GAMMA RAY REFLECTION
WITH THIN ZINC CRYSTALS

by

John Francis Wilson

A Thesis Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
MASTER OF SCIENCE

Major Subject: Nuclear Engineering

Signatures have been redacted for privacy

Iowa State College
Ames, Iowa
1958

TABLE OF CONTENTS

6

4

I. INTRODUCTION

4

The use of nuclear fuel as a source of power for mobile equipment such as airplanes, ships and locomotives holds considerable advantage over fossil fuels due to the immense amount of energy which may be stored in a small mass. This advantage is somewhat outweighed by the massive shielding required to protect personnel and equipment from injurious radiation emitted from the fuel during its storage and conversion to usable energy by nuclear fission.

Of the various types of radiation emitted during storage and nuclear fission, neutrons and gamma rays are the most difficult to attenuate. In some instances it is not necessary to attenuate radiation, rather it may be sufficient to deflect the radiation away from certain areas such as the crew compartment of an airplane or from certain types of electrical instrumentation which may be susceptible to radiation damage. If a device to deflect radiation could be made less massive than present types of radiation shielding, it would be helpful in the utilization of nuclear fuel for mobile equipment.

It has been well established that gamma ray attenuation proceeds by the mechanisms of photo-electric effect, Compton scattering and pair production. These mechanisms depend primarily upon the mass of the shielding material, therefore, little can be done to reduce the weight of this type of shield.

A reflector of electro-magnetic radiation in the energy range of x-rays and gamma rays is dependent upon the lattice structure of the material. It should be noted, the reflection referred to here does not necessarily depend upon the existence of a polished surface as is true for the reflection of ordinary light. The term is used only to simplify the description of the effect. There is no such thing as surface reflection of x-rays or gamma rays rather reflection takes place on all layers of atoms aligned properly for reflection. Under this condition, it is conceivable to reflect gamma rays by proper alignment of a crystal. This type of reflector would not necessarily be dependent upon mass of the reflecting material, rather it would depend on the lattice structure. The purpose of this investigation is to examine certain parameters of gamma ray reflectors.

II. REVIEW OF LITERATURE

The prediction and later experimental confirmation of the ability of crystals to diffract electro-magnetic radiation was first made by V. Laue in 1912 (1). He showed the lattice structure of a crystal acts as a diffracting grating with interference of waves taking place at a number of points which are associated with the atoms in the lattice structure of the crystal. V. Laue also developed a mathematical expression for the intensity of radiation diffracted to all points which confirmed his experimental results.

Shortly after V. Laue's experiments with crystal interference, W. L. Bragg and W. H. Bragg (1) discovered certain natural surfaces of a crystal, such as a cleavage face, can reflect x-rays under certain conditions. They also developed a rather simple expression for the glancing angle at which reflection takes place which is

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

where λ is the wavelength of the incident radiation, n is an integer representing the "order" of reflection, d is the distance between crystal planes and θ is the critical glancing angle.

About this time E. Rutherford and E. Andrade measured the wave lengths of soft gamma rays from Radium B by determining the angle of reflection of rays diffracted by a crystal of rock salt (2).

In 1914, Darwin (3) predicted that the velocity of x-rays in a medium would differ from that in a vacuum. He further hypothesized the equation $n\lambda = 2d \sin\theta$ would hold for the angle of reflection produced by the interior of a crystal but not for the angle of reflection at the surfaces. The refractive index calculated by Darwin was about one part per million less than one. A short time later, Senström (4), Duane and Patterson (5) and Siegbahn (6) confirmed Darwin's hypothesis with experimental evidence. They found the index of refraction differed from one by about 8×10^{-6} for x-rays of wave length 1.473 A. in calcite.

Since the refractive index is less than one, x-rays should be totally reflected under certain conditions. A. H. Compton (7) arrived at an expression for the critical glancing angle θ for total reflection which is

$$\text{Sin}\,\theta = \sqrt{2\delta} \qquad (2)$$

where δ is the Drude-Lorentz function for the index of refraction of high frequency radiation given by

$$\delta = \frac{ne^2}{2\pi m r^2} \qquad (3)$$

where n is the number of electrons per unit volume, e is the charge of the electron, m is its mass and r represents the frequency of the radiation. For crown glass, Compton states the reflection angle is of the order of twenty-two minutes.

This new knowledge of the relationship between the refractive index and the number of electrons per unit volume of a medium was used primarily to confirm existing evidence of the number of electrons per atom.

Darwin also considered the effect of crystal imperfection upon the intensity of reflection. He pointed out that in a perfect crystal, all radiation which can be reflected is reflected long before it is absorbed by conversion to cathode-ray energy, however, it has been demonstrated by experiment that this complete reflection does not take place in actual crystals. To quote from Darwin's paper, "This must be taken to indicate that the crystals are so badly twisted that their planes do not remain parallel even long enough to produce a single reflection". (3)

W. L. Bragg (8) found by grinding the surface of a crystal on emery paper, the intensity and range of the angle of reflection could be increased.

Although most of the preceding information was developed relative to x-rays, it is applicable to gamma rays since these two types of electro-magnetic radiation differ primarily in their origin. The x-rays are a function of the orbital electrons and the gamma rays originate in the nucleus of the atom.

Measurement of the reflection angle has been used by Du Mond (9) to measure the energy of gamma rays below the

1 Mev energy level in a "curved crystal spectrometer".

Gamma ray reflection as applied to a curved reflector was investigated by Crocker (10) in 1956. He studied the reflection from a curved reflector made of laminated aluminum foil. Although his reflector did not provide the correct grating for interference, he found some indication of reflection. Mergl (11) continued this investigation using a curved single crystal of zinc. His work also indicated a small amount of reflection was taking place.

III. PURPOSE OF INVESTIGATION

The effect of lattice distortion in a crystal upon the ability of the crystal to reflect gamma rays is of considerable theoretical and practical importance in the design of a reflective type gamma ray shield. If the lattice planes of a crystal are badly distorted, as Darwin indicated they may be, then perhaps only a few atomic distances within the crystal could be aligned to reflect at one time, and the remainder of the crystal would absorb the rays by the three previously mentioned mechanisms. If the distortion within the crystal is slight, it would be theoretically possible to align the lattice planes of the entire crystal and thus reflect a higher portion of the incident radiation.

Dislocation lines are the major type of crystal imperfection which accounts for distortion of the lattice. They are present in all crystals. However, the lattice structure of a single crystal is more ideally arranged than in a polymorphic crystal. Within a single crystal the amount of distortion is a rather indefinite quantity, dependent in part upon the conditions of growth and the amount the crystal has been strained.

The surface finish of the crystal also has some effect upon its reflective power. As previously noted, W. L. Bragg found the intensity of reflection could be increased by grinding the surface on emery paper.

The purpose of this investigation is two-fold. The first portion involves the design and construction of a facility for determining the critical angle of a crystal and the amount of radiation reflected through a given angle. The second part is an evaluation of the effect of surface finish and lattice distortion upon the reflective power of a representative sample of an unstrained single crystal. This will be accomplished by comparing the amount of reflection from several thin crystals with that from a single crystal of a thickness equal to that of all the thin crystals.

IV. MATERIALS AND APPARATUS

The apparatus used in this investigation is shown in Fig. 1. A detailed description of each component follows.

A. Source of Radiation

The ideal source of radiation for this investigation should meet three qualifications.

1. It should emit gamma rays in an energy range which can be reflected through a reasonably large angle using available crystals.
2. It should be of sufficient strength to provide a high counting rate at the detector.
3. It should be available for experimentation.

Of the two types of sources available, Co-60 and Tm-170, the latter met these qualifications the more satisfactorily. The energy spectrum of Tm-170 will be discussed later.

An encapsulated Tm-170 with a strength of approximately 100 millicuries was loaned by the Ames Laboratory of the Atomic Energy Commission. Since this was the only Tm-170 source readily available, it was accepted and the source to detector distance chosen to give sufficient radiation at the detector to permit high enough counting rate for good statistical accuracy in a short time.

Tm-170 has a rather broad energy spectrum. It emits one gamma ray of 84 Kev. energy and also considerable quantity of x-rays in the region of 52 Kev. The x-rays are indirectly due to the alternate method of decay by beta emission.

B. Crystal Reflectors

In order to fulfill the requirements of the experiment, the crystal should meet two conditions. First, it should be a single crystal and second, it should have a moderately low atomic number. The latter requirement was necessary to reduce the absorption of gamma rays by photoelectric effect.

A zinc crystal which met both conditions was available. The orientation of the basal plane in this crystal was determined by inserting the tip of a knife blade into the material until it split. The basal plane was considered to run parallel to the split. From this crystal five specimens were cut in such a manner that the basal planes were oriented perpendicular to the surfaces to be exposed to the collimated radiation. The dimensions of four of the crystals were ¼ by ¼ by 0.020 inch and the fifth crystal was ¼ by ¼ by 0.060 inch. The surfaces with dimensions ¼ by ¼ inch were ground smooth with carborundum and had a finish of approximately 10 micro-inches RMS.

The finished specimens appeared to be free from surface imperfections and since they were taken from an unstrained portion of a longer crystal, they were also assumed to be unstrained. During the cutting of the individual crystals, an effort was made to keep the crystal temperature low by running coolant over the surface. The cutting and surface finishing was performed on a machine of the type used by gem cutters in processing stones.

C. Description of Apparatus

The apparatus for the experiment was mounted on a long wooden platform. A photograph of the set-up is shown in Fig. 1 and a schematic arrangement drawing with the shielding bricks removed is shown in Fig. 2. The following equipment was used.

1. Source holder
2. Collimating device
3. Crystal holder
4. Crystal holder platform
5. Detector
6. Scaler

The source holder consisted of a lead block with a cavity and aperture as shown in Fig. 2. In order to align the source with the centerline of the aperture of the source holder, a wooden adapter was placed in the cavity of the holder. A lead block which served as a collimating device was placed directly in front of the source holder aperture. The block contained a 5/32 inch diameter hole which was aligned with the center line of the aperture of the source holder. Nominal dimensions are indicated in Fig. 2.

The crystal holder and holder platform are shown in Figs. 3 and 4. The crystal holder was composed of a wooden crystal mounting frame and an indicator arm. The bottom of the mounting frame was fitted with a steel bushing to provide bearing surface for rotation of the frame about a vertical axis. A wooden indicator arm was attached to the mounting frame to indicate the angular movement of the crystal holder on a scale fixed to the crystal holder platform. The specimen was glued to a small wooden rod which was supported in a horizontal position by the mounting frame as shown in Fig. 3(b). An indicator was placed on the rod end to facilitate its positioning. The basal planes of the crystal could thus be aligned in a vertical plane perpendicular to the indicator arm by rotation of this rod and could be rotated in a horizontal plane by movement of the indicator arm to enable the determination of various orders of reflection of incident radiation.

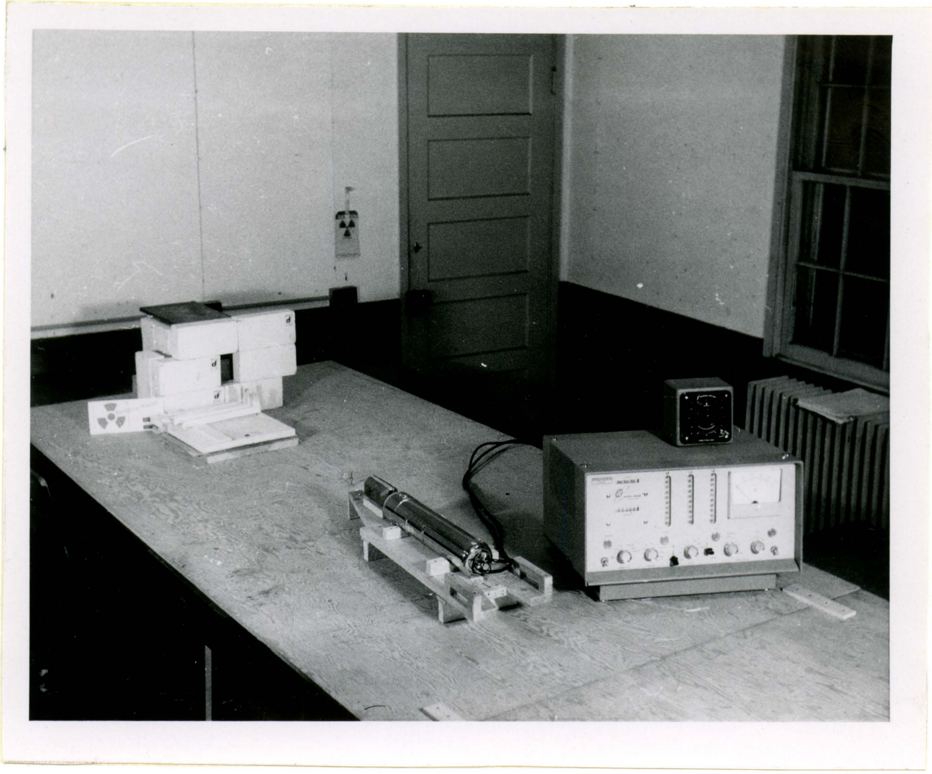
The crystal holder platform was composed of a wooden platform fitted with a row of small vertical steel posts which fit into the bushings of the crystal holder. A scale was attached to the platform to measure angular rotation of the crystal holder. The platform was aligned in the collimated beam as shown in Fig. 2.

The detector used in the experiment was a Model DS-1A Scintillation Detector manufactured by the Nuclear Instrument and Chemical Corporation. It utilizes a sodium iodide, thallium activated crystal as a sensing element.

The instrument was equipped with a removable directional shield with a one-inch diameter aperture, however, it was necessary to reduce the field being scanned to enable more exact alignment of the detector with reflected gamma rays of a certain energy range. This was accomplished by placing two lead blocks in front of the instrument, leaving a vertical slit between them as shown in Fig. 2. The detector and auxiliary collimating blocks were mounted on a movable platform which could be moved in an arc about the number one crystal. It was determined that the RC time constant of the preamplifier controls the counting rate of the instrument, resulting in a resolving time of 2-3 micro-seconds which is less than that of the scaler.

A model 186 Decade Scaler manufactured by the Nuclear-Chicago Corporation was used to provide high voltage for the scintillation counter and to count the electrical pulse received from it. The instrument had a fine voltage control

Fig. 1. Experimental apparatus



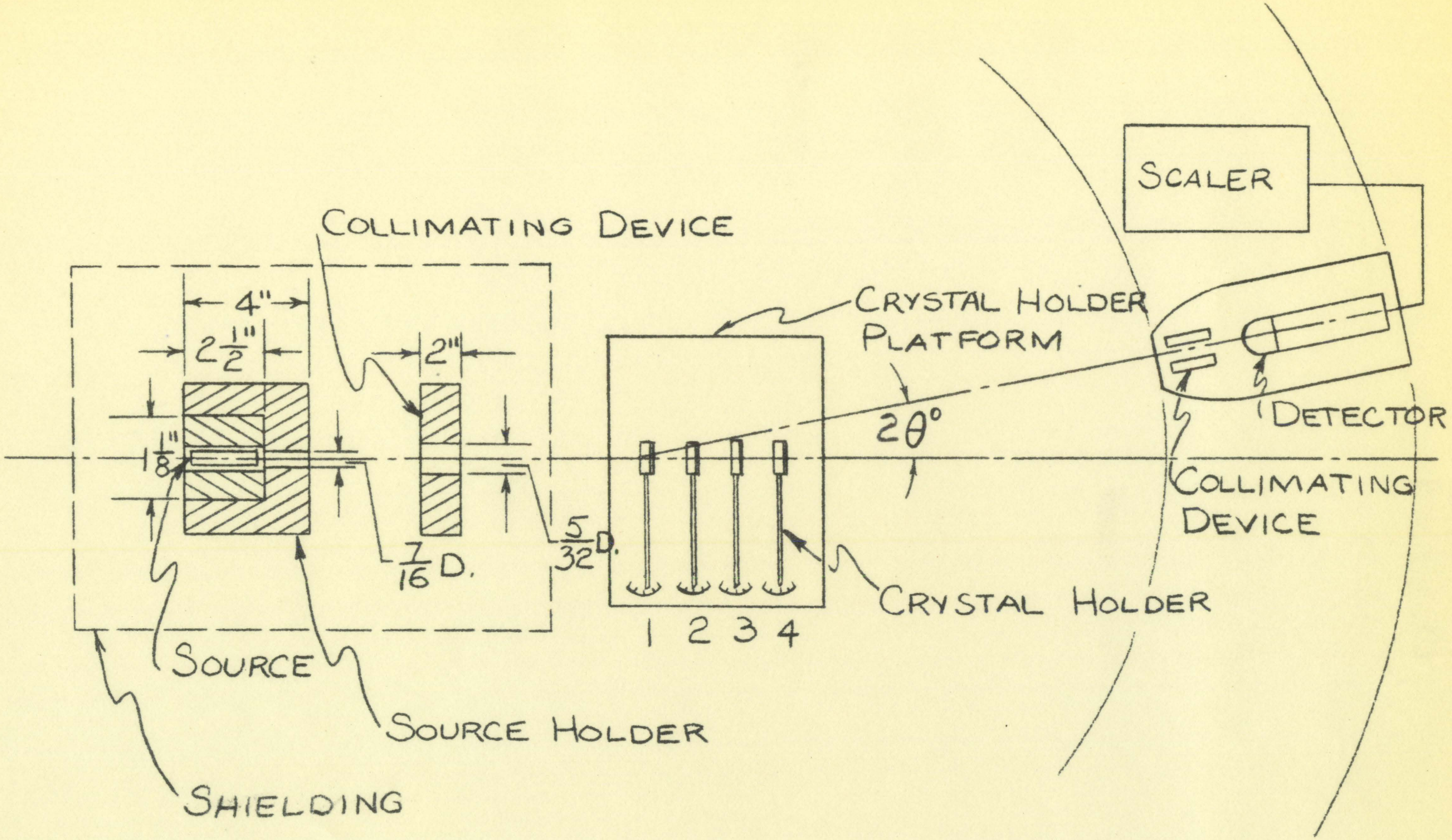


Fig. 2. General arrangement

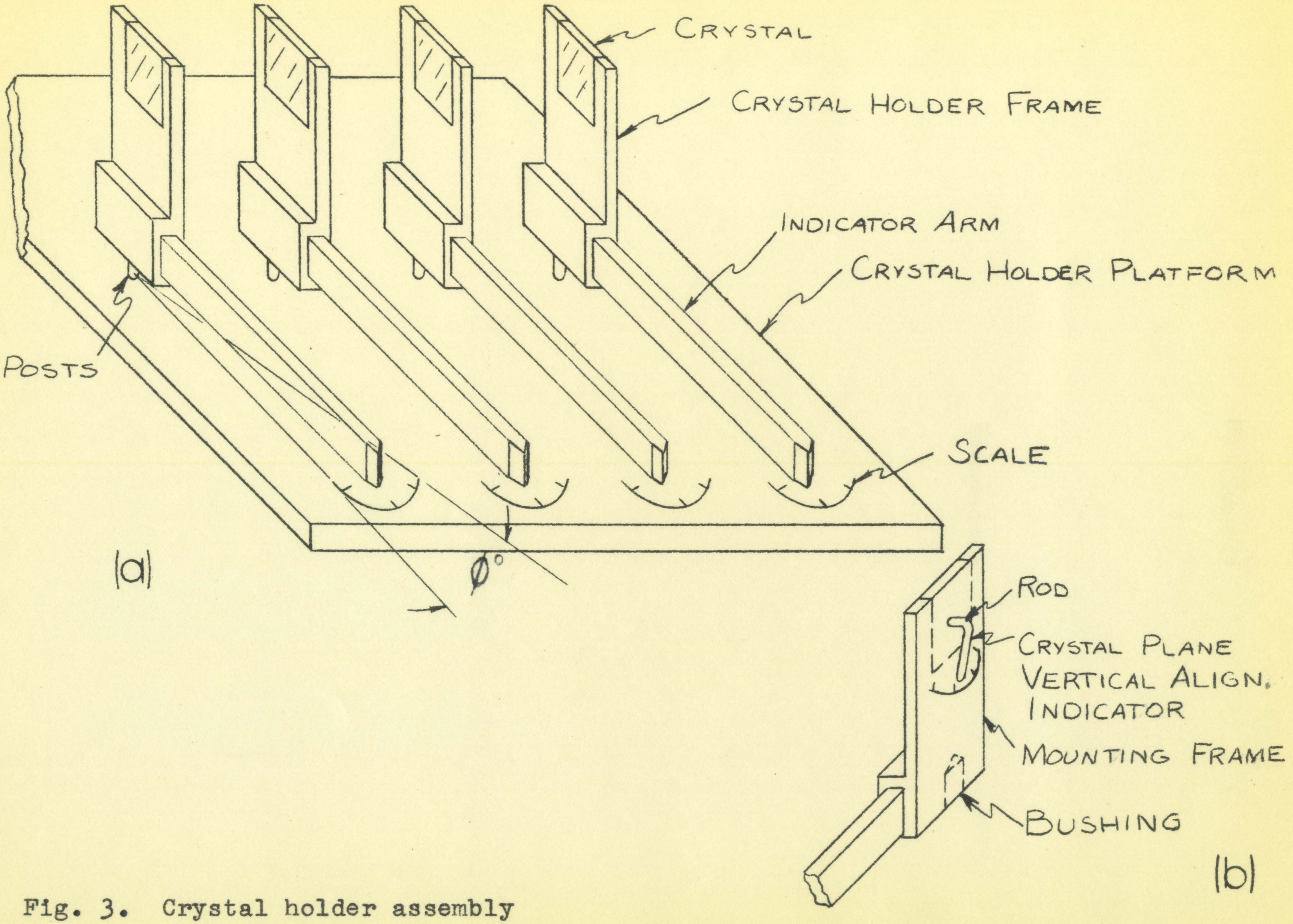
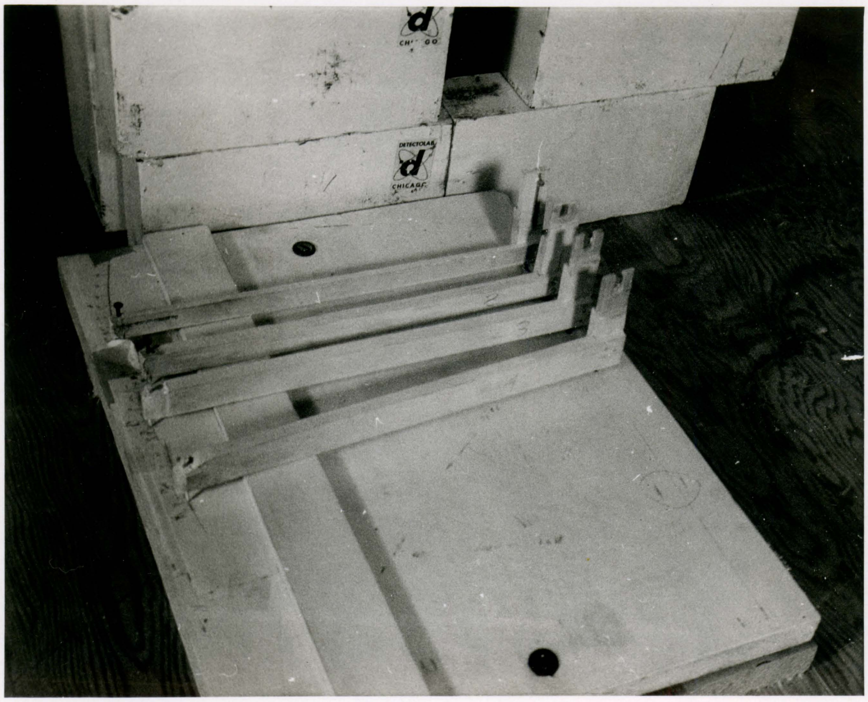


Fig. 3. Crystal holder assembly

Fig. 4. Crystal holder and crystal holder platform


DETECTOLAB
CHICAGO

which enabled precise voltage control. The scaler had a resolving time of 5 micro-seconds which is greater than that of the detector, so the scaler is the controlling factor in determining coincidence losses. The magnitude of these losses can be estimated by use of the following equation given by Friedlander and Kennedy (12)

$$R^{*} = \frac{R}{1 - R\tau} \qquad (4)$$

where R^{*} is the correct counting rate, R is the observed counting rate and τ is the resolving time. In certain portions of the investigation, the counting rate was approximately 700 counts per minute. (11.6 c.p.s.) When these values are substituted in the above equation, the corrected counting rate was found to be the same as the observed for three significant figures, therefore, these data were not corrected for coincidence loss. In other portions of the investigation, the counting rate reached 50,000 counts per minute. (835 c.p.s.) The error between the corrected and observed counting rate was also small in these instances so the correction was not applied.

The electronic equipment used in the experiment functioned adequately throughout the entire experiment. The system did occasionally give readings which were out of proportion to preceding data. It was noted that most of these spurious readings occurred on hot, humid days.

D. Accessories

Incidental items used during the experiment included a Nuclear-Chicago Model TI Dual timer, a Nuclear-Chicago Model 3612 portable survey meter and personnel film badges.

The timer was used to stop the scalar after a preset time interval, and thus reduced the amount of operator attention required.

The portable survey meter was used to determine the amount of shielding required around the source holder and also to assist in aligning the collimated beam.

Personnel film badges were provided by Ames Laboratory and were checked bi-weekly.

V. PROCEDURE

A. Experimental Arrangement

The physical arrangement of the equipment was the result of a compromise between several variables. First, the distance between the crystal reflector and the detector had to be large enough to displace the reflected radiation from the center line of the collimated beam, and far enough to be easily measured by the detector. Second, the gamma ray beam had to be well collimated to insure that all crystals would receive the same amount of radiation. Third, the counting rate had to be high enough to provide reasonable statistical accuracy in a short period of time and yet not great enough to jam the mechanical register in the scaler.

It was estimated that a minimum counting rate of 500 counts per minute with ten-minute counting periods would be satisfactory. This provided a standard deviation of 1.4 per cent at the 68 per cent confidence level. It was determined by experimentation that a maximum counting rate of 60,000 counts per minute could be handled by the scaler. Since the amount of radiation reflected by the crystal reflector was unknown, an analytical approach to the optimum reflector to detector distance was not possible and so it was solved experimentally.

The degree of collimation necessary to insure uniform radiation of all crystals was arrived at by limiting the difference in area radiated on the first and last reflectors to approximately 1 per cent of the radiation received on the first crystal. This value was arbitrarily selected to keep experimental error at a minimum. To achieve this collimation, the collimating block with a 5/32 inch diameter hole was placed adjacent to the source holder as shown in Fig. 2.

The angle of reflection of the 84 Kev gamma with respect to the centerline of the collimated beam was determined by application of the Bragg Equations as follows:

$$n\lambda = 2d \sin \theta \qquad (5)$$

where

$$\lambda = \frac{hc}{E}. \qquad (6)$$

When the value 0.135×10^{-6} erg (84 Kev) is substituted for the energy E in equation 6, $\lambda = 0.147$ A. When this value is substituted in equation 5, and using a lattice spacing d of 4.93 A for spacing between the basal planes of zinc

$\theta = 0^\circ 51'$ for 1st order reflection.

In order to distinguish clearly between the collimated beam and the reflected radiation it was decided to locate the detector at least one inch from the centerline of the beam. Since the radiation was polychromatic and emitted radially from the source, only the radiation along the centerline of the beam and which was of a certain energy range was reflected through the calculated angle θ. The remainder of the radiation was reflected through greater and smaller angles than this as is demonstrated in the results of the experiment.

In order to determine the correct distance from the crystal reflector to the detector, the detector was placed in the center of the collimated beam and gradually moved towards the crystal until a counting rate of 60,000 counts per minute was observed. The detector was then moved through the calculated angle 2θ and the counting rate was observed to be approximately 550 counts per minute. The distance from the centerline of the beams was 1.50 inches with a reflector-to-detector distance of 50 inches. This satisfied the requirements. Two arcs were then inscribed on the platform as shown in Fig. 2 and radial lines drawn on the platform to facilitate positioning of the detector when measuring the radiation reflected through various angles.

A description of the method of determining the centerline of the collimated beam is included in a latter section.

The amount of shielding required to reduce the radiation to 1 mr. per hour at the surface of the shielding was determined by experiment. Lead brick was placed around the source holder and collimator block until the radiation was reduced to this level or below. A personnel survey meter was used as the radiation measuring device. The collimated beam was blocked by placing a brick in front of the opening in the shield.

After the position of each component was determined, all components except the detector were fastened securely to the table to prevent accidental misalignment.

The scaler and timer were placed on a table adjacent to the platform.

B. Testing Procedure

The initial step in the investigation was to determine the operating voltage and sensitivity value for the scintillation counter and scaler. A graph of counting rate as a function of voltage was constructed from experimental data obtained from the arrangement to be used in the investigation. A "plateau" was noted in the region of 1650 volts using a sensitivity value of 100 Mv. and so these two values were adopted for the investigation.

The location of the centerline of the collimated beam was undertaken in several different ways. First, a light source was placed in the source holder and the outline of the collimated beam of light on a target was used to locate the centerline. The source was then placed in the source holder and a graph constructed of counts per minute as a function of angle θ of the detector as it was moved through the beam.

Since the Tm-170 source was not yet available, a Co-60 source of 75 millicuries strength was substituted. The location of the centerline was determined by the angle θ at which the highest counting rate was noted. A similar procedure was used in determining the vertical location of the centerline. The position of the centerline, as determined by these two different methods, did not agree so a third method using x-ray film to outline the gamma ray beam was attempted. The film was obtained from the Iowa State College Hospital, wrapped in light-proof paper and exposed in the beam. Repeated attempts at various exposure times did not provide a distinct outline of the beam, so this procedure was abandoned.

It was then noted that the hole in the lead collimating block was not of constant diameter through the block, due to improper drilling procedure. After reaming the hole, a check of centerline location was made using the light method and counting method. This time agreement was good.

The Tm-170 source was then inserted in the source holder. It was noted that the orientation of the source in the holder was critical as a 90 degree rotation of the source in the holder caused a 10% variation in intensity of the collimated beam.

The location and magnitude of first and second order reflection of each crystal was determined next. The number one crystal was positioned in the beam and rotated through the angle ϕ shown on Fig. 3. A plot of the counting rate as a function of the angle ϕ, with the detector positioned at the angle θ previously calculated, is shown in Fig. 5. It should be noted the crystal planes were first aligned vertically by rotation of the crystal in a vertical plane, the aligned position being determined by the maximum counting rate. Fig. 3 shows the device for this alignment. The number two crystal was then placed in the beam. Number one crystal remained in the beam and was set at an angle to reflect first order wave lengths. Crystal number two was then aligned in a vertical plane and rotated through angle ϕ as in the case of number one crystal. This procedure was continued for the four crystals of 0.020 inch thickness. The results are shown in Figs. 6,7 and 8. All four crystals and holders were then removed and a crystal of 0.060 inch thickness, which is three times that of the previous crystals, was then placed on the number one crystal holder. It was aligned in a vertical plane and rotated through an angle ϕ. A graph of counting rate as a function of the angle ϕ is shown in Fig. 9. Then with this thick crystal set to reflect first order wave lengths, the number four crystal was replaced and rotated through an angle ϕ. The information from this crystal is indicated in Fig. 10. A comparison of the relative magnitude of first and second order reflections from crystal number four when preceeded by three thin crystals or one thick crystal is thus available in Figs. 8 and 10.

In order to determine the amount of radiation of other energies reflected through various angles θ, by a crystal aligned to reflect first order wave lengths, the number five crystal was set to reflect first order wave lengths and the detector moved in an arc about the crystal. This survey reveals the amount of radiation at various angles as a result of Compton scattering and reflection. To determine the scattering contribution, the crystal was positioned not to reflect and the amount of radiation at the same points as above was again measured. In practice, the two measurements at each detector position were made one immediately after the other to avoid error which might be induced by "drift" of the electronic equipment. The information is shown in Fig. 11.

Since Tm-170 has a half-life of 129 days, and the experiment lasted over thirty days, it was necessary to correct all data to a common date, which was the last day of the experiment, with the following expression;

$$A^* = Ae^{-\lambda t} \qquad (7)$$

where A^* is the corrected activity, A is the activity at time t and λ is the decay constant obtained as follows:

$$\lambda = \frac{0.693}{T_{\frac{1}{2}}} \qquad (8)$$

where $T_{\frac{1}{2}}$ is the half-life of the nuclide. A sample correction is shown in the appendix.

VI. RESULTS

The information gained during the investigation is presented in both tabular and graphical form. The solution of the first objective of the investigation, which was the development of a suitable facility for measurement of gamma ray reflection, is best revealed in the photographs in Figs. 1 and 4 and by the drawings in Figs. 2 and 3. The results obtained from this arrangement may be somewhat perturbed by such effects as imperfect collimation and any inaccuracy in the measuring scales. The latter effect is manifest in the deviation in the relative location of the first and second order reflections as can be noted in Figs. 5-10. This imperfection does not disturb the magnitude of the reflection.

The second objective of the investigation, which was the determination of the effect of surface finish and lattice distortion upon reflective power, was accomplished by comparing the reflective ability of three thin crystals with that of one thick crystal in the following manner.

Three thin crystal specimens (0.020 in. thick) were individually aligned in the collimated beam to reflect first order wave lengths. A fourth crystal was then placed in the beam and the difference in magnitude of first and second order reflection noted. This is a measure of the efficiency of the reflective power of the three crystals and six surfaces. These crystals were then removed and a crystal whose thickness was equal to the sum of the three previous crystals, was aligned in the beam to reflect first order wave lengths. The same fourth crystal was then inserted in the beam and the difference in magnitude of first and second order reflection noted. For this measurement, the crystal was numbered six.

The data obtained from crystal one, two and three are shown in tabular form in Tables 1, 2 and 3 and in graphical form in Figs. 5, 6 and 7.

By comparing the magnitude of first order and second order reflection from each crystal, the increment of radiation reflected by each crystal can be seen. Comparison of first and second order reflection from crystal number four as shown in Fig. 8 and tabulated in Table 4 indicates the effectiveness of the three individual crystals.

Fig. 9 indicates the reflection by a crystal equal in thickness to the three previous crystals and Fig. 10 shows the effectiveness of the one thick crystal to be almost identical to that of the three individually aligned crystals. Tabulation of the data for the last two crystals is shown in Tables 5 and 6.

Since the source was polychromatic and the gamma rays emitted radially it was of some interest to determine how much radiation was reflected through various other angles θ . This investigation was accomplished as previously described and the results are shown in tabular form in Tables 7 and 8 and graphically in Fig. 11. It can be seen, the entire collimated beam was shifted slightly to the right side.

Table 1. Counts for establishing gamma ray reflection with crystal number one[a,b]

Crystal position	Observed total count	Rate cpm	Corrected rate cpm[c]	Net rate cpm	σ Net cpm
0	7930	793	743	219	10.0
1	7914	791	742	218	10.0
2	7953	795	745	221	10.0
3	8078	808	756	232	10.1
4	8153	815	761	237	10.1
5	7844	784	736	212	10.0
6	7829	783	735	211	10.0
7	7603	760	716	192	9.8
8	7457	746	705	181	9.8
9	7493	749	708	184	9.8
10	7549	755	714	190	9.8
11	7381	738	698	174	9.8
12	7408	741	701	177	9.8
13	7318	732	694	170	9.8

[a] Background rate 524 cpm (20 minute counting period).

[b] Length of counts 10 min.

[c] Adjusted for source decay.

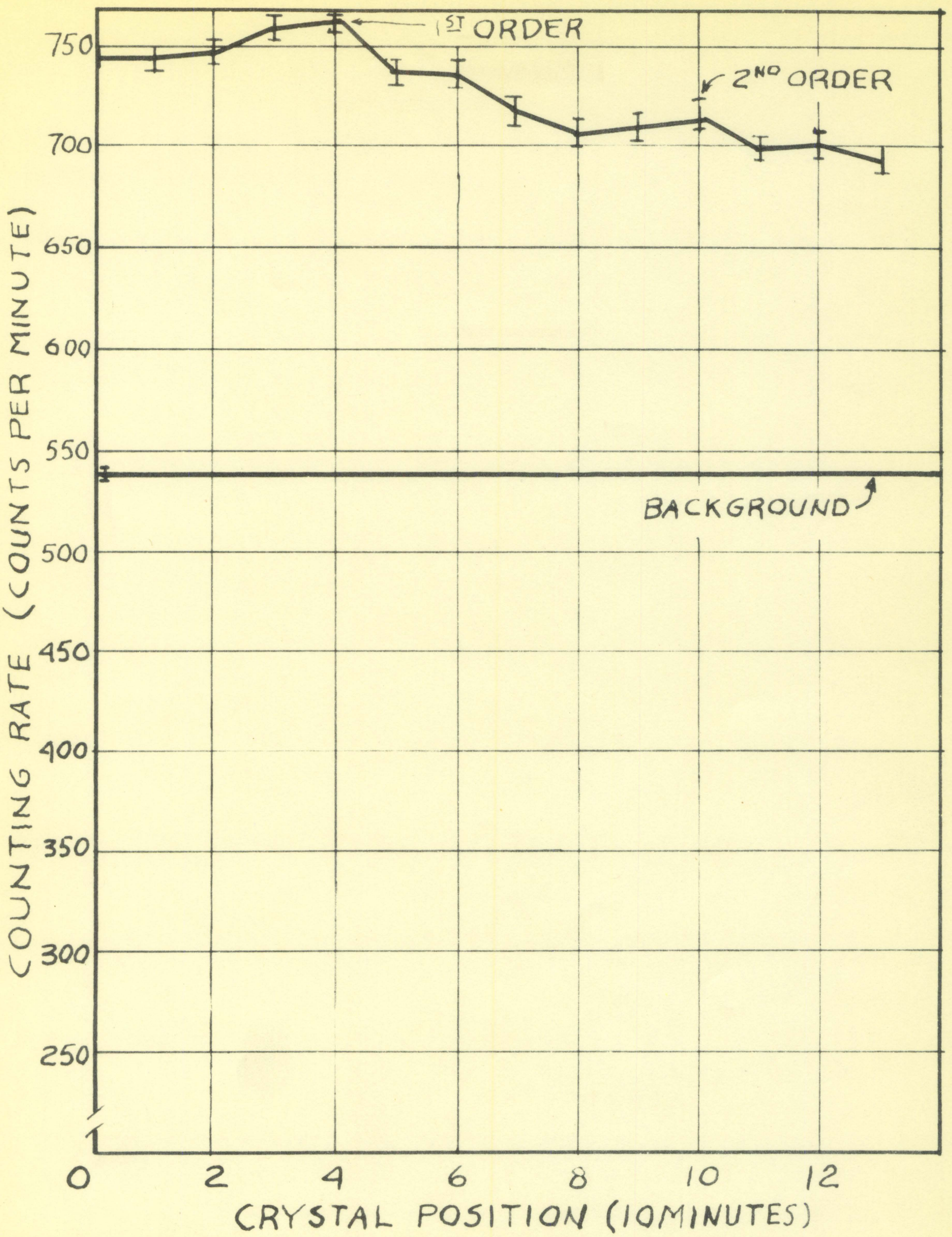


Fig. 5. Gamma ray reflection with crystal number one

Table 2. Counts for establishing gamma ray reflection with crystal number two. Crystal number one aligned to reflect first order wave lengths[a,b]

Crystal position	Observed total count	Rate cpm	Corrected rate cpm[c]	Net rate cpm	σ Net cpm
0	4942	494	462	184	7.7
1	5306	531	494	216	7.9
2	5396	540	503	225	8.0
3	5549	555	516	238	8.1
4	5620	562	520	242	8.1
5	5229	523	487	209	7.9
6	5228	523	487	209	7.9
7	5198	520	484	206	7.9
8	5323	532	494	216	7.9
9	5324	532	494	216	7.9
10	5202	520	484	206	7.9
11	5226	523	487	209	7.9
12	5089	509	475	197	7.8
13	5122	512	478	200	7.8

[a] Background rate 278 cpm (20 minute counting period).

[b] Length of counts 10 min.

[c] Adjusted for source decay.

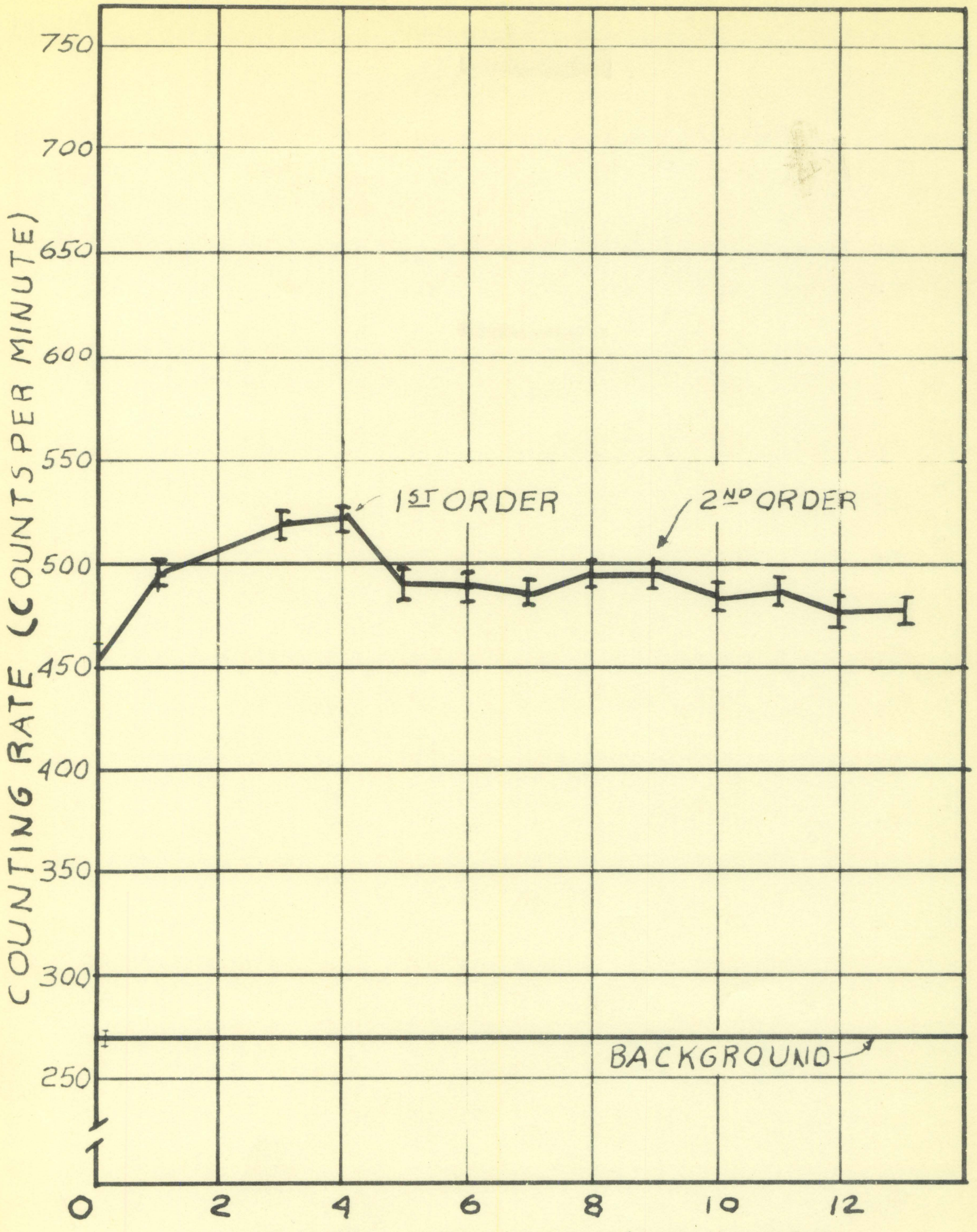


Fig. 6. Gamma ray reflection with crystal number two

Table 3. Counts for establishing gamma ray reflection with crystal number three. (Number one and two crystals set to reflect first order wave length)[a,b]

Crystal position	Observed total count	Rate cpm	Corrected rate cpm[c]	Net rate cpm	σ Net cpm
0	5386	539	504	258	7.9
1	5586	559	522	276	8.0
2	5629	563	526	280	8.0
3	5793	579	540	294	8.2
4	5829	583	543	297	8.2
5	5954	595	554	308	8.3
6	5900	590	550	304	8.3
7	5810	581	542	296	8.2
8	5850	585	545	299	8.2
9	5924	592	551	305	8.3
10	5814	581	542	296	8.2
11	5599	560	523	277	8.0
12	5599	560	523	277	8.0
13	5599	560	522	276	8.0

[a] Background 246 cpm (20 minute counting period).

[b] Length of counts 10 min.

[c] Adjusted for source decay.

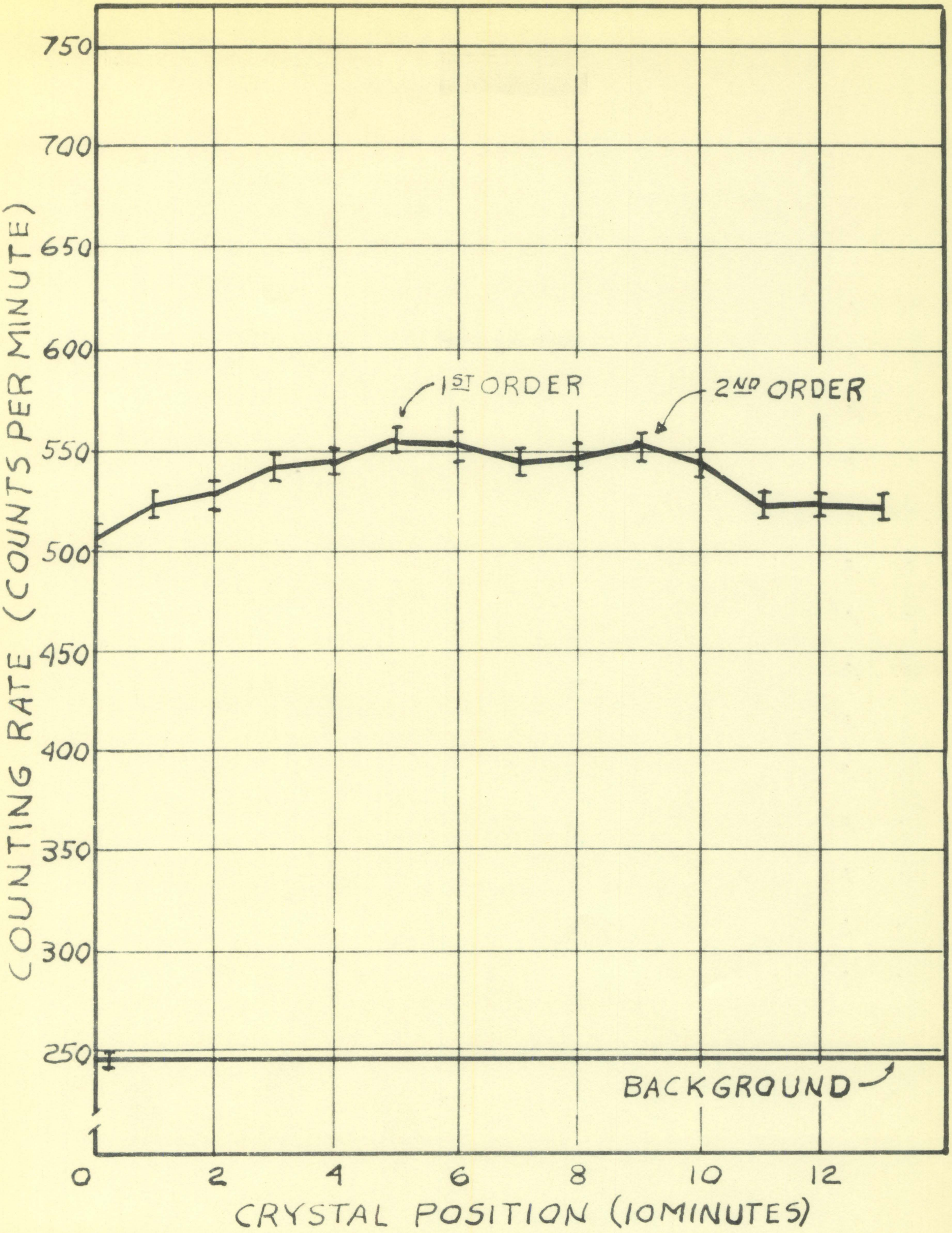


Fig. 7. Gamma ray reflection with crystal number three

Table 4. Counts for establishing gamma ray reflection with crystal number (Numbers one, two and three aligned to reflect first order wave lengths)[a,b]

Crystal position	Observed total count	Rate cpm	Corrected rate cpm[c]	Net rate cpm	σ Net cpm
0	5661	566	536	291	8.2
1	5690	569	539	294	8.2
2	5704	570	540	295	8.2
3	5843	584	553	308	8.3
4	5876	588	556	311	8.4
5	5829	583	553	308	8.3
6	5761	576	545	300	8.2
7	5695	570	540	295	8.2
8	5787	579	549	304	8.2
9	5628	563	538	293	8.1
10	5631	563	538	293	8.1
11	5667	567	537	292	8.1
12	5759	576	545	300	8.2
13	5530	553	525	280	8.1

[a] Background rate 245 cpm (20 minute counting period).

[b] Length of counts 10 min.

[c] Adjusted for source decay.

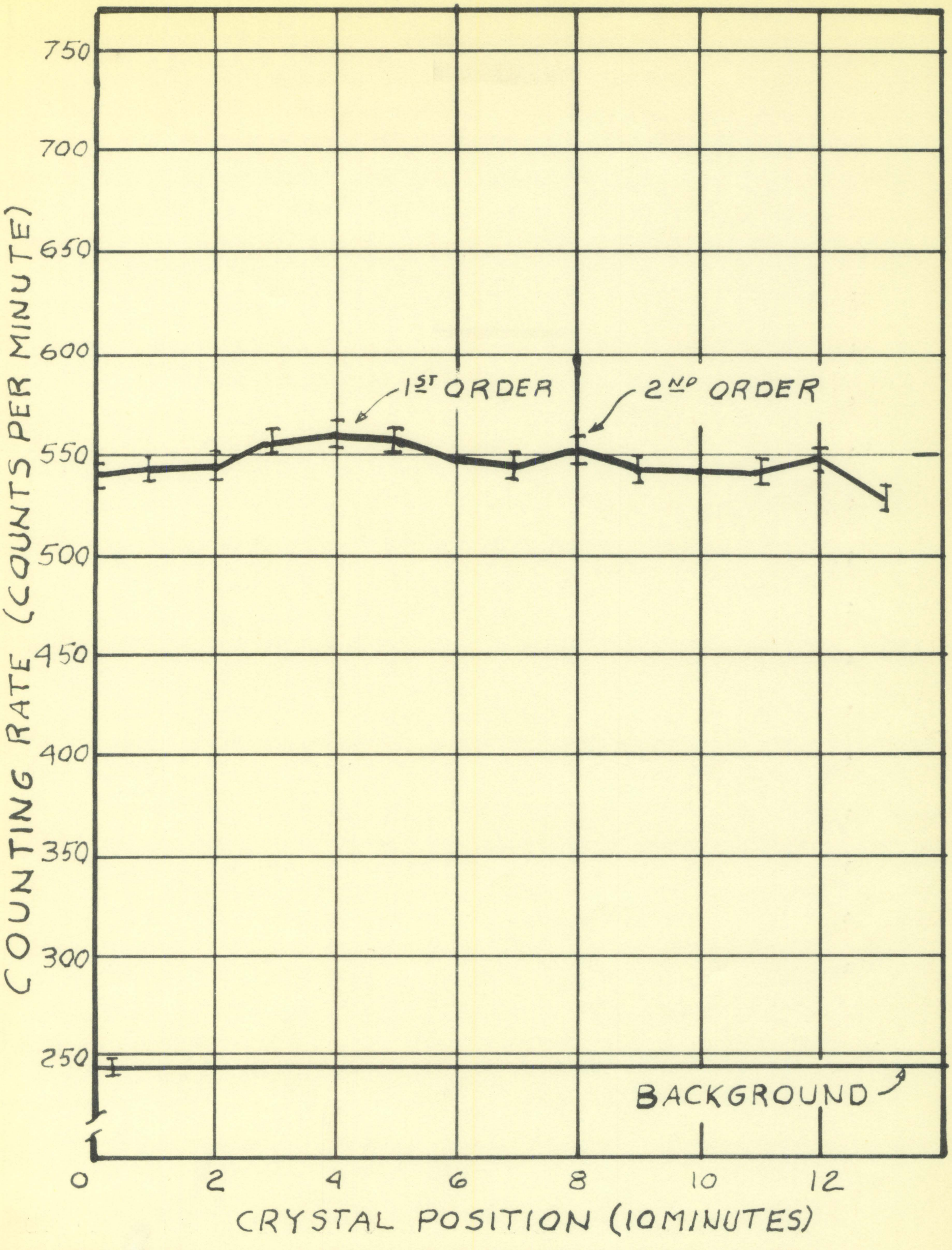


Fig. 8. Gamma ray reflection with crystal number four

Table 5. Counts for establishing gamma ray reflection with crystal number five (0.060" thick)[a,b]

Crystal position	Observed total count	Rate cpm	Corrected rate cpm[c]	Net rate cpm	σ Net cpm
0	6059	606	600	356	8.5
1	6254	625	618	374	8.6
2	6795	680	673	429	8.9
3	6812	681	674	430	8.9
4	7033	703	695	451	9.0
5	6578	658	650	406	8.8
6	6420	642	635	391	8.7
7	6372	637	630	386	8.7
8	6446	645	638	394	8.7
9	6132	613	606	362	8.5
10	6076	608	602	358	8.5
11	5754	575	569	325	8.4
12	5688	569	562	318	8.4
13	5560	556	550	306	8.4

[a] Background rate 244 (20 minute counting period).

[b] Length of counts 10 min.

[c] Adjusted for source decay.

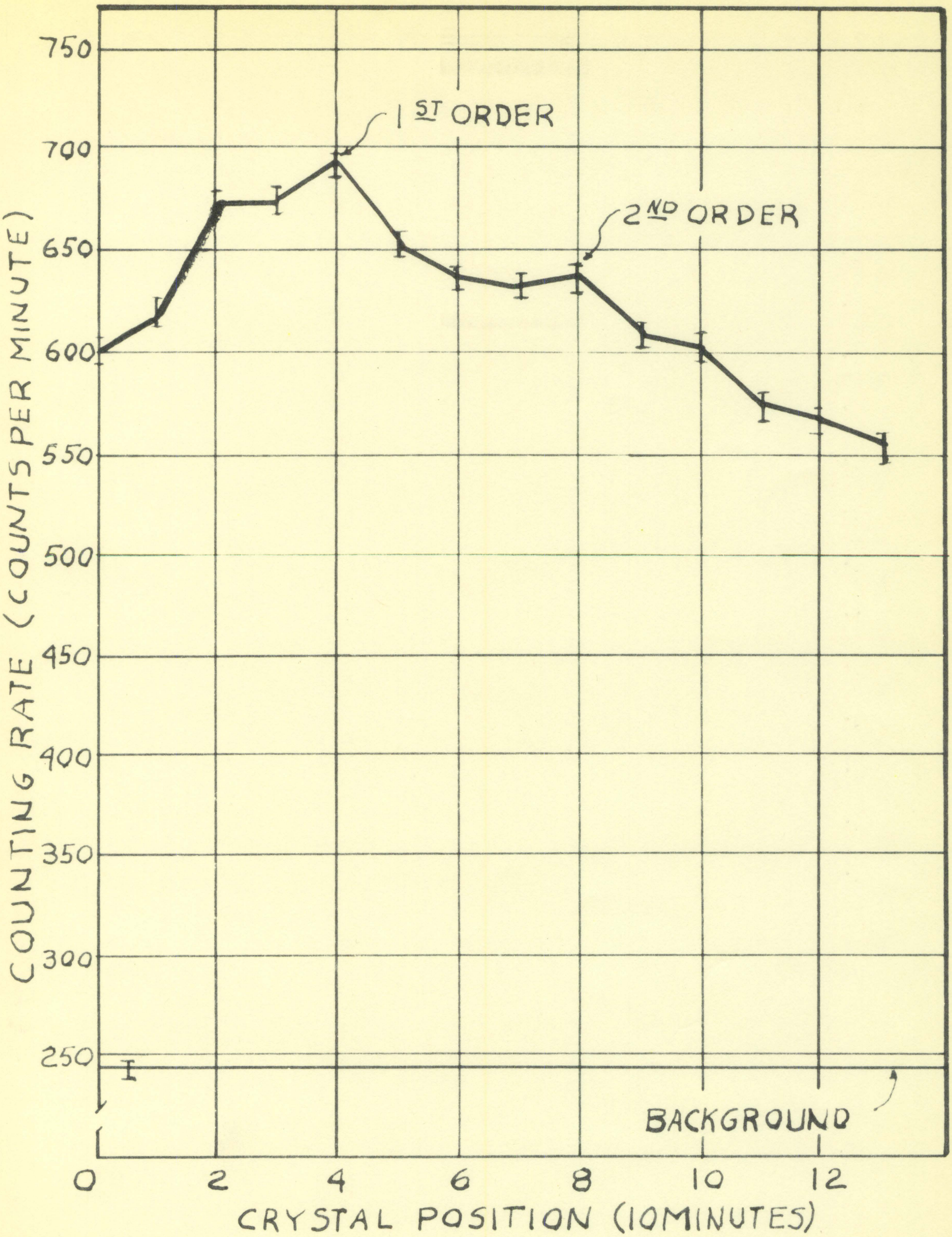


Fig. 9. Gamma ray reflection with crystal number five

Table 6. Counts for establishing gamma ray reflection with crystal number six (number five crystal aligned to reflect first order wave lengths)[a,b]

Crystal position	Observed total count	Rate cpm	Net rate, cpm	σ Net cpm
0	7096	710	464	9.1
1	7389	739	493	9.3
2	7341	734	488	9.3
3	7412	741	495	9.3
4	7390	739	493	9.3
5	7271	727	481	9.2
6	7209	721	475	9.2
7	7307	731	485	9.3
8	7444	744	498	9.3
9	7209	721	475	9.2
10	7226	723	477	9.2
11	7110	711	465	9.1
12	7285	729	483	9.2
13	7143	714	468	9.1

[a] Background 246 (20 minute counting period).

[b] Length of counts 10 min.

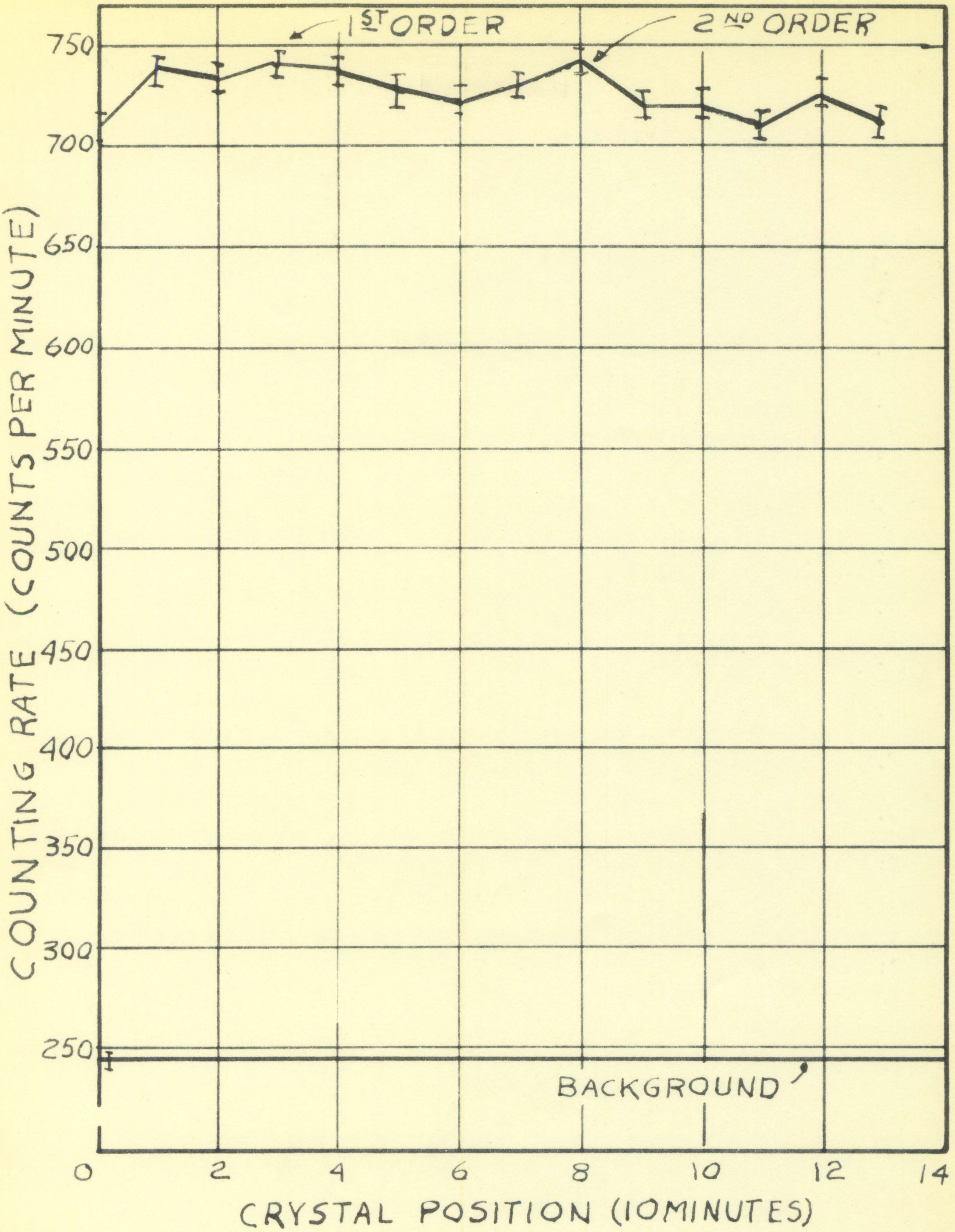


Fig. 10. Gamma ray reflection with crystal number six

Table 7. Gamma ray reflection survey using crystal number five (0.060 in. thick)[a]

Detector position (degrees)	Gross counts (observed)	Time Min.	Counting rate, cpm	Net rate cpm	σ Net cpm
+3.15	5587	10	559	314	9
+2.57	5821	10	582	337	9
+2.01	7056	10	706	461	10
+1.43	7689	10	769	524	10
+0.86	8386	5	1677	1432	18
+0.29	103551	3	34517	34272	109
0.0	137673	3	45891	45646	145
-0.29	125495	3	41832	41587	133
-0.86	17689	5	3538	3293	26
-1.43	6377	10	638	393	9
-2.01	5009	10	501	256	8
-2.57	4909	10	491	246	8

[a] Background rate 245 cpm (20 minute counting period.

Table 8. Gamma ray scattering survey with crystal number five (0.060 in. thick)[a]

Detector position (degrees)	Gross counts (observed)	Time Min.	Counting rate, cpm	Net rate	σ Net cpm
+3.15	4834	10	483	238	8
+2.57	5203	10	520	275	8
+2.01	5072	10	507	262	9
+1.43	6297	10	630	385	9
+0.86	7985	5	1597	1352	18
+0.29	97444	3	32481	32236	104
0.0	133480	3	44493	44248	121
-0.29	125713	3	41904	41659	118
-0.86	17673	5	3534	3289	27
-1.43	8016	10	802	557	9
-2.01	5650	10	565	320	9
-2.57	5218	10	522	277	8

[a] Background rate 245 cpm (20 minute counting period).

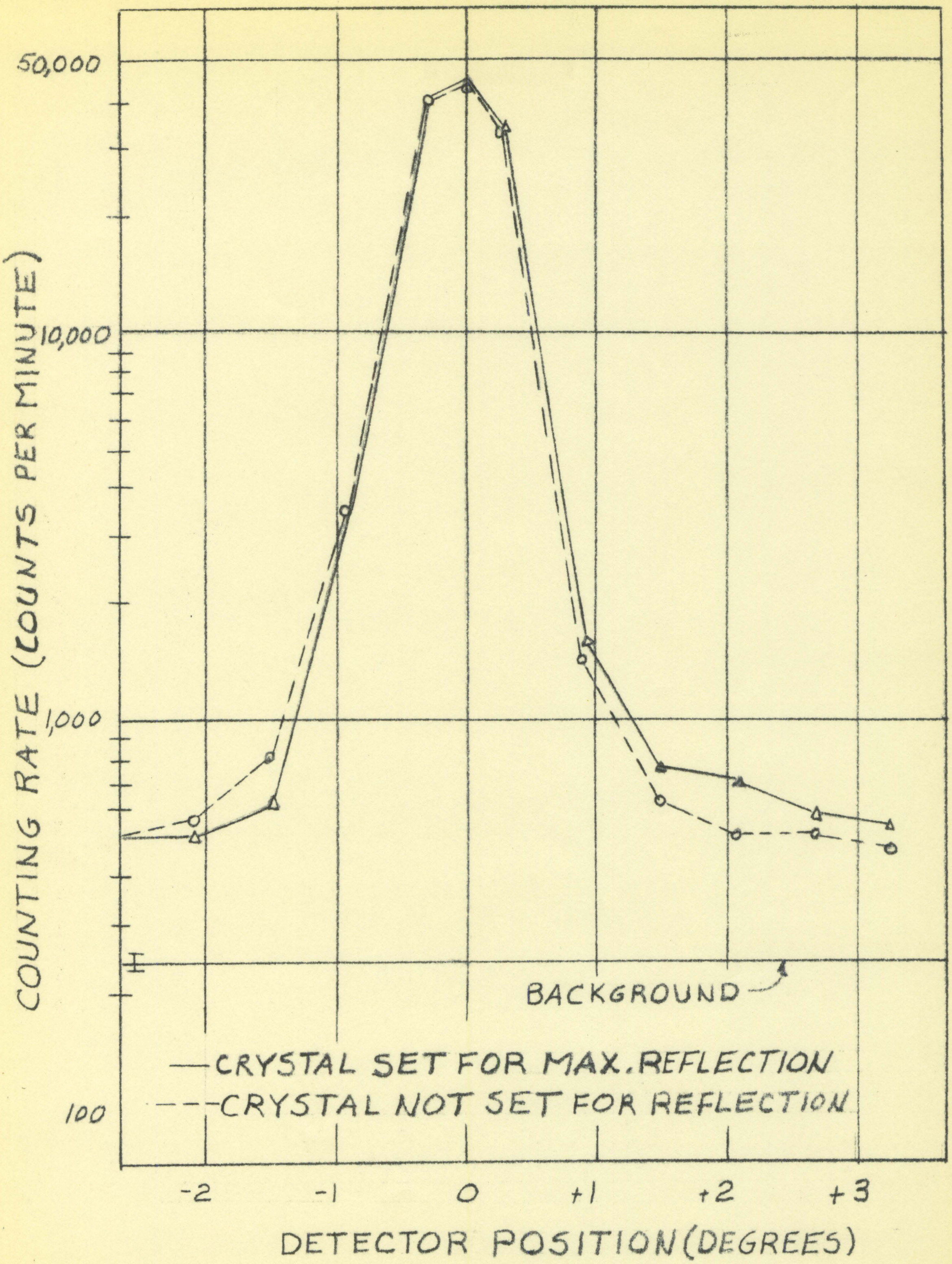


Fig. 11. Gamma ray survey

VII. SUMMARY AND CONCLUSIONS

The experimental facility developed in this investigation appears to be adequate for measuring the reflection angle of low energy gamma rays. The previously mentioned inaccuracies in the measuring scales and imperfect collimation of the gamma ray beam limit the usefulness of the facility in the high energy gamma ray range. A positive method of rotating the crystals and also a more accurate means of measuring the angle of rotation would remedy the first deficiency. The collimation of the beam could be improved by lengthening the collimating block. Since the rays are emitted radially from the source, perfect collimation would be impossible.

The total observed counting rate, when the detector is positioned to receive first order wave lengths, contains a high percentage of background counts. This leads to some statistical inaccuracy in the counting rate. A method of discriminating against this type of radiation would improve the usefulness of the facility.

The method of comparing the reflective power of several crystals by comparing the magnitude of first and second order reflection, as developed here, appears to be simple and reasonably accurate.

The results of the experimentation indicate that the distortion of the lattice structure of the specimen observed, which was assumed to be representative of a typical unstrained, single crystal grown in accordance with good laboratory practice, is not enough to affect grossly its effectiveness as a gamma ray reflector. If the lattice structure had been so badly distorted that only a few atomic distances could be aligned, one would expect the reflective power of the three individually aligned thin crystals to be three times as effective as that of one thick crystal. Comparison of Fig. 8 and 10 indicate this is definitely not the case. Also, if the surface of the crystal grossly affected its effectiveness as a gamma ray reflector, one would again expect the reflective power of the three thin crystals to be greater than that of the single thick crystal.

VIII. RECOMMENDATIONS FOR FURTHER STUDY

The experimental techniques and results developed in this investigation indicate several other areas worthy of further study.

The technique of comparing the efficiency of reflection of crystals by the method developed here can be utilized in studying the efficiency of various other types of crystals, which may be superior to the zinc crystals for certain wave lengths. Also the results of this thesis indicate relatively thick crystals can be used as reflectors; however, there may be an optimum thickness at which Compton scattering within the crystal will reduce the intensity of reflection.

This investigation was primarily concerned with the reflection of gamma rays of a certain energy. In order to develop an operational reflective type shield, efficient reflectors for many other wave lengths are necessary. The investigation of various methods of mounting crystals to reflect a broad range of energies is open to further study.

IX. LITERATURE CITED

1. Bragg, W. H. and W. L. Bragg. X-rays and crystal structure. London. G. Bell and Sons, Ltd. 1924.

2. Rutherford, E. and C. Andrade. The wave length of soft rays from Radium B. Lond. Edin. and Dublin Phil. Mag. Ser. 6, 27: 854-868. 1914.

3. Darwin, C. G. The theory of x-ray reflexion. Lond. Edin. and Dublin Phil. Mag. Ser. 6, 27: 675-690. 1914.

4. Senström, W. Title unknown. Unpublished Ph. D. Dissertation. Lund, Sweden, Lund University Library. 1919. (Original not available for examination: Cited in Compton, A. H. The total reflexion of x-rays. Lond. Edin. and Dublin Phil. Mag. Ser. 6, 45: 1121-1131. 1923.)

5. Duane, W. and R. A. Patterson. On the x-ray spectra of tungsten. Phy. Rev. 16: 532. 1920.

6. Siegbahn, M. The spectroscopy of x-rays. London. Oxford Univ. Press. 1925.

7. Compton, A. H. The total reflexion of x-rays. Long. Edin. and Dublin Phil. Mag. Ser. 6, 45: 1121-1131. 1923.

8. Bragg, W. L. The intensity of reflexion of x-rays by rock salt. Lond. Edin. and Dublin Phil. Mag. Ser. 6, 42: 1-16. 1921.

9. Du Mond, J. W. M. A high resolving power, curved-crystal focusing spectrometer for short wave length x-rays and gamma rays. Rev. Sci. Int. 18: 626-638. 1947.

10. Crocker, L. P. Reflective type shielding for gamma radiation. Unpublished M. E. Thesis. Ames, Iowa. Iowa State College Library. 1956.

11. Mergl, R. A. Gamma ray reflection. Unpublished M. S. Thesis. Ames, Iowa. Iowa State College Library. 1957.

12. Friedlander, G. and J. W. Kennedy. Nuclear and radiochemistry. N. Y., John Wiley and Sons, Inc. 1955.

X. ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Dr. Glenn Murphy, Chairman of the Nuclear Engineering Administrative Committee at Iowa State College, for his advice and helpful criticisms during this investigation.

The author wishes to thank Glenn Holmes, Los Gatos, California, for cutting the crystal specimens used in this investigation.

XI. APPENDIX

Sample adjustment of data for source decay

(Crystal 1, position 0, line 1, Table 1, page 33)

$$\frac{\text{Total counts}}{\text{length of count}} = \text{Counting rate}$$

$$\frac{7930}{10} = 793 \text{ cpm}$$

Counting rate - background rate = new rate (at time t)

$$793 - 524 = 269 \text{ cpm}$$

$A^* = A\,e^{-\lambda t}$ A^* = Activity corrected to zero time

$A^* = 269\,e^{\frac{-0.693\,(38)}{129}}$ A = Activity at time t

$A^* = 219$ cpm (net rate) t = time

λ = Decay constant

A^* + background rate = corrected rate

$219 + 524^{a} = 743$ cpm

---

[a] Not corrected for Tm^{170} decay because portion of background resulting from Tm^{170} was unknown.

Sample standard deviation calculation (σ)

(same data as above)

$$\sigma = \frac{\sqrt{(\text{Corrected rate})(\text{time})}}{\text{time}} = \frac{\sqrt{743\ (10)}}{10} = 8.6 \text{ cpm}$$

Uncorrected data (crystal 5, position 0, line 1, Table 5, page 43)

$$\sigma = \frac{\sqrt{\text{Total counts}}}{\text{time}} = \frac{\sqrt{7096}}{10} = 8.4 \text{ cpm}$$

$$\sigma_{\text{background}} = \frac{\sqrt{\text{Total counts}}}{\text{time}} = \frac{\sqrt{4880}}{20} = 3.5$$

$$\sigma_{\text{net}} = \sqrt{\sigma_{\substack{\text{counting}\\ \text{rate}}}^{2} + \sigma_{\text{Background}}^{2}} = \sqrt{8.4^2 + 3.5^2} = 9.1$$