# SHIELDING CHARACTERISTICS OF A SINGLE CRYSTAL FOR GAMMA-RAYS OF SELECTED ENERGIES

by

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# I. INTRODUCTION

One problem confronting those working in the field of reactor technology is the design of mobile power reactors. It is obvious from an investigation of the size of present-day power reactors that mobility can only be achieved by reducing the size and weight of as many of the components of the reactor as is possible.

The present stage of design of portable reactors may be likened to the design of aircraft in the last days of, and shortly after, the second world war. In order to produce an appreciable increase in the speed of an aircraft it became necessary to solve the problems of the so called "sound barrier". Today, in order to make an appreciable advancement in the design of a reactor that will be portable it becomes necessary to find some method of reducing the weight of the shielding, even if this is achieved at a high cost.

In principle, the harmful radiations which might escape from a reactor system include alpha and beta particles, gamma rays, neutrons of various energies, fission fragments, and even protons resulting from (n,p) reactions. As far as shielding design is concerned, however, only gamma rays and neutrons need be considered since these are by far the most penetrating. Any material which attenuates these radiations to a sufficient extent will automatically reduce all the others to negligible proportions.

The purpose of this investigation is to determine whether the monomorphic form of a crystaline metal, when aligned with photons in such a way as to allow Bragg reflection to occur, presents appreciably different attenuation characteristics when exposed to gamma radiation than a polymorphic form of the metal. If the attenuation characteristics of the monomorphic crystal are found to be appreciably different from the normal polymorphic crystal, it might then be possible to design a reactor shield that would be smaller and of less weight than the normal shield.

## II. REVIEW OF LITERATURE

A review of the literature was first conducted to determine the feasibility of causing reflection of gamma photons by monomorphic crystaline metal. Little information directly relating to this subject could be found.

Bragg (1) gives a complete discussion of the reflection of x-rays by various targets but does not enter into a discussion of the reflection of gamma rays. The most useful information concerning gamma ray reflection was found in an unpublished M.S. thesis by Mergl (6). In this work a theoretical analysis of the reflection of x-rays is proposed and data are presented which indicate that the reflection of gamma rays exists and that the angle at which this reflection occurs can be approximated by the Bragg x-ray equation. It was felt that the indication of reflection was sufficient to merit an attempt to reproduce it and then to observe its effect on the attenuation characteristics of gamma rays.

Discussions on gamma ray attenuation were given in Kaplan (5) and Glasstone (4) and data concerning gamma ray attenuation were presented in Davisson and Evans (3). The data presented by Davisson and Evans made it possible to predict the attenuation characteristics of photons of various energies when they were scattered by any of the common metals.

## III. ANALYSIS

The basis of all measurements of the absorption of gamma rays is the fact that the intensity of radiation decreases as it passes through material in such a way that for a small thickness $\Delta t$, the change in intensity $\Delta I$ is proportional to the thickness and to the incident intensity I. That is:

$$I = -\mu I(\Delta t)$$

If the radiation is monoenergic, if the beam is collimated and of small angle, if the absorber is thin, and if $\mu$ is constant, then the integration of the above equation yields

$$\frac{I}{I_o} = e^{-\mu t}$$

This gives the intensity of radiation I after a beam of initial intensity $I_o$ has traversed the thickness t of a particular material (3, p. 79).

The energies of most of the photons that appear in connection with a nuclear reactor are greater than 0.1 Mev and less than 6 Mev. Within this range there are three types of gamma ray interactions with matter that must be taken into consideration: (1) the Compton effect, (2) the photoelectric effect, and (3) pair production. The three processes act independently of each other so the absorption coefficient is separated into three parts which are designated as $\sigma$ for the

Compton effect, $\tau$ for the photoelectric effect, and $\kappa$ for pair production. Since the equation given for the decrease in intensity of gamma radiation holds for each process separately, the total intensity change is obtained by adding the effect of each process. That is:

$$\Delta I = -(\sigma + \tau + \kappa)\, I\, (\Delta t)$$

In order to determine how gamma radiation attenuation differs between the monomorphic and the polymorphic states of a given material at a particular gamma energy, it is desirable to determine first the relative magnitudes of the absorption coefficients for each of these individual types of gamma ray interactions. However, before this can be done, it is necessary to specify the irradiating gamma energy, since the absorption coefficients are a function of both the target material and the gamma source energy.

## A. Choice of Target and Source Material

It was desirable that the material to be irradiated in this study meet several criteria. (1) The material should be readily available in both the monomorphic and polymorphic states, (2) it should, if possible, have the crystaline form of a close-packed hexagon which will be of aid in producing Bragg reflection, and (3) it should be sufficiently dense so that a small volume of the material, when used as a target, will cause sufficient attenuation of the gamma radiation to enable an accurate measurement to be made of the scattered photons with the equipment available. The material that best met these criteria was zinc ($_{30}Zn^{65}$). It was available in both the monomorphic and the polymorphic states, has a close-packed hexagonal structure, and a density of 7.133 gm per cubic centimeter.

The desirable criteria to be met by the gamma radiation source were (1) the source should emit monoenergic photons, and (2) it should be available in sufficient strength to enable the measurement of the gamma radiation attenuated by a small target when placed approximately 180 cm from the source and (3) it should have a long half-life. The source material which best met the above criter was cobalt 60 ($_{27}Co^{60}$). The primary gamma emissions of $Co^{60}$ occur at 1.3316 Mev and at 1.1715 Mev and the material has a half-life of 5.2 years (2). The gamma radiation from $Co^{60}$ is, therefore, not monoenergic. However, if an average energy of 1.252 Mev is used and then the source is treated as monoenergic, an appreciable error is not introduced in the calculations.

## B. Type of Scattering

Using $Zn^{65}$ as the target material and $Co^{60}$ as the gamma source material it was found that at the gamma energy of 1.1715 Mev the absorption coefficients were:

$${}_a\sigma = 5.894\ (10^{-24})\ \frac{cm^2}{atom}$$

$${}_a\tau = 0.0547\ (10^{-24})\ \frac{cm^2}{atom}$$

$${}_a\kappa = 0.00$$

At the gamma energy of 1.3316 Mev they were:

$${}_a\sigma = 5.518\ (10^{-24})\ \frac{cm^2}{atom}$$

$${}_a\tau = 0.0432\ (10^{-24})\ \frac{cm^2}{atom}$$

$${}_a\kappa = 0.00$$

and at the average gamma energy of 1.252 Mev they were:

$${}_a\sigma = 5.694\ (10^{-24})\ \frac{cm^2}{atom}$$

$${}_a\tau = 0.0490\ (10^{-24})\ \frac{cm^2}{atom}$$

$${}_a\kappa = 0.00$$

Each of the above calculations shows the Compton effect contributes approximately 99% of the total absorption coefficient (3, p. 97). For this reason no other type of absorption was considered significent in this study and all attenuation was attributed to the Compton effect.

The number of photons scattered in the region where the Compton effect predominates are not scattered isotropically but rather follow the scattering probability predicted by Klein and Nishina. The Klein-Nishina probabilities ($\frac{d_e\sigma}{d\Omega}$)

in units of $\frac{cm^2}{electron}$, of a photon being scattered through an angle $\theta$ into a unit solid angle $d\Omega$ are tabulated by Davisson and Evans for different gamma energies (3, p. 82, Table III).

C. Experimental Klein-Nishina Cross Section

The Klein-Nishina cross section $\frac{d\,{}_e\sigma}{d\Omega}$ can be found by the equation

$$\frac{d\,{}_e\sigma}{d\Omega} = \frac{(B)\ e^{\,{}_e\sigma\ T}}{(T_o)\ (\Omega)\ (\phi)},$$

in which $\phi$ is the flux at target in units of $\frac{photons}{minute}$ and is found by the equation

$$\phi = \frac{\text{area of target}}{4\pi r_o^2}\ (S)$$

in which $r_o$ is the distance from the source to the target and S is the source strength in units of $\frac{disintegrations}{minute}$.

The term, $e^{\,{}_e\sigma\ T}$ is the dimensionless self-absorption factor and takes into consideration the photons that are initially scattered in the direction of the counter and are then absorbed or rescattered by the target material out of the solid angle subtended by the counter. ${}_e\sigma$ is the Compton (assumed total absorption) coefficient, in units of $\frac{cm^2}{electron}$, for the photons that are scattered in the direction of the counter. A tabulation of ${}_e\sigma$ as a function of $\alpha$ over the range of $\alpha$ occurring in this study is given by Davisson and

Evans (3, p. 82, Table II). The term $\alpha$ is found by the equation

$$\alpha = \frac{h\nu}{1 + \alpha_o(1 - \cos \theta)} \left(\frac{1}{m_oc^2}\right)$$

in which $h\nu$ is the energy of the initial or unscattered photons in Mev; $\alpha_o = \frac{h}{m_oc^2}$ where $m_oc^2$ is the rest energy of an electron in Mev; and $\theta$ is the scattering angle of the photon. It is not necessary to take into consideration any subsequent rescattering of the photons by the target back into the counter as is shown below. An estimation of the subsequent rescattering or build up can be obtained from the product of $\mu$ T. The term $\mu$ is the total absorption coefficient for Zn at the energy of the scattered photons in units of $cm^{-1}$, and is obtained from the equation

$$\mu = \rho \frac{N\ (Z)}{A}\ {}_{e}\sigma$$

in which Z is the atomic number, A is the atomic weight, N is Avogadro's number, and $\rho$ is the density in $\frac{gm}{cm^3}$. The term T is the average thickness of the target through which the scattered photon must travel to reach the counter in units of cm, and is approximated by the equation

$$T = \frac{A_t}{\left[\frac{L}{\cos}\right] \left[\sin\ (\theta + \xi\ \ )\right]}$$

in which $A_t$ is the horizontal cross sectional area of the target, $\xi$ the angle between the center line of the target and the incident gamma radiation, L the length of the target parallel to the incident radiation, and $\theta$ is the scattering angle (Figure 1, page 12). If the product of $\mu T$ is less than one, as it was in this study, then build up can be considered negligible (4, p. 596).

The term $T_o$ is the thickness of the target in the direction of the initial or unscattered photons, in units of $\frac{\text{electrons}}{\text{cm}^2}$, and is found by the equation

$$T_o = \rho \frac{N\ (Z)}{A}\ (t_o)$$

in which $t_o$ is the thickness of the target in the direction of the initial photons in units of cm.

The term $\Omega$ is the solid angle subtended by the counter in units of steradians and is found by the equation

$$\Omega = \frac{\text{area of counter}}{4\pi\ r^2}$$

in which r is the distance from the target to the counter.

The term B is the counting rate of the detector.

## D. Bragg Reflection

Few data have been published concerning the reflection of gamma photons, but many data are available concerning the reflection of x-rays. This experiment was not conducted to prove whether or not the equations that apply to the reflection of x-rays give precise results when applied to gamma rays. However, because of the identical characteristics of

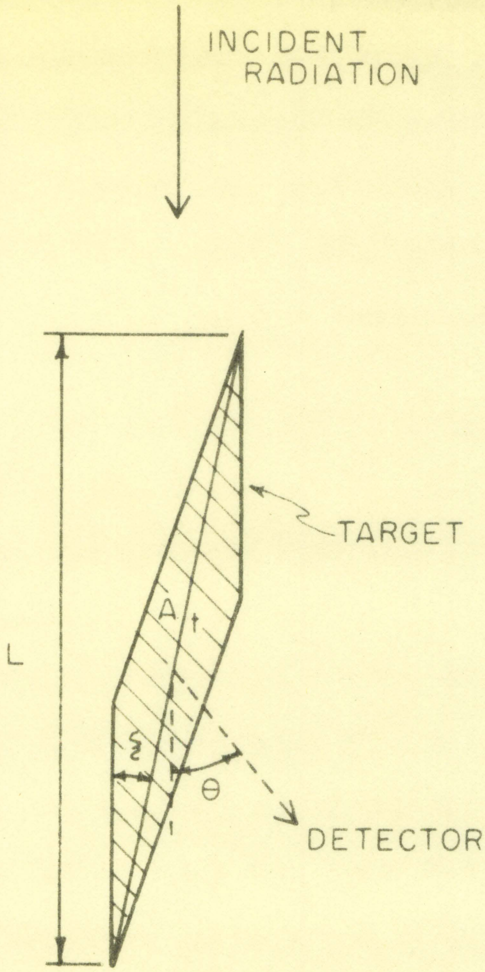



Figure 1. Top view of target

x-rays and gamma rays, and because of previously obtained experimental data concerning the reflection of gamma rays (6), it was assumed that the Bragg equation, which was developed for the reflection of x-rays, gives an indication of the angle at which the reflection of gamma rays occurs. In this equation the angle of incidence $\beta$ is given as

$$\beta = \arcsin \frac{n\lambda}{2d}$$

in which n is an integer, first order reflection being when n = 1, second order when n = 2, etc., $\lambda$ the wave length of the incident photons and d is the distance between the reflecting planes (1).

Even though total reflection of x-rays has been observed in some experiments, total reflection of the gamma rays in this experiment was not expected due to several reasons. No experimental indication has been found to lead one to expect total reflection of gamma rays, because the photons were not monocromatic, all of the crystal planes were not perfectly parallel, and each crystal plane intersected the photons at a slightly different angle. Using the preceding equation with the average energy of the two gamma photons and the distance between the crystal planes of zinc [$4.940(10^{-8})$cm] one finds that 2$\beta$, twice the angle of reflection, is 1.15 degrees.

In determining the geometry to be used in the attempt to produce Bragg reflection several criteria were established.

It was desirable that the angle of the cone of radiation be small so that a large number of the photons would intersect the planes of the monomorphic crystal at nearly the same angle; but at the same time it was desirable that the entire volume of the target be irradiated, so that the greatest number of photons could be scattered and thus improve the reliability of the readings. Since only a small percentage of the photons were expected to be reflected, it was thought necessary to place the counter outside of the cone of primary radiation so that the only photons that it would detect above background would be those scattered and reflected by the crystal.

The geometry of Figure 5 gave a cone of radiation with a half angle of 0.406 degrees, and enabled the entire volume of the target to be irradiated. By placing the detector 183 cm from the target and 3.8 cm off center line, and by modifying the circular cross section of the cone of radiation, the detector was far enough away from the target so that it did not receive any primary gamma radiation or secondary (n = 2) Bragg reflection photons. The primary disadvantage of this geometry was a small counting rate which necessitated long counts in order to obtain accurate results.

## IV. MATERIALS AND APPARATUS

A plan view of the geometry used in determining the Klein-Nishina cross section for the unaligned crystals is shown in Figure 2, and the arrangement of the apparatus used in this study with some of the shielding removed is shown in Figures 3 and 4. A plan view of the geometry used in determining the Klein-Nishina cross section for the aligned crystal is shown in Figure 5 and the arrangement of the apparatus used with some shielding removed is shown in Figures 6, 7, and 8.

### A. Source and Source Container

The source used throughout this experiment was $Co^{60}$, an isotope of cobalt, whose primary gamma emissions occur at 1.3316 Mev and 1.1715 Mev, and whose strength was 63 mc at the time of the experiment. The source material was enclosed in an aluminum capsule surrounded by a clear plexiglas or clear plastic cylinder, whose dimensions were about three-quarters of an inch in diameter and two inches in length.

The source container was a lead block with the dimensions of four inches by four inches by 5.5 inches. To accommodate the source a 7/8 inch hole was drilled in the

Figure 2. Plan view of apparatus used with unaligned crystal

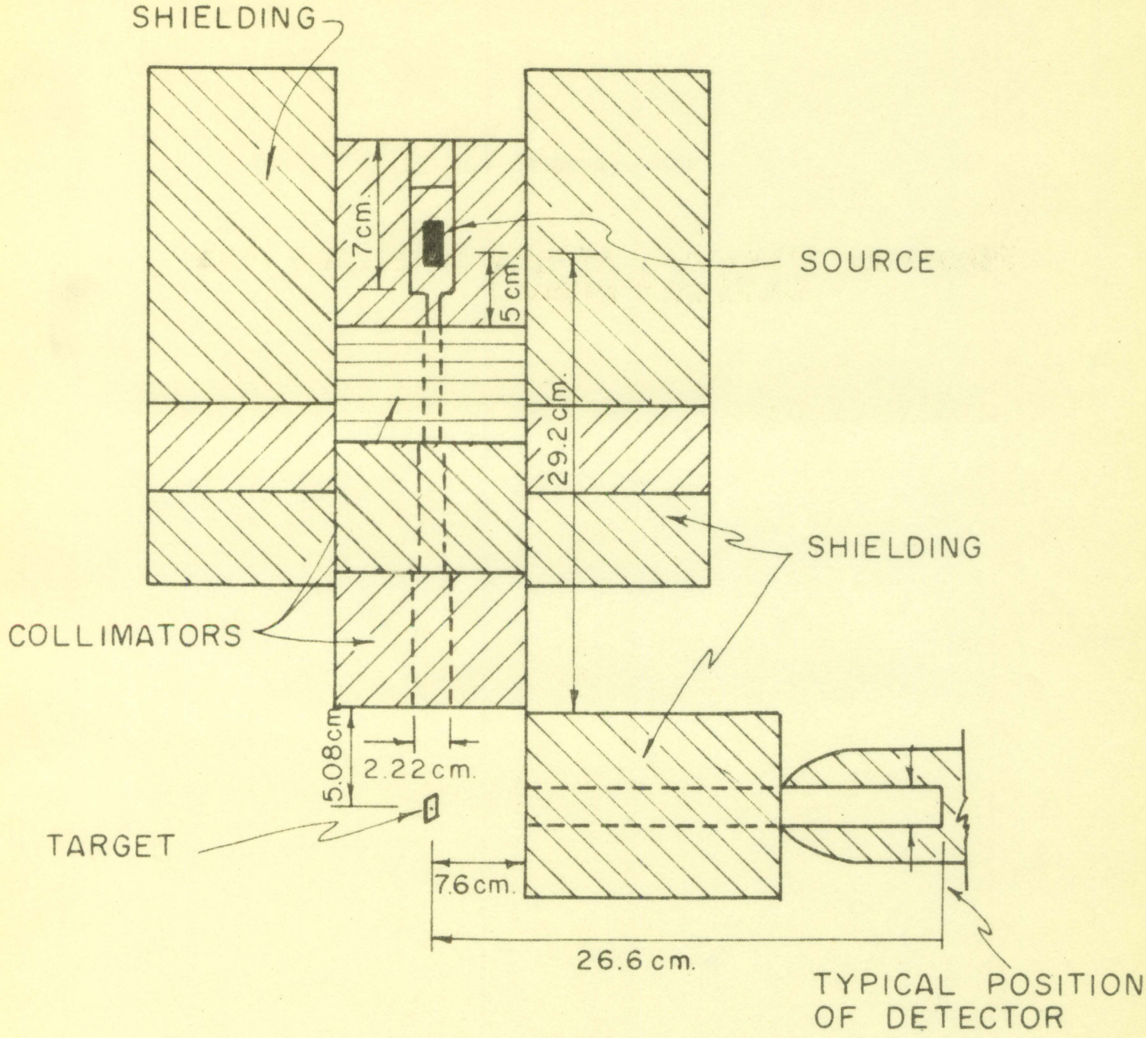
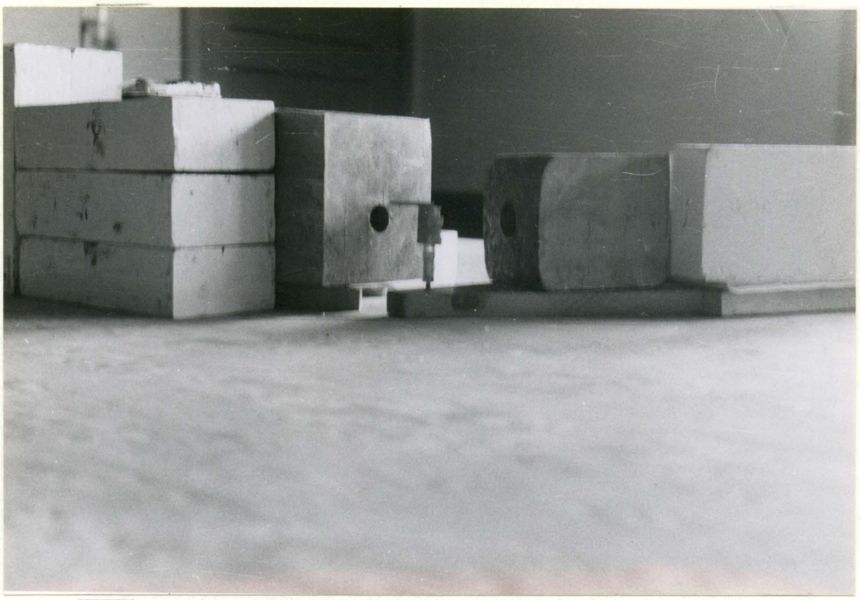

SHIELDING
7cm.
SOURCE
5 cm.
29.2 cm.
SHIELDING
COLLIMATORS
5.08cm
2.22 cm.
TARGET
7.6cm.
26.6 cm.
TYPICAL POSITION
OF DETECTOR

Figure 3. Experimental arrangement of shielding, collimators and target used with the unaligned crystals

Figure 4. Experimental arrangement of the source container, collimators, shielding, target and detector used with the unaligned crystals; some of the shielding has been removed



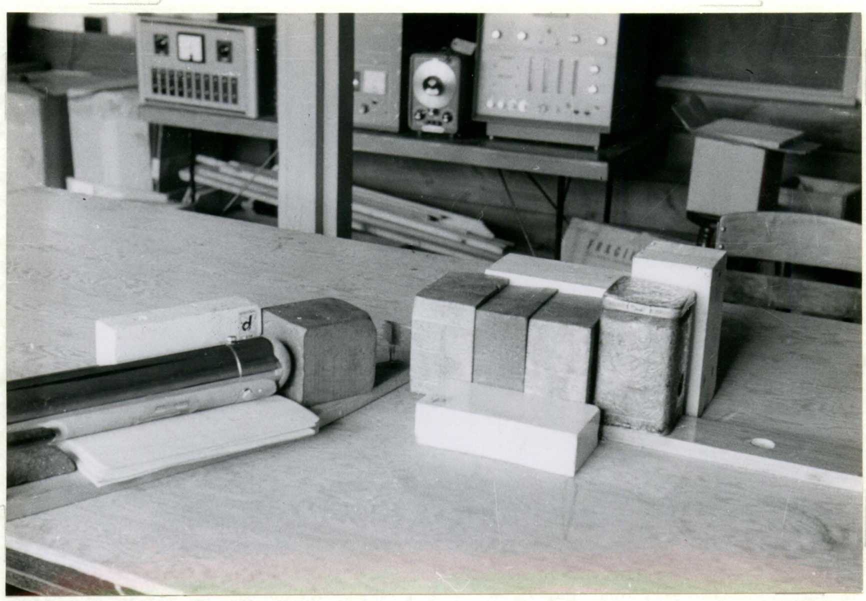

d

Figure 5. Plan view of apparatus used to obtain Bragg reflection and to determine the Klein-Nishna cross section of the aligned crystal

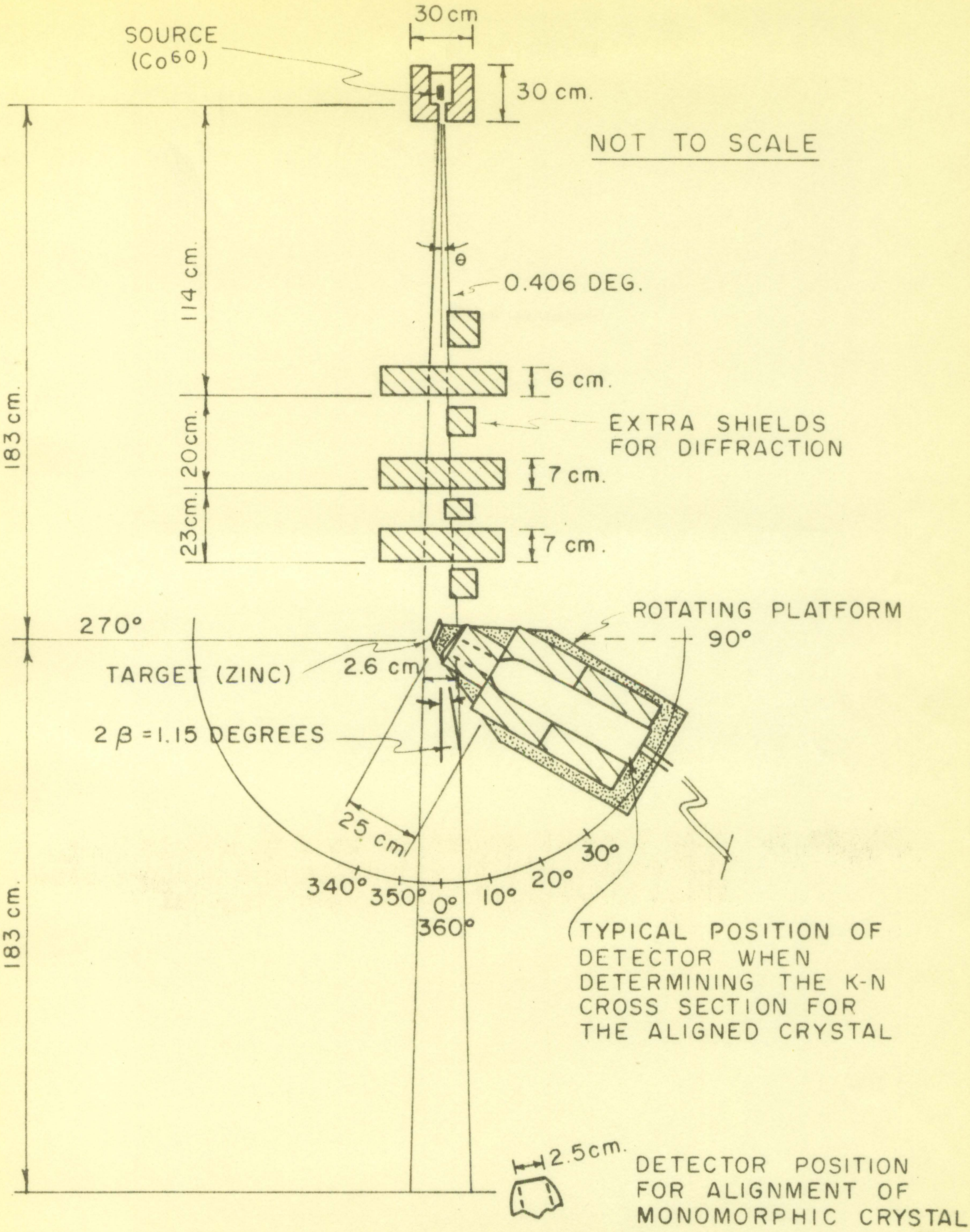
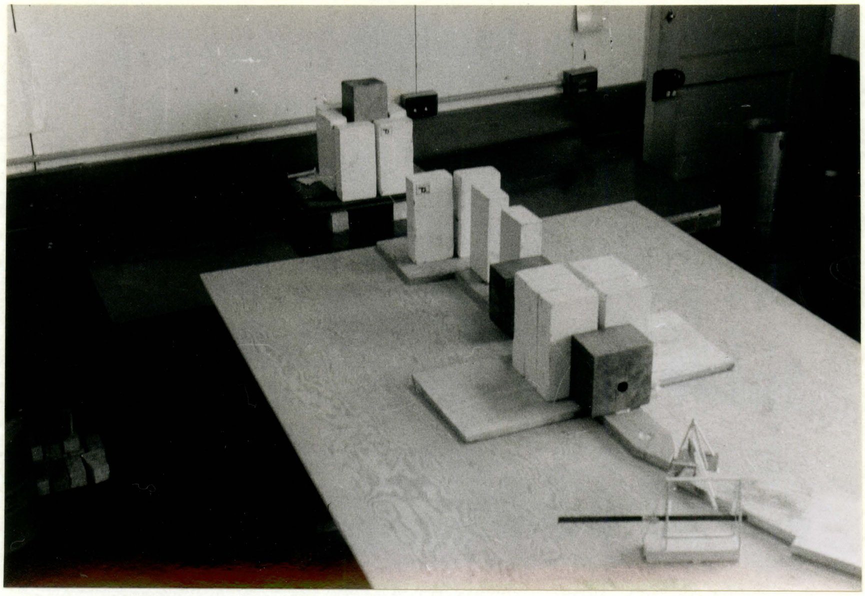

30 cm
SOURCE
(Co60)
30 cm.
NOT TO SCALE
θ
0.406 DEG.
114 cm.
6 cm.
EXTRA SHIELDS
FOR DIFFRACTION
183 cm.
20 cm.
7 cm.
23 cm.
7 cm.
ROTATING PLATFORM
270°
90°
TARGET (ZINC)
2.6 cm
2 β = 1.15 DEGREES
25 cm
30°
340°
350°
0°
360°
10°
20°
TYPICAL POSITION OF
DETECTOR WHEN
DETERMINING THE K-N
CROSS SECTION FOR
THE ALIGNED CRYSTAL
183 cm.
2.5 cm.
DETECTOR POSITION
FOR ALIGNMENT OF
MONOMORPHIC CRYSTAL

Figure 6. Experimental arrangement of source container, collimators, and target used to obtain Bragg reflection and to determine the Klein-Nishina cross section of the aligned crystal

Figure 7. Experimental arrangement of the detector and scaler used to obtain Bragg reflection



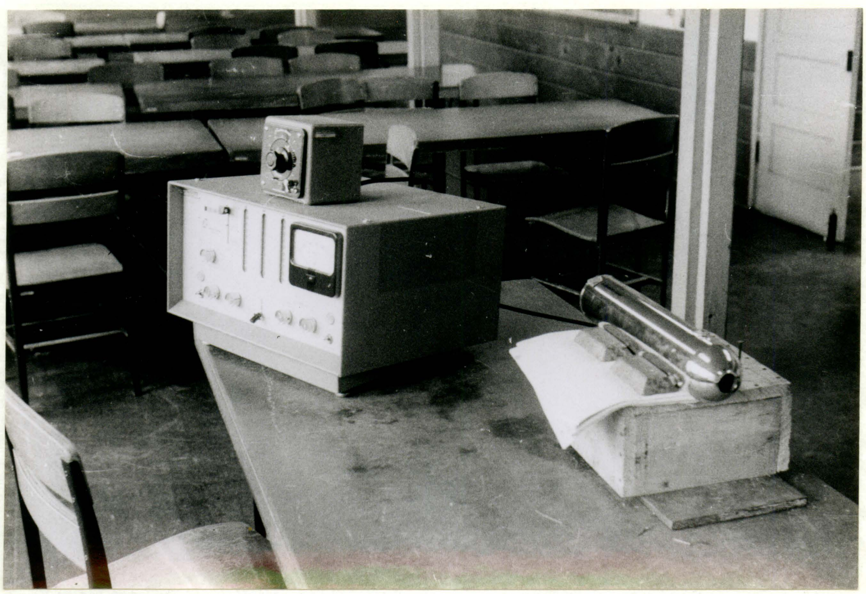
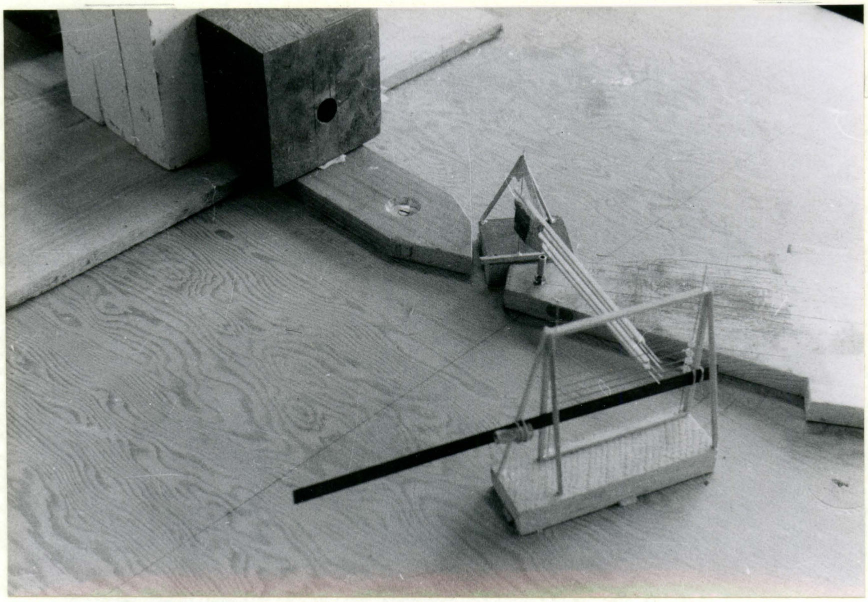


Figure 8. Monomorphic crystal target and target alignment apparatus used to obtain Bragg reflection

Figure 9. Monomorphic crystal target in the aligned position used when determining the Klein-Nishina cross section



block to a depth of two and a half inches so that the centerline of the hole was midway between the sides and parallel to the base of the container at a distance of two inches above the base. On the same centerline a 1/8 inch hole extended through the remaining one and one-half inches of the container. On the outside of the lead block were placed lead bricks which measured two inches by four inches by eight inches. This arrangement reduced the dosage in the working area to about 0.1 or 0.2 mr per hour.

B. Collimators

The three collimating blocks were made of lead and had the dimensions of four inches by four inches by three inches with a 5/8 inch hole, four inches by four inches by three inches with a 6/8 inch hole, and four inches by four inches by four inches with a 7/8 hole. The holes were drilled through the four inch by four inch sides and all holes were on a center line midway between the sides and two inches above the base. In order to obtain gamma ray reflection extra lead bricks were placed in between the collimating blocks so that the cone of radiation had an approximately semicircular instead of a circular cross section, and the target was placed about 1 cm to the left (facing toward the source from the counter) of the center of the former circular cross section.

C. Target

The targets were composed of Zn. A monomorphic crystal of zinc 1/2 cm by 1/2 cm approximately 15 cm long was obtained and split along its basal plane into sections about 4 cm long. Four of these sections were then glued together to form a target approximately 2.5 cm high, 0.5 cm wide and 4 cm long. For the unaligned crystal study the target was mounted on a small plastic cylinder which could be slipped securely on and off from a small bolt that was fixed to the supporting surface. Figure 8 illustrates the aligned crystal target arrangement.

As it was desired to obtain a comparison between the attenuation of a monomorphic crystal and a polymorphic crystal, a polymorphic crystal of the same size and shape as the monomorphic crystal was cut from a block of polymorphic zinc and mounted in a manner identical to the monomorphic crystal.

D. Rotating Platform

A rotating platform was made from a board six inches wide and about three feet long. The platform was attached at one end by means of an aluminum bearing through the wood to a screw which extended upward from the supporting platform. The target was attached to this same screw during the part of the experiment concerned with the unaligned crystal. The platform was free to rotate through 200 degrees. By this arrangement the detector, which was situated on the rotating platform, remained the same distance from the source while it was rotated 100 degrees on either side of the collimated beam of initial photons.

### E. Detector

The detector used throughout the experiment was a Model DS-1A Scintilation Detector, serial number 842, manufactured by the Nuclear Chicago Corporation. The detector was supplied with a removable directional shield which provided discrimination against activities more than 15 degrees off the axis of the probe. This removable shield had an aperture of one inch. In order to reduce background count the directional shield was not removed and an additional directional shield consisting of a lead block four inches by four inches by six inches with a one inch hole, through the four inch by four inch face, was added. In order to reduce further the background count, two inches of shielding was added around the sides and bottom of the detector in the form of lead bricks and plates, and a 3/4 inch lead plate was placed on top of the detector. The detector was operated at 1550 volts during the unaligned crystal study and at 1600 volts during the aligned crystal study. The effective center of the detector was determined to be 4 cm behind the detector window.

## F. Scaler

The scaler used in the study of the unaligned crystal was a Model 200 Scaler manufactured by the Radiation Instrument Development Laboratory. This scaler was used because it contained a discriminator which enabled an analysis to be made of the energy of the photons scattered into the detector as well as their number. The scaler, however, did not perform as well as was expected. It appeared to be very sensitive to temperature and humidity changes in the room and even at constant temperature and humidity the count decreased approximately proportionately to the length of time of operation. This might possibly have been due to an increase in temperature of the scaler. The excessive sensitivity of this scaler was further indicated by the tendency to double or triple trigger after the equipment had been in operation several hours. The double and triple triggering was observed by setting the scaler, after several hours of use, on "test" where it should count the 60 cycle line frequency. Instead of reading 3600 cpm the scaler often gave a count of 7,200 cpm and sometimes 10,800 cpm.

An additional difficulty with the scaler was found when an extensive test was made to determine the operational plateau of the equipment (Figure 12). With the discriminator set at zero, readings were taken from 1300 to 2000 volts. The count from the source of $Co^{60}$ increased steadily as the voltage increased, but the background count, which was due to photons which had been scattered one or more times before reaching the detector and were therefore at a lower energy, remained constant. It was therefore concluded that the scaler was discriminating against photons at energies appreciably lower than that emitted by the $Co^{60}$.

The combination of excessive sensitivity and unwanted discrimination in a scaler is unfortunate because if the sensitivity is increased to avoid discrimination double triggering increases, and if the sensitivity is decreased to avoid double triggering the unwanted discrimination increases. The scaler was checked by the I.S.C. instrument shop several times and though some minor adjustments were made the above mentioned difficulties were not appreciably corrected.

In the study conducted with the aligned monomorphic crystal a Model 181 A scaler manufactured by the Nuclear Chicago Corporation was used. This scaler did not have a discriminator. However, it was used in preference to the R. I. D. L. scaler because it did not exhibit the unwanted characteristics of the previous scaler.

# V. PROCEDURE

In the first studies made the crystals were unaligned and the geometry was as shown in Figure 2. Readings were taken throughout an arc of 200 degrees at 10 degree intervals. After several runs were made it was observed that the count recorded by the scaler decreased with the length of time of operation when the detector was exposed to a constant source. It was further observed that the count varied with changes in temperature and humidity.

## A. Standard Count

In order to compensate for the above variables a source of low intensity $Co^{60}$ was obtained and mounted on a plug which could be placed in the aperture of the scintilation tube. This arrangement placed a constant source at a constant distance from the detector.

The collimated source of gammas was blocked off and the target removed so that the only photons detected by the scintilation tube would be those emitted by the constant low energy source in the aperture, and the background photons. A run was then made taking 5 minute readings of the constant source and the background photons at each ten degree interval throughout the 200 degree arc, and a plot was made of these counts as a function of the position at which they were taken. This plot was thereafter used as a standard or reference count.

## B. Scattering by Unaligned Crystals

The number of photons scattered at a given direction by both the unaligned polymorphic and monomorphic crystals were obtained in the following manner. The detector was rotated to a given position. A count was taken of the number of photons scattered into the detector by the target, then a count of the standard source was obtained by blocking off the initial collimated photons and placing the standard source plug in the detector aperture. Following this, a background was taken and subtracted from both the count of the standard source and the count of the photons scattered by the target. From these data it was possible to determine what correction factor was necessary to correct the count from the standard source to the standard count. This same correction factor was then applied to the count of the photons scattered by the target. This procedure was followed because theoretically the count from the standard source should be the same each time it was taken, and the only cause for variation of this count would be the fluctuations of the sensitivity of the scaler or the detector. It was further reasoned that the count of the scattered photons would vary in approximately the same ratio as the counts from the standard source. By correcting the standard count to a given constant value and by applying this same correction factor to the counts from the target, the counts from the target should be corrected to that value which they would have had, had there been no fluctuation in the equipment.

Counts were taken at ten degree intervals throughout the 200 degree arc, but as the count was symmetrical on both sides of the collimated beam, the plot of the count as a function of position for an arc of only 100 degrees was used.

Due to trouble with the scaler as discussed in page 29, the R. I. D. L. scaler used for this run was replaced by a Nuclear-Chicago scaler for the remainder of the experiment. It was thereafter no longer necessary to correct the counts of the scattered photons with the standard count.

### C. Monomorphic Crystal Alignment

Bragg Reflection was obtained by placing the equipment in the position shown in Figure 5. The source and detector remained in fixed positions and the monomorphic crystal was rotated by means of the apparatus shown in Figure 8 in increments of 0.25 degrees through an angle of about 10 degrees on each side of what appeared, by eye, to be the proper angle for Bragg Reflection, i.e., the basal plane of the monomorphic crystal intersecting the collimating photons at 0.4 degrees. A plot of this count as a function of position of the crystal is shown in Figure 10. What appeared to be Bragg Reflection occurred throughout about 1.5 degrees of this run. The

Table 1. Bragg Reflection data

| Position of crystal | Counting rate (cpm) |
|---|---|
| 2-8/32 | 392±3.6 |
| 1-31/32 | 409±2.3 |
| 1-20/32 | 396±3.1 |

target was then placed in the center of this region of possible Bragg Reflection and several long counts were made in this position and in positions on either side of this region. As is shown in Table 1, the counting statistics indicated that Bragg Reflection was occurring, therefore the target was glued in this position and braced as shown in Figure 9 so that it would not be jarred or knocked out of place.

D. Scattering by Aligned Monomorphic Crystal

Without changing the position of the target, collimators, or source from that described, the detector was moved to the rotating platform and a run was made taking 10 minute

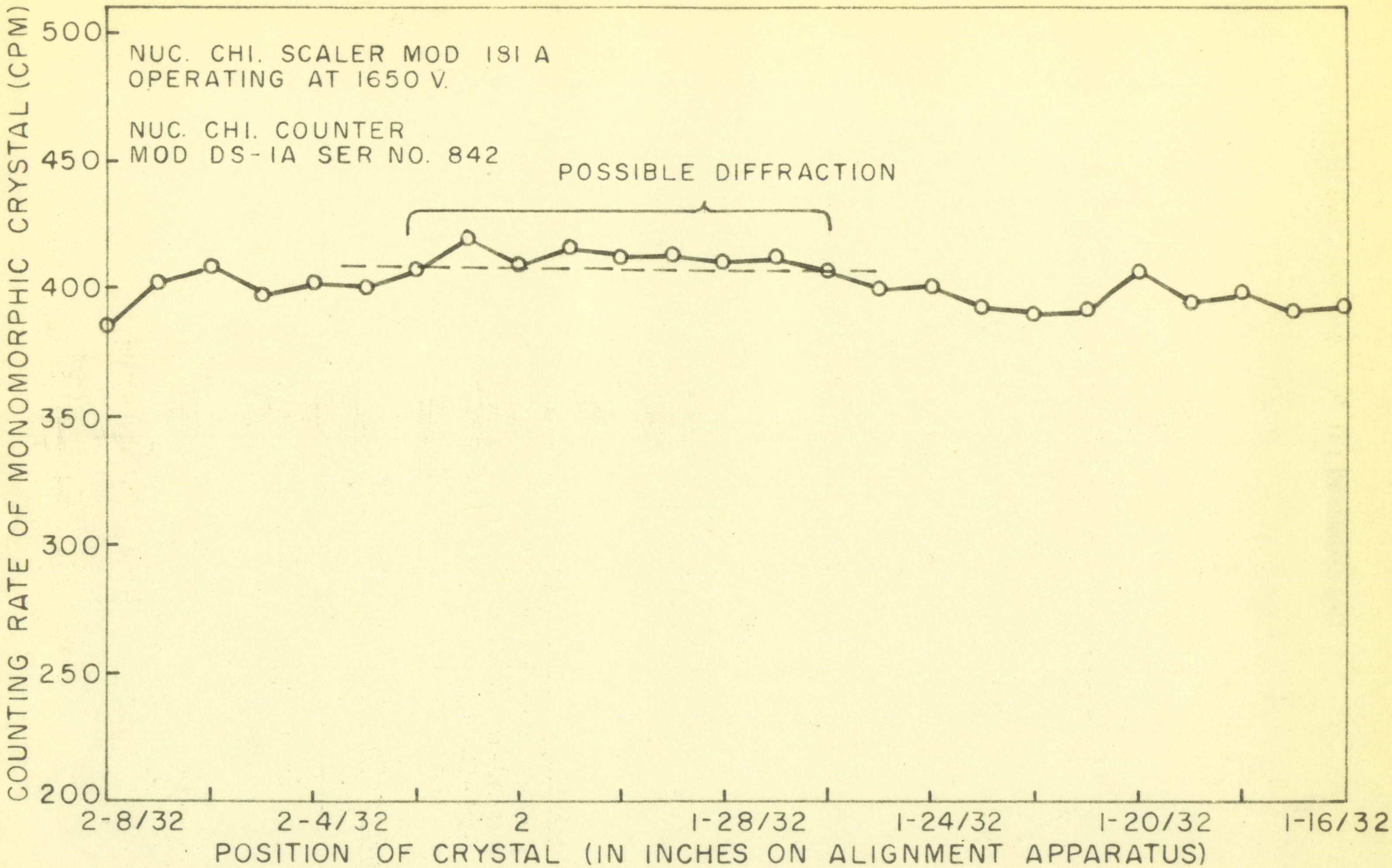



Figure 10. Bragg Diffraction

readings of the count and background every 10 degrees throughout an arc of 100 degrees.

## VI. DISCUSSION AND RESULTS

The results of this study are presented in the form of a plot of the Klein-Nishina cross section as a function of the scattering angle in Figure 11. In order to determine whether the scattering characteristics of a given shield composed of a polymorphic crystaline material differs from the scattering characteristics of a similar shield composed of monomorphic crystaline material when it is aligned to reflect some gamma photons, it should be necessary only to compare the theoretical scattering probability (known to pertain to polymorphic crystals) to the scattering probability determined experimentally from the aligned monomorphic crystals. If the probability that a photon will be scattered in a given direction is the same for both the polymorphic and monomorphic crystals, then it could be concluded that the building of shields for gamma radiation composed of monomorphic crystals aligned so that Bragg Reflection occurs, could not be justified by the assumption that the use of monomorphic crystals enable an appreciable change to be made in the scattering pattern of the photons.

The theoretical probability that a photon of 1.252 Mev will be scattered in a given direction by a zinc target is given by the Klein-Nishina cross section and is plotted in

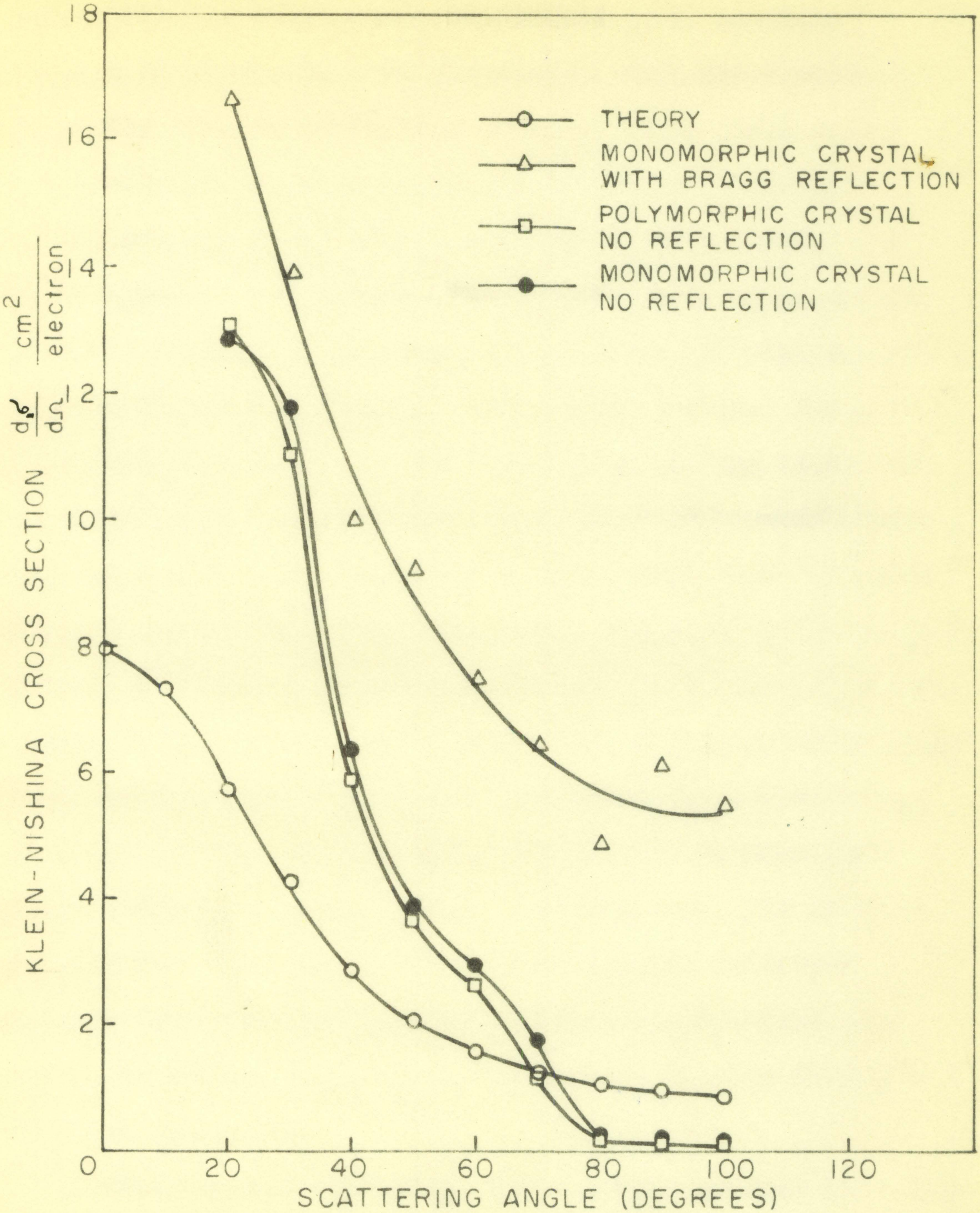



Figure 11. Compton differential cross section $\alpha = 2.45$

Figure 11. The plot of the experimentally determined cross sections for the polymorphic and monomorphic crystals appearing in Figure 11 should coincide with the theoretical probability when no reflection occurs. That these curves do not coincide is possibly explained by several factors.

One source of probable error may be the scaler. For the unaligned crystal study a Model 200 R. I. D. L. scaler was used. Attempts were made over a period of several months to obtain consistent readings using this scaler. The scaler was checked over twice by the Iowa State College instrument shop, tubes were replaced and other minor adjustments were made. The scaler then appeared to be in good working order and the runs to obtain the scattering data for the unaligned crystals were made. It was not noticed that these data were so obviously in error until the theoretically expected Klein-Nishina cross section for these crystals was plotted and a comparison of the two was made. Due to the trouble that occurred with this scaler a further check was made on its operation to determine if it had been giving erroneous readings. An extensive plateau curve was made using the geometry of Figure 5 with the detector 90 degrees from the collimated gamma beam.

Several unusual characteristics appear on this plot that might help explain why the Klein-Nishina cross section obtained from the unaligned crystal does not coincide with the

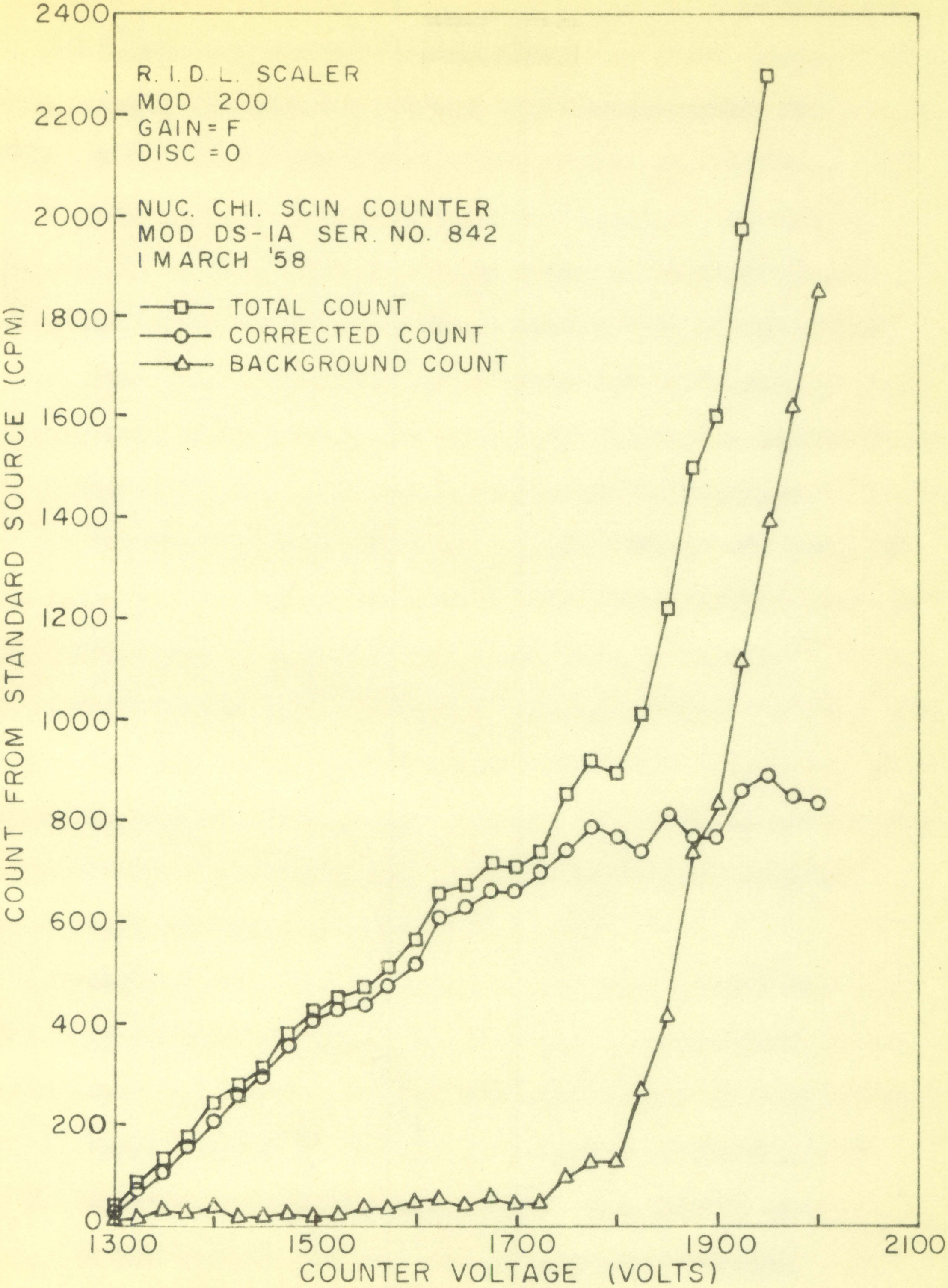



**Figure 12. Plateau curve**

theoretically expected cross section. It can be noted that no counts occur below 1300 volts, and, even more significant, the background was constant until the scaler reads about 1750 volts. At all times the discriminator was set at zero. If, however, the scaler was discriminating against low energy gamma radiation when it was set on zero, a curve of this shape would be expected. The low voltage end of the curve would be cut off because at low voltage the pulses might not have been amplified enough to be "seen" above the discriminator. Since the gamma source was shielded by 8 inches of lead and the detector by approximately 4 more inches of lead, it is reasonable to assume that the background count is due almost exclusively to photons that have been scattered several times before reaching the detector and are therefore at a low energy. Thus if it is again assumed that the scaler was discriminating against low energy photons it would be reasonable to expect that the background count would remain constant until a high voltage was reached.

Proceeding with the assumption that the scaler was discriminating it can be explained that the experimental curves for the unaligned crystals, between zero angle of scattering and a 60 degree angle of scattering, have a greater slope than the theoretically expected curve. The photon energy emitted by the source was not completely monoenergic. Some scattered photons, which were of less energy than the primary photons, reached the target and were scattered into the detector, and some of the primary photons that reached the target were scattered more than once before they reached the detector. Therefore a spectra of photon energy and not monocrymatic energy reached the detector.

As the angle through which the photons were scattered was increased, the energy spectra of the scattered photons decreased. Thus it would be expected that the percentage of the photons discriminated against would increase with increasing scattering angle.

The sharp decrease in the Klein-Nishina cross section to the scattering angle of 60 degrees can be explained by the assumption that the maximum energy of the spectra was approaching that energy against which the scaler was discriminating. Since those factors which caused the detected photon energy to be in a spectra were of a secondary nature, it would be expected that the greatest density of energy would be near the maximum energy of the spectra. Thus as the maximum energy of the spectra approached the cut-off energy of the discriminator, a sharp increase in the photons discriminated against would be expected. At scattering angles greater than 80 degrees it can be assumed that the entire energy spectra is below that energy against which the scaler was discriminating.

If it is assumed that the R. I. D. L. scaler was discriminating against low energy gammas then we must assume that the curves for the unaligned crystals should have a higher value than that which appears in Figure 11. Some factors that might explain why the curves for both the aligned and unaligned crystals have a higher value than the theoretically expected curve are that the exact location of the effective center of the detector was not known and it was possible that a small error occurred in measuring the distance from the target to the detector; the exact location of the effective center of the source was not known and the distance from the source to the targetmight be slightly in error; and an additional small error might have been made in estimating the volume of the target.

## VII. CONCLUSION

Due to the apparent discrimination of the R. I. D. L. scaler, no conclusions can be reached using the curves for the unaligned crystals.

The reasons that the unaligned and the aligned curves were higher than the theoretical curve was probably due to errors in measuring distances. As all of the distances were constant values, an error in their measurement would change the height of the experimental curves, but would not change their slope or shape. Therefore, in order to obtain a comparison between the curve for the aligned monomorphic crystal and the theoretical curve, it is significant to compare their shapes and not their heights. An overlay of the two curves shows neither coincidence nor (considering the accuracy of the equipment) what may be called a significant difference.

From this it may be concluded that there is an indication that the Klein-Nishina cross section is altered for monomorphic crystals when they are aligned so that Bragg reflection occurs, but this alteration cannot be determined quantitatively from the data obtained in this experiment. This conclusion is not unreasonable when it is considered that the number of reflected photons reaching the detector were on the order of magnitude of 4% of the number of photons scattered into the detector at the position where reflection occurred, and no reflection occurred at any other position. Thus the total number of photons reflected were negligible in comparison to the number of photons scattered.

From this experiment it may also be concluded that Bragg reflection will occur with a monomorphic crystal when it is properly aligned, and if proper steps are taken it should be possible to determine the scattering characteristics of this radiation.

## VIII. RECOMMENDATIONS

Since the Klein-Nishina cross section does not take into consideration Bragg reflection, the probability predicted by this equation must be altered when Bragg reflection occurs. Therefore, in order to obtain an experimental Klein-Nishina cross section for monomorphic crystal under the condition of Bragg reflection that might differ significantly from the cross section for a polymorphic crystal, it is recommended that the crystal be cut and the geometry arranged so that the percentage of the photons reflected is appreciable when compared to the percentage of the photons scattered.

To accomplish this the crystal might be cut into a thin disc with the surface of the disc perpendicular to the basal planes. It can then be aligned with the incident gamma radiation so that the basal planes will reflect the photons. A high gamma source (several hundred mc) and a small angle collimating cone (approximately 0.25 degrees) would be desirable. The advantages of this arrangement would be that a large per cent of each basal plane will be exposed to primary gamma radiation, which will increase the probability of Bragg reflection, the percent of the primary photons scattered will be small, and the amount of scattering of the photons that have been reflected will be small. Because of the small crystal size this experiment would not have a high percentage of the primary photons scattered or reflected, but the percentage of the photons that are reflected might be appreciable when compared to the percentage of the photons that are scattered.

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# XI. APPENDIX

Table 2. Experimental data for unaligned crystals

| Scattering angle counter clockwise (degrees) | Counting rate (cpm) | Net rate (cpm) | Standard* counting rate (cpm) | Corrected net rate (cpm) |
|---|---|---|---|---|
| | | Polymorphic crystal | | |
| 100 | 189 | 12 | 95 | 15± 6 |
| 90 | 92 | 29 | 96 | 36± 4 |
| 80 | 123 | 41 | 99 | 54± 5 |
| 70 | 387 | 329 | 93 | 463± 9 |
| 60 | 692 | 646 | 108 | 774±12 |
| 50 | 912 | 860 | 110 | 1020±14 |
| 40 | 1450 | 1390 | 108 | 1665±17 |
| 30 | 2072 | 1965 | 84 | 3020±20 |
| 20 | 4334 | 2071 | 85 | 3180±20 |
| | | Monomorphic crystal | | |
| 100 | 194 | 17 | 95 | 21± 6 |
| 90 | 83 | 20 | 96 | 25± 4 |
| 80 | 115 | 33 | 99 | 43± 5 |
| 70 | 380 | 322 | 93 | 454± 9 |
| 60 | 633 | 587 | 108 | 690±11 |
| 50 | 845 | 793 | 110 | 949±13 |
| 40 | 1340 | 1280 | 108 | 1530±16 |
| 30 | 1952 | 1845 | 84 | 2850±20 |
| 20 | 4350 | 2087 | 85 | 3210±20 |

*Standard counting rate corrected to 130 cpm.

Table 3. Klein-Nishina cross section for unaligned crystals

| Scattering angle counter clockwise (degrees) | B Corrected net rate (cpm) | $e^{e\sigma T}$ Self-absorption factor (dimensionless) | $\frac{d\,e\sigma}{d\Omega}$ Klein-Nishina cross section $\frac{cm^2}{electron}$ ($10^{-26}$) |
|---|---|---|---|
| | | Polymorphic crystal | |
| 100 | 15 | 1.326 | 0.062 |
| 90 | 36 | 1.260 | 0.141 |
| 80 | 54 | 1.244 | 0.208 |
| 70 | 463 | 1.229 | 1.73 |
| 60 | 774 | 1.223 | 2.94 |
| 50 | 1020 | 1.223 | 3.87 |
| 40 | 1665 | 1.231 | 6.36 |
| 30 | 3020 | 1.257 | 11.75 |
| 20 | 3180 | 1.308 | 12.85 |
| | | Monomorphic crystal | |
| 100 | 21 | 1.326 | 0.086 |
| 90 | 25 | 1.260 | 0.098 |
| 80 | 43 | 1.244 | 0.166 |
| 70 | 454 | 1.229 | 1.69 |
| 60 | 690 | 1.223 | 2.62 |
| 50 | 949 | 1.223 | 3.64 |
| 40 | 1530 | 1.231 | 5.84 |
| 30 | 2850 | 1.257 | 11.0 |
| 20 | 3210 | 1.308 | 13.1 |

$$(T_o)(\Omega)(\phi) = 323(10^{26})\ \frac{\text{electrons-photons}}{\text{cm}^2 - \text{min}}$$

Table 4. Experimental data for aligned monomorphic crystal

| Scattering angle counter clockwise (degrees) | Counting rate (cpm) | Net rate (cpm) |
|---|---|---|
| 100 | 3811 | 64±6 |
| 90 | 3255 | 73±6 |
| 80 | 2640 | 59±5 |
| 70 | 2257 | 78±5 |
| 60 | 2065 | 89±5 |
| 50 | 2286 | 108±5 |
| 40 | 2175 | 117±5 |
| 30 | 2303 | 157±5 |
| 20 | 2546 | 179±5 |

Klein-Nishina cross section for aligned monomorphic crystal

| Scattering angle counter clockwise (degrees) | B net rate (cpm) | $(T_o)(\Omega)(\emptyset)$ electron-photon / $cm^2$-min ($10^{-26}$) | $e^{e\sigma T}$ Self-absorption factor (dimensionless) | $\frac{d\sigma}{d\Omega}$ Klein-Nishina cross-section $\frac{cm^2}{electron}$ |
|---|---|---|---|---|
| 100 | 64 | 15.49 | 1.326 | 5.48 |
| 90 | 73 | 15.22 | 1.260 | 6.05 |
| 80 | 59 | 15.01 | 1.244 | 4.89 |
| 70 | 78 | 14.80 | 1.229 | 6.46 |
| 60 | 89 | 14.59 | 1.223 | 7.46 |
| 50 | 108 | 14.39 | 1.223 | 9.20 |
| 40 | 117 | 14.28 | 1.231 | 10.1 |
| 30 | 157 | 14.18 | 1.257 | 13.9 |
| 20 | 179 | 14.08 | 1.308 | 16.6 |

Table 5. Experimental data for plateau curve, R. I. D. L. scaler, Nuc-Chi scintilation counter

| Voltage (volts) | Counting rate (cpm) | Background (cpm) | Net counting rate (cpm) |
|---|---|---|---|
| 1300 | 35 | 9 | 26± 3 |
| 1325 | 83 | 13 | 70± 4 |
| 1350 | 132 | 30 | 102± 5 |
| 1375 | 177 | 22 | 155± 6 |
| 1400 | 243 | 38 | 205± 7 |
| 1425 | 273 | 15 | 258± 8 |
| 1450 | 311 | 16 | 295± 8 |
| 1475 | 379 | 22 | 357± 9 |
| 1500 | 422 | 17 | 405± 9 |
| 1525 | 446 | 21 | 425± 9 |
| 1550 | 469 | 32 | 437±10 |
| 1575 | 508 | 34 | 474±10 |
| 1600 | 562 | 49 | 513±11 |
| 1625 | 656 | 52 | 604±11 |
| 1650 | 666 | 39 | 627±12 |
| 1675 | 712 | 54 | 658±12 |
| 1700 | 702 | 46 | 656±12 |
| 1725 | 739 | 47 | 692±12 |
| 1750 | 825 | 92 | 734±13 |
| 1775 | 912 | 128 | 784±14 |
| 1800 | 893 | 128 | 765±13 |
| 1825 | 1006 | 269 | 737±14 |
| 1850 | 1214 | 410 | 804±16 |
| 1875 | 1497 | 733 | 764±17 |
| 1900 | 1593 | 829 | 754±18 |
| 1925 | 1973 | 1115 | 858±20 |
| 1950 | 2279 | 1391 | 888±21 |
| 1975 | 2464 | 1615 | 849±22 |
| 2000 | 2868 | 1848 | 838±23 |

Table 6. Experimental data for Bragg reflection

| Run 1 | | Run 2 | | |
|---|---|---|---|---|
| Position of target (in inches on alignment apparatus)[a] | Counting rate (cpm) | Position of target (in inches on alignment apparatus) | Counting rate (cpm) | |
| 2-8/32 | 386 | 2-8/32 | 391 | |
| 2-7/32 | 402 | 2-8/32 | 388 | $\bar{n}$=392±3.6 |
| 2-6/32 | 408 | 2-8/32 | 397 | |
| 2-5/32 | 397 | | | |
| 2-4/32 | 401 | | | |
| 2-3/32 | 400 | | | |
| 2-2/32 | 406 | | | |
| 2-1/32 | 419 | 1-31/32 | 412 | |
| 2-0/32 | 409 | 1-31/32 | 400 | |
| 1-31/32 | 415 | 1-31/32 | 406 | |
| 1-30/32 | 412 | 1-31/32 | 410 | $\bar{n}$=409±2.3 |
| 1-29/32 | 412 | 1-31/32 | 407 | |
| 1-28/32 | 410 | 1-31/32 | 415 | |
| 1-27/32 | 411 | 1-31/32 | 406 | |
| 1-26/32 | 407 | 1-31/32 | 414 | |
| 1-25/32 | 399 | | | |
| 1-24/32 | 400 | | | |
| 1-23/32 | 392 | | | |
| 1-22/32 | 390 | 1-20/32 | 395 | |
| 1-21/32 | 391 | 1-20/32 | 399 | $\bar{n}$=396±3.1 |
| 1-20/32 | 407 | 1-20/32 | 395 | |
| 1-19/32 | 395 | 1-20/32 | 397 | |
| 1-18/32 | 398 | | | |
| 1-17/32 | 391 | | | |
| 1-16/32 | 393 | | | |

[a]Each 1/32 of an inch change in position of the alignment apparatus represents a 0.26 degree change in the angle between the incident photons and the basal planes of the crystal.

## Sample Calculations

Counting statistics for Bragg reflection data.

$$\bar{h} \pm \sigma = \frac{h}{t} \pm \frac{1}{t}\left(\frac{h}{N}\right)^{\frac{1}{2}}$$

or $$\bar{h} \pm \sigma = \bar{h} \pm \left(\frac{\bar{h}}{tN}\right)^{\frac{1}{2}}$$

$\bar{h}$ = Average activity

h = Total activity per time interval

t = Time interval

N = Number of times measurement is repeated

where $\bar{h} = 392$

t = 10 min

N = 3

$$\bar{h} \pm \sigma = 392 \pm \left(\frac{392}{(10)(3)}\right)^{\frac{1}{2}}$$

$$\bar{h} \pm \sigma = 392 \pm 3.6 \text{ cpm.}$$

Klein-Nishina cross section for unaligned crystal with a scattering angle of 60 degrees.

$$\frac{d\sigma}{d\Omega} = \frac{(B)\, e^{\mu d} \;\; T}{(T\;)(\Omega\;)(\emptyset)\eta}$$

B

Counting rate = 692 cpm
Background = 46 cpm
Net rate = 646 cpm

Standard counting rate = 108 cpm

Correct standard counting rate to 130 cpm
108 cpm (120%) = 130 cpm

Correct net rate
646 cpm (120%) = 747 cpm
B = 747 cpm

$\eta$ = 0.1

$e^{{}_e\sigma T}$

${}_e\sigma$ is obtained from a plot of ${}_e\sigma$ as a function of $\alpha$ in Davisson and Evans (3, p. 82, Table II).

$$\alpha = \frac{h\nu}{1 + \alpha_o(1-\cos\theta)} \left(\frac{1}{m_o c^2}\right)$$

$$\alpha = \frac{1.252}{1 + 2.45(1 - 0.500)} \left(\frac{1}{0.5108}\right)$$

$$\alpha = 1.102$$

and $${}_e\sigma = 2.75(10^{-25}) \ \frac{\text{cm}^2}{\text{electron}}$$

$$T = \frac{A_t}{\left[\frac{L}{\cos\xi}\right]\left[\sin(\theta + \xi\ )\right]}$$

$$T = \frac{1.525}{\frac{4.15}{\cos 11.4^o}\left[\sin(\theta + 11.5^o)\right]}$$

For $\theta = 60^o$

$$T = \frac{1.525}{4.24 \sin 71.5^o} = \frac{1.525}{(4.24)0.946}$$

$$T = 0.380 \text{ cm}$$

or $$T = 0.380 \text{ cm}\left[\frac{6.02(10^{23})\text{atoms}}{65 \text{ gm}}\right]\left[\frac{30 \text{ electrons}}{\text{atom}}\right]\left[\frac{7.133 \text{ gm}}{\text{cm}^3}\right]$$

$$T = 0.734(10^{24}) \ \frac{\text{electrons}}{\text{cm}^2}$$

thus $$e^{{}_e\sigma T} = e^{0.275(10^{-24})(0.734)(10^{24})}$$

$$e^{{}_e\sigma T} = 1.223$$

$T_o$

$$T_o = \frac{1.525}{4.24 \sin 11.4}$$

$$T_o = 3.50(10^{24}) \ \frac{\text{electrons}}{\text{cm}^2}$$

$\Omega$

$$\Omega = \frac{\text{Area of detector}}{4 \pi r^2}$$

$$\Omega = \frac{\pi (1.10)^2 \text{cm}^2}{4 \pi (26.00)^2}$$

$$\Omega = 0.449(10^{-3}) \text{ ster}$$

$\phi$

$$\phi = \frac{\text{Area of target (s)}}{4 \pi r^2}$$

$$\phi = \frac{(1.90)(2.70)(2)(63)(3.7)(10^7)}{4 \pi (0.310)^2 (10^4)} \quad \frac{\text{photons}}{\text{sec}}$$

$$\phi = 0.198(10^7) \ \frac{\text{photons}}{\text{sec}}$$

$$\frac{d\sigma}{d\Omega} = \frac{\left(\frac{747 \text{ photons}}{\text{sec}}\right)(1.223)\left(\frac{1}{0.10}\right)}{\left(\frac{3.50(10^{24})\text{electrons}}{\text{cm}^2}\right)\left(0.479(10^{-3})\text{ster}\right)\left(\frac{0.198(10^7)\text{photons}}{\text{sec}}\right)}$$

$$\frac{d\sigma}{d\Omega} = 2.94 \ (10^{-26}) \ \frac{\text{cm}^2}{\text{electron steradian}}$$