STUDY OF BORRMANN SCATTERING IN SILICON CRYSTAL

by

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CHAPTER I

INTRODUCTION

Purpose of the Experiment

There are two different theories[1] which are used to explain the intensities observed in the x-ray diffraction studies: the kinematical theory and dynamical theory. Kinematical theory is based on the main assumption that waves once scattered by electron cloud surrounding an atom, are supposed to pass out of the crystal without further scattering. But the secondary waves might produce scattering as it passes through the crystal. This is the break-down of the validity of kinematical theory. However, dynamical theory takes the secondary scattering into account properly, including all the wave interactions inside the crystal lattice while diffraction is taking place as a single entity.

A very remarkable confirmation and extension of theory of x-ray diffraction began in 1948[2] with the first observation by G. Borrmann[3] of what is now called the "Borrmann effect". The Borrmann effect demonstrates the property of anomalous transmission with a nearly perfect crystal. A nearly perfect crystal becomes more transparent to a collimated monochramatic x-ray beam as the crystal is rotated through the Bragg angle in transmission type of Bragg reflection.

The Borrmann transmission was demonstrated photographically using a calcite crystal of thickness 0.27 cm for Cu-Kα rays. An exposure of one hour was necessary.[4] By simple mass action the incident beam should have suffered a reduction in intensity by a factor 10^{-12}, whereas observation showed a factor of about 10^{-4}.

The purpose of the experiments reported here is to study the Borrmann effect in silicon crystal:

1. To study the properties of the Borrmann transmitted beam involving (111) planes of silicon crystal, cut at an angle of 70.53° with respect to the surface, using a collimated beam of copper $K\alpha_{1,2}$ radiation.

2. To study the intensity variation of Borrmann transmitted beam for different currents in x-ray tube, keeping the voltage constant.

3. To measure the mass absorption coefficient of silicon at Borrmann setting angle and compare it with the normal value of the mass absorption coefficient of silicon.

CHAPTER II

PHENOMENOLOGICAL THEORY OF ANOMALOUS TRANSMISSION THROUGH NEARLY PERFECT CRYSTAL

The phenomenon of anomalous transmission was first observed by Borrmann. The basic feature of Borrmann effect[5] is sketched diagrammatically in Figure 1 and 2. In Figure 1, a single crystal is cut in a parallel-sided slab such that the planes used in the diffraction are perpendicular to the slab face. When the crystal is arranged for diffraction-setting, the intensity of the transmitted beam as a function of the angle of incidence is expressed in Figure 3. It is observed when $\theta \neq \theta_\beta$ as given by the Bragg law $\lambda = 2d\sin\partial_\beta$,[6] the transmitted beam is given by the usual expression that involves predominantly the photoelectric absorption:

$$I_t = I_o e^{-(\mu/\rho)\rho\, t}$$

where:

I_t is the intensity of the transmitted beam;

I_o is the intensity of the incident beam;

μ/ρ is the mass absorption coefficient;

ρ is the density of the crystal;

t is the thickness of the crystal.

But when $\theta = \theta_\beta$ (the Bragg angle), suddenly a peak is observed in the transmitted intensity and the value of μ/ρ decreases significantly. The experimental sketch in Figure 2 demonstrates that this peak is due to a diffraction effect. In Figure 2, the film shows three spots

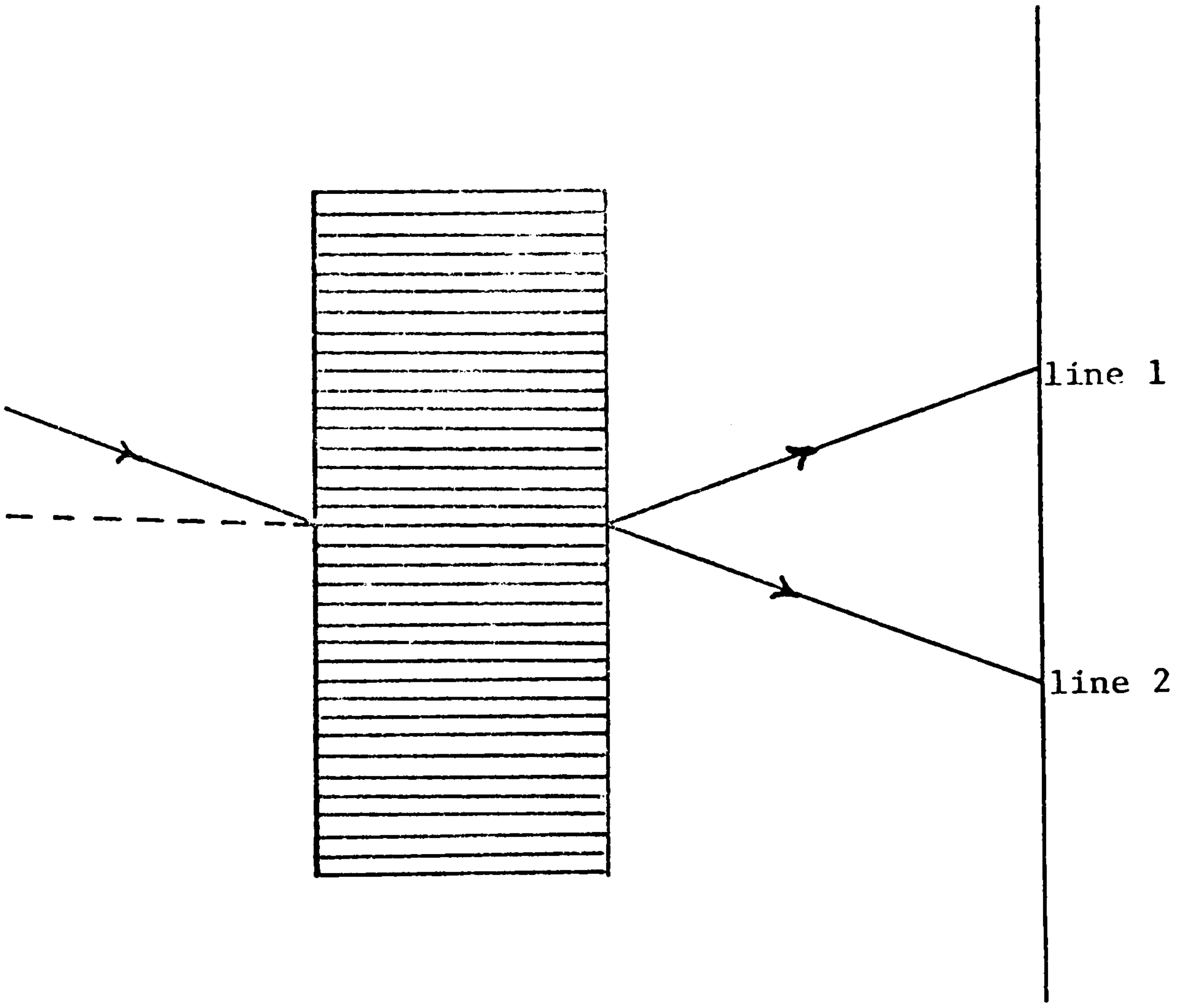

Figure 1. Borrmann transmission

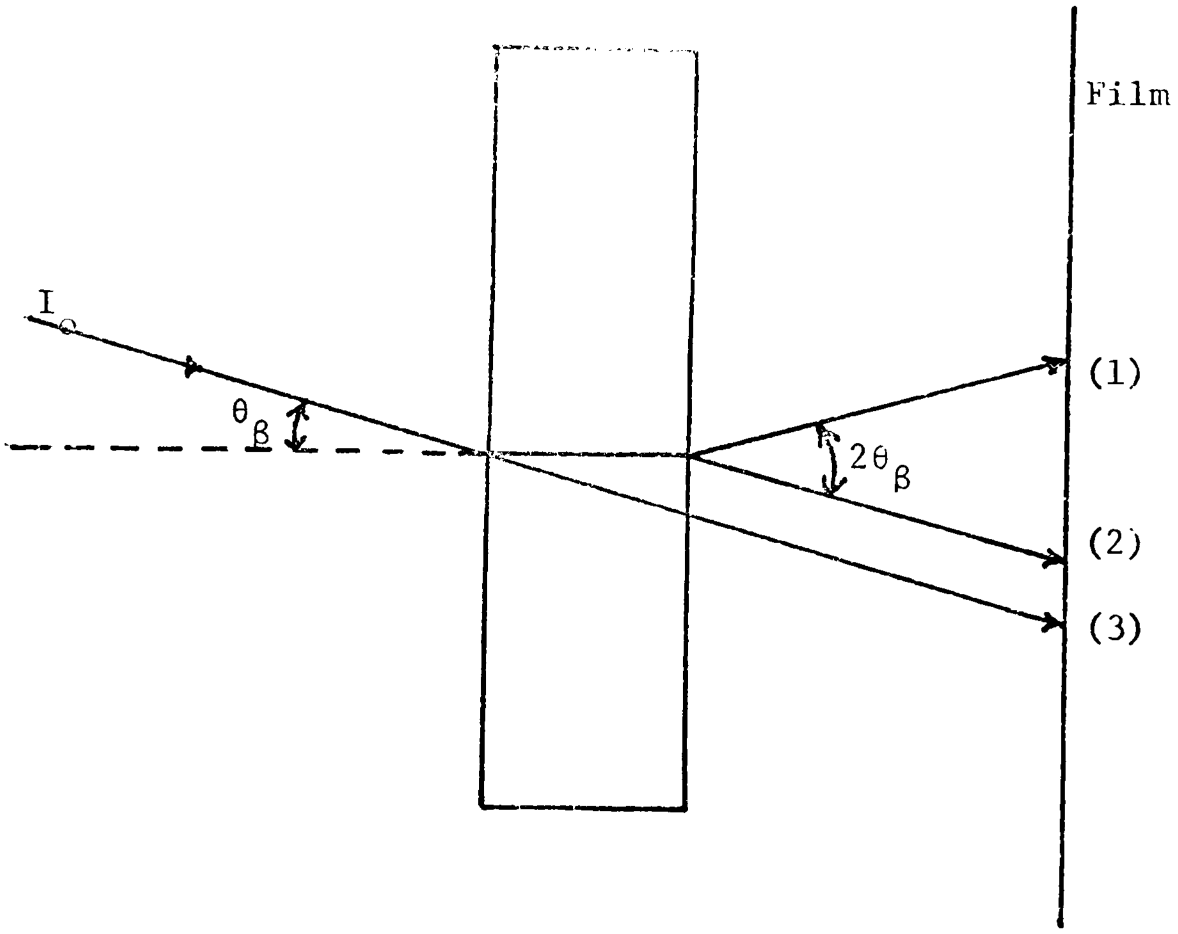

Figure 2. Geometry of the beams when anomalous transmission is occurring.

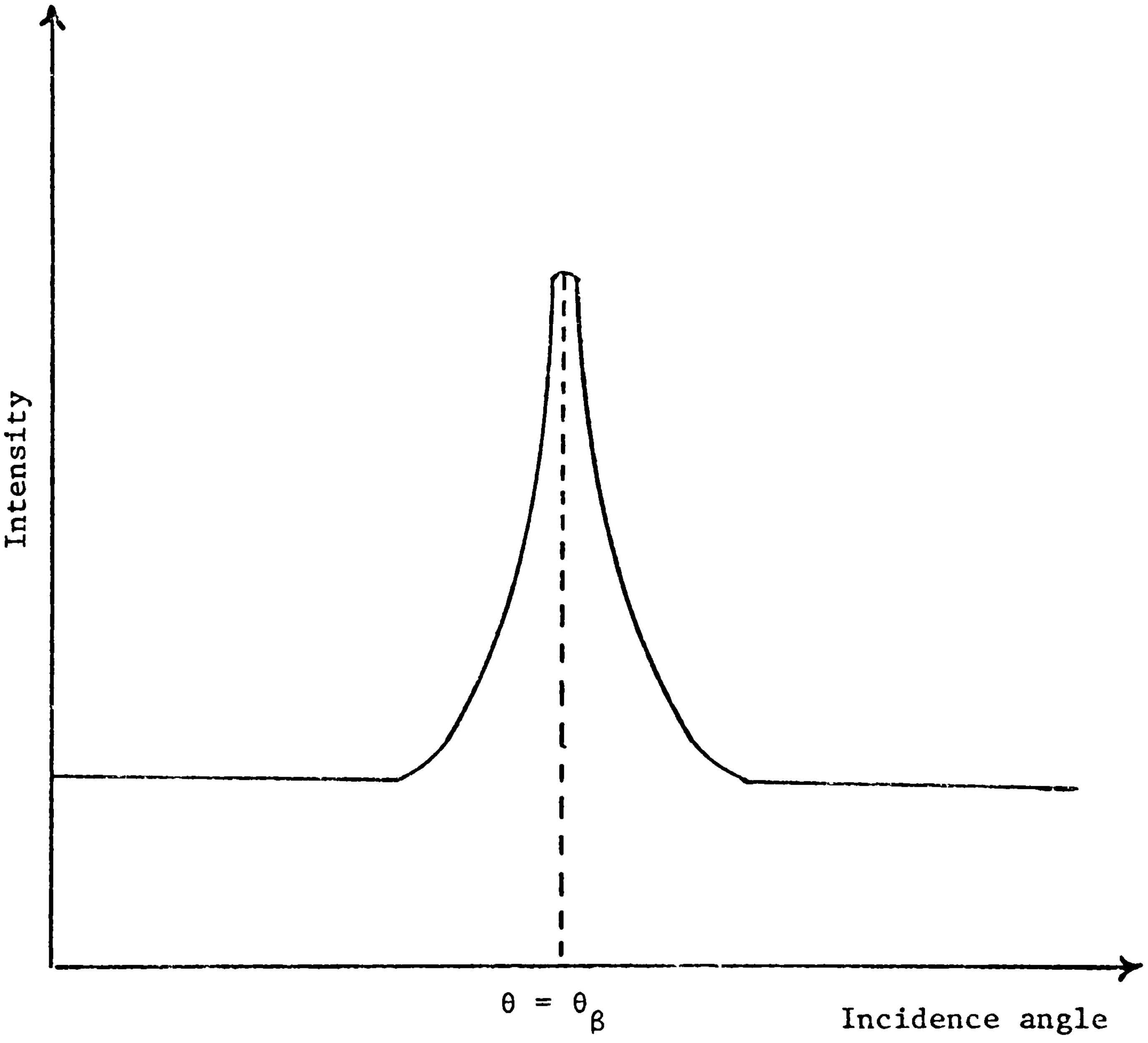

Figure 3. Intensity of transmitted beam vs angle of incidence (schematic)

Spot 1 is the forward diffracted beam, spot 2 is also a forward diffracted beam of about the same darkening as spot 1 parallel to the primary incident beam. The separation between the primary beam producing spot 3 and spot 2 is determined by the thickness of the crystal. The angle between the beams producing spot 2 and spot 3 is $2\theta_\beta$.

Spot 3 is the transmitted beam. From the geometry shown in Figure 2, it is clear that the radiation forming spot 1 and 2 emerged from the crystal at a point opposite the point where the incident ray struck the crystal. These two spots 1 and 2 are called "Forward diffracted beam" rather than the transmitted beam.

It has been argued[7] that at the Bragg angle setting in transmission type configurations, the standing mode of photons exist inside the lattice, with nodal planes parallel to the atomic planes. The same thing happens when a light beam bounces back and forth between two parallel mirrors. This is attributed to the experimental observation of a decrease in photoelectric effect at the Bragg setting. Batterman and Cole pointed out, "In the x-ray case, if the crystal structure is simple enough the nodes of the standing-wave pattern can coincide with the atomic sheets and so very little photoelectric absorption can take place."[8] A rather direct verification of the nodal picture described above was given by Batterman[9] who used the secondary fluorescent emission as a probe of electric field strength (and absorption) at the atom. In the x-ray case, Mo-Kα radiation is sufficiently energetic to excite the K fluorescence of Ge, which, itself is of sufficiently short wavelength to readily escape from the crystal and be easily detected. Thus if the

GeKα fluorescence radiation is measured while a perfect crystal of Ge, exposed to a beam of Mo Kα radiation is slowly rotated through a strong Bragg reflection, the field at the atoms can be determined.

In the experimental curve as expressed in Figure 4, the upper curve is the Bragg reflection of Mo Kα radiation while the lower curve is the Ge K fluorescence.

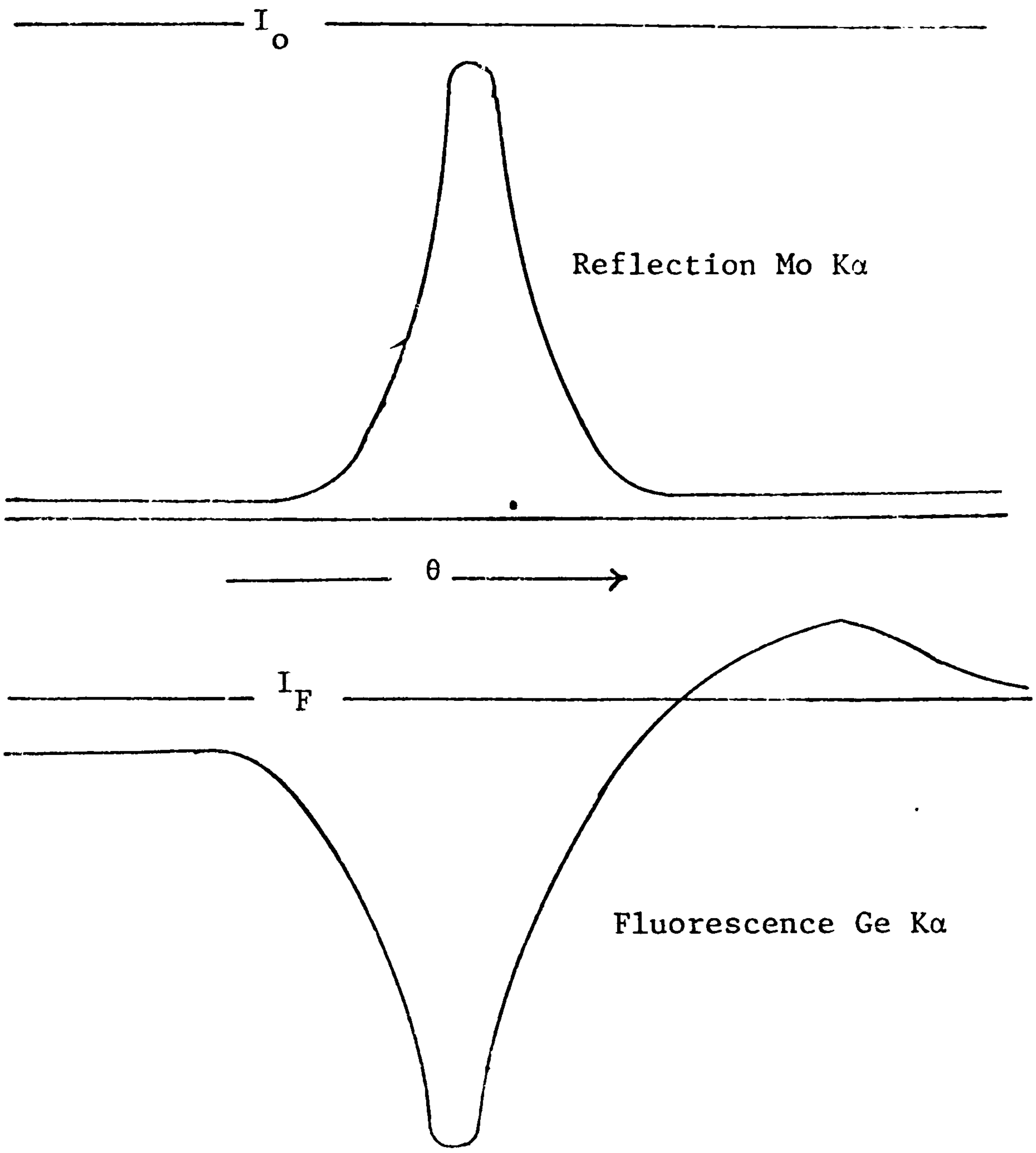

Figure 4. Fluorescence measured during a rotation through a Bragg peak.

CHAPTER III

EXPERIMENTS AND RESULTS

Intensity of Borrmann Transmission Lines As a Function of Tube Current

In the experiment the x-ray tube has a copper target. The width of the slit is 0.25 mm and the length is 4 cm. A monochromator is used for the Borrmann transmission. The crystal is silicon, cut especially for (111) plane, n-type, doped with phosphorus; the thickness is 0.040 inch = 1.016 ± 0.003 mm. The resistance is 0.008 ohm-cm. The silicon crystal used in the Borrmann transmission is expressed as Si(1).

The silicon crystal Si(1) is set first for surface Bragg reflection in the monochromator. The angle between planes for the silicon crystal, which is a cubic lattice, is expressed by:[10]

$$\cos \phi = \frac{h_1h_2 + k_1k_2 + l_1l_2}{\sqrt{(h_1^2 + k_1^2 + l_1^2)\,(h_2^2 + k_2^2 + l_2^2)}}$$

where ϕ is the angle between the plane $(h_1k_1l_1)$ and $(h_2k_2l_2)$ and h, k, and l are the Miller indices. In this experiment, silicon is cut for (111), so that the angle between (111) and $(\bar{1}11)$ is:

$$\cos \phi = \frac{-1 + 1 + 1}{\sqrt{(1^2 + 1^2 + 1^2)\,(-1^2 + 1^2 + 1^2)}}$$

where:

$$\cos \phi = 1/3$$

$$\phi = \cos^{-1} 1/3$$

$$\phi = 70.53°$$

The crystal Si(1) is set for the Bragg reflection from the surface (111) planes at 14°13' Bragg angle for copper Kα radiation. According to the orientation of the crystal being used, the rotation of the crystal is counter-clockwise, through an angle of 70°30', as expressed in Figure 5. To obtain the Borrmann setting angle a peak is recorded by the Geiger-counter. The Borrmann effect for copper Kα radiation is registered photographically as shown in Figure 6. The x-ray tube was operated at 40 Kev, 15 mA. The photographic film was kept at a distance q = 80 cm away from the crystal and the exposure time was 3.5 hours.

In order to study the intensity variation of Borrmann transmission lines, a scintillation counter is used to record the intensity (expressed as counts/second) with respect to various voltages and currents. Tables I, II, and III show the intensity of Borrmann transmission lines of Kα_1 and Kα_2 with voltages at 35 Kev, 40 Kev, and and 45 Kev currents changing from 5 mA, 7.5 mA, 10 mA, 12.5 mA, 15 mA, 17.5 mA, 20 mA, 22.5 mA, and 25 mA. Figures 7, 8, and 9 are the graphs of the intensity vs. currents at various voltages.

A set of four pictures of Borrmann transmission are shown in the contact print in Figure 10. The conditions of the four pictures are:

1. Voltage is 40 Kev, current is 5 mA, exposure time 9 hours;
2. Voltage is 40 Kev, current is 10 mA, exposure time 4.5 hours;

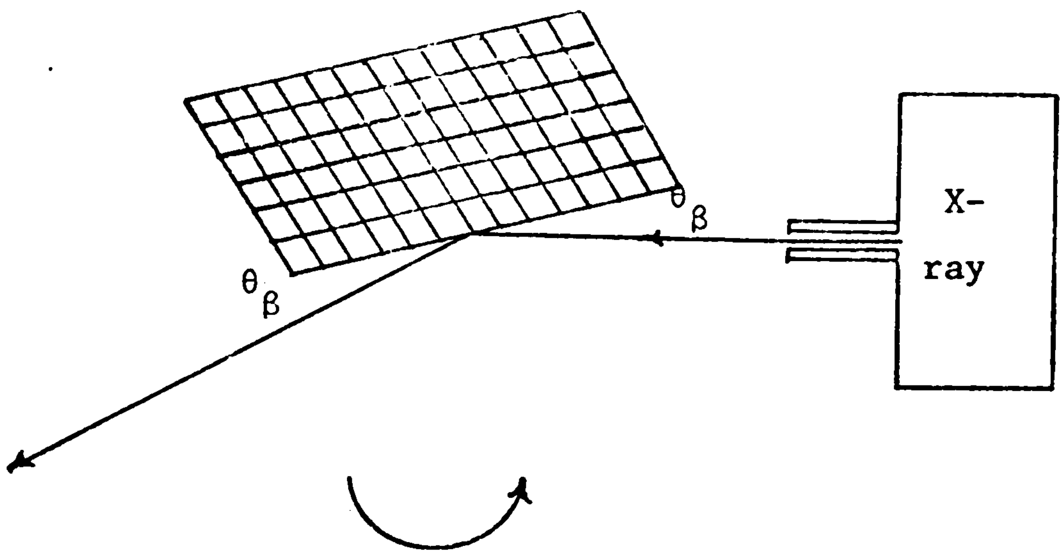

Figure 5a. A collimated Cu target radiation with angle divergence = 0.71° is in Bragg reflection position from surface of crystal wafer cut parallel to (111) planes. Observed angle = 14° 13' on the spectrometer scale.

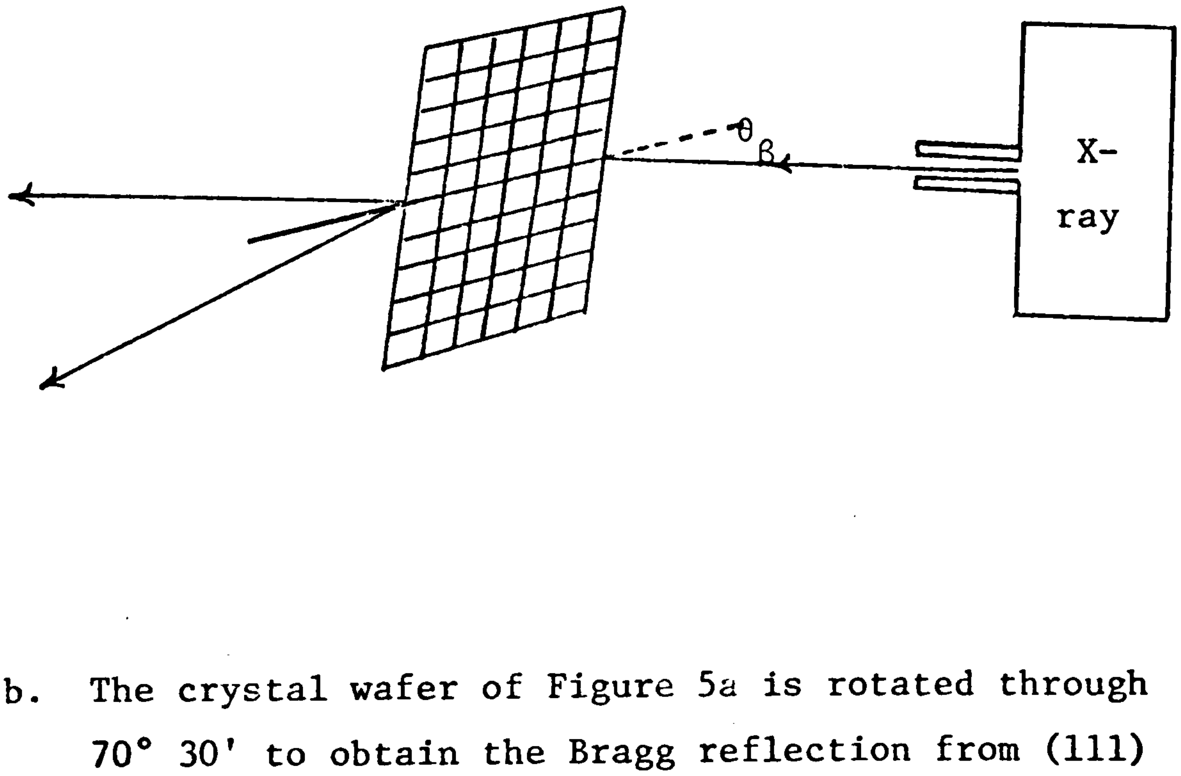

Figure 5b. The crystal wafer of Figure 5a is rotated through 70° 30' to obtain the Bragg reflection from (111) plane for the beam transmitted through the crystal.

Figure 6. Borrmann transmission. The crystal is 800 times transparent to Cu Kα radiation at the Bragg-Borrmann angle.

Table I. Intensity of Borrmann transmission with respect to currents at voltage 35 Kev. (Silicon, n-type crystal phosphorus doped, thickness is 1,016 mm.).

Voltage : 35 Kev

Tube Current (mA)	Observed Intensity (counts/100 sec)	Intensity (count/sec)
5	8124	81
	8070	
	8051	
7.5	10530	105
	10541	
	10514	
10	13422	134
	13303	
	13378	
	13433	
12.5	16571	166
	16615	
	16629	
15	19557	197
	19738	
	19673	
	19801	
17.5	22601	226
	22640	
	22559	
20	25406	254
	25518	
	25327	
22.5	27793	278
	28012	
	27699	
	27694	
25	30068	301
	30295	
	30175	
	30053	

Table II. Intensity of Borrmann transmission with respect to currents at voltage 40 Kev. (Silicon, n-type crystal, phosphorus doped, thickness is 1,016 mm.).

Voltage : 40 Kev

Tube Current (mA)	Observed Intensity (counts/100 sec)	Intensity (count/sec)
5	13362	134
	13417	
	13392	
7.5	18765	188
	18843	
	18791	
10	23477	234
	23312	
	23459	
12.5	28650	289
	28934	
	29054	
15	34648	345
	34235	
	34505	
17.5	39298	391
	39114	
	38892	
20	45033	451
	45215	
	44928	
22.5	49981	497
	49637	
	49439	
25	54906	550
	55008	
	55213	

Table III. Intensity of Kα_1 and Kα_2 of Borrmann transmission lines with respect to currents at voltage 45 Kev. (Silicon, n-type crystal, phosphorus doped, thickness is 1.016 mm.).

Voltage : 45 Kev

Tube Current (mA)	Observed Intensity (counts/100 sec)	Intensity (count/sec)
5	19997	201
	19999	
	20158	
7.5	27576	276
	27722	
	27574	
10	34782	347
	34560	
	34898	
12.5	41094	410
	41028	
	41010	
15	49742	497
	49658	
	49780	
17.5	57728	479
	57289	
	57553	
20	64807	646
	64445	
	64473	

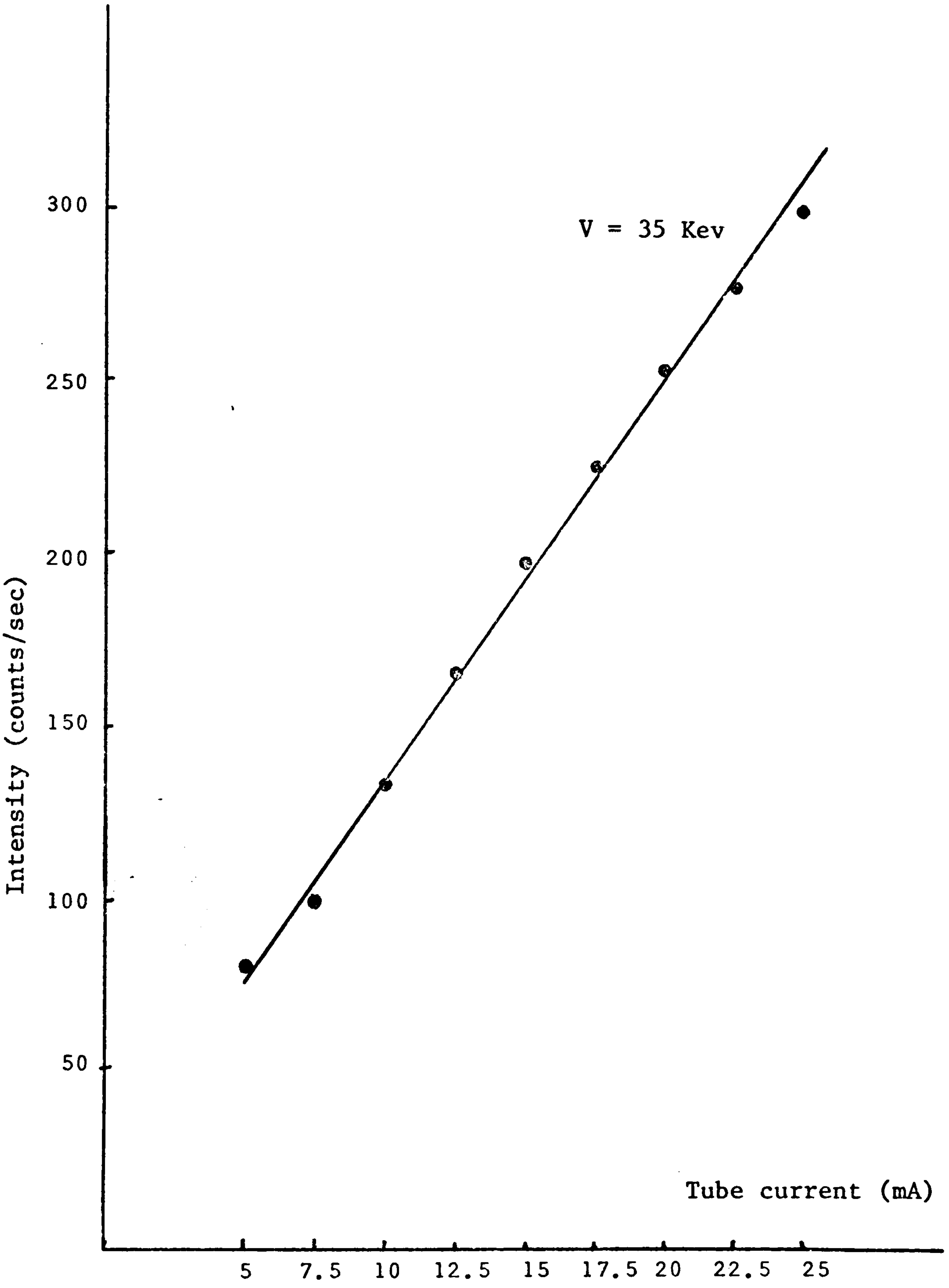

Figure 7. Intensity of Cu Kα_1 and Kα_2 of Borrmann transmission vs tube currents at constant voltage 35 Kev. (Silicon, n-type crystal, phosphorus doped, thickness is 1.016 mm).

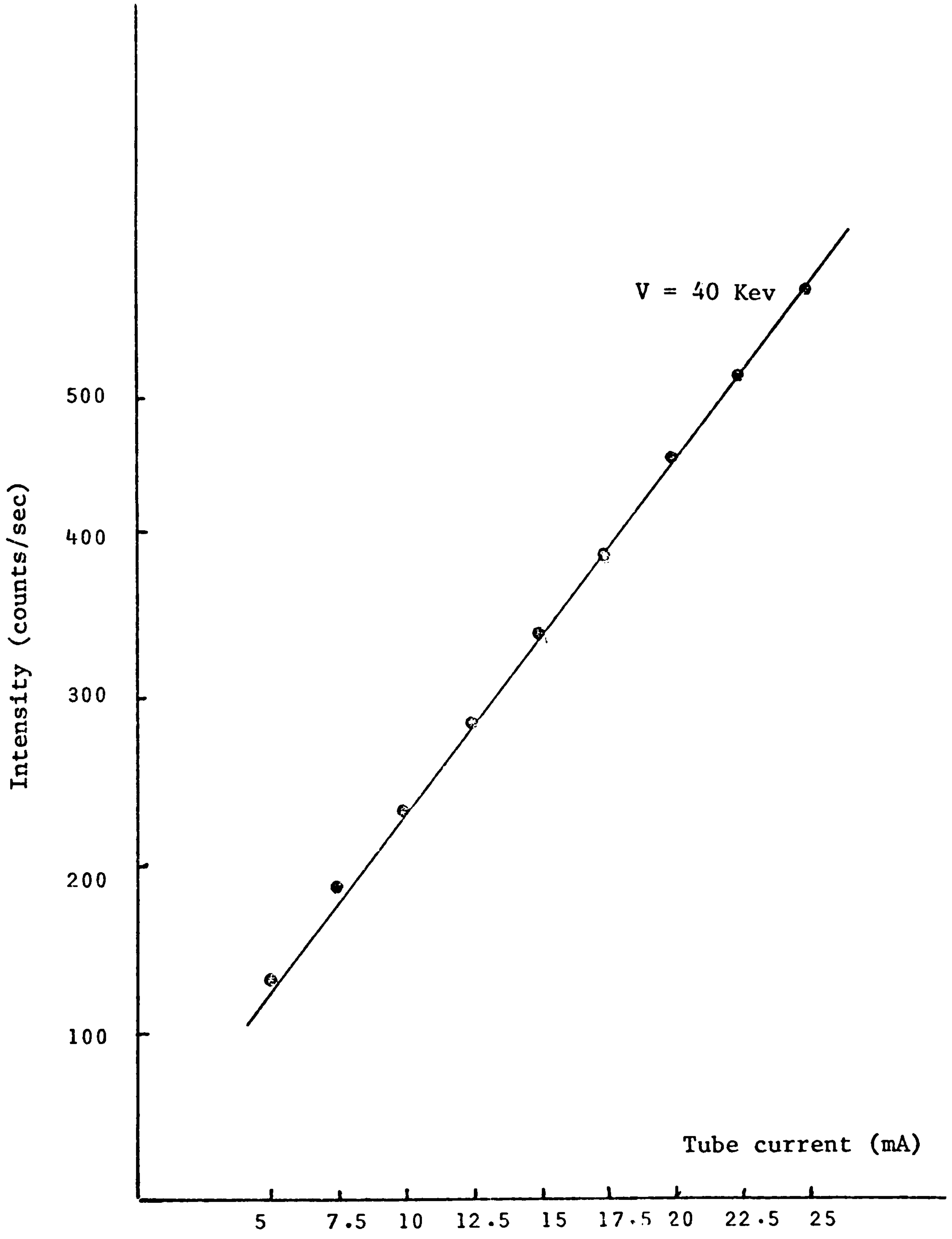

Figure 8. Intensity of Cu Kα_1 and Kα_2 of Borrmann transmission vs tube currents at constant voltage 40 Kev. (Silicon, n-type crystal, phosphorus doped, thickness is 1.016 mm).

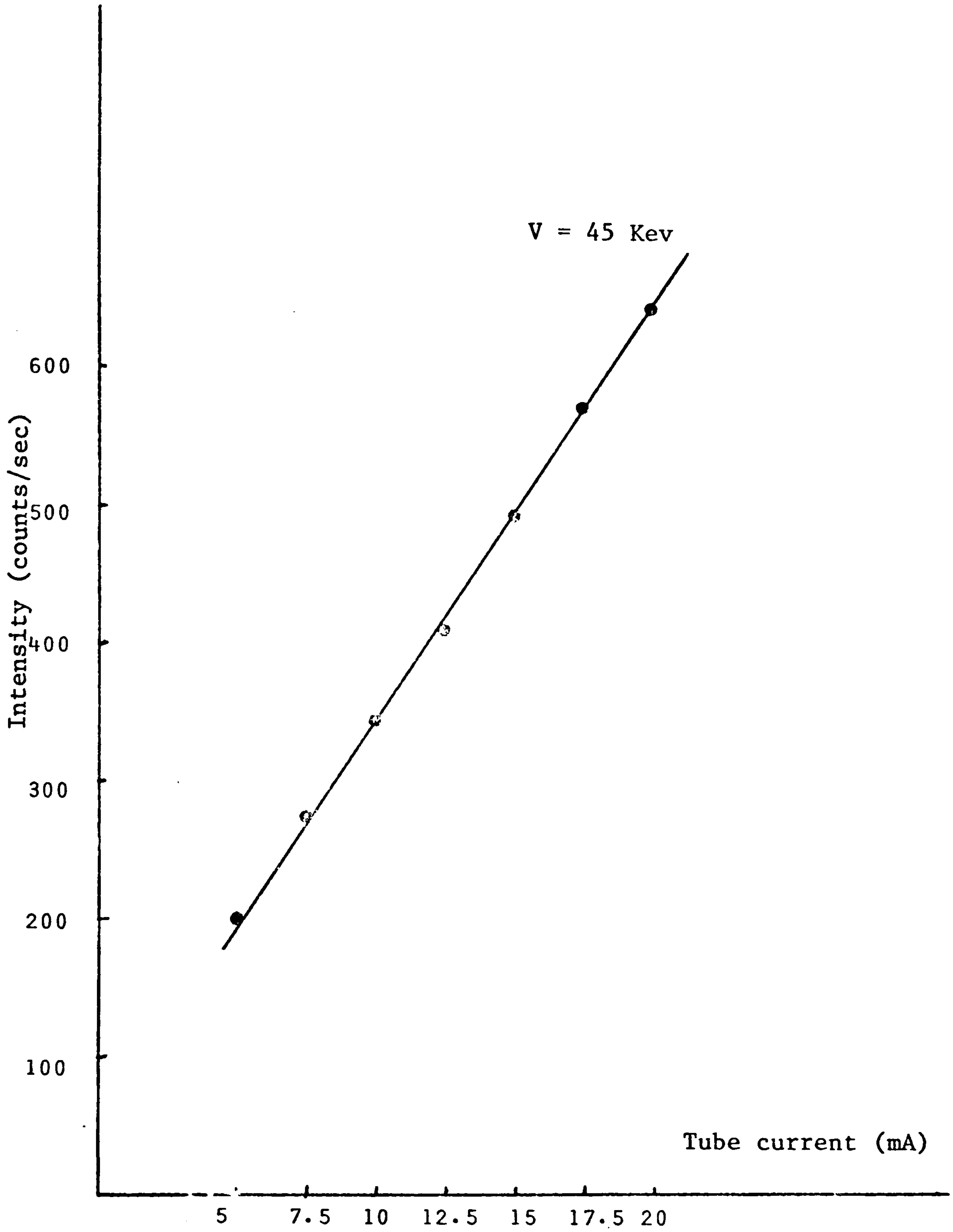

Figure 9. Intensity of Cu Kα_1 and Kα_2 of Borrmann transmission vs tube currents at constant voltage 45 Kev. (Silicon, n-type crystal, phosphorus doped, thickness is 1.016 mm).

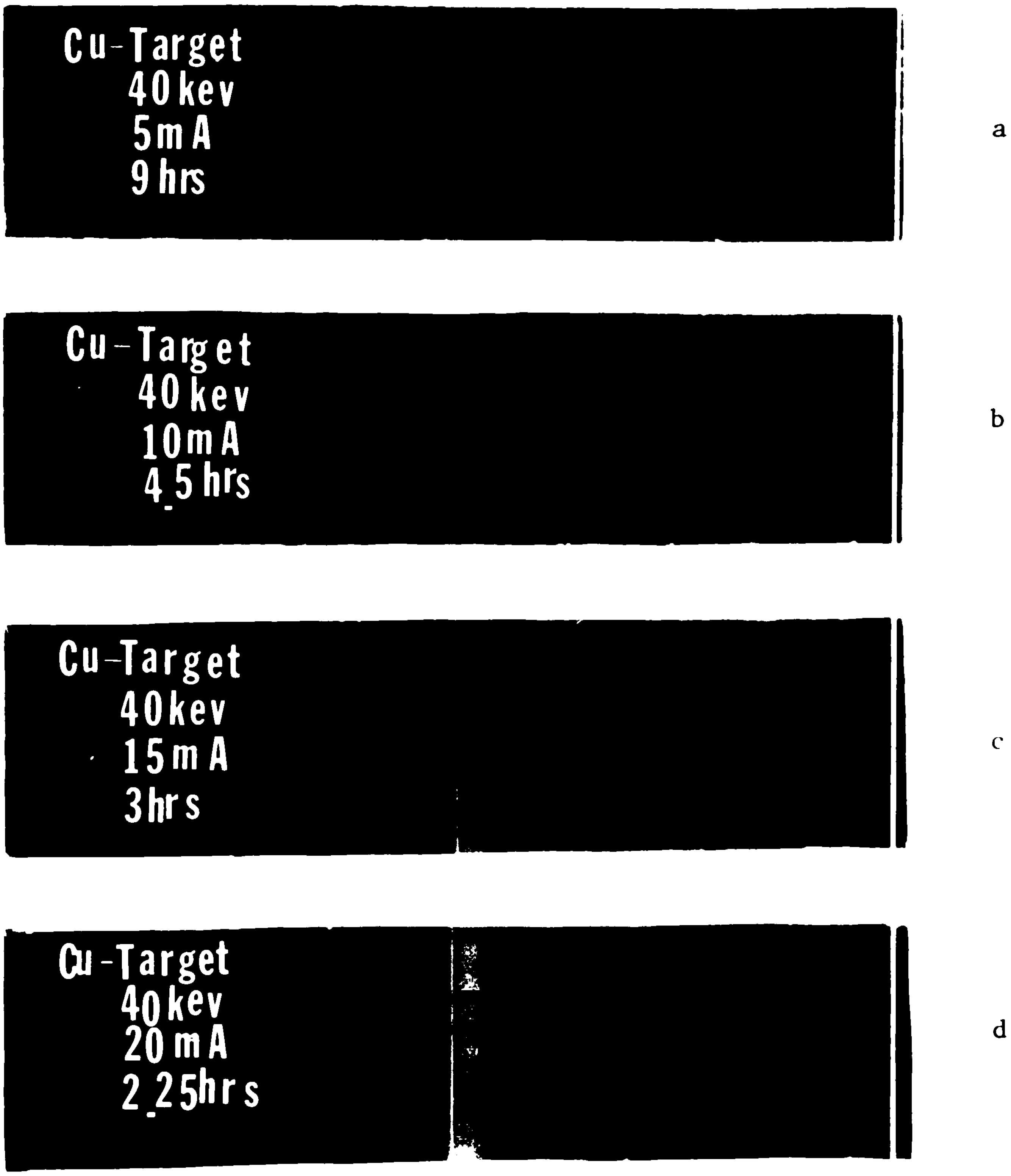

Figure 10. Borrmann transmission of $K\alpha_1$ and $K\alpha_2$ for same Watt-hour = 1800 for a, b, c and d.

3. Voltage is 40 Kev, current is 15 mA, exposure time 3 hours;

4. Voltage is 50 Kev, current is 20 mA, exposure time 2.25 hours.

Each picture had the same watt-hour value = voltage x current x time = 1800 watt-hours, and the same developing time, which is 2.5 minutes in the developer. The light transmitted through each film of $K\alpha_1$ and $K\alpha_2$ has been recorded by microphotometer as shown in Figure 11. In Figure 11, the minimum value of transmittance at the center of the lines on each of four films, is the same. (Variation in transmittance was caused by the variation in the temperature of the developer for the four films (± 2° C difference), and any difference in development of four films which was within two days.)

Measurement of Bragg Reflection Coefficient

In this part of the experiment a double spectrometer (one monochromator and one spectrometer) is used for measuring the Bragg reflection coefficient.[11] Two pieces of the same silicon crystal were set in the double spectrometer; both were (111) cut, undoped, with thickness of 1.27 mm. There are two main types of positions in the double spectrometer,[12] parallel and antiparallel, as shown in Figure 12 and Figure 13. In order to receive both $K\alpha_1$ and $K\alpha_2$, the parallel position was chosen. Let I_o be the intensity of the x-ray beam coming from the tube; I_1 be the intensity of reflection from the first crystal; I_2 be the intensity of reflection from the second crystal; and R_c be the Bragg reflection coefficient. Therefore,

$$R_c = I_2 / I_1$$

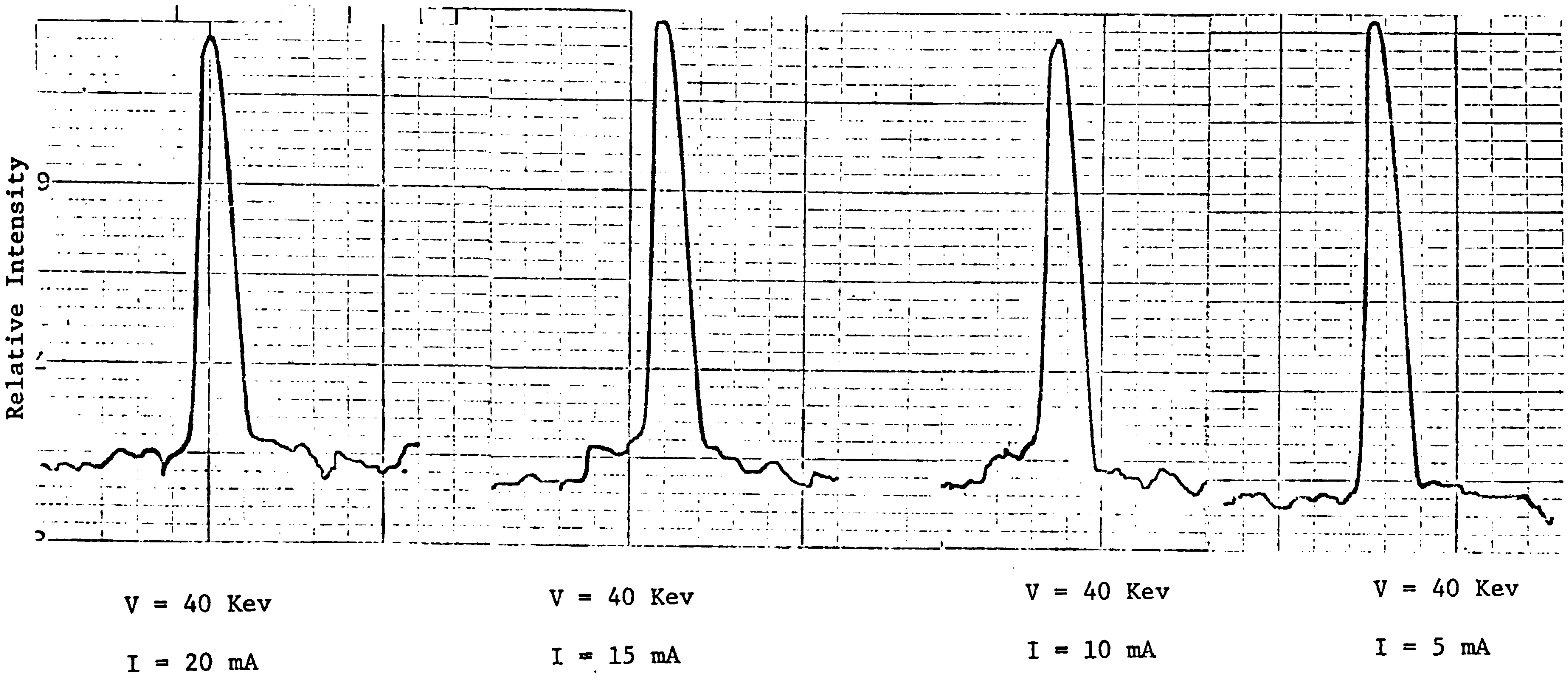

Figure 11: Microphotometer recording of Kα_1 and Kα_2 of Borrmann transmission and background on either sides.

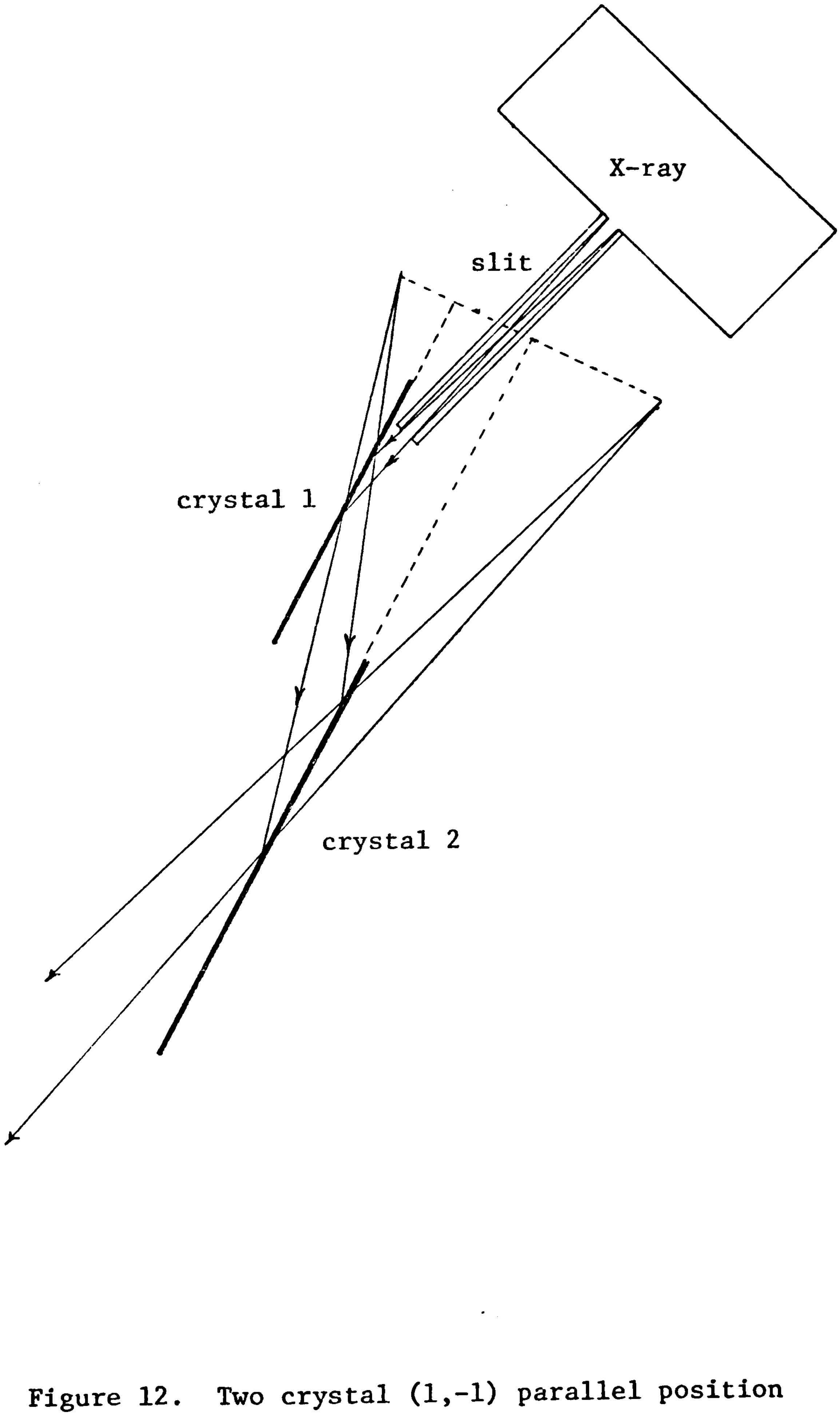

Figure 12. Two crystal (1,-1) parallel position

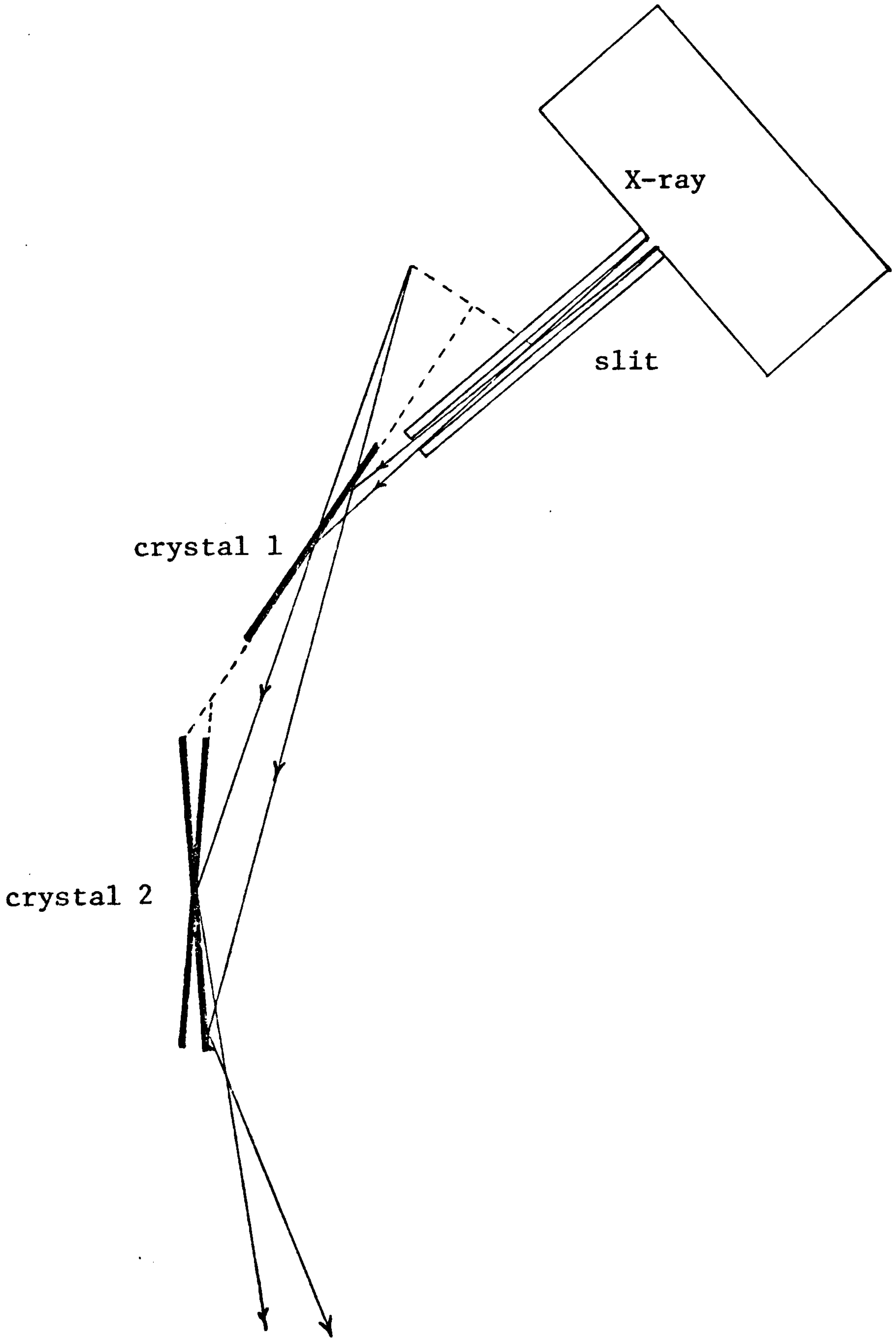

Figure 13. Two crystal (1,+1) dispersive position

or

$$R_c = I_1 / I_o$$

The intensity recorded from the scintillation counter was at voltage 35 Kev and current 5 mA. Two different widths of slit were used in measuring the Bragg reflection coefficient. One is 0.25 mm; the other is 0.51 mm. For width of slit 0.25 mm:

$$I_2 = 1387.42 \text{ counts/sec.}$$

$$I_1 = 50124.38 \text{ counts/sec.}$$

Therefore,

$$\begin{aligned} R_c &= 1387.43 / 50124.38 \\ &= 0.02768 \\ &= 2.77 \times 10^{-2} \end{aligned}$$

Also,

$$R_c = I_1 / I_o$$

so,

$$\begin{aligned} I_o &= I_1 / R_c \\ &= 50124.38 / 0.02768 \\ &= 1810884.5 \\ &= 1.81 \times 10^6 \text{ counts/sec.} \end{aligned}$$

In Borrmann transmission it is assumed that the incident x-ray beam penetrates the crystal with an incident angle at Bragg angle with the plane. The beam passing through the crystal is assumed by multiple Bragg reflections between two consecutive planes, as shown in Figure 14. If d is the interplanar spacing of the crystal, and θ is the angle of incidence which is the Bragg angle of the crystal, then for one reflection be beam has passed a distance x = d / tan θ, as expressed in Figure 15.

For silicon crystal (cubic lattice) the interplanar spacing[14] d is expressed by:

$$d = a / \sqrt{h^2 + k^2 + l^2}$$

where h, k, and l are the Miller indices, and a is the length of the unit cell. For cubic silicon crystal of (111) cut, a = 5.4282 Å at 20° C. Therefore, for silicon of (111):

$$\begin{aligned} d &= 5.4282 \ / \sqrt{1^2 + 1^2 + 1^2} \\ &= 5.4282 \ / \sqrt{3} \\ &= 5.4282 \ / \ 1.73205 \\ d &= 3.1339 \text{ Å} = 3.1340 \text{ Å} \end{aligned}$$

Therefore, for one reflection the beam has passed a distance x = d / tan θ, where θ = 14.216° for silicon Kα, so

$$x = d \ / \ \tan 14.216°$$

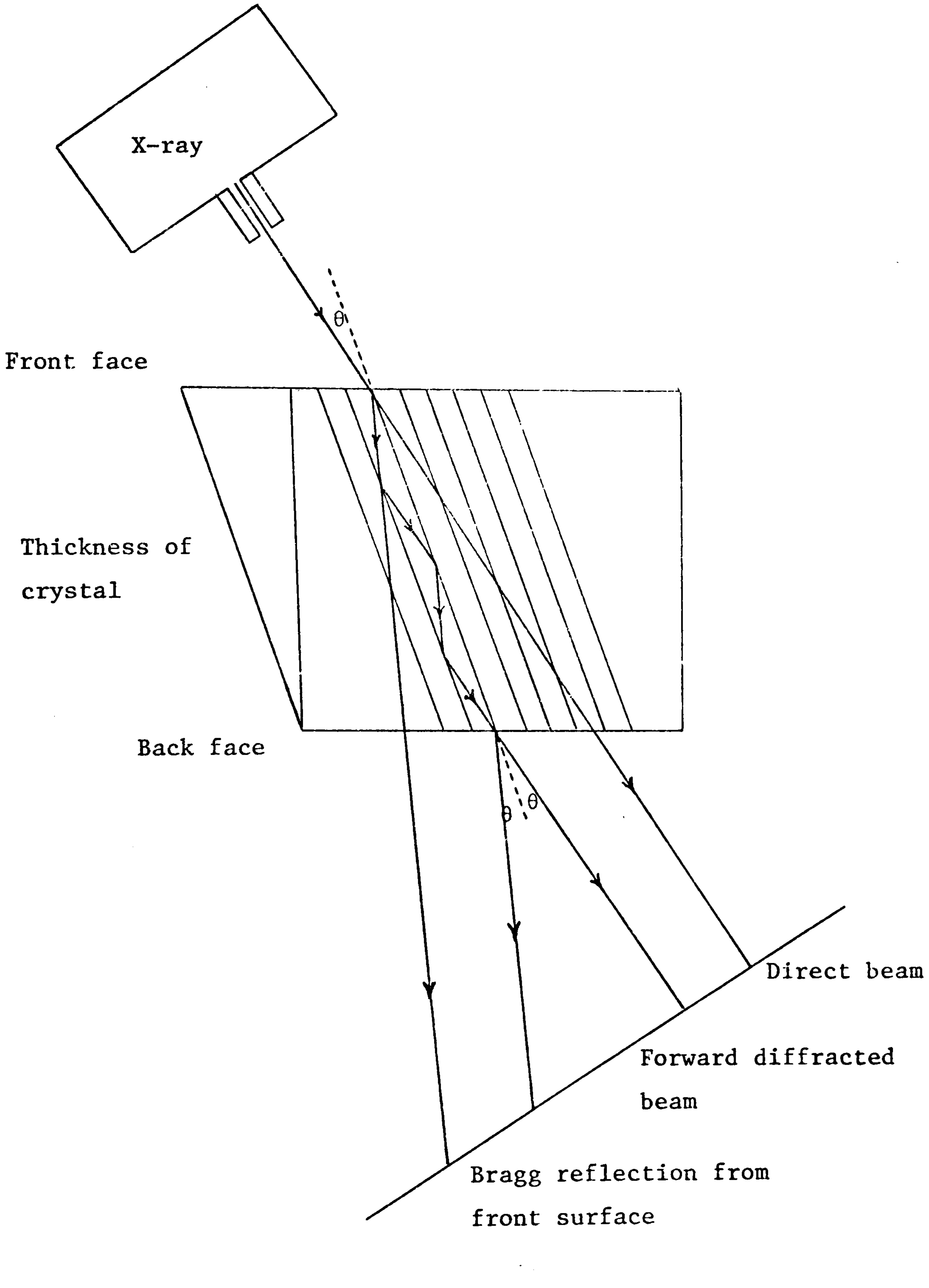

Figure 14. Schematic diagram showing Borrmann diffraction through thick crystal of $K\alpha_1$ beam.

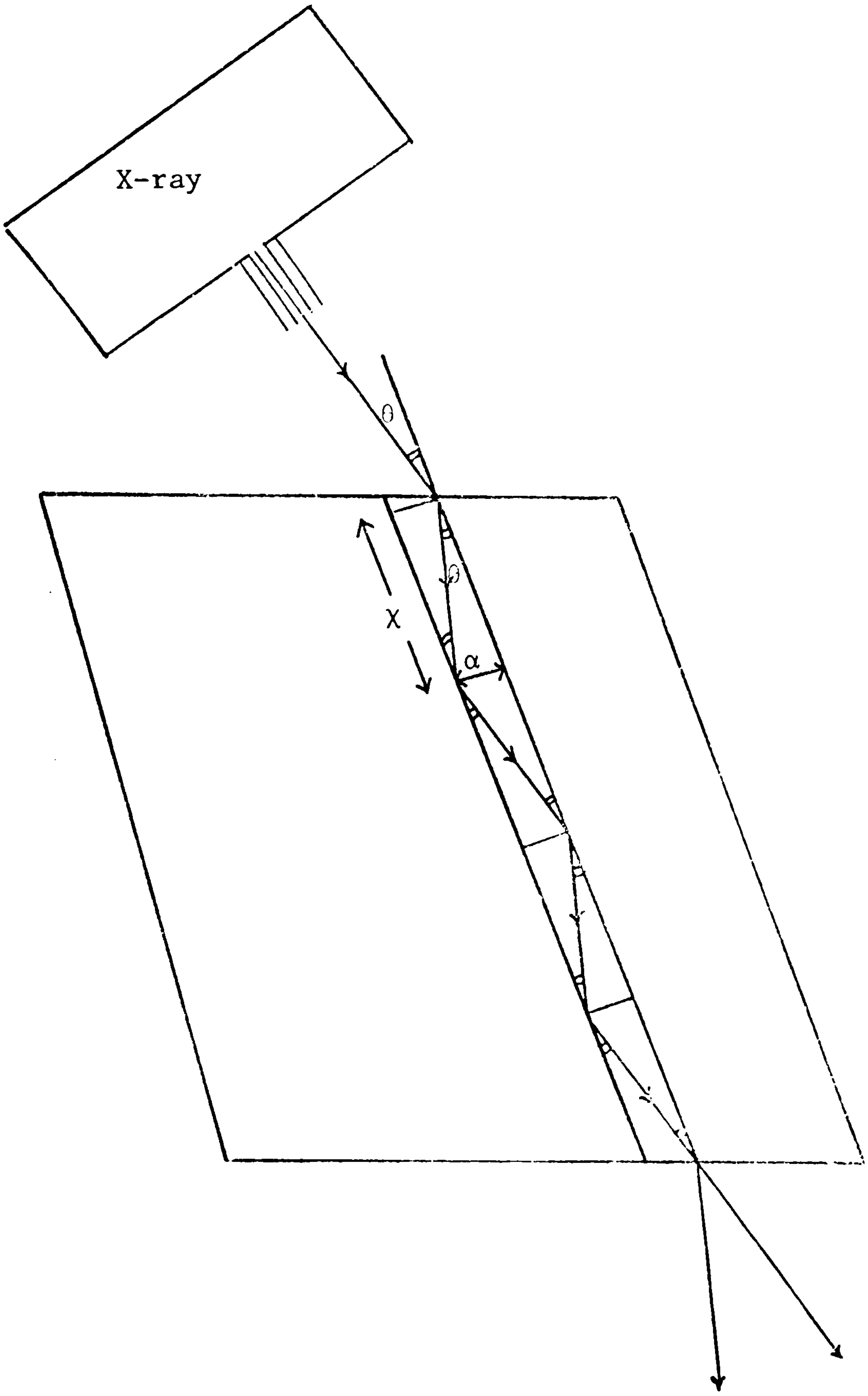

Figure 15. Borrmann transmission as a multiple Bragg reflection process.

$$= 3.13397 / 0.25336$$
$$= 12.371\ \text{Å}$$

In the experiment the thickness of the silicon crystal is t = 1.016 mm; t' is the distance of the x-ray actually passed through the crystal when Borrmann transmission happens. t' = t / sin 70.53°, t' = 1.016 / 0.942816 = 1.0776 mm. So t' / x is the number of reflections that the beam has taken when passing through the crystal.

Thus,

$$t' / x = 1.0776\ \text{mm} / 12.37082 \times 10^{-7}\ \text{mm}$$
$$= 0.08711 \times 10^{7}$$
$$= 871100$$

This means that the x-ray beam has taken 871100 reflections after passing through the silicon crystal with a thickness of 1.0776 mm if we consider that in Borrmann transmission the forward diffraction is due to the multiple Bragg reflection in the crystal planes. The Bragg reflection coefficient is $R_c = 10^{-2}$ (for one reflection) so, according to the usual photoelectric absorption, there will not be any appreciable intensity of the beam which could be received after passing through the crystal. This is proof of the experimental result. Figure 2 shows Borrmann transmission.

The equation of photoelectric absorption is $I_t = I_o e^{-(\mu/\rho)\cdot\rho\cdot t}$, where I_o is the initial x-ray beam intensity; I_t is the intensity of the transmitted beam; μ/ρ is the mass absorption coefficient; ρ is the density of the crystal; and t is the thickness of the crystal. In the experiment, for silicon crystal, the mass absorption coefficient of Kα for Cu target is $\mu/\rho = 60.6\ \text{cm}^2\ /\ \text{gm}$;[13] the density of the silicon crystal is $\rho = 2.328\ \text{gm/cm}^3$,[14] and the distance of x-ray actually passed through the crystal is $t' = 0.10776$ cm. So,

$$I_t = I_o\ e^{-\ 60.6\ \times\ 2.328\ \times\ 0.10776}$$

$$I_t\ /\ I_o = e^{-\ 141.0768\ \times\ 0.10776}$$

$$I_t\ /\ I_o = e^{-\ 15.2024}$$

$$I_t\ /\ I_o = 0.0000002498$$

$$= 2.5 \times 10^{-7}$$

This means after the beam has passed through the silicon crystal with thickness of 0.1016 cm, $I_t\ /\ I_o$ will be in the power of 10^{-7}. From the intensity of initial x-ray beam at voltage 35 Kev, current 5 mA is found to be $I_o = 1.8 \times 10^6$; thus the transmitted beam $I_t = I_o \times I_t\ /\ I_o$, $I_t = 1.8 \times 10^6 \times 10^7 = 0.1$ (counts/sec.). But in the Borrmann transmission the intensity at 35 Kev, 5 mA (as in Table I) is found to be 81 counts/sec. This means the Borrmann transmission has increased about 800 times more in intensity than in the usual transmission.

For width of slit 0.51 mm:

The counter is covered with aluminum foil of thickness 0.021 inch = 0.0533 cm. With voltage at 35 Kev, current at 5 mA:

$$I_2 = 13\ \text{counts/sec}$$

$$I_1 = 515\ \text{counts/sec}$$

So,

$$R_c = I_2 / I_1$$
$$= 13 / 515$$
$$= 0.025$$
$$R_c = 2.5 \times 10^{-2}$$

Also

$$R_c = I_1 / I_o$$
$$I_o = I_1 / R_c$$
$$= 515 / 0.025$$
$$I_o = 20600$$

Since the counter has been covered with Al-foil of thickness 0.0533 cm, therefore, I_t is 20600 counts/sec.

Thus, with Al-foil,

$$I_t = 20600 \text{ counts/sec}$$
$$t = 0.0533 \text{ cm}$$
$$\rho_{Al} = 2.699 \text{ gm/cm}^3$$
$$\mu/\rho = 48.7 \text{ (Cu K}\alpha)$$

So,

$$20600 = I_o \, e^{-48.7 \times 2.699 \times 0.0533}$$
$$20600 = I_o \, e^{-7.00582}$$
$$20600 = I_o \, 0.00090659$$

$$I_o = 20600 \;/\; 0.00090659$$

$$I_o = 22722509.62$$

The intensity of Borrmann transmission lines with this width of slit (0.51 mm), at voltage 35 Kev, current 5 mA, is:

$$I_t = 4219.8 \text{ counts/sec}$$

$$I_o = 22722509.62 \text{ counts/sec}$$

$$\begin{aligned} t &= 1.016 \;/\; \sin 70.53° \\ &= 1.016 \;/\; 0.94282 \\ &= 1.0776 \text{ mm} \\ &= 0.10776 \text{ cm} \end{aligned}$$

So,

$$\begin{aligned} I_t \;/\; I_o &= e^{-(\mu/\rho)\ \rho\ t} \\ 4219.8 \;/\; 22722509.62 &= e^{-(\mu/\rho)\ 2.328\ 0.10776} \\ 0.0001857 &= e^{-(\mu/\rho)\ 0.25086} \\ -8.59132 &= -(\mu/\rho)\ 0.25086 \\ (\mu/\rho) &= 34.25 \end{aligned}$$

This means, according to Borrmann transmission, that the mass absorption coefficient of silicon crystal changes from 60.6 to 34.25. Therefore, if the intensity of the incident beam is assumed to be 100000 counts/sec, then, by the regular transmission through the crystal (mass absorption coefficient is 60.6).

$$I_t = 100000 \times e^{-60.6 \times 2.328 \times 0.1016}$$
$$= 100000 \times e^{-14.3334}$$
$$= 100000 \times 0.0000005957$$
$$= 0.05957$$

By Borrmann transmission through the crystal (mass absorption coefficient is 34.25)

$$I_t = 100000 \times e^{-34.25 \times 2.328 \times 0.10776}$$
$$= 100000\ e^{-8.53632}$$
$$= 100000 \times 0.0001962$$
$$= 19.62$$

Therefore, the Borrmann transmission has increased about 19.62 / 0.05957 = 329 times more in intensity than the usual transmission.

Measurement of Mass Absorption Coefficient of Silicon and Aluminum

In measuring the mass absorption coefficient of silicon crystal and aluminum which is used in the experiment, first the x-ray beam is made monochromatic by an initial Bragg surface reflection from a fixed crystal in the monochromator. Because use of radiation direct from the x-ray tube is not allowed, this will contain a continuous range of wavelengths as well as the monochromatic characteristic radiation. The monochromatic beam coming from the fixed crystal has been aligned, passing through two 1 mm pinholes separated by 20 cm to minimize the continuum. The monochromatic beam I_o and the transmitted beam I_t were recorded by the scintillation counter. In measuring the mass absorption coefficient of silicon crystal, in order to avoid receiving the scattering beam after it passed through the crystal, another lead plate with 1 mm pinhole is placed 2 cm in front of the counter. Voltage is at 35 Kev, current at 5 mA, for a silicon crystal of thickness 0.017 inch = 0.04318 cm, n-type.

$$I_t = 1.15 \text{ counts/sec}$$

$$I_o = 240.02 \text{ counts/sec}$$

so,

$$I_t / I_o = e^{-(\mu/\rho)\ \rho\ t}$$

$$1.15 / 240.02 = e^{-(\mu/\rho)\ 2.328 \times 0.04318}$$

$$0.0004792 = e^{-(\mu/\rho)\ 0.100523}$$

$$-\ 5.34096 = -\ (\mu/\rho)\ 0.100523$$

$$\mu/\rho = 53.13$$

If the density has a value of 2.328 ± 1% = $\frac{2.351}{2.305}$, then for $\rho = 2.351$

$$(\mu/\rho)_{Si} = 5.34096 / 0.10152 = 52.61$$

and for $\rho = 2.305$,

$$(\mu/\rho)_{Si} = 5.34096 / 0.09953 = 53.66$$

Considering an error of 1% in measured thickness, the values of t are t = 0.04361 cm and t = 0.04275 cm.

Then for t = 0.04361 cm

$$(\mu/\rho)_{Si} = 5.34096 / 0.10152 = 52.61,$$

and for t = 0.04275 cm

$$(\mu/\rho)_{Si} = 5.34096 / 0.09952 = 53.67.$$

For a silicon of p-type, doped with Boron of thickness 0.03048 cm, $I_t = 3.42$, $I_o = 240.02$. Then,

$$I_t / I_o = 3.42 / 240.02 = e^{-(\mu/\rho)\ 2.328 \times 0.03048}$$

$$-\ 4.251082 = -(\mu/\rho)\ 0.0142488$$

$$(\mu/\rho)_{Si} = 59.91$$

If the density has a value of 2.328 ± 1% = $\frac{2.351}{2.305}$, then for $\rho = 2.351$

$$(\mu/\rho)_{Si} = 4.251082 / 0.07166 = 59.32;$$

and for $\rho = 2.305$

$$(\mu/\rho)_{Si} = 4.251082 / 0.07026 = 60.51.$$

If the thickness has a value of t = 0.012 ± 1%, then t = 0.03075 cm or t = 0.03020 cm. For t = 0.03075 cm

$$(\mu/\rho)_{Si} = 4.251082 / 0.07166 = 59.32,$$

for t = 0.03020 cm

$$(\mu/\rho)_{Si} = 4.251082 / 0.070306 = 60.47.$$

For measuring the mass absorption coefficient of aluminum, 25 pieces of aluminum foil were used, being put in front of the couter. The thickness of the foil is 0.0167 inch = 0.042418 cm. The density of Al is 2.699 gm/cm^3.

Voltage is at 30 Kev, current at 5 mA.

$$I_t = 16.7 \text{ counts/sec}$$

$$I_o = 2388.9 \text{ counts/sec}$$

So

$$16.7 \ / \ 2388.9 = e^{-(\mu/\rho)\ 2.699 \times 0.042418}$$

$$0.006991 = e^{-(\mu/\rho)\ 0.114486}$$

$$-\ 4.963175 = -(\mu/\rho)\ 0.114486$$

$$(\mu/\rho)_{Al} = 43.35$$

If density has an error of 2.699 ± 1% = $\begin{matrix}2.72599\\2.67201\end{matrix}$, then for $\rho = 2.72599$

$$(\mu/\rho)_{Al} = 4.963175 \ / \ 0.11563 = 42.92$$

for $\rho = 2.67201$

$$(\mu/\rho)_{Al} = 4.963175 \ / \ 0.11334 = 43.79.$$

If thickness has an error of t = 0.0167 ± 5%, then, for t = 0.044539 cm

$$(\mu/\rho)_{Al} = 4.963175 \ / \ 0.12021 = 41.29$$

for t = 0.040297

$$(\mu/\rho)_{Al} = 4.963175 \ / \ 0.108765 = 45.63.$$

CHAPTER IV

CONCLUSION AND FURTHER SUGGESTION

The Borrmann transmission through silicon crystal was demonstrated. Two sharp lines of copper Kα_1 and Kα_2, were clearly visible on the film. The intensity of Borrmann transmission lines was 800 times the intensity which would have been transmitted through this thickness of silicon not utilizing the Borrmann effect.

The intensity of the Borrmann transmission lines is linearly proportional to currents at a fixed voltage. There is no evidence of a non-linear increase in intensities in Borrmann beam, at least for the flux of x-ray beam I have used. The value of the mass absorption in coefficient of silicon in literature is 60.6 for copper Kα radiation. This was verified at other angles than that at which the Borrmann transmission occurs. When Silicon crystal was set at Borrmann transmission angle the mass absorption coefficient was 34.25. The Borrmann effect disappeared when the crystal was put under mechanical stress.

The following suggestions may be added for further consideration:

1. To extend the study of the Borrmann effect to higher radiation flux in search for the threshold of a non-linear effect.

2. To measure accurately the mass absorption coefficient as the crystal is set at various angles close to the Borrmann angle.

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