of a crystal for cross-section measurements determines the useful range over which data can be taken with diffracted beams uncontaminated by higher order components.

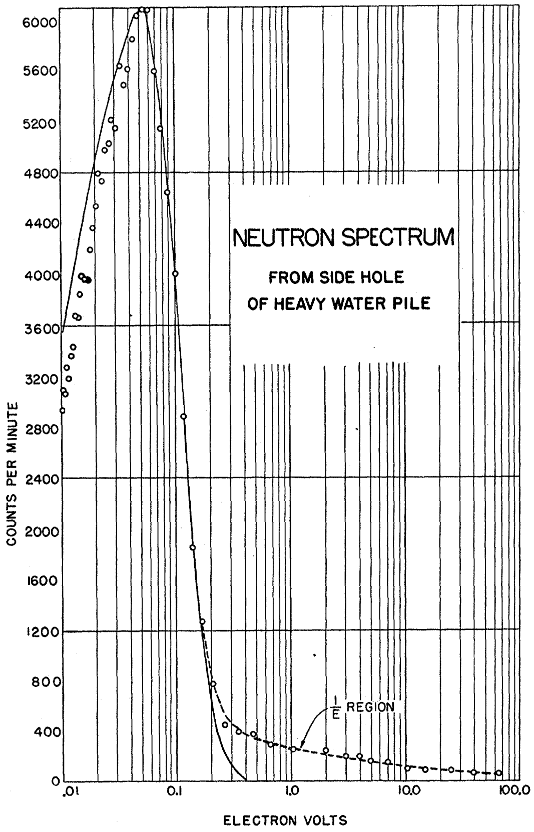

FIG. 2. Spectrum of reactor as measured with LiF(100) crystals. The solid line represents the theoretical Maxwellian distribution for $T = 400°\mathrm{K}$.

From Eq. (2) we see that for a constant glancing angle, θ, the energies of the first and second order have a ratio 1 to 4 in energy. A series of experiments were performed to evaluate approximately the fractional composition of the beam quantitatively to determine the useful range of the spectrometer for measurements of cross section.

** M. L. Goldberger and F. Seitz, Phys. Rev. 71, 294 (1947).

[13] Fermi and L. Marshall, Phys. Rev. 70, 103 (A) (1946).

Experimental Determination of the Order Composition of the Diffracted Beam

Since total cross sections were calculated from measurement of transmission, the effect of a beam composed of several energy components will alter the observed transmission of a sample as a function of both quantity of flux having each energy and of the cross section of the substance at each energy. A series of measurements was made on the samarium sample discussed below, the cross section of which is shown in Fig. 13. This sample has a strong resonance level at 0.1 ev, and detailed measurement of its cross section shows two artificial peaks at 0.025 ev and at 0.011 ev, corresponding to absorption of large fractions of the second and third order components at these energies by the primary resonance at 0.1 ev.

Although the position of the two peaks in cross section at low energy is exactly that expected for absorption of second and third-order components from the diffracted beam ($0.025\times 4=0.10$ and $0.011\times 9=0.099$ ev), a preliminary experiment was performed to show that the two observed peaks at low energy are not real resonance levels. A very large part of the 0.1-ev component of the primary neutron beam at 0.025 ev was removed by filtering this beam through a second samarium solution, the transmission of which, for the high order component was about 0.10. A measurement of the transmission of the first solution was made with and without the filter in place. Without the filter the transmission was 0.441, with the filter the transmission measured 0.814, indicating a lower absorption because the strongly absorbed 0.1-ev component was minimized in this filtered beam.

In order to get a quantitative estimate of the amount of second-order component in the beam diffracted by LiF(100) at 0.025 ev, a measurement of a standardized thin film of boron was made at this energy. The boron layer was a plate of Pyrex, the transmission of which had been previously measured in a mechanical velocity selector in which order effects were absent. Measured in this way, the transmissions of this plate for the first-order (0.025 ev) component was 0.441 and for the second-order (0.1 ev) component was 0.663. A measurement on the crystal spectrometer yielded a transmission of 0.490, intermediate between the values for the first and second orders alone.

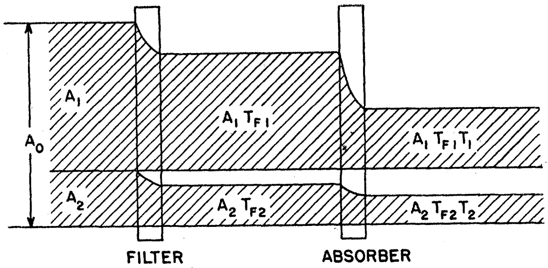

Fig. 3.

It is clear that in this measurement with a beam of several energy components impinging on an absorber of energy-dependent cross section, if A_n is the fractional order component, and T_n is the transmission of the absorber for the energy of the order n, then

$$A_0T_0=A_1T_1+A_2T_2+A_3T_3\cdots \tag{4}$$

where T_0 is the observed transmission and A_0 is the total flux and is equal to one. Since there are but two orders of significance at this angle, substitution of the transmission values given above and combining with the knowledge that

$$A_0=A_1+A_2=1, \tag{5}$$

showed that, for first order equal to 0.025 ev, the fraction of first and second-order components was: $A_1=0.78$; $A_2=0.22$.

A second evaluation of the composition of the diffracted beam at the same energy was made by altering the composition of the beam as in the case above, with a filter having known absorption for the two energy components. The filter for this measurement was a second and thicker samarium sample, having very low transmission for the second-order (0.10 ev) energy component, thus lessening the fractional absorption of this strongly absorbable component at 0.025 ev by the sample. A schematic representation of the transmission of this series of absorbers is shown in Fig. 3. The primary beam of intensity A_0 is considered to be divided into its first and second-order components A_1 and A_2, and the lessening of their intensities is shown schematically in the figure. The observed transmission of the samarium absorber in the filtered beam is given by

$$T_0=\frac{T_1A_1T_{f1}+T_2A_2T_{f2}}{A_1T_{f1}+A_2T_{f2}} \tag{6}$$

where T_n = the transmission of the absorber for neutrons of the energy of the order n, T_{fn} = transmission of the filter for neutrons of the energy of the order n, A_n = the intensity of the order n. Values of T_n and T_{fn} were obtained by calculation from the quantity of absorber in each cell and from the cross section shown in the Breit-Wigner curve plotted in Fig. 13. The values thus obtained were: $T_{f1}=0.374$, $T_{f2}=0.090$, $T_0=0.593$, $T_1=0.613$ and $T_2=0.280$. Again combining these by use of Eq. (5) we calculate that $A_1=0.78$ and $A_2=0.22$.

As a third method of evaluation of the ratio of order components at 0.025 ev, a filter measurement, similar to the last one was made. In this case the filter used was the same standardized Pyrex plate of the earlier measurement, and the principle the same as that of the previous experiment. Values of T_n were calculated from Fig. 13 and those of T_{fn} from the standardization mentioned earlier. The values used in Eq. (6) were: $T_{f1}=0.441$, $T_{f2}=0.663$, $T_1=0.436$, $T_2=0.294$, and $T_0=0.400$. The calculated fractions of first and second order in this case were: $A_1=0.79$ and $A_2=0.21$. The average value of the first-order component of the reflected beam, 78 percent, agrees quite well with the theoretical value at this energy calculated from Eq. (3).

The theoretical order intensity curve calculated from Eq. (3) which was used for all cross-section corrections is shown in Fig. 4.

Reduction of the Effect of Higher Order Components

In an effort to remove the effect of high order components in the diffracted beam at large glancing angles several techniques were used. Since the total cross sections for neutron reactions in this energy region in general show a decreasing cross section with increasing neutron velocity, cross sections in the region of hundredths of electron volts were measured using samples with transmissions somewhat greater than 0.5. In this manner, since the transmission of the higher energy components of the reflected beam is generally much higher than that of the first order, the effect of the second-order neutrons on the observed cross section is minimized.

Other means of reducing the effects of higher order components involved reduction of the intensity of these components in the primary beam. This was accomplished by use of filters with resonance levels at the energy of the second and higher order components, or by using the primary neutron beam of lower mean energy and minimal $1/E$ component which is emitted from the thermal column. Attempts were made also to remove neutrons of the energy of the second, fourth, etc., orders, by introducing a second (mica) crystal in advance of the lithium fluoride in the primary beam at the angle necessary to diffract these components from the beam. These efforts were unsuccessful, since, aside from reflectivity considerations, the imperfection of even a mica crystal is not as great as was the geometrically determined divergence of the primary beam. These methods of beam purification were considered necessary only for the measurements made at energies less than 0.04 ev, below which energy the diffracted beam contained less than 95 percent first-order neutrons. The small correction necessary at energies lower than 0.08 ev was applied to the observed data at the end of the cross-section measurement by use of relations (4) and (5). Since no order correction was made to data taken at energies above 0.08 ev, this correction was applied only to the few points

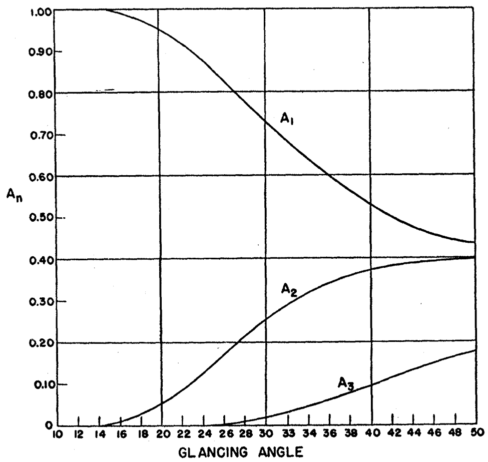

FIG. 4. Fractional order composition of diffracted beam as a function of glancing angle.

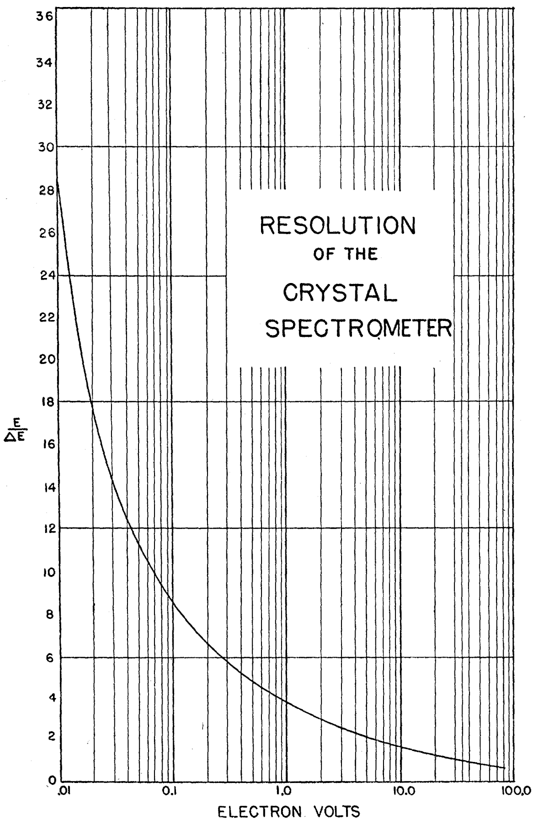

FIG. 5. Resolution of the neutron spectrometer calculated from the width of the rocking curve.

measured at very low energies, and had little effect on the final results.

VII. RESOLUTION

The angular divergence of the diffracted beam, as obtained from measurements of the crystal rocking curve, can be taken as a first approximation and upper limit to the energy spread of that beam. The crystal rocking curve, as experimentally measured for glancing angles between 45° and $3\frac{1}{2}°$, showed uniform shape and half-width; and although the shape of the rocking curve was not exactly triangular because of the $1/v$ detector used, the shape of the energy distribution function was assumed to be an ideal triangle for calculation of the resolution function and for resolution correction. The base of these triangles indicated an energy spread corresponding to the base of the rocking curve, 44 minutes, for energies up to 1.4 ev, and the corresponding values of $E/\delta E$ vary between 28 at 0.01 ev and somewhat less than 1 at 65.0 ev. (See Fig. 5.)

The spectrometer resolution as a function of neutron energy varies as $1/d$, the extent of the useful energy range varies as $1/d^2$. Thus the cleavage (100) face of LiF because of its small d, provided a wide range of energies of sufficiently well-resolved monoenergetic neutrons for cross-section measurements. In practice, the resolving power of the instrument was determined by the minimum width of collimating slits which provided ample diffracted intensity at high energies. This width, 1.25 cm, could have been made smaller at low energies where the intensity was higher, but this was not considered necessary, as the resolution was more than ample with the wide slit in this region, and under these conditions the intensity was considerably increased.

The base width of the rocking curve was not constant for energies greater than 1.4 ev with LiF(100), since for glancing angles less than 3° 28′ and energies greater than 1.4 ev, the 18-cm bank of crystals was not sufficiently long to intercept the entire primary beam. As a consequence, the Bragg-reflected beam at these small glancing angles is less divergent and the width of the rocking curve smaller, varying from 44′ base width for a 3° 28′ glancing angle to 19′ at 30′ glancing angle. This resulted in an improvement in resolution and a loss of intensity in the high energy region. The triangles shown on the curves of cross section indicate the idealized shape of the final intensity-energy distribution of the diffracted neutron beam at the energy of the apex.

Resolution Correction

It was possible to correct the transmission measurements in the energy region below 0.2 ev for the slight distortion in the nature of this curve caused by the finite resolution.[14] To do this, we note (see Fig. 6) that the measured transmission, Φ, is given by

$$\Phi=\frac{\int_{E'-\gamma}^{E'+\gamma} f(|E-E'|)\phi(E)N(E)dE}{\int_{E'-\gamma}^{E'+\gamma} f(|E-E'|)N(E)dE} \qquad (7)$$

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[14] M. Goldberger, unpublished work.

where $f(|E-E'|)$ is the resolution function, $\phi(E)$ is the true transmission at energy E, and $N(E)$ is the incident flux distribution over the energy interval. Assuming that $N(E)$ in the region of interest is very nearly constant, we can substitute in the simplified expression the triangular resolution function (Fig. 6)

$$f(|E-E'|)=(\delta/\gamma)\{(|E-E')+\gamma\} \tag{8}$$

we obtain

$$\gamma^2\Phi(E')=\int_{E'-\gamma}^{E'} E\phi(E)dE-\int_{E'}^{E'+\gamma} E\phi(E)dE+\int_{E'}^{E'+\gamma}(E'+\gamma)\phi(E)dE-\int_{E'-\gamma}^{E'}(E'-\gamma)\phi(E)dE.$$

Expanding the right side of the equation about $\gamma=0$,

$$\Phi(E')=\phi(E')+\frac{\gamma^2}{12}\phi''(E')+\frac{\gamma^4}{360}\phi''''(E'). \tag{9}$$

To express ϕ, the true transmission, in terms of operations on Φ, the measured transmission, we neglect in the first approximation the term involving the fourth derivative. Solving the simplified last equation for ϕ, we find

$$\phi(E)=\sum_{K=0}^{\infty}\frac{(-1)^k\Phi^{(2k)}(E)}{\alpha^{2k}}$$

in which $(2k)$ refers to the $2k$th derivative, and $\alpha=[12/\gamma^2]^{\frac{1}{2}}$, whence to this degree of approximation,

$$\phi(E)=\Phi(E)-(\gamma^2/12)\Phi''(E). \tag{10}$$

By perturbation theory, taking into account the term in the fourth derivative,

$$\phi(E)=\Phi(E)-(\gamma^2/12)\Phi''(E)-(\gamma^4/360)\Phi''''(E), \tag{11}$$

the final form of the relation, valid where γ is small relative to the half-width of the resonance level.

VIII. MEASUREMENT OF TOTAL NEUTRON CROSS SECTIONS

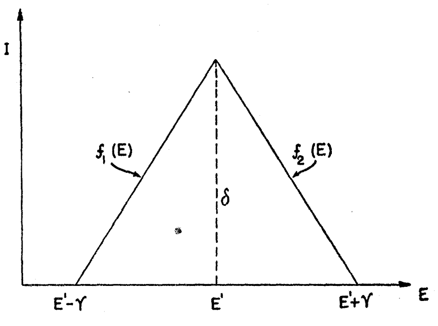

FIG. 6.

Cross sections can be measured by transmission or by activation in the monoenergetic diffracted neutron beam of the crystal spectrometer. Because, however, the intensity of the Bragg beam does not exceed 30,000 neutrons per minute. Activation measurements are thus limited by the low neutron flux to elements with large cross sections and short periods, and that only in the energy range of high flux near the peak of the Maxwellian distribution. Results reported here were made by measuring transmissions of a small sample of the absorbing substance by means of a boron counter.

Total cross sections are calculated from the measured transmission, T, from the relation

$$T=e^{-\sigma N}, \tag{12}$$

in which σ is the total neutron cross section in square centimeters per atom and N is the surface density of atoms in the sample. Solving for σ, we have

$$\sigma=(1/N)\ln(1/T) \tag{13}$$

which is the form of the relation used for the calculation of σ. The value of N was obtained by simple assay of the foil, powder, or solution containing the element of interest, and T was obtained from the measurement of the intensity of the diffracted beam with and without the sample in place. In general, the thickness of the sample was made such that its transmission was somewhat over 0.5 for reasons indicated above. It was not necessary to apply a correction to the transmission data for beam hardening because of the fact that the diffracted beam consisted almost entirely of neutrons of a single energy.

It was, however, necessary to correct both the numerator and denominator of the transmission measurement for a background of neutrons incoherently scattered by the crystal. Since, in addition, the absorbing sample was interposed between the crystal and the detector, the background varied when the sample was placed in the diffracted beam. Because of this variation, together with variations in background caused by the differing positions taken by the crystal and detector, it was found necessary to measure this background counting rate for both the directly diffracted beam and the diffracted beam with sample interposed at each energy. The background measurements were taken by turning the crystal one degree off the Bragg maximum, an angle at which only the incoherently scattered neutrons reached the detector. The transmission of the sample was then calculated from the four measurements according to the relation

$$T=(R_1-r_1)/(R_2-r_2) \tag{14}$$

in which R_1 is the counting rate of the beam transmitted through the sample, R_2 the counting rate of the open diffracted beam, and r_1 and r_2 the background rates with and without the sample interposed.

Samples

Samples for cross-section measurement were prepared in one of four ways. For rhodium, gold, and iridium varying thicknesses of metal foils of these substances were used. Part of a preliminary boron curve was taken with pellets of amorphous boron powder pressed into the form of cylindrical disks of varying thicknesses and one inch in diameter. A third method, involving the use of a sulfur binder in the pressed pellets, was used for samples with high total cross sections (part of the iridium curve), where it was impossible to get samples sufficiently thin otherwise. Transmission measurements in these cases involved the use of very fine powders of the substance, and necessitated the use of a second blank pellet of sulfur of weight equal to that of the sulfur binder in the first disk.

The method most frequently used was a solution method, which was used particularly for the rare earths gadolinium, samarium, europium, and dysprosium, where cross sections were usually high and samples were small. For this purpose two very precisely ground quartz cells, 1 inch in diameter and 1 centimeter thick were employed. The nitrate of the rare earth was prepared, a proper amount dissolved in a known amount of heavy water and this solution added to one cell. Heavy water was used as the solvent in order to avoid the loss in beam intensity due to the strong scattering of hydrogen-containing solvents. To the heavy water in the second cell was added a sufficient amount of DNO_3 to equal the effect of the nitrate ion in the rare earth cell. Measurements were made then as in the case of the sulfur bound pellets.

Evaluation of Approximate Theoretical Constants for the Resonance Levels

Although the experimental data are not sufficiently precise to make very definite assignments to the constants in the Breit-Wigner relation, and thus cannot be considered either a test of the theory or the last word on the exact shape of the cross-section curves, it was considered of interest to evaluate the constants of the theoretical expression which best fitted the experimental curves. The form of the Breit-Wigner one-level equation for the energy dependence of the cross section is

$$\sigma E^{\frac{1}{2}}=\frac{\sigma_0 E_0^{\frac{1}{2}}}{1+[(E-E_0)/\frac{1}{2}\Gamma]^2}$$

in which E_0 is the energy of the resonance level, Γ is the width of the level at half-maximum, σ_0 is the cross section at the resonance maximum. The values of σ_0, E_0 and Γ can be assigned from the observed data, and are included in the discussion of cross sections below where their values can be considered to approximate the correct values because of the quality of the experimental data.

In general, the observed data taken at neutron energies less than one electron volt, when corrected for the effect of higher orders and resolution as discussed above, were considered sufficiently precise to justify evaluation of these constants. Data at higher energies are seriously disturbed by lack of resolution, and although the energy of the peak is probably accurate, the measured widths of the levels are in general much too broad, while the peaks are for the same reasons very much flattened.

IX. RESULTS

The total, absorption plus scattering cross sections for neutron reaction have been measured

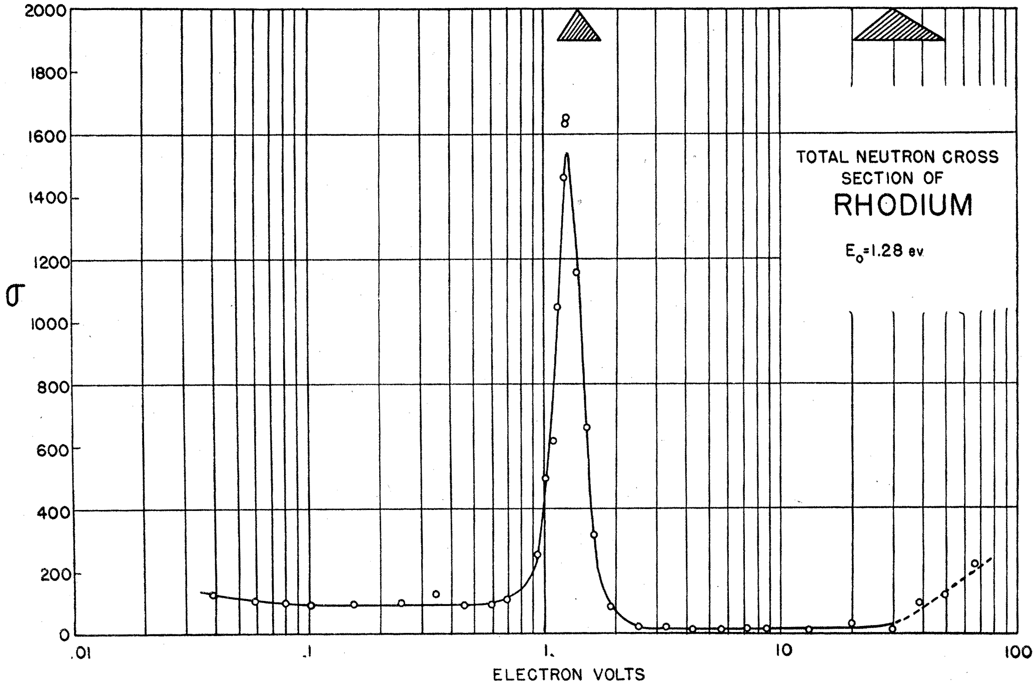

FIG. 7. Total cross section of rhodium. The cross section, σ, is given in units of 10^{-24} cm^2/atom (barns).

of a series of well-known strong absorbers, detectors, and rare earths using the method discussed. All the cross sections reported have been calculated from measurements of the transmission of a sample of the substance over the range of energy indicated. Although isolated measurements of the activation cross sections have been made on the same instrument, notably in the case of indium, dysprosium, and europium, these results were not nearly as complete nor as accurate.

In the cross-section curves shown in Figs. 7 to 16 corrections to the observed data have been made for the variations in background caused by change in the amount of scattering as discussed above. In addition, these data are corrected for resolution and for order composition in the ranges of low energy where the methods of correction discussed are valid. An assay of the chemical composition of each sample was made, and corrections for the energy dependent effects of highly absorbing impurities upon the measured transmission at each energy were made. In the range of energies higher than 1.0 ev, only background and impurity corrections were applied and the cross-section values in the maxima are lower limits only. The effect of the poorer resolution at these energies also widened these peaks, and the half-widths taken from the curves are maximum values. None of the cross sections have been reduced to isotopic cross sections or cross sections of the absorbing isotope, but all have been reported as cross sections per average atom. Data taken at energies greater than 30 ev, where the detector was very near to the primary beam, can be considered to give only an indication of the nature of the cross-section function in this region.

Rhodium

Attempts to evaluate the energy-dependent variations in the cross section of rhodium have been made using the boron method[6] and by varying the mean energy of the reaction neutron source by changing the moderator temperature.[7] Further, self and resonance absorption techniques have been used to obtain the width and relative position of the resonance level.[15–18] By

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

[16] H. Feeney, C. Lapointe, and F. Rasetti, Phys. Rev. **61**, 469 (1942).

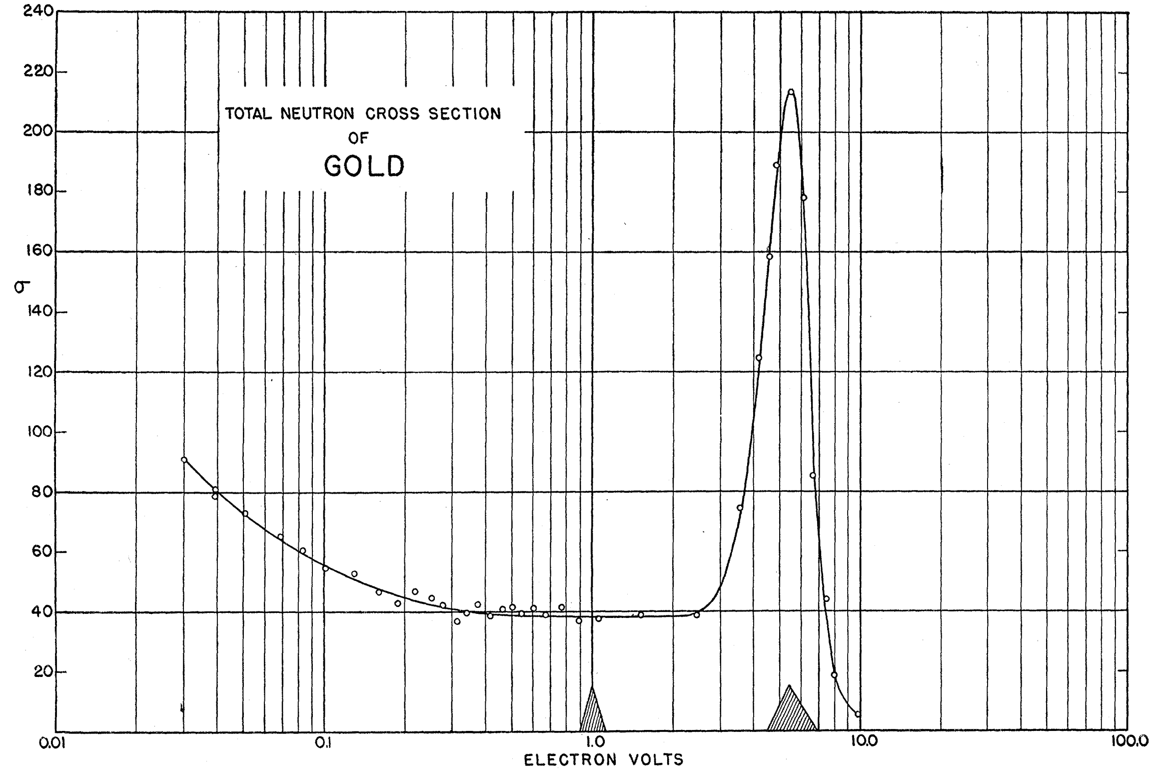

FIG. 8. Total cross section of gold, σ in units of 10^{-24} cm^2/atom.

use of a series of six metal foils of the element augmented by an assortment of sulfur-bound pellets of the finely powdered element, it has been possible to measure this cross section in the continuous energy range from 0.04 ev to 65 ev with the crystal spectrometer (Fig 7).

It has been possible to place the resonance peak, the existence of which was predicted by the self-absorption and activation measurements, at 1.28 ev. However, because of the insufficient resolution of the spectrometer in this region, the observed maximum in the cross section represents only a lower limit, and since, for the same reason, the measured width is not correct, no attempt was made to evaluate theoretical constants. At the high energy end of the curve evidence is indicated for some increase in cross section at energy greater than 30 ev.

Combining this result for the energy of the level with a cyclotron measurement of the position of indium level (1.44 ev) recently made by Havens and Rainwater,[11] we find the value of 0.16 ev for the energy difference between the peaks. This is in very good agreement with the results of Hornbostel, Goldsmith, and Manley who by mutual absorption methods found $|E_{0\mathrm{In}}-E_{0\mathrm{Rh}}|=0.15$ ev.

Gold

Two gold plates, which alone and in combination provided three thicknesses of absorber for the various cross-section regions, were used for the measurements. The surface densities of these samples, 1.674 g/cm^2, 2.898 g/cm^2 and 4.572 g/cm^2, made it possible to measure the cross section of gold in the region between 0.04 and 8.0 ev. The variation (Fig. 8) below 2.5 ev is very nearly as $1/v$, and the cross section at kT was found to be 99.3×10^{-24} cm^2/atom, in close agreement with other measurements of the cross section at this energy.

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[17] J. H. Manley, H. H. Goldsmith, and J. Schwinger, Phys. Rev. **55**, 39 (1939).

[18] J. Hornbostel, H. H. Goldsmith, and J. H. Manley, Phys. Rev. **58**, 18 (1940).

[18a] See also spectrometer measurements of L. B. Borst, A. J. Ulrich, C. L. Osborn, and B. Hasbrouck, Phys. Rev. **70**, 557 (1946); Phys. Rev. **70**, 108 (A) (1946).

Earlier measurements of the position of the resonance level by absorption methods[16] and by modulated cyclotron beam[11] placed it at 2.6 ev and 4.8 ev, respectively. Crystal data indicate the position of the level to be at 5.4 ev. The more detailed recent studies using the time-of-flight technique, however, indicate this value to be somewhat high. The resolving power of the crystal, very nearly the same as that of Rainwater and Havens' earlier apparatus in this region, results in agreement with regard to the apparent width and height of the level as measured by the two methods. ($\Gamma_{\text{apparent}}=2.48$ ev, cyclotron, $=2.50$ ev, crystal; $\sigma_{0\text{apparent}}=198\times10^{-24}$ cm²/atom, cyclotron, $=211\times10^{-24}$ cm²/atom, crystal.)

Iridium

Early measurements which Amaldi and Fermi made of the absorption of cadmium-filtered neutrons showed strong *A* group neutron absorption by iridium ($\sim$5 ev), and later evidence from boron absorption data of resonance absorption in iridium was obtained by Goldsmith and Rasetti,[6] and the energy of this level was placed by them at 1.16 ev.

Spectrometer measurements (Fig. 9) of the total cross section of iridium, at energies up to 8.0 ev, show three absorption resonances, one at 0.635 ev, a second at 1.35 ev, and the third at 6.0 ev. Samples used were foils of the metal 1.09, 2.22, and 3.29 g/cm². Although the resolution of the instrument is not sufficient to make very precise the determination of the theoretical constants, approximate values have been assigned for the two low energy peaks. The two sets of constants for the one-level expression when added together account very well for the observed points. The two sets are: (1) $E_0=0.635$ ev, $\sigma_0(E_0)^{\frac{1}{2}}=425$, $\Gamma=0.250$ ev; (2) $E_0=1.35$ ev, $\sigma_0(E_0)^{\frac{1}{2}}=710$, $\Gamma=0.36$ ev.

Gadolinium

The rare earth, gadolinium, long known to have a very large cross section for *kT* neutrons[6,19] was measured in heavy water solution. Three concentrations of the nitrate were needed to cover the various energy ranges measured,

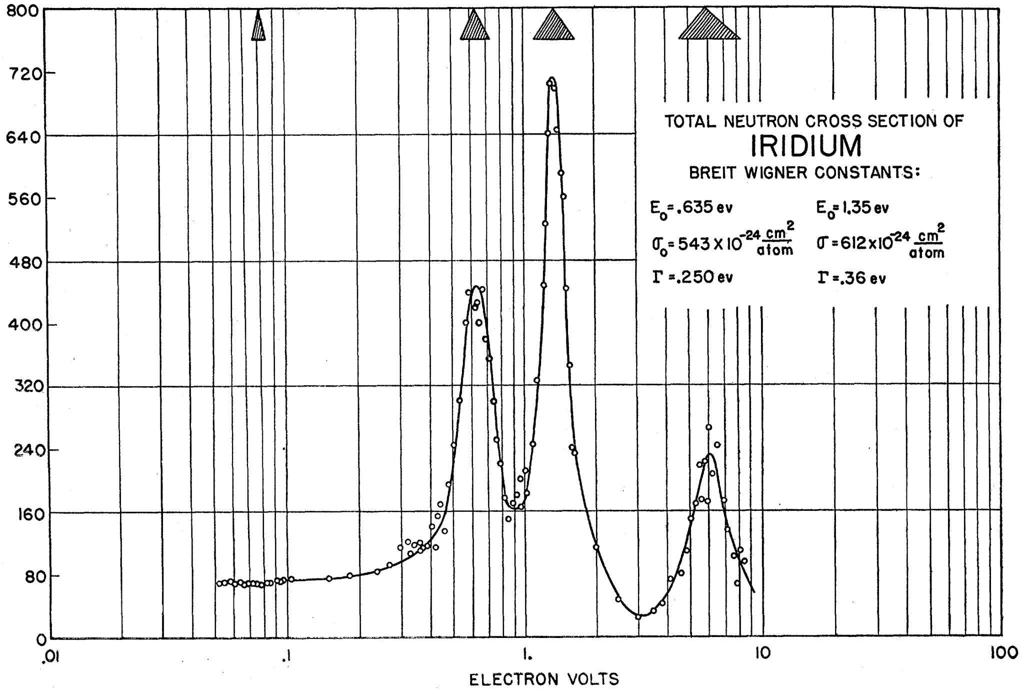

FIG. 9. Total cross section of iridium. Cross-section values are multiplied by $E^{\frac{1}{2}}$ to show the $1/v$ region as a horizontal line.

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[19] W. Stupp, Ann. d. Physik **43**, 630 (1943).

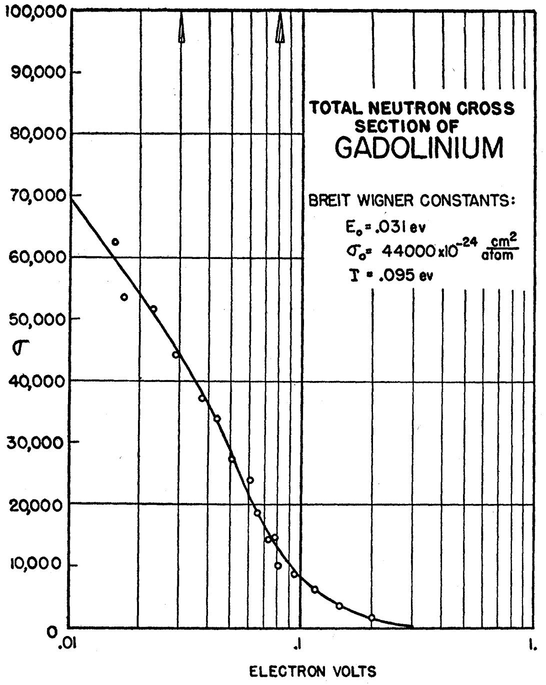

FIG. 10. Total cross section of gadolinium, σ in units of 10^{-24} cm^2/atom.

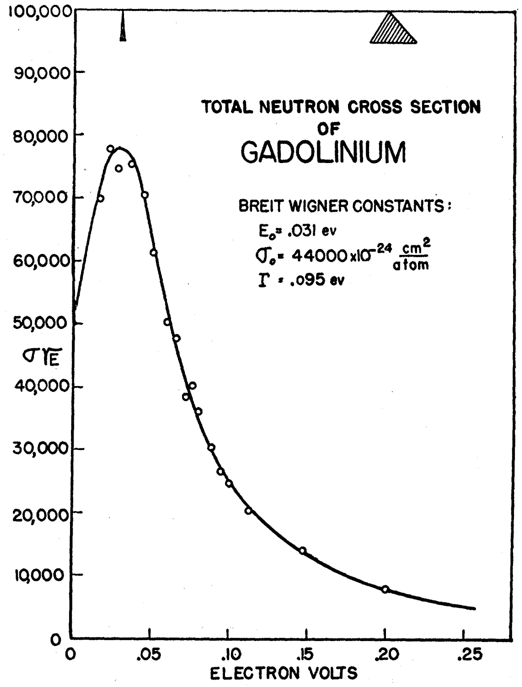

FIG. 11. $\sigma E^{\frac{1}{2}} \times 10$ plot of gadolinium data showing resonance level symmetrical about E_0.

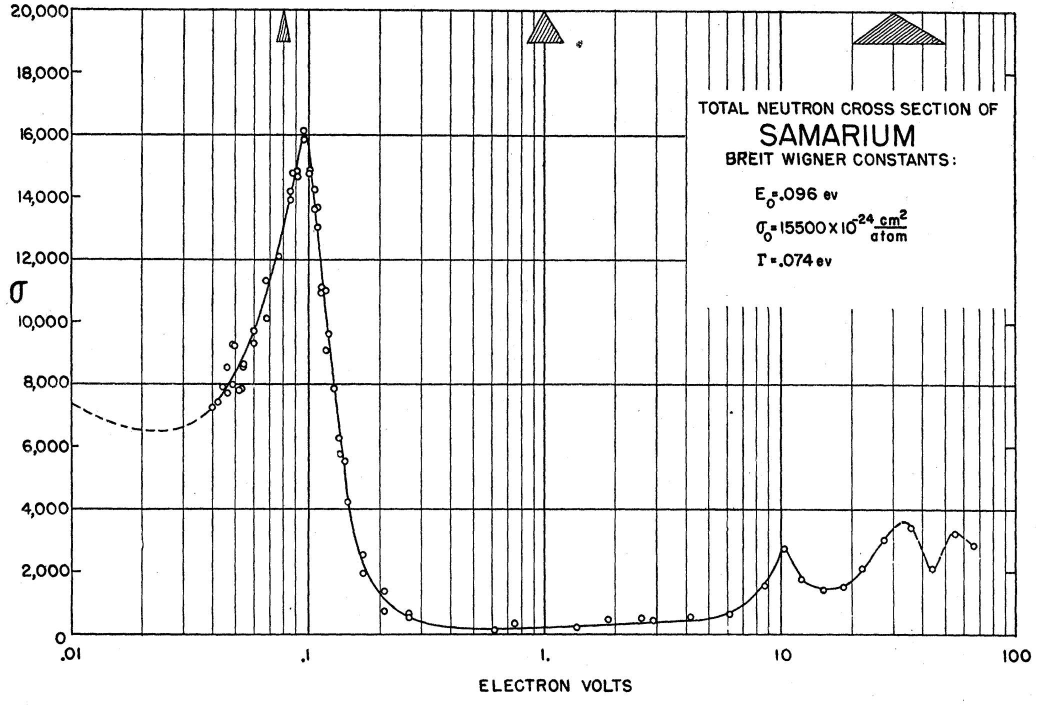

FIG. 12. Total cross section of samarium, σ in units of 10^{-24} cm^2/atom.

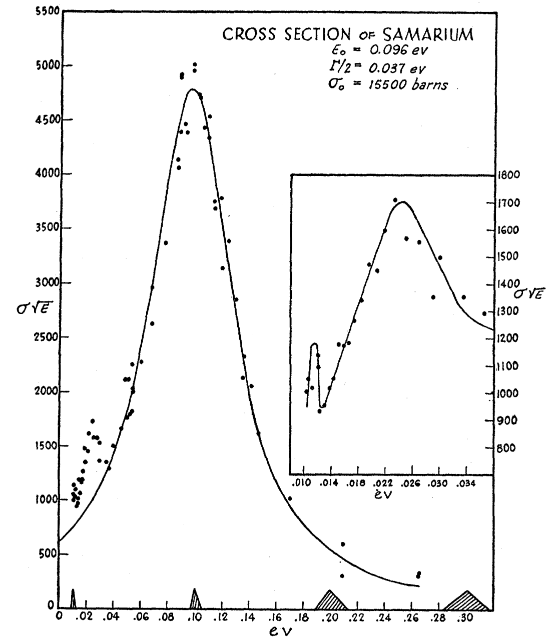

FIG. 13. Samarium cross section for low neutron energies. Two false peaks (shown on expanded scale in insert) correspond to absorption of second and third-order neutrons by the strong resonance level at 0.096 ev.

0.0108, 0.00624, and 0.000867-g gadolinium nitrate per square centimeter. The cross section (Fig. 10) was found to rise rapidly and continuously as the energy of the reacting neutrons decreased, and the rate of rise was greater than that expected for a $1/v$ absorber. Plotting the data in a different manner (Fig. 11) serves to show the resonance level which is superimposed on a strong $1/v$ component of the total cross section. Since in this case, with $\sigma(E)^{\frac{1}{2}}$ and E as the ordinate and abscissa, respectively, a $1/v$ absorber appears as a horizontal straight line, the resonance level is shown as a symmetrical peak superimposed upon it. Thus the level in this element is shown to be at very nearly thermal energy which accounts for its very large kT cross section. The Breit-Wigner constants for these data are: $\sigma_0 = 44{,}000 \times 10^{-24}$ cm²/atom, $E_0 = 0.031$ ev, $\Gamma = 0.095$ ev.

Samarium

Measurement of the total cross section of samarium made in the energy range between

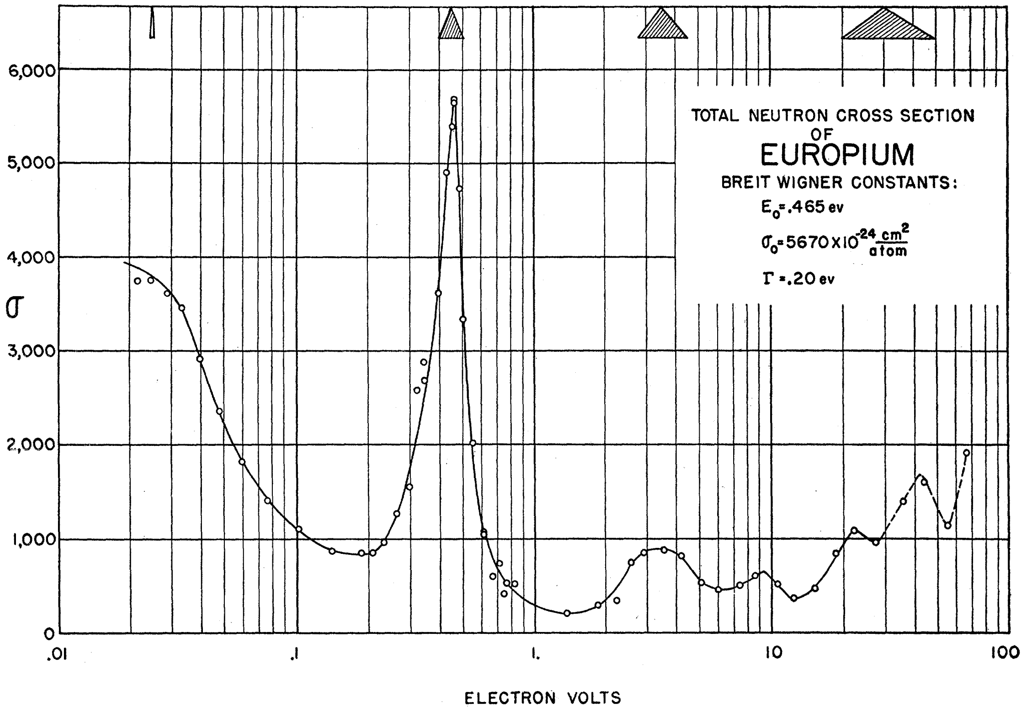

FIG. 14. Total cross section of europium. Slope of curve between 0.035 and 0.10 ev steeper than $1/v$.

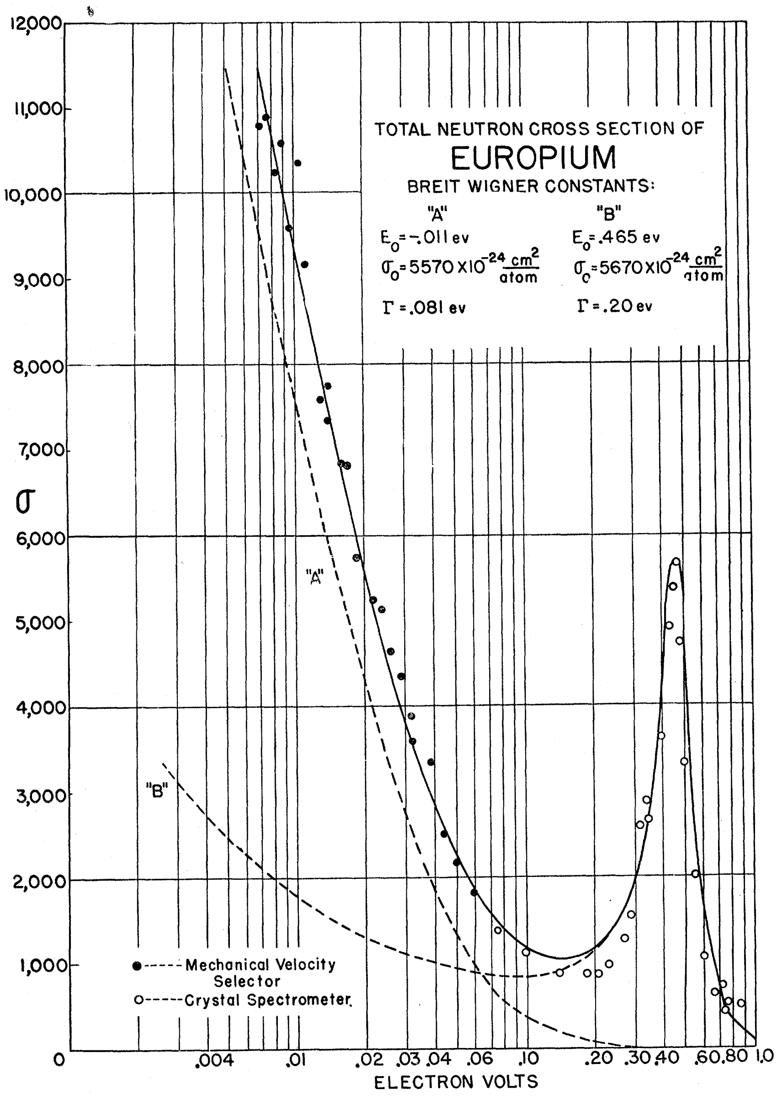

Fig. 15. Extension of europium cross-section measurements to very low energy region showing presence of resonance level at very nearly zero energy.

0.04 ev and 65 ev, showed the presence of strong absorption levels at 0.096 ev, 10 ev, and 33 ev and a possible resonance at higher energy (Fig. 12). As with gadolinium, several heavy water solutions of the nitrate and blank cells of dilute DNO_3 were used for the transmission measurements in the various energy regions. An attempt to fit the data theoretically was made only for the case of the resonance at lowest energy, its constants being: $\sigma_0=15500\times10^{-24}$ cm²/atom, $E_0=0.096$ ev, and $\Gamma=0.074$ ev. Previous indication of structure in this cross section at low energies was obtained from absorption data and showed the existence of the lowest level, although no definite energy value could be assigned.[19]

A plot of the uncorrected cross-section data at energies less than 0.04 ev shows strikingly the effect which the high energy, high order components in the diffracted beam can have on the observed cross section. The true resonance at 0.096 ev reappears as two false subsidiary maxima at 0.096/4 ev, when the second-order component of the beam is strongly absorbed, and again at 0.096/9 ev when the third-order component is strongly absorbed. The data are shown on an expanded energy scale in the insert of Fig. 13, indicating that these energies are just the expected values for the absorption of second and third-order components of the beam by the primary resonance at 0.096 ev.

Europium

Measurements of the transmission of a sample of very pure europium were made with the crystal spectrometer using the solvent method. Nitrates containing deuteryl water of crystallization were prepared and dissolved in heavy water, preparing thus samples containing 7.42×10^{20} and 2.16×10^{20} atoms Eu per square centimeter. A survey of this element for neutron energies (Fig. 14) to 65 ev, showed the presence of resonance levels at 0.465 ev, 3.3 ev, 9.2 ev, and 22 ev, and possible levels at higher energy. Since in this case the maximum cross section observed in the peak of the resonance at 0.465 ev represents only a lower limit, assignment of a value to σ_0 is necessarily low. The constants best fitting the observed points are: $\sigma_0=5670\times10^{-24}$ cm^2/atom, $E_0=0.465$ ev, $\Gamma=0.20$ ev. The 3.3-ev level is probably due to capture by Eu^{151} which Goldhaber[20] has shown from boron absorption measurements to have a level at about 4 ev. From self-absorption measurements this level shows evidence of being somewhat wider than the usual levels measured, and appears here to have characteristics not inconsistent with this point of view. It is, however, not possible to distinguish, by present spectrometer measurements at this energy between a wide resonance and a group of narrow ones with close spacing.

Crystal spectrometer measurements shows a rise in the cross section at energies less than 0.15 ev at a rate greater than that expected for a $1/v$ absorber. It was considered that this region, although outside the range of the crystal spectrometer, merited special emphasis. As a consequence, measurements of cross section in the energy range between 0.007 and 0.2 ev were made with a mechanical velocity selector which had this range.*** This instrument, the rotary shutter of which periodically releases bursts of polychromatic neutrons and by suitable delay mechanism counts them electronically at measured intervals after the release, was able to meas-

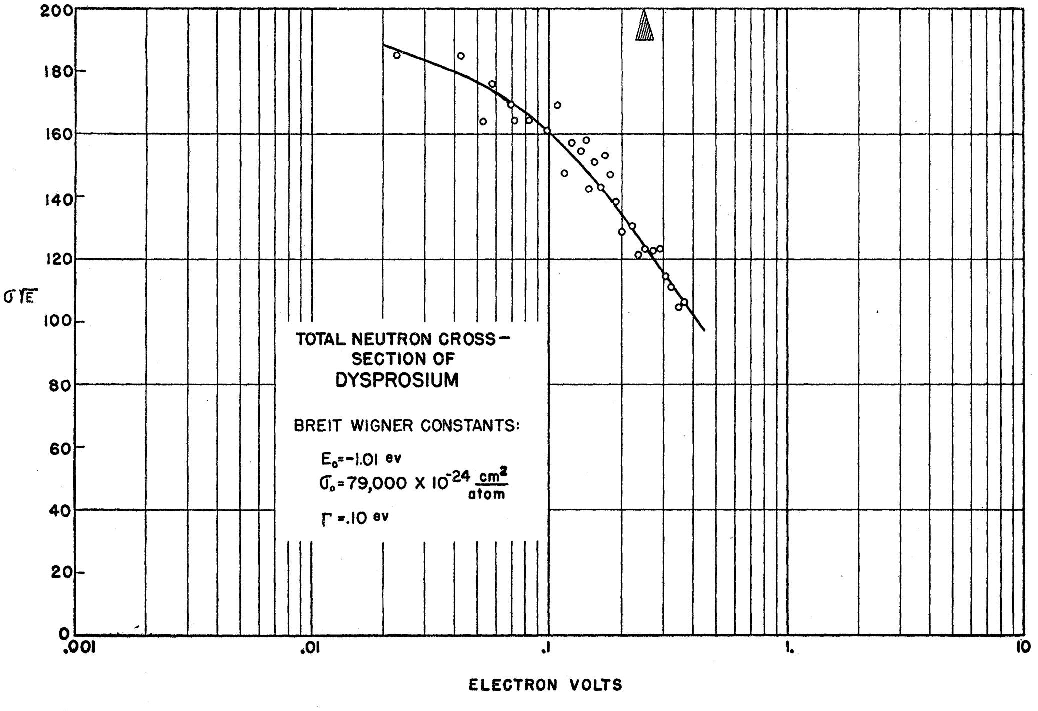

FIG. 16. Total cross section of dysprosium, cross-section values multiplied by $E^{\frac{1}{2}}$. Negative slope indicates resonance level at energy less than zero.

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[20] M. Goldhaber, personal communication.

*** The assistance of G. Arnold, H. Kanner, and R. Nobles in making these measurements with the mechanical velocity selector is gratefully acknowledged.

ure transmission as a function of neutron energy. These data at low energy, combined with those from the crystal are shown plotted in Fig. 15. The constants of this low energy level were found to be: $\sigma_0 = 5570 \times 10^{-24}$ cm^2/atom; $E_0 = -0.011$ ev; $\Gamma = 0.081$ ev.

Dysprosium

Although the limited supply of dysprosium available at the time of the measurements shortened the energy range covered by the data for this element, sufficient evidence was obtained to indicate the existence of a neutron resonance in the cross-section curve. As with the other rare earths, quartz cells of the nitrate dissolved in D_2O were used for the transmission measurements, the surface density of sample used here being 5.87×10^{20} atoms of dysprosium/cm^2.

The $\sigma(E)^{\frac{1}{2}}$ curve of these data (Fig. 16) shows a continuously rising function with decreasing energy, which, by its slope, indicates a resonance level at energy less than zero. The cross section at kT neutron energy was found to be 1180×10^{-24} cm^2 atom, a value considerably higher than an earlier measurement[21] of 870×10^{-24} cm^2/atom at this energy. The constants assigned to the theoretical curve are of necessity highly uncertain because the only experimental data it is possible to obtain in this case is far from the peak of the level and represents but one wing of the resonance. The constants assigned to fit the data, assuming a half-width of 0.10 ev, are: $-E_0 = 1.01$ ev, $\sigma_0 = 79{,}000 \times 10^{-24}$ cm^2/atom, $\Gamma = 0.10$ ev.

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[21] L. Meitner, Arkiv. Mat. Astr. Fys. **27A**, 3 (1941).