A NEUTRON DIFFRACTION SPECTROMETER

by

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IV. INTRODUCTION

In an effort to explain the results of some of the experiments involving the interaction between radiant energy and matter, such as the photoelectric effect, it has been necessary to assign to radiant energy some properties characteristic of a particle. In 1924, the dual characteristics, wave and particle, were hypothesized by L. de Broglie (3) to be exhibited by all fundamental entities. Thus matter should possess wave properties with a wavelength given by Planck's universal constant divided by the linear momentum.

In 1927, this hypothesis was validated by the diffraction of electrons with a single crystal where the crystalline lattice served as a three dimensional "grating." Since for thermal energies the de Broglie wavelengths of neutrons are about the same as crystal interplanar spacings, the diffraction of thermal neutrons by crystals was predicted in 1936. Mitchell and Powers (11), using a Rn-Be source, were among the first that same year to present evidence of a coherent component for a neutron beam scattered from an array of crystals. It was not until after high intensity neutron beams from reactors became available that diffracted beams of sufficient intensity were obtained for the study of the energy dependence of neutron reactions by methods similar to those of X-ray spectrometry.

The initial phase of the project was the construction of a beam collimator and crystal spectrometer. Then the total neutron cross section of cadmium and the neutron energy spectrum of the reactor

were studied with the instrument. These experiments have the ultimate aim of confirming the calibration and defining the reliable energy range of the spectrometer.

V. REVIEW OF LITERATURE

The first measurements with a neutron diffraction spectrometer were made by W. H. Zinn (19) at Argonne Laboratory. The (1,0,0) planes of a single calcite crystal were used to diffract the neutron beam from a "thermal column" and a side port of the reactor. A collimated beam from the thermal column was obtained with two thick cadmium slits, five meters apart. An eight-foot long steel block through the shielding containing a channel one-half inch wide and one inch high provided a well collimated beam from the side port. Zinn found that the intensity of the diffracted neutrons could be increased two fold by roughing the crystal surface. Spectral measurements of the direct beam from the reactor and the thermal column between 0.004 ev and 0.03 ev show a strong Maxwellian component distorted on the long wavelength (low energy) side of the maximum by more than one diffraction component. An attempt by Goldberger and Seitz (5) to fit these experimental data theoretically was quite good in the region of the spectral maximum. The total cross section of cadmium has been measured by Zinn and the resonance parameters at 0.176 ev were in good agreement with those obtained by the modulated cyclotron beam method.

William J. Strum (13) used the (1,0,0) planes of a LiF crystal for diffraction purposes with the same instrument described by Zinn. A study of the relative reflectivity and maximum energy obtainable was made for LiF, calcite, mica, and copper. The LiF crystal was chosen for the experimental cross section determinations because of a relatively

high reflectivity and because the energy range could be extended up to 65 ev. Copper has a comparable reflectivity but can only be used out to 20 ev. Measurements were made of reflectivity as a function of crystal surface finish and of total neutron cross section between 0.04 and 65 ev by the transmission method for several strongly absorbing rare earth elements and elements commonly used as neutron filters and detectors. Attempts were made to increase the neutron intensity at high energies by varying the temperature of the reactor moderator.

Some of the early experiments utilizing neutron diffraction were done by Fermi and Marshall (4) in determining the magnitudes and sign of the scattering length by observing the intensities of various orders of Bragg reflection.

A discussion of the theoretical conditions for neutron scattering and measurements of resonance absorption has been presented by Wollan and Shull (15, 16). A comparison of total cross section data for iridium has been made between two crystal spectrometers and a velocity selector. It was observed that the resonance peaks obtained with a spectrometer operated at reduced resolution were approximately 4,000 barns lower than those obtained with a high resolution instrument of the same type, as would be expected.

The Debye-Scherrer-Hull powder crystal method has been applied to neutrons (16, 17). This was done by allowing a monoenergetic neutron beam diffracted from a single crystal to be incident on a powdered sample. The equivalent of Laue photography can also be used for diffracted neutrons to study crystal structure by placing a sheet

of indium next to the X-ray film. The film is sensitive to the beta rays from the radioactivity induced by neutron capture (16).

Hurst, Pressesky, and Tunnicliffe (9) at Chalk River developed a neutron spectrometer which exhibited improvements in resolution and intensity over previously described instruments. For a particular experiment the choice of crystal depends upon a number of factors: (a) the spacing of the diffraction planes determines the upper and lower energy limits, (b) the crystal structure, chosen planes, and relative phases of neutron scattering determine the intensity and contamination by higher orders, (c) the mosaic structure governs the resolution and also the intensity. A study of diffracted neutron intensity and higher order contamination has been made for several crystals, e.g. NaCl (1,0,0), LiF (1,0,0) and (1,1,1) cut from samples grown synthetically, and calcite (2,1,1) cut from natural calcite. NaCl yielded a much higher intensity than most crystals and was used for experimental work below a few electron volts. LiF (1,1,1) yields less order contamination since even orders are almost absent due to the opposite sign of the scattering lengths of atoms in successive planes (8, 4). LiF (1,0,0) has the smallest crystalline plane spacing,

$$\lambda = 0.285E^{-1/2} \leq 2d,$$

and thus gives the highest energy for a given angle, but the intensity is low. Calcite provides high resolution because of negligible mosaic structure but poor intensity. The shape, intensity, and position of the neutron spectrum depend upon the crystal planes used, whether

the crystal is used for reflection or transmission, and the condition of the surface of the diffracting crystal (13).

Borst and Sailor (2) found that a beryllium crystal extended the useful range of their instrument to about 50 ev with good resolving power, the resolution being determined primarily by the angular divergence of the collimated neutron beam and the rocking curve width of the crystal. The rocking curve is obtained by "rocking" the crystal through the Bragg maximum. The resultant of the above is approximately a triangle having a full width at half-maximum $\Delta\theta$. This constant can be estimated with reasonable accuracy by the relationship

$$\Delta\theta = \left[(\beta)^2 + (\tfrac{1}{2}\alpha)^2\right]^{1/2}$$

where β is the full width at half-maximum of the rocking curve, and α is the angular divergence of the incident beam.

The neutron diffraction spectrometer has become a tool in nuclear and solid state physics (8, 14, 18). One of the most fruitful applications of the neutron diffraction technique has been the analysis of organic crystal structure. The X-ray scattering cross section for hydrogen is so low relative to heavier elements that it is almost impossible to locate the atomic positions of hydrogen by X-ray diffraction, but the coherent neutron cross section is comparable to that of other atoms. Perhaps the most fascinating problem has been the location of hydrogen in the structure of ice. Neutron data by Wollan in 1949, and Peterson and Levy in 1953, confirmed the model proposed by Pauling (18).

VI. THEORY

A. Neutron Diffraction.

Bragg's Law

Interference effects similar to those exhibited by electromagnetic radiation can be demonstrated with neutrons, but complications arise due to characteristics of this particle not exhibited by electromagnetic radiation (7). The interference properties of neutrons are determined by the coherent scattering cross section of the individual atoms in the crystal; in addition there will usually be some incoherent scattering arising from spin effects, magnetic moment interactions, the presence of different isotopes in the crystal, and the thermal motion of the atoms.

The neutrons diffracted from a crystal obey the Bragg equation,

$$n\lambda = 2d \cdot \sin\theta . \qquad (1)$$

Here θ is the angle between the incident neutron beam and a set of planes in the crystal, n is the order of diffraction, and d is the distance between atomic planes.

Resolution

A schematic diagram of the apparatus and the experimental site is shown in Fig. 1. The resolution of the instrument depends upon a number of factors: the angular divergence of the collimated beam, the mosaic structure of the crystal, and the angle of acceptance of the BF_3 counter. At this point the discussion will be restricted temporarily to the first order (n=1).

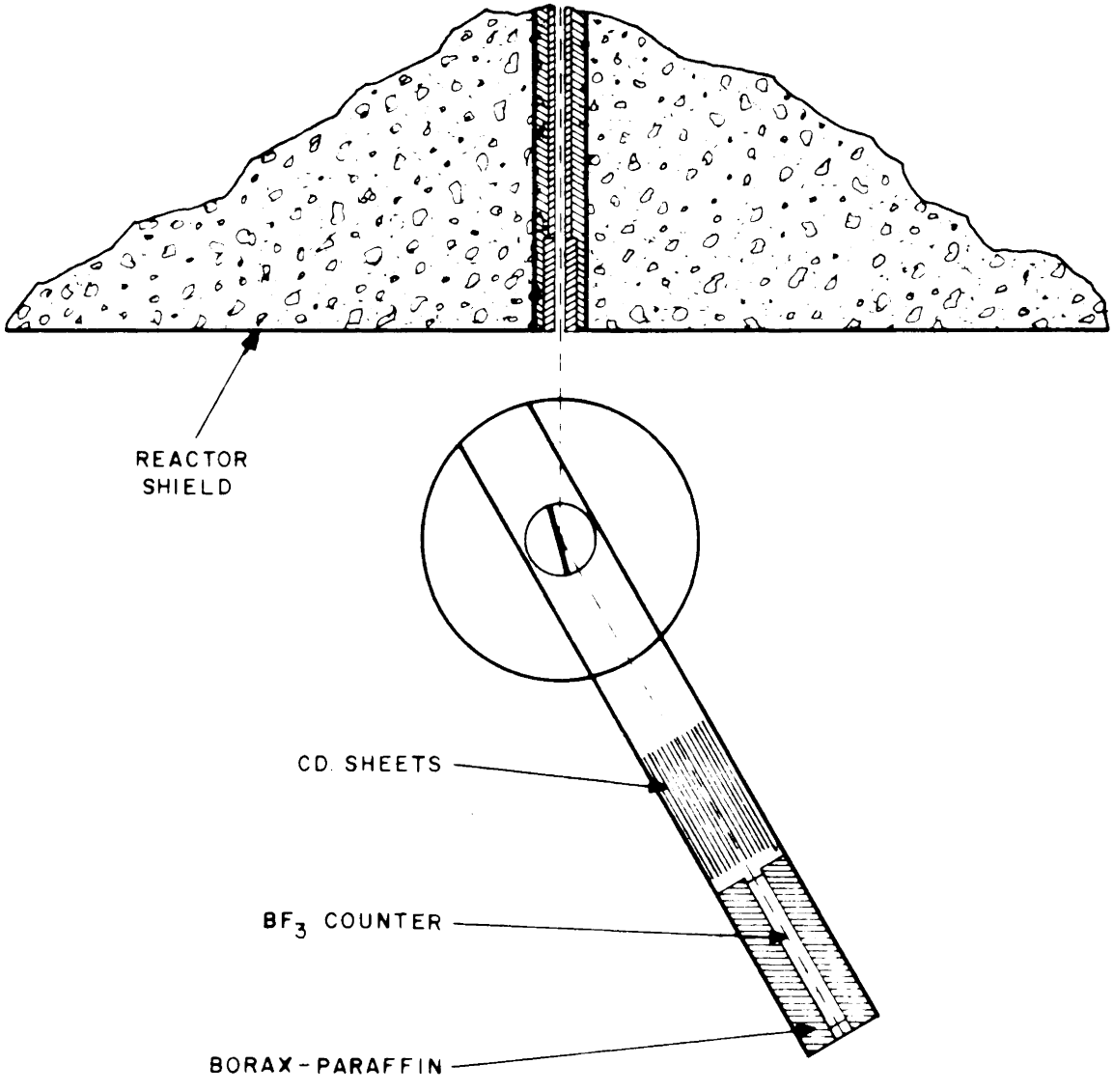

Figure 1. A schematic diagram of the experimental site

The de Broglie relation is

$$\lambda = \frac{h}{mv} ,$$

$$= (0.285)E^{-1/2} , \qquad (2)$$

where h is Planck's constant, m is the neutron mass, v is the neutron velocity, and E is the kinetic energy expressed in electron volts. The energy resolution is defined by

$$E/\Delta E = (E/\Delta\theta)(d\theta/dE) . \qquad (3)$$

Combining Eq. (1) and Eq. (2), one obtains

$$(0.285)E^{-1/2} = 2d \cdot \sin\theta , \qquad (4)$$

and differentiating Eq. (4)

$$\frac{d\theta}{dE} = -\frac{(0.285)E^{-3/2}}{4d \cdot \cos\theta} . \qquad (5)$$

Thus,

$$E/\Delta E = \frac{\tan\theta}{2(\Delta\theta)} . \qquad (6)$$

The resolution is a function (2, 12) which is approximately a triangle having a full width at half-maximum of $\Delta\theta$.

$$\Delta\theta = \left[(\beta)^2 + (\tfrac{1}{2}\alpha)^2\right]^{1/2} \qquad (7)$$

It may be seen from Eq. (4) that for increasing energy the angle decreases, and from Eq. (6) that the resolution decreases. Also, above the thermal spectrum the number of neutrons having energy E is expected to decrease. These two factors limit the spectrometer on the high energy side of the thermal peak.

Higher Order Effects

From Eq. (1) and Eq. (2), it may be seen that

$$E_n = n^2 E_1 \ ,$$

where

$$E_1 = (0.285/2d \sin\theta)^2 \ ,$$

and

$$E_2 = 4E_1 \ . \qquad (8)$$

The first and second order energies are E_1 and E_2 respectively. As E_1 decreases, the number of neutrons of energy E_2 in the incident beam is expected to increase as E_2 approaches the thermal peak. Thus, there will be more neutrons of energy E_2 in the diffracted beam. This factor will limit the instrument at low energies where E_1 is below the Maxwellian distribution and E_2 may be in it.

B. Detector Efficiency.

The efficiency of the neutron detector is given by

$$\epsilon = 1 - \exp(-KXBE^{-1/2}) \ , \qquad (9)$$

in which the number of boron atoms per unit volume is $K = 1.42 \times 10^{19}$ atoms per cubic centimeter, $X = 61$ cm is the length of the counter, and $B = 612 \times 10^{-24}$ is the slope of the boron (n,) cross section curve.

C. Theoretical Spectrum.

Thermal Spectrum

The neutron spectrum from a reactor should represent a Maxwellian energy distribution up to about 0.125 ev. Above this region the number

of neutrons having energy E should decrease as the inverse of the energy. Goldberger and Seitz (5) have presented the following expression for the diffracted neutron spectrum which agrees with most experimental data in the region of the peak (2, 15).

$$\frac{N_R}{N_I} = \frac{n\pi|a_k|}{k^2\sin^2\theta}\left(\frac{\hbar^2k^2}{2mk_oT}\right)^2\exp\left(-\frac{\hbar^2k^2n^2}{2mk_oT}\right) .$$

$$= \frac{n\pi|a_k|}{k^2\sin^2\theta}\left(\frac{E}{k_oT}\right)^2\exp\left(-\frac{En^2}{k_oT}\right) . \qquad (13)$$

N_R = intensity reflected from crystallographic planes.

N_I = intensity incident on crystal.

$k = 2\pi/\lambda$.

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

$\sigma_s^j(b)$ = scattering cross section of the j^{th} atom in the unit cell.

k_o = Boltzmann's constant.

T = average neutron temperature.

(h_1,h_2,h_3) are the Miller indices of the diffracting planes.

(x_j,y_j,z_j) describe the position of the j^{th} atom in the unit cell.

$$N_R = CnE^2\exp\left(-\frac{En^2}{k_oT}\right) , \qquad (14)$$

where C is a constant.

Epithermal Neutrons

The epithermal flux in the central core of the V.P.I. reactor has been shown to be proportional to 1/E by E. Stem.* An estimate of this 1/E component will represent part of the theoretical spectrum curve. However, the resolution may not be sufficient for these higher energies.

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*This work by E. Stem has been published for Project number 365.

VII. INSTRUMENTATION AND EXPERIMENTAL PROCEDURES

The thermal flux in the Virginia Polytechnic Institute reactor is approximately 10^{11} neutrons per square centimeter per second, which is relatively low. At the outer end of the collimator in Figs. 2a and 2b, preliminary experiments with indium foils indicated that a resonance flux at 1.414 ev between 5.4×10^7 and 7.1×10^7 could be expected. It was felt that this flux was sufficient to continue with the construction of the spectrometer.

The outer part of the collimator is a stepped rectangular sleeve of galvanized steel (Fig. 2b) with the space between the inner and outer walls filled with a solidified slurry of borax and paraffin. The inner section of the collimator (Fig. 2a), which slides telescopically into the sleeve, is a stepped rectangular box in which an aluminum waveguide is centered. The space between the walls of this inner section and the waveguide is also filled with the borax-paraffin mixture. This collimator is 78.75 inches long and extends through the reactor shielding to within eight inches of the core. An eight-inch graphite stringer may be placed between the core and the collimator when desired.

The detector is a two-inch diameter, 24-inch long BF_3 counter filled to a pressure of 40 centimeters of mercury. Scattered neutrons from the room are thermalized and absorbed by a borax-paraffin mixture in a box nearly surrounding the counter. To further insure that no thermal neutrons reach the detector, its cylindrical sides are pro-

tected by a 0.03-inch cadmium sheet. Pulses from the detector were counted by a Nuclear of Chicago Ultra-Scalar.

A Nike-Ajax antiaircraft radar antenna mount is used as the spectrometer base. It is approximately 28 inches high, 40 inches in diameter, and consists of an upper plate, henceforth referred to as the detector table, and a gear system connecting the detector table directly to a circular scale. The table turns by means of a bearing surface which is sandwiched between six roller bearings on the top and six on the bottom. Mounted on this detector table is a counter weighted frame which supports the detector assembly so that the front end of the detector is four feet from the axis of rotation of the base.

Extending up through the center of the detector table is a shaft which supports the crystal table. It is a brass disk one-fourth inch thick and eight inches in diameter on which the crystal mount is located. The height of the mount is such that the center of the copper crystal lies on horizontal lines passing axially through the detector and the collimator. It was found that a point on the surface of the crystal table one and one-fourth inches from its center did not wobble in the vertical more than three-thousandths of an inch during one complete revolution, indicating the stability of the assembly.

In order to maintain the Bragg condition a ratio of two to one must be maintained between the motions of the detector and crystal tables. This is accomplished with a pair of reduction gears between the circular scale and the crystal table shaft. Thus when the detector

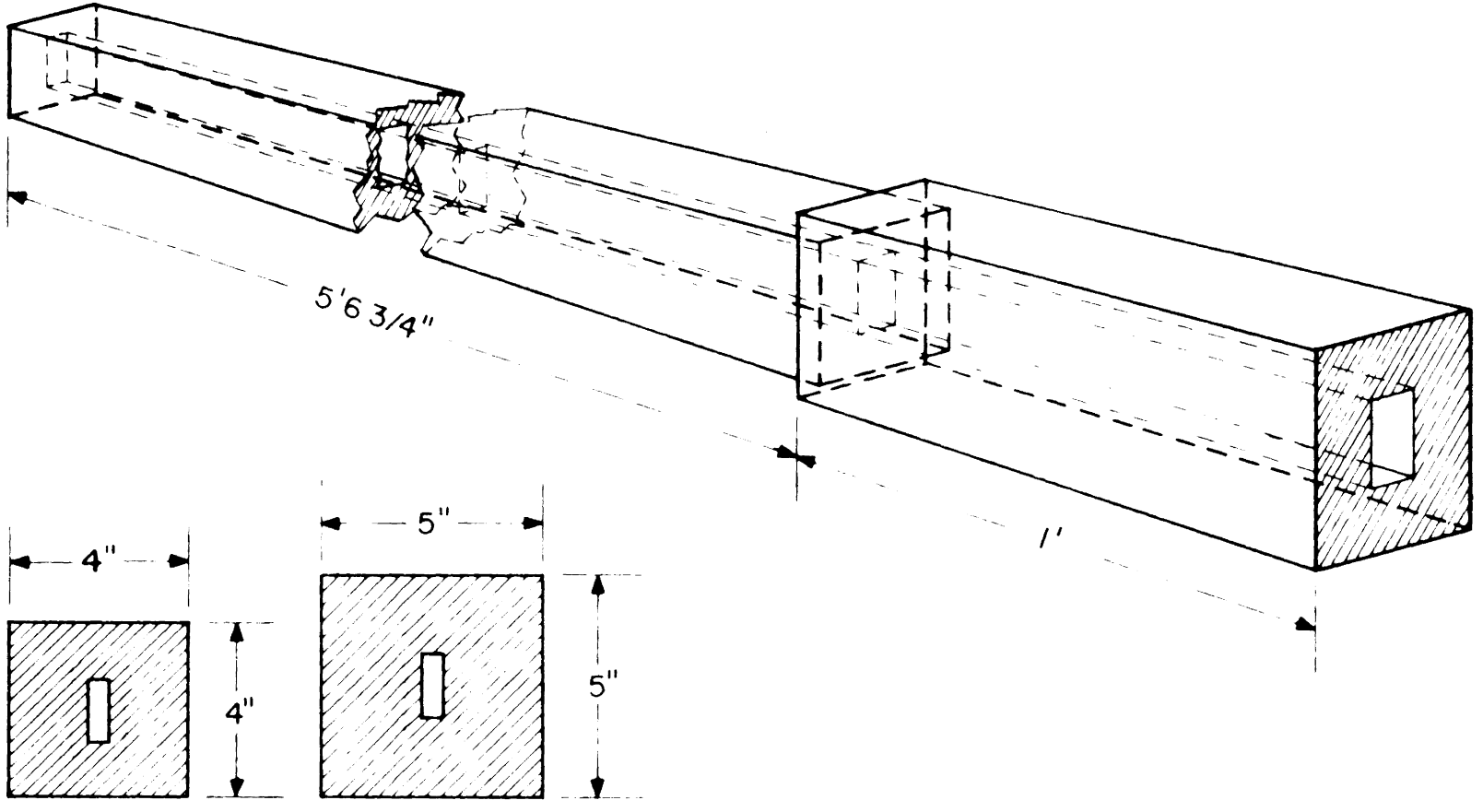

Figure 2 (a). Neutron collimator (inner section). The shaded area represents borax-paraffin.

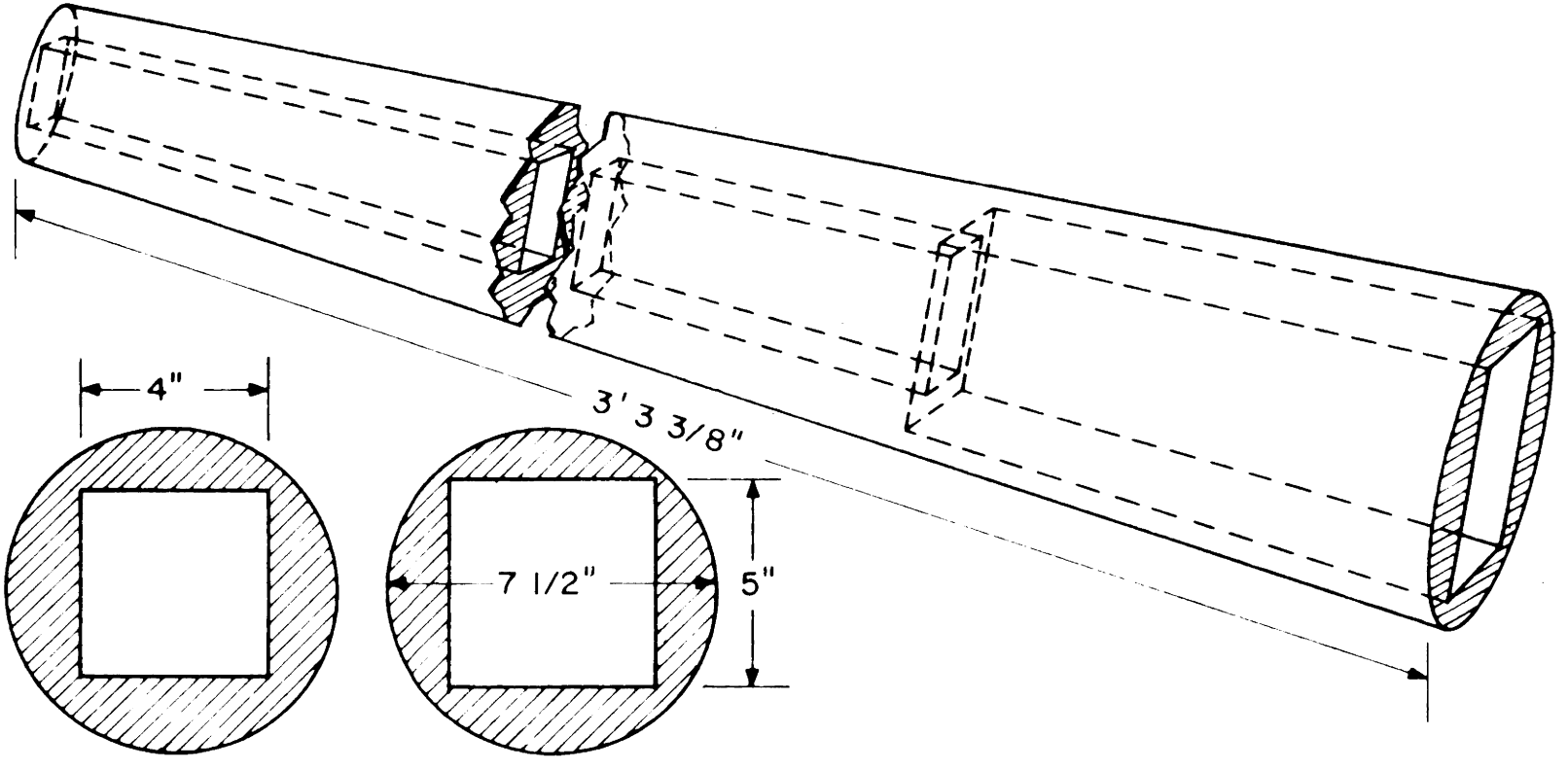

Figure 2 (b). Neutron collimator (outer section). The shaded area represents borax-paraffin.

table is turned through one complete revolution, the scale is turned through the same angle and the crystal table is driven through one-half revolution.

It is necessary for the center of the crystal to be positioned as nearly as possible in the center of the neutron beam, i.e., with respect to the collimator. An aligning tool consisting of a wooden plug from which a pointed steel rod protrudes is fitted into the waveguide. The point of the rod defines the exact position for the center of the crystal table. To bring it to this given position a second pointed steel rod is substituted for the crystal table on the shaft, and the base is moved until the point of the first rod just touches the point of the second. The apparatus is now aligned, since the crystal mount is so constructed that the center of the copper crystal, the detector, and the collimator are the same distances above the floor. (The crystal mount is centered above the crystal table shaft.)

Before placing the crystal on the mount the zero reading of the circular scale is determined by rotating the detector through the neutron beam and counts are taken as a function of angle. A reactor power of five watts provides adequate counting rates for this step. A plot of counting rate versus angular reading yields a symmetrical curve, the peak of which corresponds to the zero reading. Thereafter, each angular determination is made with respect to this zero reading.

The (1,1,1) planes of the copper crystal are vertically arranged

and the Bragg condition is determined for some small crystal angle ($< 30^{\circ}$) by rotating the detector with the crystal fixed. While the reactor is operated at ten kilo-watts, the detector is rotated and a count taken about every ten mils of detector displacement. A plot of counting rate versus detector angle is a curve representing diffracted neutrons, the peak of which corresponds to the angular position which satisfies the Bragg law. This condition is now maintained by engaging the reduction gears. See Figs. 3a and 3b. The Bragg condition is always fulfilled such that when the detector is rotated back until the circular scale is on the zero reading, the (1,1,1) planes make an angle of zero degrees with the incident neutron beam.

A second collimator is placed between the detector and the crystal. It consists of many parallel, two-foot long, 1/32-inch thick cadmium sheets, and is located about four inches in front of the detector. This second collimator is aligned by rotating it in front of the detector until a maximum counting rate is observed, after which it is bolted to the detector supports and remains stationary with respect to the detector.

The resolution of the instrument is given by Eq. 6. The constant α is determined by the dimensions of the collimator while β depends upon the rocking curve. This curve is obtained by rotating the crystal through the Bragg angle, leaving the detector fixed and recording the observed counting rates. This procedure requires the uncoupling of the detector table which involves the removal of a nine-inch diameter

spur gear. This gear is under the detector table and directly above the circular scale. Access may be made through one of the three holes in the top of the base to remove the three socket screws.

The energy of the diffracted neutrons for a set of planes in any crystal may be calculated from the Bragg equation if the lattice constants are known. The lattice constant for copper is 3.608 Angstroms (12); thus the neutron energy can be calculated for a range of crystal angles.

An experimental verification of the calculated energy may be obtained by measuring the total cross section as a function of energy for a suitable substance with the spectrometer. The location of the cadmium resonance at 0.175 ev provides an excellent check. Other resonances which could be used are near thermal resonances in samarium, europium, and lutetium.

The intensity of the beam transmitted through a sample in the diffracted beam is given by the following equation:

$$I = I_o \exp\left[-N\sigma(E)\right] \quad , \tag{15}$$

where I_o is the intensity of the incident beam, N is the number of atoms per square centimeter in the sample, and $\sigma(E)$ is the energy dependent cross section of the sample. Since the Bragg condition is satisfied for every angle due to the coupling between the crystal and detector tables, the neutron energy of the diffracted beam can be determined from the circular scale reading. The transmission T is found by taking counts for equal time intervals with the sample

in and out of the diffracted beam.

$$T = \exp\left[-N\sigma(E)\right] \quad . \tag{16}$$

$$\sigma(E) = (1/N)\ln(1/T) \quad . \tag{17}$$

A comparison of the resonance energy obtained by this transmission method with other sources should show good agreement.

One can get a representation of the neutron energy spectrum by recording the counting rate over a range of energies. The desired energies may be obtained from Eq. 4 by careful selection of the crystal angles or, alternatively, angles can be arbitrarily chosen and the energy calculated.

A determination of the background counting rate at different energies was obtained by inserting a moderator and an absorber between the cadmium collimator and the BF_3 counter. This shutter consisted of a one and one-half inch thick piece of paraffin sandwiched between two sheets of 1/32-inch thick cadmium. This combination effectively absorbed any diffracted neutrons from the crystal, leaving the remaining counting rate due to neutrons directly from the reactor or scattered from the beam. The background was never more than 10% of the total count and was usually less than 5%.

VIII. RESULTS

Due to the orientation of the crystal it was expected that only a single diffraction peak from the (1,1,1) planes of the copper crystal would be obtained. However, when the crystal was set at an arbitrary unknown angle and the counting rate was observed as the detector rotated, a double, rather than a single, diffraction peak was found (Figs. 3a and 3b). After a close scrutiny of the reciprocal lattice constants for this face-centered cubic crystal, it was concluded that the second peak could not be attributed to another set of planes in a single crystal. Therefore, under the assumption that the crystal was a double crystal, it was determined that the average angle between the two sets of (1,1,1) planes was 1.685 degrees. The detector was coupled to the crystal on the first peak by means of the reduction gears because it afforded greatest intensity and resolution. The rocking curve in Fig. 4 seems to exhibit the same double-peaked form.

From Fig. 4 one finds β of Eq. 7 to be 0.0118 radians. Internally the collimator is 78.75 inches long and 5/8 inches wide from which one obtains $\tan(\alpha/2)$ equal to 0.00309, $\alpha/2$ is 0.00308 radians, and $\Delta\theta$ is 0.0118 radians from Eq. 7.

The resolution as a function of crystal angle calculated from Eq. 6 is tabulated in Table 1 and shown in Fig. 5. These values are based on the assumption that the diffracting crystal is a single crystal; thus the resolution is actually less than that indicated

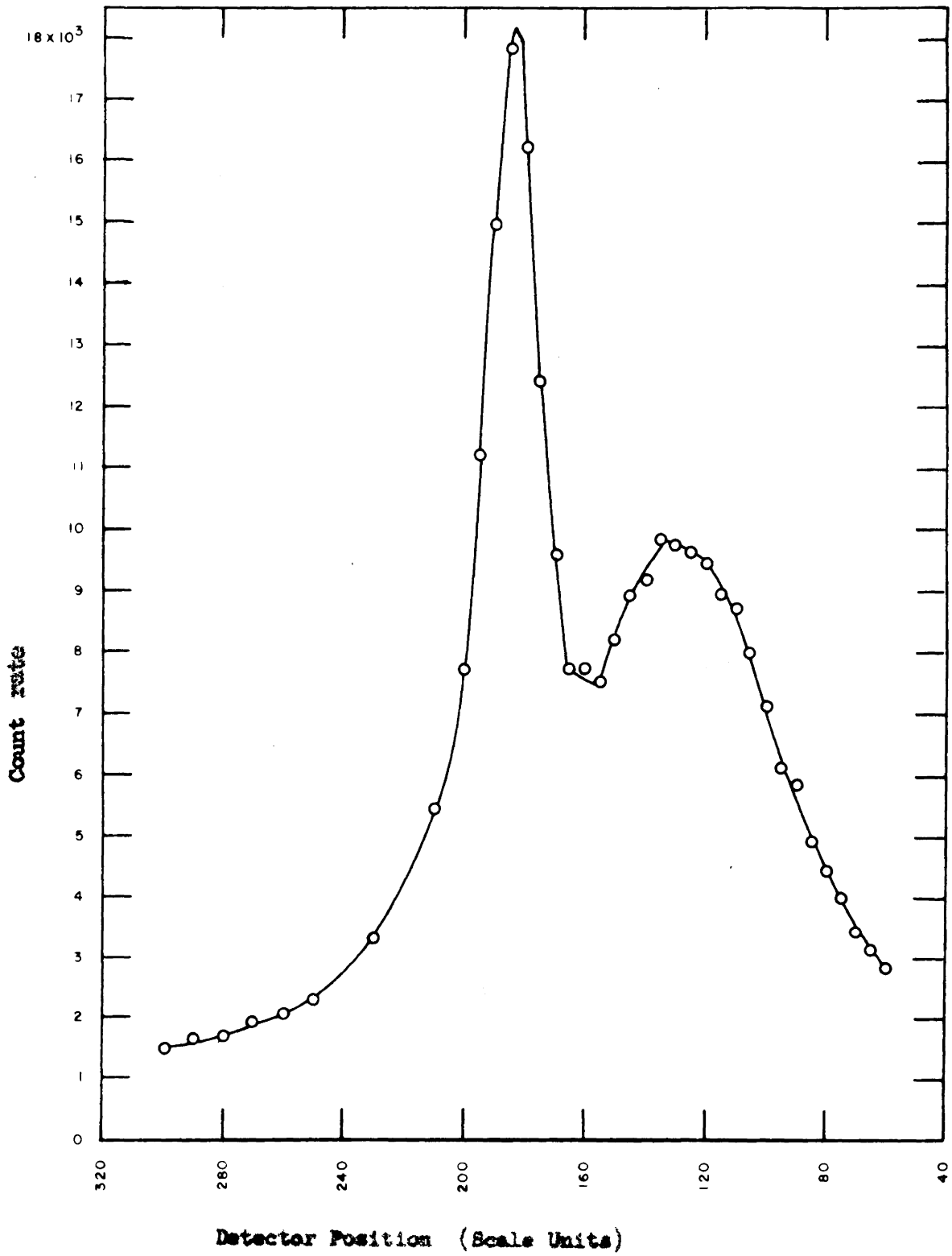

Figure 3 (a). Counts per 1.5 minute time interval as a function of detector angular position for a fixed crystal angle θ_1. One scale unit represents 10 mils and the zero reading is 717.

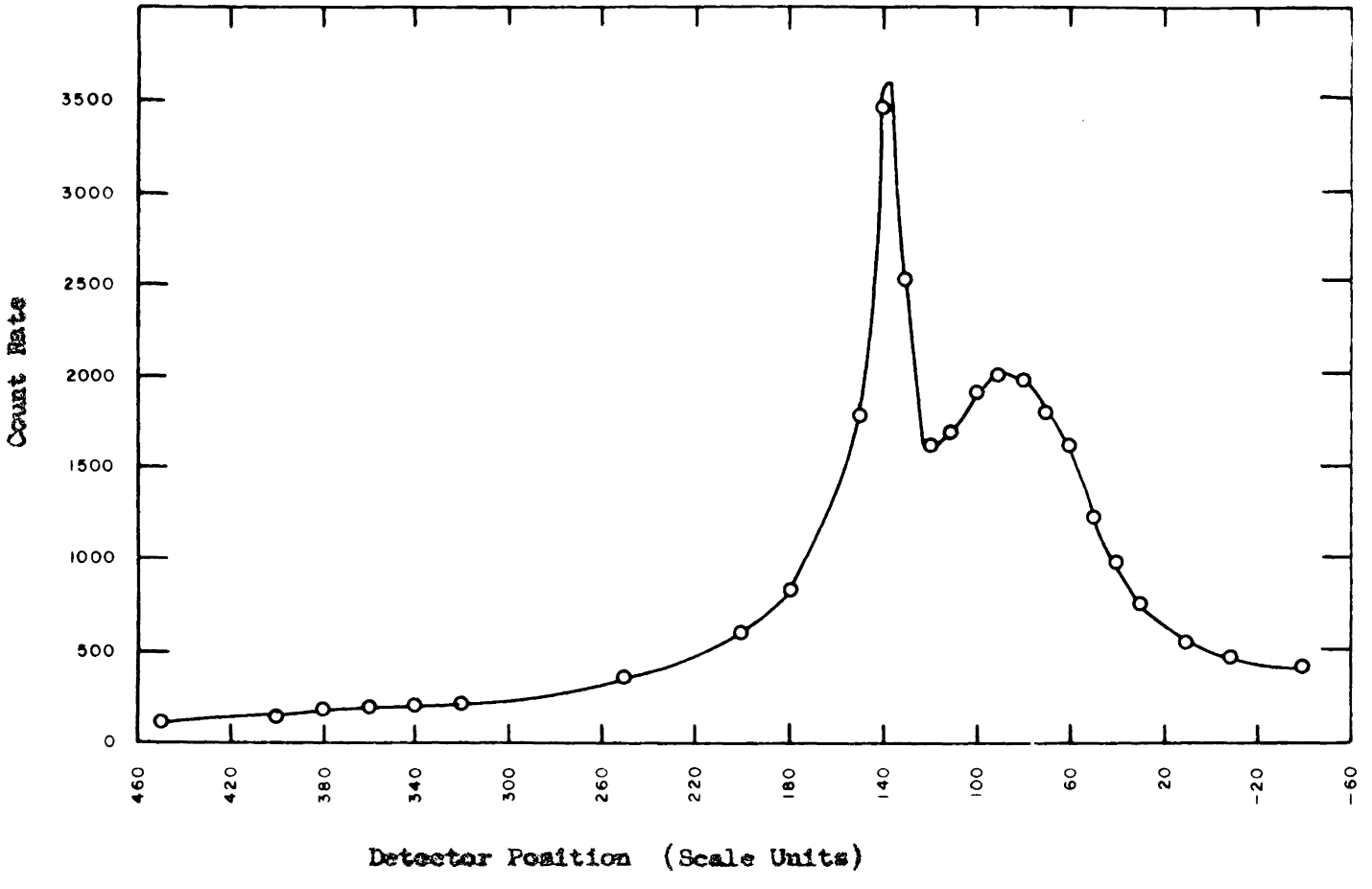

Figure 3 (b). Counts per 0.3 minute time interval as a function of detector angular position for a fixed crystal angle θ_2.

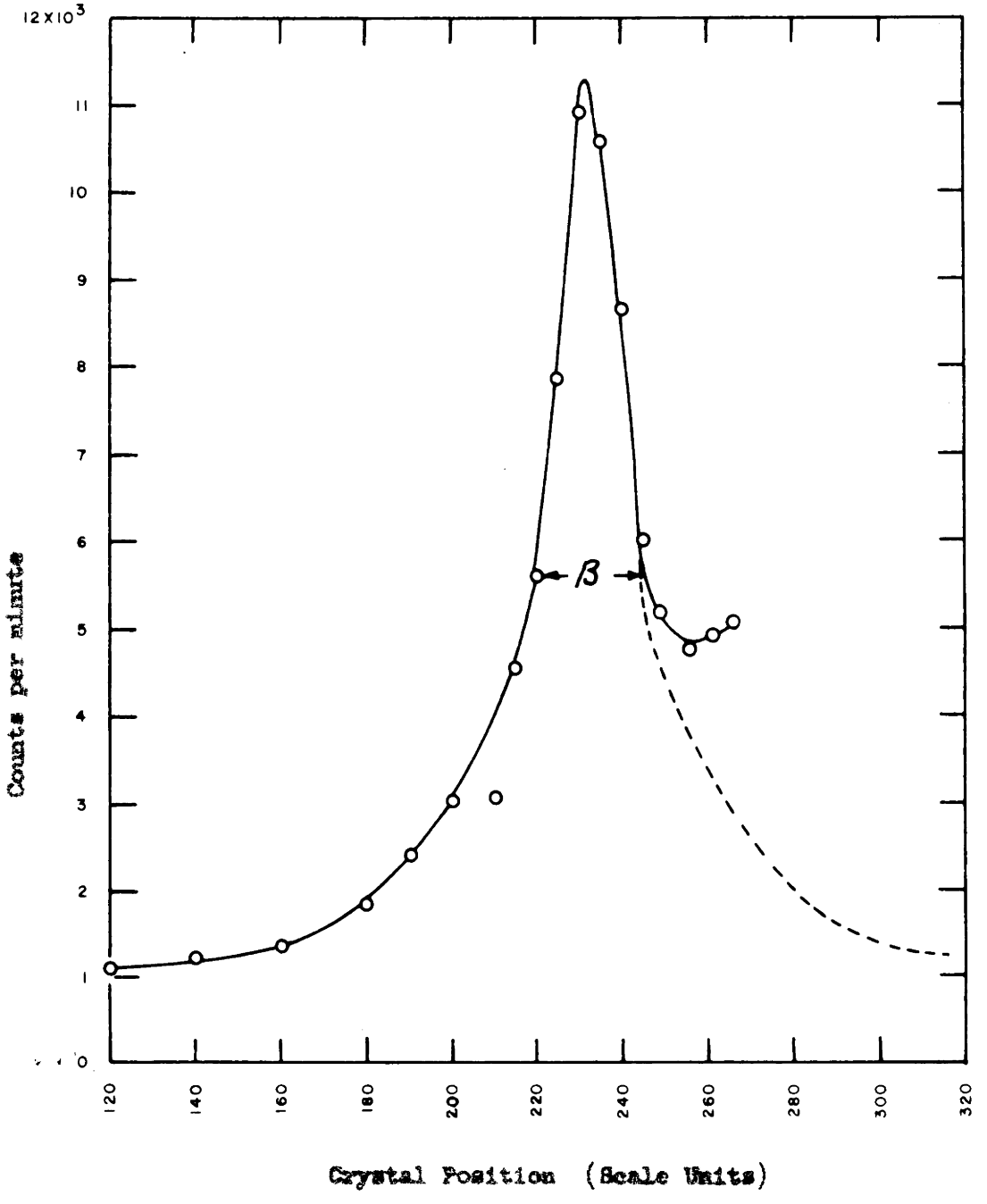

Figure 4. Rocking curve. One scale unit represents 5 mils.

Table 1. Resolution of the spectrometer assuming a single crystal.

Energy (ev)	θ	$E/\Delta E$
1.00	3°55'	2.90
0.90	4 08	3.06
0.80	4 23	3.25
0.70	4 41	3.47
0.60	5 03	3.75
0.50	5 32	4.11
0.40	6 12	4.62
0.30	7 10	5.34
0.20	8 47	6.57
0.10	12 28	9.36
0.09	13 09	9.92
0.08	13 58	10.6
0.07	14 57	11.3
0.06	16 11	12.3
0.05	17 47	13.7
0.04	19 58	15.4
0.03	23 13	18.2
0.02	28 13	22.8
0.01	43 03	39.6

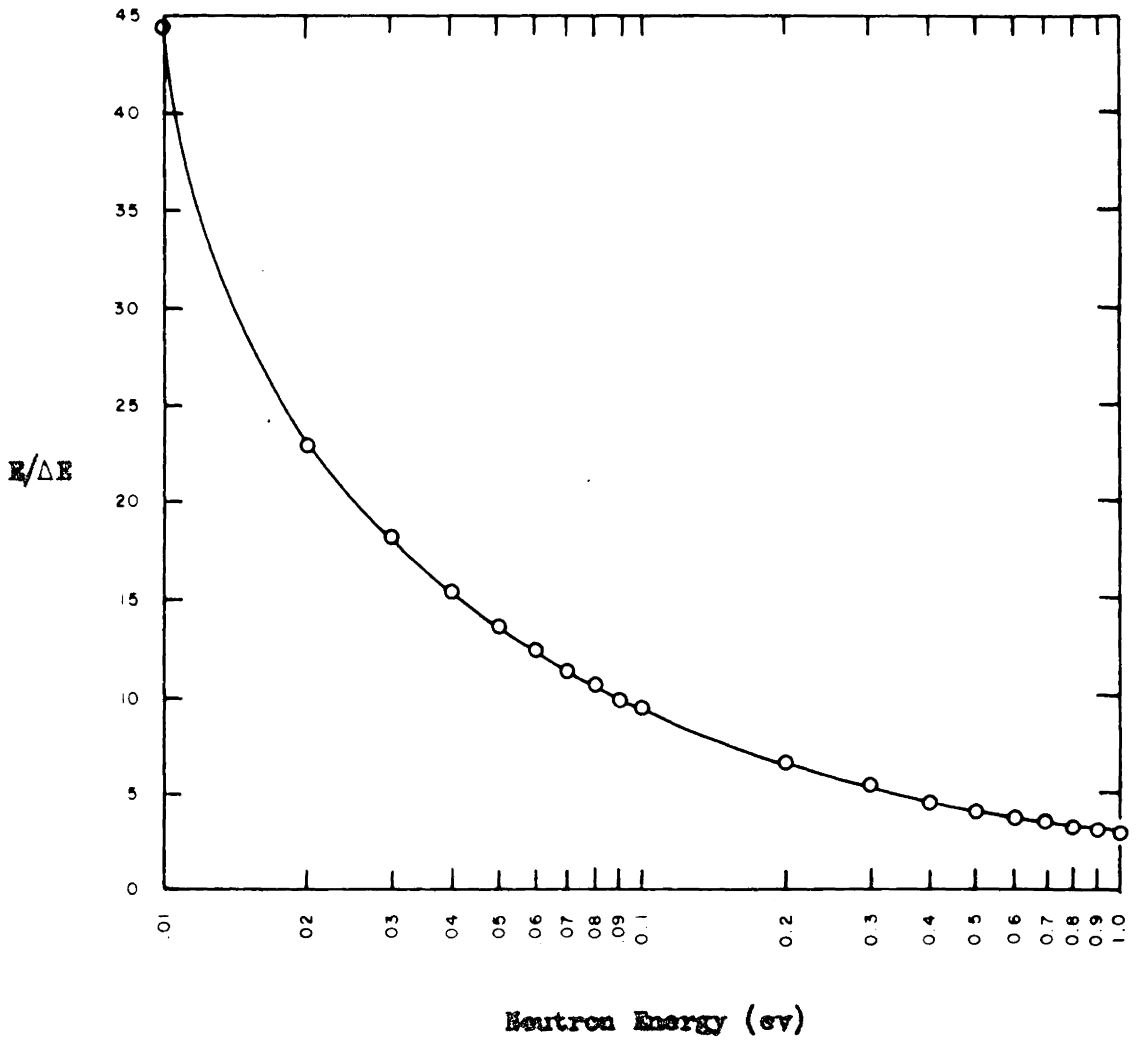

Figure 5. Calculated resolution versus neutron energy from Table 1.

by the curve.

The surface density, N, of atoms in the cadmium foil used for measuring cross sections was determined to be 0.0032×10^{23} atoms per square centimeter. The experimental total cross section calculated with the aid of Eq. 12 agrees quite well with the theoretical curve over the energy range from 0.03 to 0.1 ev, but departs rapidly as higher energies are approached (Fig. 6). This departure is attributed to poor resolving power at small angles and, also to the previously discussed crystal imperfection, since neutrons with different energies are diffracted into the detector from the second set of planes. Approaching low energies from the resonance peak one observes a deviation from the BNL curve beginning at 0.03 ev. The presence of these second order neutrons was predicted by Eq. 8 and the second order spectrum in Fig. 9. Of significance is the fact that the energy of the resonance peak is within experimental error of 0.175 ev, which is indicated by the horizontal error triangles. The poorer resolution at higher energies would have just the effect seen, a slight shifting of the observed resonance peak to lower energy. The cross section and spectrum data are corrected for detector efficiency and background in accordance with Figs. 7 and 8.

The peak of the thermal spectrum in Fig. 9 for the V.P.I. reactor is shifted toward higher energy from that of the theoretical curve. Sturm and Arnold (13) indicate that this is to be expected for a neutron spectrometer operated at reduced resolving power. A Maxwellian distribution of thermal neutrons, second order neutrons, and epithermal neutrons varying as the inverse of the energy compose

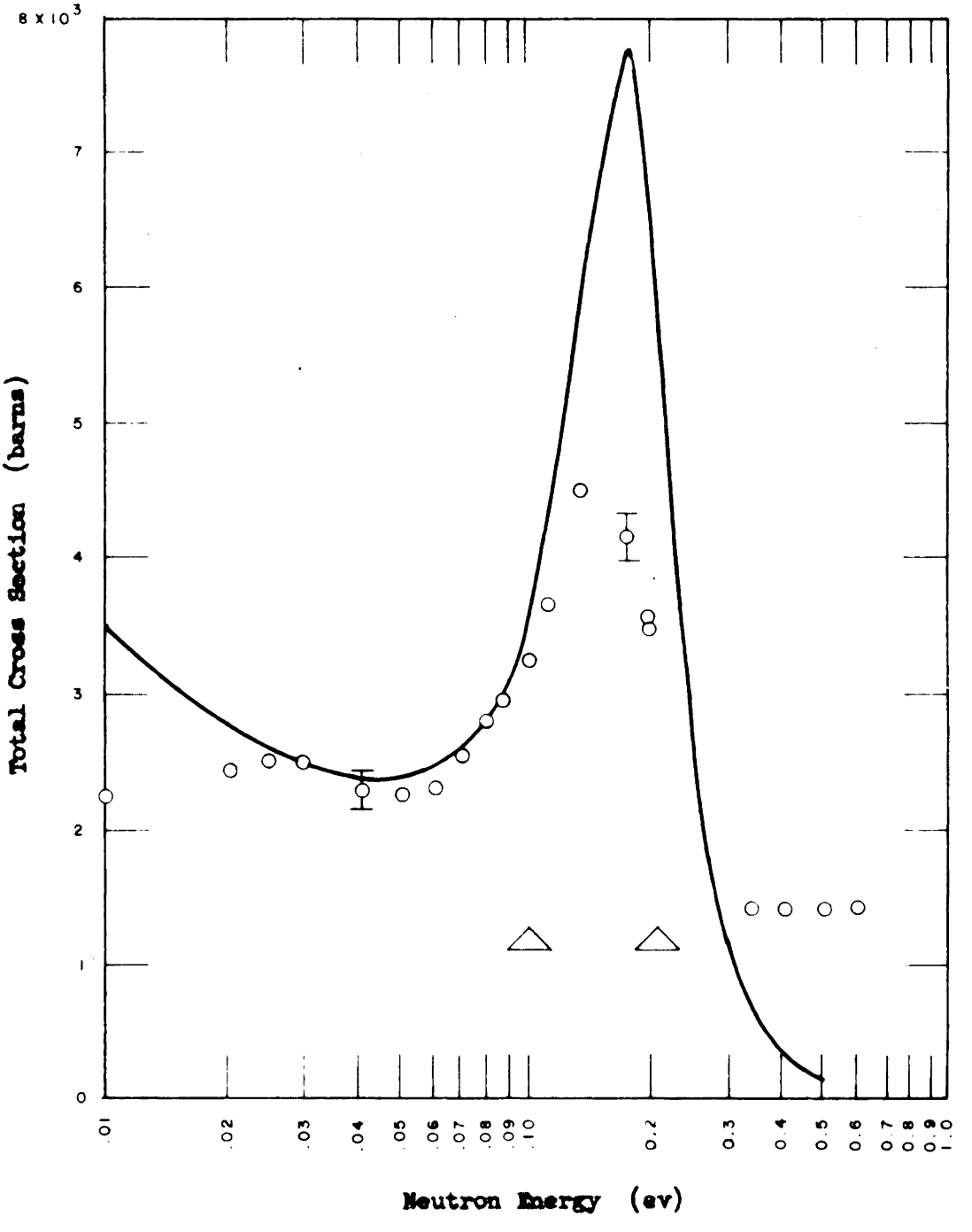

Figure 6. A comparison of cadmium total cross section data as a function of neutron energy with BNL 325 curve.

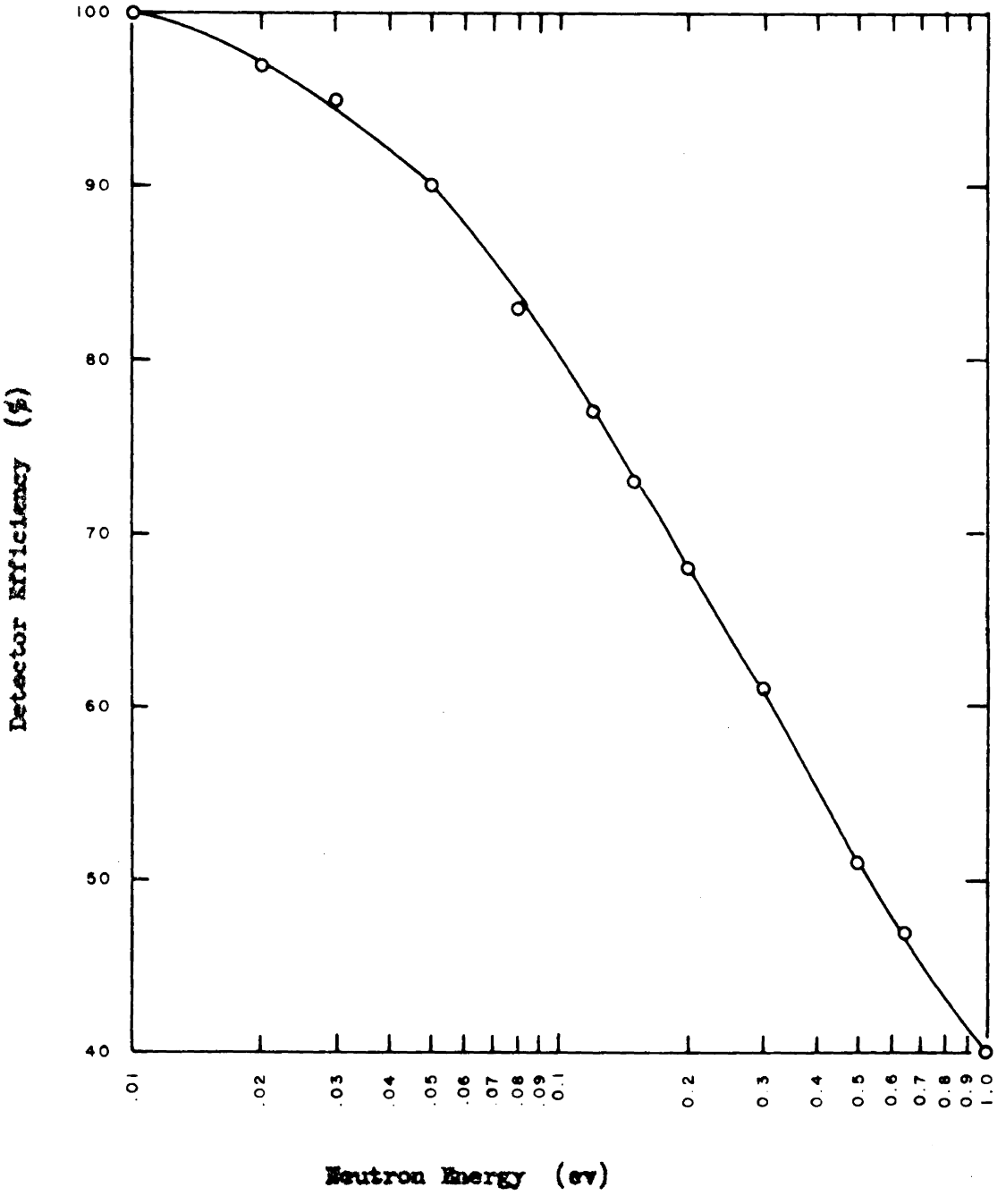

Figure 7. Detector efficiency for a range of neutron energies.

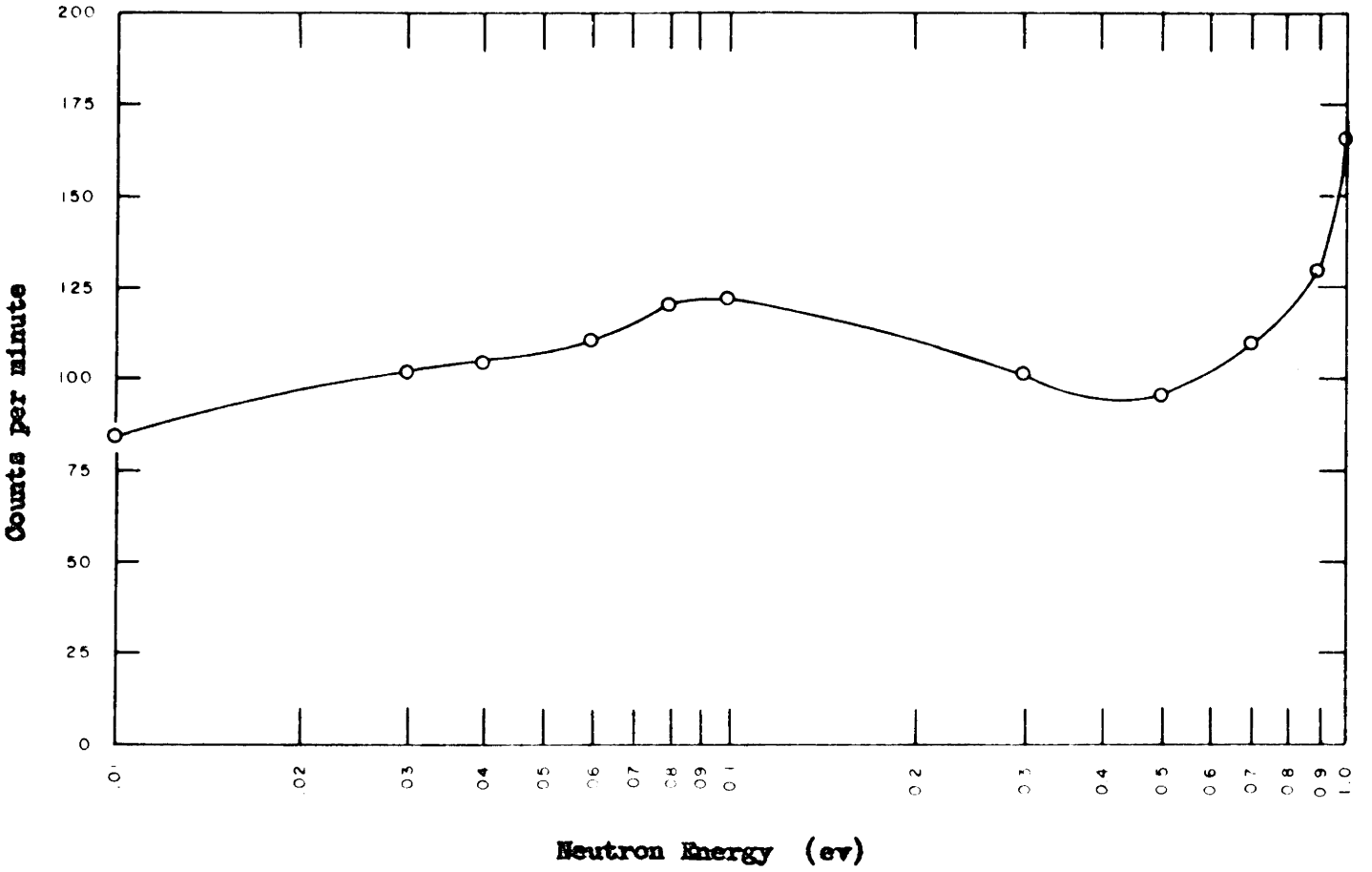

Figure 8. Background counting rate. There are no expected values with which to compare this curve.

Table 2. Neutron energy spectrum from north reactor side port corrected for background and detector efficiency. T = 310°K. The counts for which errors were calculated are average values.

Energy	Counts	Time (minutes)	CPM	CPM minus background	$\frac{CPM-BG}{\epsilon}$
1.00	4130	5	826	660	1650 ± 228
0.90	4205	5	841	712	1758 ± 228
0.80	4473	5	895	751	1746
0.70	4716	5	943	833	1852
0.60	4799	5	960	850	1771
0.50	5111	5	1022	927	1818
0.40	5400	5	1080	995	1809
0.30	6652	5	1330	1230	2016
0.20	10261	5	2052	2042	3003
0.144	3742	1	3742	3625	4866
0.103	6829	1	6829	6707	8436
0.100	38821	5	7764	7642	9553
0.090	7420	1	7420	7300	8957 ± 201
0.086	7909	1	7909	7789	9499
0.083	9255	1	9255	9135	11006
0.080	10066	1	10066	9946	11983
0.078	9471	1	9471	9351	11132
0.076	9301	1	9301	9187	10937
0.073	10087	1	10087	9970	11729
0.070	9537	1	9537	9422	11085
0.060	9073	1	9073	8962	10242 ± 77
0.050	6457	1	6457	6352	7058
0.040	5213	1	5213	5100	5543
0.030	3287	1	3287	3187	3355
0.025	5088	2	2544	2444	2546
0.020	6679	3	2226	2130	2196
0.010	5323	5	1117	1033	1033

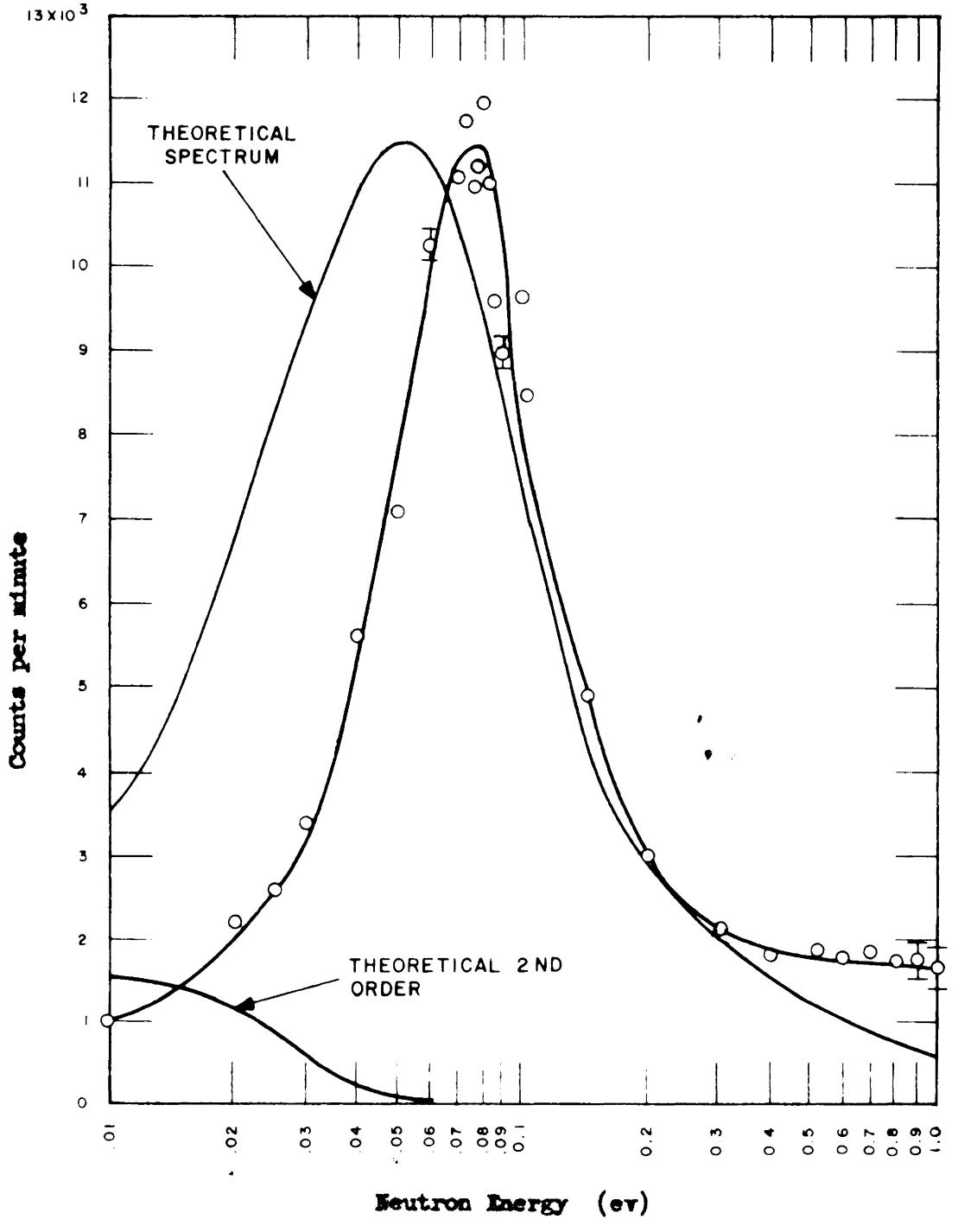

Figure 9. Neutron energy spectrum from the reactor obtained with the V. P. I. spectrometer, and the theoretical spectrum at 310°K.

the theoretical spectrum curve. The experimental spectrum exhibits a rough Maxwellian distribution peaked at 0.075 ev, distorted on the low energy side of the peak by second order neutrons, and on the high energy side by the presence of high energy neutrons. Perhaps the deviation between these two curves is partially due to incomplete thermalization, since these neutrons have not diffused through any considerable column of moderator material.

IX. CONCLUSIONS

These data confirm the calibration of the instrument and demonstrate the necessity of a carefully selected single crystal for experimental applications. The (1,1,1) planes of LiF are recommended since the second order neutrons are suppressed. Care should be taken to match up the rocking curve half width to the divergence angle of the beam because matching these two components affords a much needed compromise between intensity and resolution. The intensity may be increased at the expense of the resolution by roughing the surface of the crystal (12) thus increasing the mosaic spread.

It is felt that the mechanical reliability of the instrument has been clearly demonstrated while the deviations from the anticipated results may probably be attributed to the unfortunate and unexpected difficulty of having a twinned crystal.

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ABSTRACT

A single crystal neutron spectrometer using a copper crystal has been designed and constructed for the purpose of studying the low energy (< 1 ev) neutron spectrum from the V. P. I. reactor. The basic theory necessary for the design, the details of the spectrometer, calibration data and method of operation are presented in this thesis. A relation between angle of diffraction and neutron energy is obtained from the known lattice spacings of the copper crystal. A measure of the total cross section of cadmium from 0.01 to 1.0 ev has been obtained from transmission data for a thin cadmium sheet. The position of the low energy resonance peak confirms the computed calibration. The resolution of the instrument and the intensity of the diffracted beam as a function of energy were studied in order to ascertain the usable range of the spectrometer.