Interaction of gamma rays with single crystals of lead

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INTERACTION OF GAMMA RAYS WITH
SINGLE CRYSTALS OF LEAD

by

Charles White Sayles

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

Major Subject: Nuclear Engineering

Iowa State University
Of Science and Technology
Ames, Iowa

1960
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I. INTRODUCTION

In recent years it has become possible to convert the energy of the nucleus of nuclear fuels into power by fission. Accompanying this fission there is liberated a large quantity of radiation. To protect personnel and equipment from this harmful radiation, massive shielding must be used. If nuclear fuels are to be used as a source of power for some types of mobile equipment such as airplanes and spacecraft, this massive shielding is somewhat of a disadvantage.

The most difficult of the harmful radiation to attenuate are neutrons and gamma rays. In some instances it will not be necessary to attenuate all of the radiation, but it will be sufficient to keep the radiation from a small area. This area could be the crew compartment of an airplane or spacecraft or the location of electronic instruments which are susceptible to damage by radiation. This radiation could be kept from the specified areas by being deflected. If a device for deflecting radiation could be made less massive than shielding that attenuates radiation, it would result in a saving of weight. This would be an advantage for nuclear powered airplanes and spacecrafts.

There are three primary processes by which gamma rays are attenuated. These are the photo-electric effect, Compton scattering, and pair production; all of which depend primarily on the mass of the shielding material.

A device to deflect radiation could possibly be built using the principle of reflection of electromagnetic radiation. In such a
reflector the gamma rays would be reflected from layers of atoms in the deflecting devices in much the same manner as ordinary light is reflected from a polished surface. This device would not be dependent on the mass of the shield, but on the arrangement of the planes of atoms in the shield. The purpose of this investigation is to examine this reflection on single crystals.
At the present time there is a great deal of literature written about the primary mechanisms of the interaction of gamma rays with matter. One of the better works written about the interaction of gamma rays with matter is written by Goldstein (5). In this he discusses not only the primary mechanisms of gamma ray reaction, i.e. Compton effect, photoelectric effect, and pair production, but also some of the secondary methods. Another work that is applicable to this investigation is that of Davisson and Evans (3). They present a thorough theoretical discussion of the theory and equations of the primary mechanisms of gamma ray interaction with matter, along with the results of experimental investigators of the measurements of the properties of these three primary mechanisms.

Much has also been written about the diffraction and reflection of X-rays. Since most of this is concerned with either the measurement of X-ray wave lengths or the use of X-rays in the determination of crystal structure, very little of this is applicable to this investigation except for the basic equation:

Eq. 1. \( \lambda n = 2d \sin \theta \)

developed by Bragg and Bragg (1). This equation gives the angle of reflection of X-rays on the cleavage plane of a crystal. In this equation \( n \) is an integer, the order of reflection, \( \lambda \) is the wave length of the X-ray, \( d \) is the distance between planes, and \( \theta \) is the critical angle for reflection. This equation is used in both the measurement of
X-ray wave lengths and the distances between planes of crystals.

Since gamma rays and X-rays differ only in origin and are similar in all other properties, X-ray data should be applicable to gamma ray reflection, but little information has been published concerning the reflection of gamma rays. In general gamma rays are more energetic than X-rays and hence the angles of reflection for gamma rays would be less.

In 1956 Crocker (2) attempted to measure the reflection from a curved reflector made of laminated aluminum. Although the distance between layers was many times the distance between the planes of a crystal he did note some reflection. In 1957 Mergl (3) continued this work using single zinc crystals bent in an arc. Although the crystalline planes were probably distorted during the bending, nonetheless, he did observe a measurable amount of reflection. In 1958 Wilson (10) studied the effect of surface reflection of gamma rays. He did this by examining the effectiveness of several thin zinc single crystals as compared to a single zinc crystal of the same total thickness as the several thinner crystals. From his studies he observed the surface had no measurable effect and the effectiveness of the several crystals was the same as the large crystal of the same size. In 1959 Sassoer (9) continued these studies with zinc single crystals. He attempted to present the results in the form of the Klein-Nishina cross section. He used both single and polycrystalline zinc specimens. He contended that any changes in scattering because of reflection would show up in variation of the Klein-Nishina cross section for the single crystal. The polycrystalline crystal's scattering was supposed to follow the Klein-Nishina cross section. Although the shape of the curve of scattering from the
polycrystalline specimen as a function of angle was similar to that predicted by Klein-Nishina cross section, its value was less. This may be due to difficulties associated with the source, geometry and measuring equipment.

At the same time that the investigation reported in this thesis was being done with single lead crystals, Holmes (6) was investigating reflection on a single copper crystal. Holmes noted that there was a small change in scattering from single copper crystals and this change appeared to be dependent on the angle of incident radiation.

The results of this review of literature show that reflection of gamma rays from metals in measurable amounts is feasible. Since the measurement of this reflected radiation directly is difficult, the most promising method for its determination of its effectiveness for shielding is to compare the scattering and attenuating properties of single crystals with polycrystalline crystals.
Gamma rays interact with matter by three principal mechanisms: (a) photoelectric effect, (b) Compton effect, and (c) pair production. The photoelectric effect is observed when a photon gives all of its energy to a bound electron which uses part of this energy to overcome its binding to the atom and takes the rest of the energy in the form of kinetic energy. The Compton effect is the process by which a photon is scattered by an electron of the atom, the photon leaves in a different direction and with decreased energy and the electron recoils with the remaining energy. Pair production is the process in which a photon in the field of the nucleus produces an electron-positron pair, having a kinetic energy equal to the energy of the photon minus the mass energy of the two particles which have been created. Pair production can only take place when the energy of the photon is equal to or greater than the mass energy of the electron positron pair. The probability that one of these processes will occur is dependent on the energy of the gamma quanta.

The radiation emitted by cobalt-60 is primary gamma rays of energy of 1.3316 and 1.1715 MeV. To show the effects of the different methods of interaction, the radiation can be considered to be monochromatic of energy 1.252 MeV without appreciable error.

Using a cobalt-60 source and lead as a target the absorption coefficients are given as follows: (3, p. 97), Photoelectric effect $4.65 \times 10^{-24}$ cm²/atom, Compton effect $15.56 \times 10^{-24}$ cm²/atom, and pair production $0.1320 \times 10^{-24}$ cm²/atom. This shows the Compton scattering accounts
for approximately three-fourths of the interaction. Therefore any variation in Compton scattering would be significant.

One method to observe the change in Compton scattering would be to investigate the change in Klein-Nishina cross section. Davisson and Evans (3) give a discussion of the Klein-Nishina cross section. This equation is derived from quantum mechanical considerations of the Dirac equation of the Electron.

\[ I = I_0 \frac{\hbar}{2m^2 c^2 r^2} \frac{1 + \cos^2 \phi}{1 - \alpha(1 - \cos \phi)^3} \times \left\{ 1 + \frac{2(1 - \cos \phi)^2}{(1 + \cos \phi)(1 + \phi(1 - \cos \phi))} \right\} \]

\( I_0 \) = intensity of incident gamma ray radiation

\( I \) = intensity of gamma ray at angle \( \phi \) and distance \( r \) from scattering electron of charge \( e \) and mass \( m \)

\( \alpha \) = \( \hbar \psi / mc^2 \)

This equation can also be written as

\[ I = I_0 \frac{\hbar \psi k(\phi)}{r^2 \hbar \psi} \]

\( \psi \) = the energy of the incident gamma radiation

\( \psi' \) = the energy of the scattered photons

\( k(\phi) \) = cross section for number of photons scattered per electron per unit solid angle in the direction \( \phi \). This is the Klein-Nishina cross section.

Rearranging the above equation

\[ k(\phi) = r^2 \frac{I(h \psi)}{I_0(h \psi)} \]

If \( I \) is equal to \( h \psi 0 \) then

\[ k(\phi) = \left( B/B_0 \right) r^2 \]
$B_0$ = the incident flux

$B$ = flux scattered at the angle $\phi$

Experimentally the incident flux can be calculated from the source strength and geometry factors, and this together with a measurement of the distance $r$ and scattered flux $B$, can be used in determining the cross section $k(\phi)$. If the target used is a single crystal this value of $k(\phi)$ can be compared with those values of $k(\phi)$ from the Equation 4.

To do this with equipment that was available several difficulties would be encountered. Exact measurement of distance and collimator geometry would be difficult to obtain, unless more precise experimental equipment is used. The equations for the Klein-Nishina cross section are based on monochromatic incident energy gamma rays, and although the source can be considered to be monochromatic nonetheless there is a lot of low level radiation incident on the crystal. This low level radiation comes from Compton gamma rays, x-rays, and bremsstrahlung from the collimator and source container. This low level radiation comprises a considerable fraction of the total incident radiation. Another difficulty is that of self absorption in the crystal. Once a gamma ray has been scattered by reaction with an electron and is headed in a specified direction, it may be scattered again and would not be counted. On the other hand gamma rays may be scattered into the detector which were originally scattered in some other direction. Because of these difficulties, it is hard to obtain correlations between experimental and theoretical values of $k(\phi)$. A simpler method to note the effect of a single crystal is to compare the scattered radiation from it with the scattered radiation from a similar size polycrystalline specimen. By
using this comparison technique, the adverse effects encountered above would be eliminated.

In this investigation consideration is given to reflective-scattering of gamma rays. When a photon enters the crystal it may be scattered or it may be reflected. These processes may occur singly or in multiples and combinations of scatterings and reflections, and its direction and energy, if it leaves the crystal, is a rather complex function of the incident energy, the incident angle, crystal material, and the scattering angle.

It is beyond the scope of this investigation to examine all of these variables. However two of these variables can be investigated with the equipment available. These are the incident angle of gamma radiation and the scattering angle. This can be done by comparing the scattering angle for single crystal and polycrystalline specimens at different incident angles. In this investigation the incident angle for most probable reflection is compared with an angle where little or no reflection is to be expected.
IV. EQUIPMENT

A photograph of the equipment used in this investigation is shown in Figure 1. A plan view of the apparatus is shown in Figure 2. The equipment consists of a Co$^{60}$ source, a single crystal lead crystal, a polycrystal lead crystal, crystal holders, a collimator, a scintillation counter, and a scaler with a built in timer.

A. Source of Radiation

In this investigation the source should ideally meet the following specifications:

1. It should emit monochromatic gamma rays.

2. It should be of sufficient strength to provide a reasonable count rate.

3. It should emit gamma rays of energy that might be encountered in an actual shielding situation.

Of the types of sources available, a cobalt-60 source with a strength of approximately 2 curies was chosen. The facilities for working with a source of this strength were available in the Department of Nuclear Engineering. Although Co$^{60}$ does not emit gamma rays monochromatically, it emits gamma rays of energies of 1.1715 Mev and 1.3316 Mev. The energies of these gamma rays are close enough to each other that an average energy of 1.252 Mev can be used without introducing any serious error. Using this value of 1.252 Mev the gamma rays emitted from the source can be considered monochromatic.

The Co$^{60}$ source is strong enough to provide a reasonable count rate
Figure 1. A view of equipment used showing source facility, collimator, grid, detector, detector platform, scaler–timer, and survey meter.

(The detector shield and part of the source shield are removed.)
Figure 2. Plan view of experimental apparatus
TYPICAL DETECTOR POSITION FOR MEASUREMENT OF SCATTERED RAYS.
during the investigation. In a nuclear reactor gamma rays are produced with energies as high as 2 or 3 Mev. The gamma rays of energy 1.252 Mev can be considered typical of those encountered in a nuclear reactor.

The source was housed in a facility built especially for it in the West Chemical Engineering Building on the Iowa State University campus. The facility was designed by McDermott (?). The facility consisted of a container for the source in the form of a lead cylinder 16 inches in diameter and 19 inches in height mounted on a concrete support. The facility has six 1/4 inch radiation ports, which are equally spaced around the cylinder. The ports are 2-1/4 inches above the table which surrounds the cylinder. The source is mounted on the lower end of a rack which is located in the center of the cylinder. By means of an electric motor and reduction gears the rack moves up and down. When not being used the rack is lowered to a "safe" position. When it is being used it is raised so that the cobalt-60 source is the inside of the ports. The movement in both upward and downward directions is stopped automatically by micro switches which turn the electric motor off. The facility is also equipped with a red warning light. The light is turned on by the action of a micro switch and comes on when the source is not in the "safe" position. When the source is in the irradiating position, the beam is attenuated at the edge of the table by slabs of lead five inches thick.

The radiation doses at various points around the facility were checked by the Health Physics Group for the Ames Laboratory. They found that the dose at the perimeter of the table was less than 0.2 mR/hr. The maximum dose was found to be 3.8 r/hr and this was in front of an
open port. Since only one port was being used in this investigation, 
lead bricks were placed in front of the other five ports. See Figure 3. 
This reduced the dose at one foot from these ports to less than 4 mr/hr.

B. Collimator

The diameter of the ports of the facility are 1/4 inch. For parts 
of the investigation it was desired to have a beam that was narrower than 
this. This was accomplished by means of the collimator. The collimator 
is a lead block 4 x 4 x 8-1/4 inches long. Lengthwise in the block there 
is a 3/32 inch diameter hole. This is such that when the collimator is 
placed before a port this hole is in line with the port. This collimates 
the beam to 3/32 inch leaving the collimator or an angle with of 0.3°.

C. Crystals

The mechanism of attenuating gamma radiation is by interaction of 
the gamma quanta with electrons. Therefore to reflect gamma radiation 
it is desirable to have as high as possible electron density. Lead has 
a high electron density and a simple crystal structure and for these 
reasons lead was chosen as the target material.

The single lead crystal was obtained from the Metallurgy Group of 
the Ames Laboratory of the Atomic Energy Commission. The crystal was in 
the form of a cylinder measuring 2 centimeters in diameter and approxi-
mately 6 centimeters in height.

It was desired that the finished specimen be approximately 1/2 
centimeter thick and that at least one face of the crystal be nearly 
perpendicular to the [111] direction of the crystal. The crystal
Figure 3. Arrangement of equipment for reflection measurements

(This view shows the crystal mounted on the sextant, and the detector shield and all of the source shields are in place.)
orientation was determined by means of Laue photographs. After the
crystal orientation was determined, the crystal was cut by means of an
acid saw using a cutting solution of one part 30% hydrogen peroxide
(H₂O₂) and three parts glacial acetic acid (CH₃CO₂H). The crystal was
cut so that height was approximately 3/4 centimeters and one end was
nearly perpendicular to the [111] crystal direction. Once the crystal
had been cut the ends were carefully ground smooth, with special care
being taken to avoid recrystallization. The crystal was etched with an
etching solution of the same composition as the cutting solution above.
This was done to make sure the crystal was still a single crystal and had
not recrystallized. Etching revealed that another grain had formed in
the crystal, but since this was on the edge of the crystal it could be
kept out of the beam of radiation.

The polycrystal was cut from a chunk of lead that had been worked
to assure that it was polycrystalline. The single crystal in its
finished condition served as a guide for the cutting of the polycrystal-
line crystal. This cutting was done by the Instrument Shop of Iowa
State University.

The thickness of the two crystals was checked with a micrometer,
and finished so that their thickness agreed to within one ten thousandths
of an inch.

As a final check of thickness the crystals were checked with the
gamma ray beam. This indicated that the polycrystalline crystal is 0.68%
thicker than the single crystal. Therefore scattering data had to be
corrected by this factor. The counting rates for the polycrystalline
crystal were corrected by this factor.
Figure 4. Arrangement of equipment for scattering measurements

(This view shows the crystal mounted on the wooden platform.)
Once the crystal had been cemented to the crystal mountings it was desired to determine the alignment of the 111 planes in the single lead crystal. This was done by taking a Laue photograph of the crystal on its mounting. This photograph indicated that when the mounting was aligned such that the face of the mounting made an angle of 88°4′ with the center line of the beam, the 111 plane of the crystal would be aligned parallel to the center line of the beam.

D. Crystal Holders

To obtain the results desired in this investigation it was necessary to have a means of accurately aligning the crystal when it was exposed to the gamma ray beam. This was accomplished by use of a U. S. Navy sextant which was modified so that the crystal could be mounted in the position normally occupied by the sextant's reflection mirror. This permitted the crystal to be rotated and the amount of rotation to read 0.05 minutes increments if necessary. The crystal was held on the sextant by a crystal mounting made of plexiglass to which the crystal was attached by rubber cement.

Rotation of the sextant through the desired angular range was impossible because the legs of the sextant. To obtain measurements of scattered radiation it was necessary to use another type of holder. This second type of holder was made of a block wood mounted on one of the movable plotter arms of a U. S. Navy three-arm navigation platform on which the detector was mounted. See Figure 4. The same type of crystal mountings was used as was used with the sextant.
E. Detector

The detector used in this experiment was a model DS-1A scintillation detector manufactured by Nuclear Instrument and Chemical Corporation. A thallium activated sodium iodide crystal was used as a sensing element of the detector. The detector was equipped with a removable lead shield with a 1 inch diameter aperture. To further sharpen the field of radiation scanned, two lead bricks were placed in front of the detector with an 1/8 inch gap between them as shown in Figure 4.

F. Detector Platform and Grid

The detector platform was used to hold the detector during the experiment. The detector platform was made so that it could be free to rotate with a center of rotation directly beneath the crystal. The platform was made of plywood and attached to one of the movable arms of a U. S. Navy three-arm navigational plotter, which consists of a stationary grid and two movable plotter arms whose rotation can be measured by a vernier on the arms and the grid. The platform was attached so that the centerline of the detector would coincide with the centerline of the plotter arm. Stops were attached to the platform so that the detector could be removed and then returned to its exact original position. The rotating of the scintillation detector, the detector platform, and two lead bricks was found to be quite difficult. To facilitate the rotation, boards were firmly attached to the sides of the platform. On these boards were placed the lead bricks. See Figure 3. This not only eased rotation but kept the distance between the lead bricks a constant distance. To further facilitate the rotation of the system, paraffin was
used as lubricant between the platform and the table top. Even with these improvements the detector had to be removed from the platform for each change of rotation.

**G. Scaler**

The scaler used in this investigation was a Baird-Atomic Model 132 general purpose high speed glow-tube scaler. This scaler provided the high voltage to the detector and also counted pulses from it.

The published resolving time of the scaler was less than five microseconds. This was the controlling factor in determining coincidence losses during the counting. To determine the effect this had on the resulting counting rate, the following equation from Friedlander and Kennedy (4) was used:

\[ R^* = \frac{R}{1 - \tau} \]

where \( R^* \) is the counting rate with no coincidence loss, \( R \) is the observed counting rate, and \( \tau \) is the resolving time. For a counting rate of 600,000 counts per minute the loss is approximately 1%. Since all count rates observed in this investigation were considerably less than this, these losses are negligible.

Built in with the scaler was a Baird-Atomic Model 960R dual purpose precision timer.

**H. Miscellaneous Equipment**

Other items used were a Model 305A Tracerlab portable survey meter and personnel film badges.

The survey meter was used to measure radiation levels around the
The personnel film badges were provided by the Health Physics Group and were checked bi-weekly.
V. PROCEDURE

A. Operating Voltage

The operating voltage of the scintillation detector was determined by placing the detector in the beam so that it counted approximately 50,000 counts per minute. One minute counts were taken at various operating voltages, and a curve of counting rate versus operating voltages, and a curve of counting rate versus operating voltage was plotted. The midpoint of the plateau of the curve was at 1675 volts. This value of voltage was used as the operating voltage.

B. Experimental Geometry

The centerline of the beam was determined by placing the source in the radiation position and measuring the gamma ray beam with the detector. This was first attempted without the collimator, but the count rate was found to be too high, and only an approximation could be located. However this did check with further measurements of the centerline. The collimator was put in place and was aligned with the cylinder port by inserting a 3/32 inch diameter steel rod through the collimator. This steel rod also indicated the location of the centerline of the beam. Since the collimator reduced the amount of radiation, the centerline of the beam could be determined with the detector. The location of the centerline of the beam found by the detector checked with the location found by the other methods. A line was inscribed on the table indicating the centerline of the beam of gamma rays.

The centerline of the grid was placed on this line. The location
of the grid was determined by the geometry of the facility. The center of the grid had to be far enough away from the collimator so that two lead bricks could be placed in front of the collimator when adjustments were being made. This limited the minimum distances of the grid from the source. The maximum limit of the distance of the grid from the source was such that there be clearance between the detector, which was attached to the grid, and the beam stop.

The width of the beam with collimator was determined to be 0.3 degrees at half the maximum counting rate. Although there was a considerable rate as far as 1.0 degree from the centerline.

C. Reflection Data

Using the Bragg equation as an indication of the amount of reflection of cobalt-60 gamma rays by a single crystal of lead,

$$\sin \theta = \frac{n \lambda}{2d}$$

where \( \lambda = 9.8336 \times 10^{-3} \text{A}^0 \), and \( d \) is the distance between the (111) planes of the lead crystal and is equal to 2.11 \( \text{A}^0 \).

$$\sin \theta = 0.00230 \quad \theta \approx 0.8 \text{minutes}$$

To measure this reflection the detector angle would have to be approximately 12 minutes. A detector angle of this amount with the available collimation would be so close to the beam of radiation that it would be impossible to discern any effects of the crystal. The detector was moved so that the angle between the detector and the centerline of the beam was 0.65 degrees. With the detector in this position, reflection will be noted when the planes bisect the angle between the
centerline of the beam and the centerline of the detector. This angle is approximately 20 minutes. Therefore when the crystal is aligned so that the 111 planes are at 20 minutes from the centerline of the beam, the crystal will be $88^0 24' + 20'$ or $88^0 26'$. Since $90^0$ from the centerline of the beam is equivalent of $105^0$ on the sextant and $2^0$ on the sextant corresponds to $1^0$ measured from the centerline of the beam, reflection will be noted when the sextant angle reads $102.8^0$.

With the detector fixed at $0.65$ degrees from the centerline of the beam the crystal was rotated, and 5 minute counts were taken over a range of 20 degrees on the sextant.

Following each count with the crystal, a count was made without the crystal, and the results plotted as the ratio of gamma rays through the crystal to the total gamma rays incident on the crystal. This method was used instead of plotting counting rate of gamma rays passing through the crystal because the electronic equipment was believed to "drift" with time. This method of plotting the results greatly reduced this effect. The results using the single crystal showed a peak in the counting rate, see Figure 5 and Table 1. (Table 1, see Appendix)

The single crystal was removed and the polycrystalline crystal was mounted on the sextant and the same procedure followed. This time there was no peak. From this it can be concluded that some of the gamma rays are being reflected by the single lead crystal.
Figure 5. Results of reflective measurements
2 DEGREES SEXTANT READING = 1 DEGREE ROTATION

ATTENUATION RATIO

0.7400
0.7300
0.7200
0.7100
0.7000

SEXTANT READING, DEGREES, RELATIVE

95 100 105 110 115
D. Scattering Data

When the sextant was on the grid, it was difficult to move the detector. To facilitate the movement of the detector, the sextant was replaced by the other target platform. The wood platform was aligned on the grid, and then secured. By means of a pin arrangement it was possible to remove one crystal and its holder, and replace it with the other crystal and its holder. With this equipment it was possible to place the detector, and obtain a background count and counts for the same alignment of the single crystal and polycrystalline crystal.

For the measurement of scattered radiation, the platform and the crystal were so aligned that the crystal was in the same alignment as it was for the reflection peak in the reflective measurements with the single crystal. With the target platform secured, the detector was rotated in increments of 10 degrees from 10 degrees to 100 degrees. At each increment, a background count was taken and 10 minute counts with each of the crystals of the target platform. Geometrical limitation prevented investigation of scattering angles of more than 100 degrees.

To investigate the effect when the single crystal was aligned in some manner other than that for which reflection was observed the target platform was aligned and secured at 92.5 degrees which is 4.1 degrees from the alignment for reflection.
VI. RESULTS AND DISCUSSION

The results of this investigation are presented both graphically and in tabular form. Figures 6 and 7 are plots of the counting rate as a function of scattering angle.

The counting rate for both polycrystalline and single crystals decrease approximately exponentially with increased angle of scattering. A minimum is at 80° and 90° and the count increases to 100°. The reason for this dip can be explained by the fact that at 90° scattering angle there is more crystal between the detector and the point of scattering. This decreases the counting rate.

The purpose of this investigation was to examine the possibility of using single crystals for the shielding of gamma radiation. In this investigation the effectiveness of single crystalline lead is compared with polycrystalline lead for both the case where reflection will be observed and in the case where there is little or no reflection. By examining the graph for the reflected case in Figure 6 it is observed that the scattering from the single crystal is less than the polycrystalline crystal between the angles of 10 and 60 degrees, and between 80 and 100 degrees. The reason that the single crystal is less perhaps can be explained as follows. When the radiation strikes the single crystal some of it is reflected as observed in the maximum reflection peak, and this that is reflected is not scattered and this accounts for the decrease in scattering at the measured angles. By examining the graph for the case where the single crystal is not aligned for reflection in
Figure 6. Results of scattering measurements

(Crystal set at reflective peak.)
○ POLYCRYSTAL
△ SINGLE CRYSTAL
STATISTICAL DEVIATION
NO GREATER THAN ± 27
Figure 7. Results of scattering measurements

(Crystal set at angle of 4.1 degrees from reflective peak.)
○ POLYCRYSTAL
△ SINGLE CRYSTAL
STATISTICAL DEVIATION NO GREATER THAN ± 27
Figure 7 the difference between the scattering of the single and polycrystalline crystals is less than the previous. By the reasoning as in the first case, little or no reflection occurs and the difference between the polycrystal and single specimen is less.
VII. CONCLUSIONS

From the results of this experiment it is indicated that there is a change in the scattering characteristics of single lead crystals, and the amount of this change is a function of the incident angle of radiation on the crystal planes. It appears that for certain alignments of the planes of a single crystal with the direction of incident radiation, reflection takes place. This fact may be used in the designing of shielding by arranging the crystals so that reflection from one crystal is reflected to a second and then to a third. By a series of such crystals it might be possible to deflect the radiation away from certain areas. No calculations were made, but the amount of lead in the form of single crystals to accomplish this deflection may be greater than the amount of lead needed to attenuate the radiation by conventional means.
In this work and in the works of Sasscer (9) and Holmes (6) with zinc and copper, the results show that there is some contribution to scattering from reflection. Possible work in the future could be a theoretical analysis of the complex method by which this occurs. Another possible area of study would be to examine this scattering and reflection in three dimensions. In this investigation all measurements were made in the plane of the table of the facility, and the rotation of the crystals was in an angle of this plane. If measurements were made in three dimensions, the maximum numerical differences between the single crystalline and polycrystalline would be greater than those observed for the two dimensional measurements. The reason for this is that some of the radiation is reflected upward and downward and in the two dimensional investigation changes and variation of this radiation can not be measured. Another way this work could be improved would be to examine the energy of the reflected and scattered radiation. This could be done by using a recording spectrometer in conjunction with the scaler. The use of three dimensional measurements and recording spectrometer could be used to check any theoretical analysis of mechanisms for reflection.
IX. REFERENCES


X. ACKNOWLEDGMENTS

The author would like to express his gratitude to Dr. Glenn Murphy, Head of the Nuclear Engineering Department of Iowa State University for his advice and guidance given during this investigation.

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Finally the author would like to express his sincere appreciation to the Oak Ridge Institute of Nuclear Studies, under whose fellowship the author received this education in Nuclear Engineering at Iowa State University.
XI. APPENDIX

Sample Calculations

Reflection Ratio (Table 1, line 1)

\[
\frac{\text{counts with crystal}}{\text{counts without crystal}} = \frac{110,888.8}{154,250} = 0.7189
\]

Standard Deviation for scattering data (Table 2, line 1)

\[
\begin{align*}
\sigma_t &= \left( \frac{\text{total counts}}{\text{counting time}} \right)^{\frac{1}{2}} = \left( \frac{4620}{10 \text{ min.}} \right)^{\frac{1}{2}} = 21.5 \\
\sigma_{bg} &= \left( \frac{\text{background count}}{\text{counting time}} \right)^{\frac{1}{2}} = \left( \frac{2278.3}{10 \text{ min.}} \right)^{\frac{1}{2}} = 17.61 \\
\sigma_{net} &= \left( \sigma_t^2 + \sigma_{bg}^2 \right)^{\frac{1}{2}} = 26.6
\end{align*}
\]

Critical angle for reflection Page 27

\[
\sin \theta = \frac{n \lambda}{2d} \\
\begin{align*}
n &= 1 \\
\lambda &= \frac{hc}{\lambda} = \frac{5.625 \times 10^{-27} \text{erg-sec} \times 2.9776 \times 10^{10} \text{cm/sec}}{1.602 \times 10^{-6} \text{erg/mev} \times 1.252 \text{mev} \times 10^{-8} \text{cm/Å}} \\
\lambda &= 9.8338 \times 10^{-2} \text{Å} \\
d &= 2.14 \text{ Å} \\
\sin \theta &= 0.00230 \\
\theta &= 8 \text{ minutes}
\end{align*}
\]
Table 1. Experimental data for reflection

Detector angle: 0.65 degree

Counting time: With crystal 5 minutes
               Without crystal 2 minutes

<table>
<thead>
<tr>
<th>Sextant angle (degrees)</th>
<th>Counting rate with crystal</th>
<th>Counting rate without crystal</th>
<th>Attenuation ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>95.0</td>
<td>110,888.8</td>
<td>154,250</td>
<td>0.7189</td>
</tr>
<tr>
<td>96.0</td>
<td>112,077.6</td>
<td>156,013</td>
<td>0.7184</td>
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<tr>
<td>97.0</td>
<td>111,918.8</td>
<td>157,147</td>
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<tr>
<td>98.0</td>
<td>111,866.0</td>
<td>155,901</td>
<td>0.7175</td>
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<tr>
<td>99.0</td>
<td>111,871.6</td>
<td>155,835</td>
<td>0.7153</td>
</tr>
<tr>
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</tr>
<tr>
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<tr>
<td>102.0</td>
<td>111,517.2</td>
<td>154,978</td>
<td>0.7195</td>
</tr>
<tr>
<td>103.0</td>
<td>112,721.6</td>
<td>155,887</td>
<td>0.7261</td>
</tr>
<tr>
<td>104.0</td>
<td>112,234.8</td>
<td>157,268</td>
<td>0.7141</td>
</tr>
<tr>
<td>105.0</td>
<td>111,668.8</td>
<td>156,300</td>
<td>0.7145</td>
</tr>
<tr>
<td>106.0</td>
<td>111,487.2</td>
<td>155,776</td>
<td>0.7157</td>
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<tr>
<td>107.0</td>
<td>112,018.0</td>
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<td>109.0</td>
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<td>112.0</td>
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<tr>
<td>114.0</td>
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<td>155,901</td>
<td>0.7116</td>
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<tr>
<td>115.0</td>
<td>110,986.4</td>
<td>155,616</td>
<td>0.7132</td>
</tr>
</tbody>
</table>
Table 2. Experimental data for scattering

<table>
<thead>
<tr>
<th>Detector angle (degrees)</th>
<th>Background (cpm)</th>
<th>Single crystal (cpm)</th>
<th>Single crystal net (cpm)</th>
<th>Poly-crystal (cpm)</th>
<th>Poly-crystal net (cpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>111</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>2274.0</td>
<td>1623.0</td>
<td>2350 ± 27</td>
<td>1631.2</td>
<td>2341 ± 27</td>
</tr>
<tr>
<td>20</td>
<td>517.6</td>
<td>2987.2</td>
<td>2070 ± 20</td>
<td>3008.8</td>
<td>2075 ± 20</td>
</tr>
<tr>
<td>30</td>
<td>611.6</td>
<td>2231.4</td>
<td>1590 ± 17</td>
<td>2269.2</td>
<td>1608 ± 17</td>
</tr>
<tr>
<td>40</td>
<td>522.2</td>
<td>1679.6</td>
<td>1157 ± 15</td>
<td>1706.6</td>
<td>1183 ± 15</td>
</tr>
<tr>
<td>50</td>
<td>465.6</td>
<td>1306.6</td>
<td>811 ± 13</td>
<td>1332.6</td>
<td>858 ± 13</td>
</tr>
<tr>
<td>60</td>
<td>430.4</td>
<td>1053.0</td>
<td>623 ± 12</td>
<td>1065.5</td>
<td>630 ± 12</td>
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<td>70</td>
<td>403.2</td>
<td>938.2</td>
<td>495 ± 11</td>
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<tr>
<td>80</td>
<td>388.0</td>
<td>765.2</td>
<td>377 ± 11</td>
<td>755.2</td>
<td>370 ± 11</td>
</tr>
<tr>
<td>90</td>
<td>383.6</td>
<td>661.2</td>
<td>278 ± 10</td>
<td>682.8</td>
<td>303 ± 10</td>
</tr>
<tr>
<td>100</td>
<td>374.0</td>
<td>661.4</td>
<td>307 ± 10</td>
<td>702.8</td>
<td>322 ± 10</td>
</tr>
</tbody>
</table>

(1) 111 crystal planes in position of observed reflection

(2) 111 crystal planes at angle of 4.1 degrees to (1)

*aThis rate is corrected for crystal thickness.*