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Diffraction of Neutrons by a Single Crystal

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The intensity of neutrons emitted by the nuclear chain reactor has been shown to be sufficiently great to permit the observation of the Bragg reflection of neutrons by a single crystal. A single crystal monochromator has been constructed and used for the investigation of resonances. The well-known resonance in Cd has been measured and the Breit-Wigner constants determined.

INTRODUCTION

A NUMBER of experiments designed to demonstrate the diffraction of slow neutrons by crystals have been made in the years following the discovery of the neutron. Early methods of treating the interaction between the neutron and the nucleus, developed by Fermi[1] and extended by Wick,[2] anticipated difference in scattering in crystalline and disordered substances. Experimental verification was attempted by Preiswerk and von Halban[3] who measured the temperature variation in the distribution of neutrons transmitted by a polycrystalline medium, and Mitchell and Powers,[4] as well as Preiswerk,[5] presented evidence for a coherent component of a neutron beam scattered from an array of crystals.

More recently, further observations of neutron diffraction have been made in the measurements of slow neutron scattering by Whittaker and Beyer[6] and in the work of Anderson, Fermi, and L. Marshall[7] and of Rainwater and Havens[8] who observed variations with the energy of the neutron beam in the scattering of crystalline substances. The high neutron flux generated by the chain reacting pile has permitted, as reported here, a series of experiments which show the existence of an intense diffracted beam of neutrons from a single crystal, and which demonstrate that this beam is of sufficient intensity for the study of the energy dependence of neutron reactions by methods similar to those of x-ray spectrometry. The work of this paper has been reported briefly[9] and similar results have been given by Borst *et al.*[10]

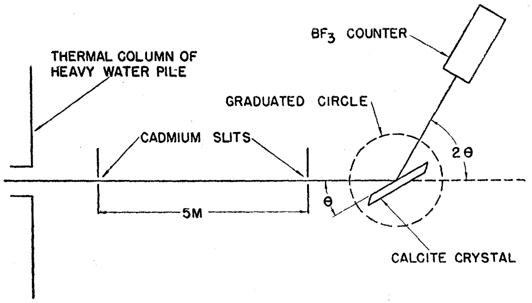

FIG. 1. First experimental arrangement.

DESCRIPTION OF APPARATUS

Neutrons diffusing from the main part of the chain reacting pile are permitted to enter a large block of graphite which acts as a slowing down column, bringing the average neutron energy to the equilibrium value for graphite at room temperature. Since the de Broglie wavelength of these neutrons is of the same order of magnitude as that of x-rays, it was possible to attempt the diffraction experiments with the customary crystals, using a spectrometer similar to that used with x-rays. As is shown schematically in Fig. 1, a collimated beam of neutrons was obtained by introducing two thick cadmium slits, 5 meters apart, in the neutron beam from the graphite thermal column of the heavy water pile. Cadmium slits sufficed here since the neu-

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[1] E. Fermi, Ricerca Scient. **7**, pt. 2, 13 (1936).

[2] Wick, Physik. Zeits. **38**, 403 (1937).

[3] Von Halban and Preiswerk, Comptes rendus **203**, 73 (1936).

[4] Mitchell and Powers, Phys. Rev. **50**, 486 (1936).

[5] Preiswerk, Helv. Phys. Acta **10**, 400 (1937).

[6] Whittaker and Beyer, Phys. Rev. **55**, 1101 (1939); Beyer and Whittaker, Phys. Rev. **57**, 976 (1937).

[7] Anderson, Fermi, and L. Marshall, Phys. Rev. **70**, 102 (1946).

[8] Havens and Rainwater, Phys. Rev. **70**, 154 (1946); Rainwater and Havens, Phys. Rev. **70**, 136 (1946).

[9] W. H. Zinn, Phys. Rev. **70**, 102A (1946).

[10] L. B. Borst, A. J. Ulrich, C. L. Osborne, and B. Hasbrouck, Phys. Rev. **70**, 108A (1946); Phys. Rev. **70**, 557 (1946).

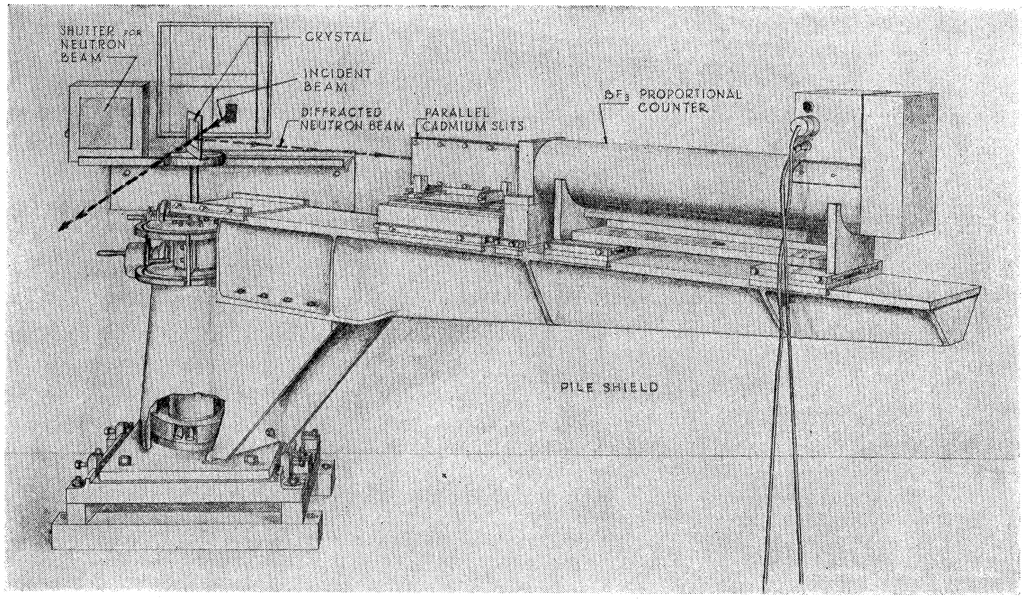

FIG. 2. The crystal spectrometer.

tron radiation from a thermal column is singularly free from fast neutrons. The collimated beam fell upon the (1, 0, 0) planes of a large single calcite crystal, and the diffracted beam was detected by means of a BF_3 proportional counter filled, for greater detection efficiency, with gas enriched in the B^{10} isotope. Only early experiments were performed at the thermal column; subsequently the apparatus was set up at a side hole of the reactor where the high energy neutron flux is much greater than at the thermal column.

The final form of the spectrometer (Fig. 2) is identical in principle with the usual x-ray instrument; however, in order to support the heavier collimators and detectors which are necessary for neutron diffraction experiments, the unit is made very massive. To improve the resolution the arm is long, having a length of 80 inches and a width of 8 inches. A 6-inch diameter crystal table is provided for mounting the crystals. The two graduated circles indicating the position of the arm and crystal table are 12 inches in diameter and are calibrated in degrees, while greater precision is attainable from readings on a cylindrical scale calibrated in quarter minutes and placed at the drive wheel. The table and arm are driven by means of large knurled wheels through a train of gears, and in use can be adjusted independently or coupled by a friction clutch. The table and arm are driven in the two to one angular ratio necessary for reflection experiments.

In order to measure with greatest efficiency the flux of diffracted neutrons, the beam was passed axially through the proportional counter. In this manner it was possible to detect nearly 100 percent of all the neutrons of the low energies. The counter was 5 cm in diameter, 60 cm long, and filled to a pressure of 40 cm of Hg with boron trifluoride. This gas was enriched about five times in the B^{10} isotope and thus transmitted but 5 percent of neutrons of kT energy. The required degree of collimation was obtained by inserting into the shield of the reactor a steel block containing a long channel. This channel was approximately $\frac{1}{2}''$ wide, $1''$ tall, and $8'$ long. The channel was directed at a part of the reactor containing heavy water and uranium. The beam collimated by this means contains neutrons ranging in energy from thermal to those of the fission spectrum itself. The intensity obtainable is a sharp function of the degree of collimation desired and the spectral region to be investigated. At the maximum of the thermal spectrum, with quite excellent reso-

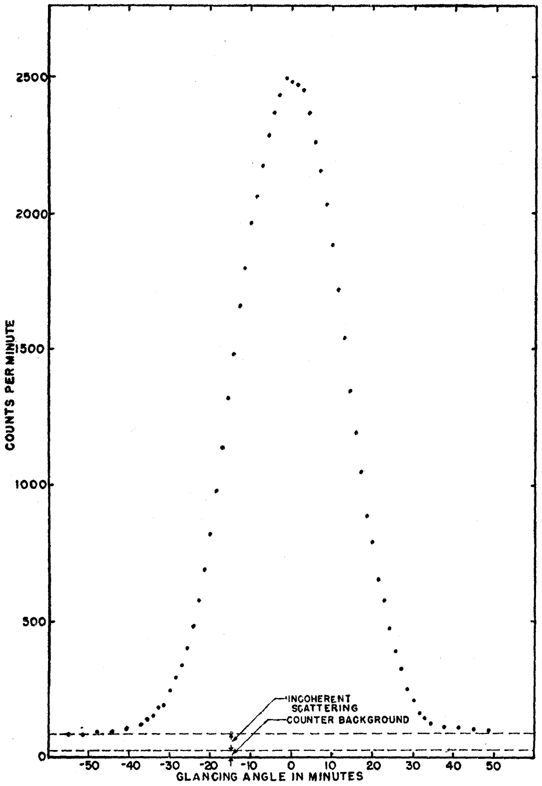

FIG. 3. Rocking curve (1, 0, 0) LiF crystal.

lution, counting rates of 5000 counts per minute can be obtained. At the suggestion of W. H. Zachariasen, roughening the crystal surfaces was tried and gives an improvement in intensity of about a factor of two. At energies in the so-called resonance region considerably smaller counting rates are obtained. A detector more sensitive to neutrons in this region is very much to be desired.

RESULTS

A typical rocking curve is shown in Fig. 3. No attempt has been made to correct these data for resolution or detector sensitivity. The detector, boron, follows a $1/v$ law for absorption, and as a result the sensitivity of the counter is not uniform over the entire range of velocities. Therefore, the rocking curve is not exactly symmetrical, showing relatively higher values on the low energy side of the diffraction peak.

Sufficient intensity of diffracted neutrons existed throughout the range of energies emitted from the thermal column to make measurement of its neutron spectrum possible by this method. Intensities at low energies, since they are contaminated by higher order components and are more efficiently detected, show considerably higher values than the real distribution in this region. Figure 4 shows the distribution of neutrons from the thermal column as obtained with a calcite crystal. Figure 5 shows the spectrum of neutrons directly from the reactor. These neutrons have not diffused through any considerable column of moderator material. Again no correction to the data has been made for detector sensitivity or for resolution. Neither of the corrections is sizable in the low energy region covered in these curves. Conversion from glancing angle to energy was made by the relation

$$\mathrm{ev}=(2.22\times10^{-3})/\sin^2/\theta,$$

where θ is the glancing angle. Measurements were made in the energy interval between 0.004 ev and 0.30 ev, which is in the range of glancing angles between 50° and 2°. Both spectra show a strong, approximately Maxwellian component, distorted by high order contributions on the long wave-length side of the maximum. The spectrum of neutrons from the wall of the reactor, having passed through a smaller amount of moderator, has an additional component at small glancing angles representing neutrons not yet in equilibrium with the moderator. Attempts to fit the experimental data theoretically have been made by Goldberger and Seitz[11] for various moderator temperatures and are included on the figures.

To demonstrate that the diffracted beam consists primarily of neutrons in a very small energy band, a measurement of the transmission of a Pyrex plate was made over the range 0.018 to 0.5 ev. This plate, previously standardized by means of a mechanical velocity selector, was shown to have a total cross section, because of its boron content, very close to $1/v$ in the region investigated. With the calcite crystal, measurements were made of the transmission of the plate from which effective neutron velocities were obtained by comparison with the measurements made on the mechanical velocity selector.

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[11] Goldberger and Seitz, Phys. Rev. **70**, 116 (1946). A complete discussion of their method will be published shortly.

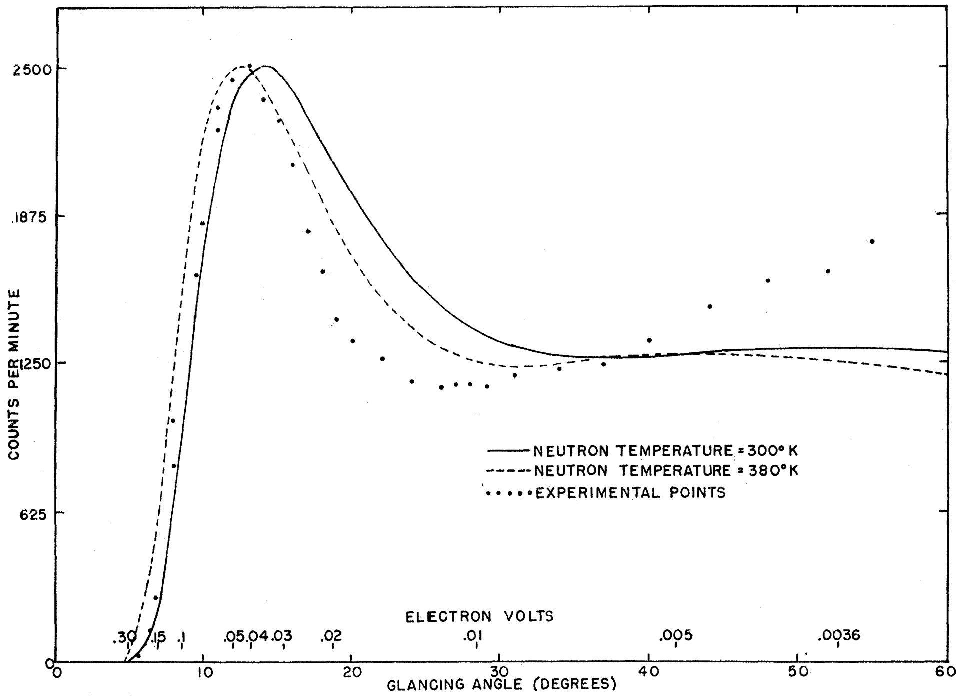

FIG. 4. Spectrum of thermal column radiation, calcite crystal. Solid line is the theoretical curve calculated by Goldberger and Seitz.

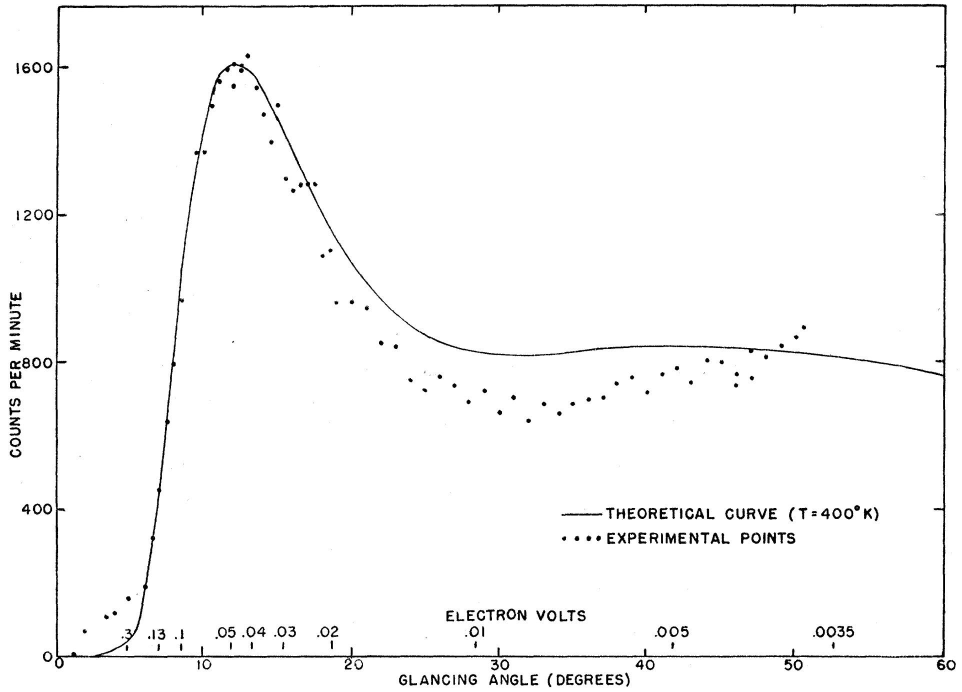

FIG. 5. Spectrum of reactor radiation, calcite crystal. Solid line is the theoretical curve calculated by Goldberger and Seitz.

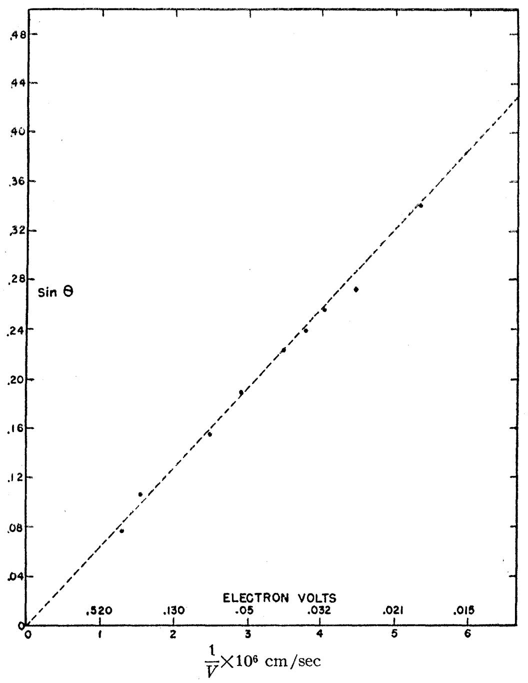

FIG. 6. Boron absorption as a function of neutron energy. The dotted curve is a plot of $(h/mv)=2d\sin\theta$. The points are experimentally determined values of $1/v$ and $\sin\theta$.

Reciprocals of these velocities as a function of the sine of the glancing angle are plotted as points in Fig. 6. The dotted curve gives the reciprocal velocity as calculated from the glancing angle and the crystal spacing. Similar measurements show that the straight line behavior shown extends to 15 volts which was the upper limit of the instrument at the time these measurements were made.

The total cross section of cadmium has been measured by the method of the modulated cyclotron beam[12] and a single strong level observed. The results obtained for cadmium with the crystal monochromator are shown in Fig. 7. The constants of the resonance are similar to those of Rainwater and Havens[8] but show a greater maximum than those of Baker and Bacher. The measurements of Fig. 7 extend to 15 electron volts, and no further resonance structure is found. A series of six foils of cadmium of thickness varying from 0.000142×10^{24} to 0.115×10^{24} atoms per square centimeter were required for the measurement. Wherever possible the range of acceptable transmissions was held

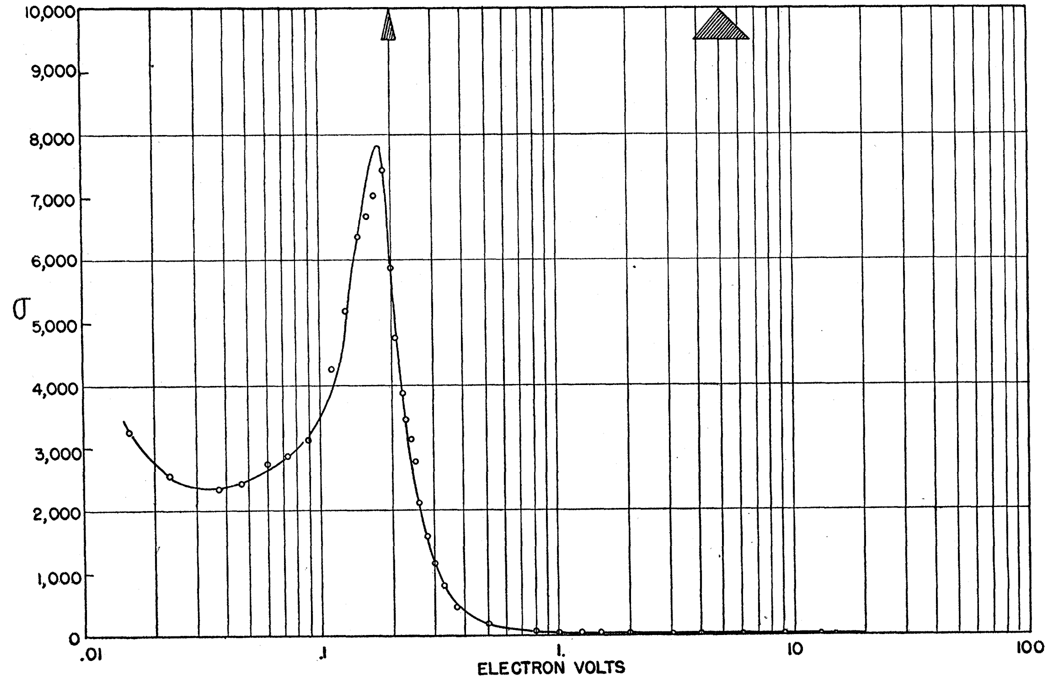

FIG. 7. Total cross section of cadmium. Solid curve is Breit-Wigner fit to experimental points. σ in units of 10^{-24} cm^2 per atom.

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

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.

Acknowledgment is hereby made for the invaluable advice and skill in construction of the instrument contributed by T. J. O'Donnell, D. DiCostanzo, and J. Getzholtz of the laboratory work shop.

The initial results reported here were obtained in July–September, 1944. This work was carried out under the auspices of the Manhattan District.

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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).

[†] This document is based on work performed under Contract No. W-31-log-eng-38 for the Manhattan Project and the information covered therein will appear in Division IV of the Manhattan Project Technical Series as part of the contribution of the Argonne National Laboratory.

[**] 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).

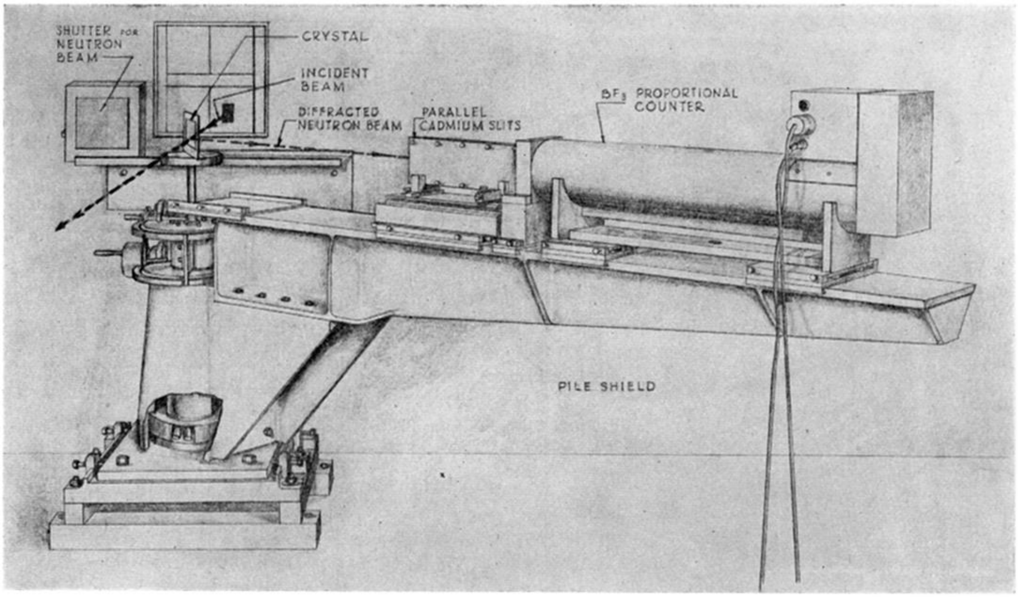

FIG. 2. The crystal spectrometer.