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ANGULAR DISTRIBUTION OF PHOTONS IN SHOWERS

Jack W. Rosengren

October 31, 1952

Berkeley, California

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ANGULAR DISTRIBUTION OF PHOTONS IN SHOWERS

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ABSTRACT

A study has been made of the angular distribution of the photons in electron-photon cascade showers initiated in Cu and Pb by high energy bremsstrahlung radiation. Targets of thicknesses 1.17, 2.52 and 5.30 radiation lengths of Pb and 0.85 radiation lengths of Cu were exposed individually to the 322 Mev bremsstrahlung beam of the Berkeley synchrotron. The angular distribution of all but the lowest energy photons emerging from the far side of the targets should be identical with the distributions at the same depths in an infinite medium.

The photons were detected by the beta-activity produced in Cu foils by the Cu^{63} (γ, n) Cu^{62} reaction. This reaction is known to be produced mainly by photons of energies near 17.5 Mev. Evidence is presented that the observed activity was not produced by electrons or neutrons.

The target thicknesses of Pb employed corresponded to depths in the shower of T/2, T and 2T, where T is the depth of the shower maximum. Angular distributions were measured in the range from 6° to 50°. Rough agreement is shown between the results and the theoretical calculations of Eyges and Fernbach.

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* Now at Dept. of Physics, M. I. T

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Introduction

For a theoretical interpretation of many experiments concerned with cascade photon-electron showers, application of so-called one dimensional shower theory is sufficient$^{e.g. 1.}$. This theory considers the longitudinal development of a shower under the assumption that there is no transverse spreading. For an interpretation of many experiments, particularly some concerning showers produced in air by cosmic rays, one needs to deal specifically with this lateral development. Considerable theoretical work has been done on this subject. In general, one wishes to find four distribution functions defined by the following:

$P_r(r, t, E)rdr$:	the relative number of electrons of energy E at longitudinal depth t in the annular ring between r and r + dr independent of direction of motion.
$P_\theta(\theta, t, E)\theta d\theta$;	The relative number of electrons of energy E at longitudinal depth t with velocity vectors in the solid angle between θ and $0 + d\theta$ independent of lateral displacement from the shower axis.
$Q_r(r, t, E)rdr$	and
$Q_\theta(\theta, t, E)\theta d\theta$;	the corresponding functions for photons.

Often, rather than seeking the distribution functions, the attempt is made to calculate the root mean square angular or radial displacement.

The first treatment of the lateral development of showers was given by Euler and Wergeland[2]; however, their results are now considered to give far too small an extension of showers. L. Landau[3] set up diffusion equations for the sidewise development, but his numerical results were in error. G. Moliere[4] has made an extensive investigation using an extension of Landau's method and has calculated the radial distributions of both electrons and photons and the angular distribution of electrons. His work is carried out under approximation A[*]. Roberg and Nordheim[6] have evaluated the mean square angular and lateral spreads of both electrons and photons at the shower maximum as functions of their energy.

Eyges and Fernbach have calculated the first several moments of the distribution functions and by means of a trial and error fitting have inferred the distributions. Using approximation A, they have determined the angular distributions of photons and electrons[7] and the radial distribution of electrons[8] at the depth of the shower maximum, t_{max}, and at $1/2\ t_{max}$ and $2t_{max}$. They have also calculated all four distributions at the shower maximum, taking ionization losses into account, for E equal to twice the critical energy, ϵ, and for 5ϵ and 10ϵ[9,10].

In the past, most of the experiments involving photon-electron cascades dealt with the showers produced in the atmosphere by cosmic rays. Now with the availability of sufficiently high energy x-ray machines, experiments involving cascade showers can be done in the laboratory[e.g. 11, 12].

Crowe and Hayward[13], using a cloud chamber in the 322 Mev bremsstrahlung beam of the Berkeley synchrotron, measured the energy spectrum and angular distribution of electrons at about the shower maximum in lead, obtaining reasonable agreement with theory. The purpose of the present experiment was to study the angular distribution of the photons in showers in lead.

Qualitative Description of the Spread of a Shower

The mechanism of the cascade shower is well known, the electrons producing numerous photons by radiation, the photons in turn forming electrons[**] by pair production. At high energies, Compton scattering and loss of energy by ionization are relatively unimportant. Since at these high energies the radiation and pair production processes propagate at very small angles with the forward direction, the shower develops essentially along a straight line, the number of particles nultiplying, the average particle energy constantly

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[*] Rossi and Greisen[5], in their review article, introduce the notation "approximation A" for a treatment in which the ionization loss of electrons is neglected.

[**] Throughout this paper, the term, "electron" includes both positive and negative electrons.

decreasing. For the lower energy particles, ionization loss becomes important, and eventually the critical energy*, is reached at which the average space rate of loss of energy by ionization is equal to that for loss by radiation. These lower energy particles are then lost to the shower as far as continued multiplication is concerned.

At a certain depth, t_{max}, in the shower medium, the attenutation processes start to exceed the cascade processes and the shower reaches a maximum development in number of particles, ionization, etc. Beyond this depth the shower declines; eventually it dies completely, and the energy of the incident primary electron or photon is reduced to heat energy of the gross medium.

Although until near its very end the main body of the shower proceeds directly forward, there is lateral spreading from near the start. This spreading is caused almost completely by the multiple Coulomb scattering of the shower electrons by the nuclei of the medium. This process gives in one radiation length about ten times the deflection inherent in the radiation or pair production processes. The root mean square deviation, $\sqrt{\theta^2}$, acquired by an electron of energy E in one radiation length is roughly E_s/E, where E_s is the so-called characteristic energy**, about 21 Mev. The consequence of this energy dependence is that scattering becomes important only at lower energies and that, on the average a photon's deviation is due to the scattering of its most recent electron ancestors in the last few radiation lengths.

The high energy particles travel forward, maintaining a densely populated, very narrow central core (narrow when measured in radiation lengths).*** Lower energy particles when formed are scattered outward

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* Definitions of the various terms used in shower theory are given in the review article by Rossi and Greisen[5].

The critical energy is the energy lost by an electron through ionization in one radiation length.

E critical is very roughly 600/Z Mev.

** E_s, the "characteristic energy" is merely a constant with the dimensions of an energy. $E_s = mc^2 (4\pi \cdot 137)^{1/2} = 21$ Mev.

*** A radiation length, the thickness Xo, is defined in gm/cm^2 by the equation $1/X_o = 4\alpha n Z^2 r_o^2 \ln (183 Z^{-1/3})$. Where α = fine structure constant = 1/137 r_o = classical electron radius = 2.8×10^{-13} cm. Z = atomic number and n = number of atoms/gm. The radiation length is the fundamental unit of length of cascade shower theory. The description of radiation phenomena is only slightly dependent on Z when thicknesses are measured in terms of this unit.

from this core, diverging at large angles to give the shower its transverse spread. This expansion radially is not of indefinite extent; low energy particles do not cascade much and their energy is soon attenuated. The shower will spread to a limit determined by the range of the low energy particles, and this limit will be roughly maintained for the remainder of the shower's length, the low energy, divergent particles being constantly supplied from the narrow, high energy, central core.

For shower photons and electrons of the same energy, the root mean square angular deviation of the photons will be less than that of the electrons, since the deviation of a photon is inherited directly from a higher energy electron. Because photons have longer mean free paths than electrons of the same energy, it happensthat, despite the smaller angular deviation, the root mean square radial spread of the photons is larger than that of the electrons of the same energy.

Experimental Arrangement and Procedure for Measurement of Angular Distribution

Arrangement To determine the angular distribution of photons at various depths in a shower medium, the experimental arrangement shown in Fig. 1 was used. The 322 Mev bremsstrahlung beam of the Berkeley synchrotron, collimated to a diameter of one-quarter inch, impinged on a thick lead of copper target placed directly on the collimator wall. Photon-electron cascade showers were produced in the target medium, and these photons and electrons emerged from the far side traveling at various angles with the shower axis, which was the axis of the incident bremsstrahlung beam. The angular distribution of high energy particles at a given depth in a shower medium will in no way be determined by the material beyond that depth; therefore the angular distribution of the particles emerging from a target of thickness t will correspond to the distribution in an infinite medium at depth t.

Detectors To detect the photons, the radioactivity produced by a (γ, n) reaction in copper was used. The .016 inch thick copper detector foils were positioned beyond the target on a lucite mount as shown in Fig. 1. The foils were mounted as segments of cylinders with the beam as their axis. The basic foil was three inches square, but to obtain reasonable angular resolution at larger angles, the foils were cut into two 1-1/2 inch strips or into four 3/4 inch strips and mounted as shown. The radial separation between the foils was 2 cm. (An expression for the relative effective solid angle per foil is derived in the appendix.)

To obtain data between 5.5° and 30°, the mount was positioned 24 cm from the target. In this position each foil subtended an angle of about 2 degrees. To obtain data at larger angles, the mount was moved into a position 11 cm from the target. In this close position only the four outer foil positions were used. The angles were between 30° and 55° and each foil subtended an angle of about 6 degrees. To monitor the incident beam flux, a .016 inch copper foil (not shown in Fig. 1) was placed between the collimator and the target where it intercepted the total incident beam.

The reaction used to detect the photons was Cu^{63} (γ, n) Cu^{62}. The resulting Cu^{62} is beta-active with a ten minute half-life. The excitation curve for this (γ, n) reaction has been extensively investigated[14, 15]. The curve has a resonance shape with a peak at 17.5 Mev and a full-width at half-maximum of about 5.5 Mev; therefore, the photons detected in this experiment were of energy near 17.5 Mev.

Other investigations[16] have shown that a negligible fraction of the observed activity would be produced by electrons. The cross section for the Cu^{63} (γ, n) Cu^{62} reaction is of the order 400 times the cross section for electro-disintegrations.

For comparison of experiment with shower theory, which is most reliable at high energies, it would have been desirable to use a detector sensitive to photons of energy higher than 17.5 Mev. Unfortunately, such detectors (e.g. C^{12} (γ, n) C^{11} peaked at about 27 Mev) have much lower relative yields and also for many materials, the radioactivity produced is inconvenient to separate from that of more predominant low energy reactions. When one is limited to photons of energy of the order of 17.5 Mev, the comparison of experiment with theory should be most easily made for a high Z target medium, such as lead. This is because high Z materials have a low critical energy* and the present theory of lateral spread is reliable only for energies much above the critical energy.

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* Defined in footnote on page 5.

Procedure The experimental procedure was the following: After about a twenty-minute bombardment, the various fractional foils at a given angle were taped together with cellophane tape to form a standard three-inch square foil. To measure their beta-activity these foils were then rolled into the form of cylinders and were slipped over Victoreen 1B85 aluminum walled Geiger tubes. The activity of these foils relative to that of the monitor foil was determined by counting them all simultaneously for about fifteen minutes. Under these conditions only the desired ten minute beta-activity was observed.

Evaluation of Neutron Contribution

There is a possibility that the Cu^{62} radioactivity used to detect photons was produced by the Cu^{63} (n, 2n) Cu^{62} reaction instead of by the (γ, n) process. To estimate the contribution of the (n, 2n) process, the relative yield of the Al^{27} (n, p) Mg^{27} reaction was investigated using the same geometry. For the neutron spectrum to which the foils would be exposed, the Al reaction should have the larger cross section and its yield should set an upper limit on the yield of the Cu reaction[17, 18*]. The Mg^{27} activity is convenient since it has about the same half-life of ten minutes as Cu^{62}, and there is no other comparable half-life in this region of the isotope chart to interfere. The important point, of course, is that the Mg^{27} cannot be produced from aluminum by x-rays. When bombarded in the same geometry as the copper detector foils, a small activity was observed to be produced in the aluminum which, within statistical variations, decayed with a ten minute half-life. From the yield ofthis activity, an upper limit

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* Cohen[17] measured the average cross sections for two reactions using the neutron spectrum produced by bombarding Be with 15 Mev deuterons and found:

$$Al^{27}\ (n, p)\ Mg^{27} = 25\ \text{mb}$$
$$Cu^{63}\ (n, 2n)\ Cu^{62} = 19.6\ \text{mb}$$

The neutron spectrum produced by the synchrotron x-rays will be more predominantly low energy than in the case of Cohen's measurements. The lower threshold of the Al reaction will thus make its relative yield even larger.

to the relative yield of the Cu^{63} (n, 2n) Cu^{62} process was estimated and is plotted as curve 6 in Fig. 2. It can be seen that the neutron contribution may be important at large angles.

Results

General The angular distributions of 17.5 Mev photons were measured at depths of 1.17, 2.52, and 5.30 radiation lengths in lead (7.60, 16.4 and 34.4 gm/cm^2 respectively)* and for 0.85 radiation lengths (11.3 gm/cm^2) in copper. These four curves, all normalized to the same incident flux at zero depth, are plotted in Fig. 2.

Also, shown, as curve 5 of Fig. 2, is the relative intensity with no target; its spread being produced by interaction of the beam with the walls of the one-quarter inch collimator. This incident deviated radiation is not as important as it might first seem. At any reasonable depth in the shower medium, most of the 17.5 Mev photons observed will be descended from incident photons of appreciably higher energies; these higher energy quanta would exhibit much less spread upon emerging from the collimator than do the photons of curve 5.

For comparison with theoretical results the distribution curves at the three depths in lead are plotted individually in Figs. 3, 4 and 5. It should be noted that each point represents the average of two or more determinations. 2.5 radiation lengths is roughly the depth in lead of the shower maximum for 322 Mev bremsstrahlung incident. It is the depth where the transition curve for the photons producing the reaction Cu^{63} (γ, n) Cu^{62} has its maximum[11] and is about the depth of maximum ionization.[12] The other two depths, 1.2R.L.and 5.3R.L., are in the vicinity of half and twice the depth of the shower maximum.

Normalization to Unit Incident Flux

The total flux (in arbitrary units) of photons near 17.5 Mev between about 5.5° and 50° was obtained by numerical integration of $\int_{5.5^\circ}^{50^\circ} I(\theta) \sin\theta d\theta$. The net flux between 0° and 5.5° was obtained experimentally for each depth using a circular copper detector foil which intercepted the central flux out to 5.5°. The yield of this foil relative to the monitor foil was normalized to the same conditions as for the detector foils at larger

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* The value of 5.9 gm/cm^2 given by Rossi and Greisen[5] for the radiation length in Pb has been increased by ten percent to agree with results of recent experiment[19].

angles. Because of its smaller size the central foil beta-activities were counted on the Geiger tubes with higher efficiency than were those of the three inch square foils, and a correction factor of 0.80 (uncertainty = ± 0.05) was necessary for normalization.

Neglecting the small contribution outside 50°, the total flux at the shower maximum was normalized to 1.55, which is known to be the value at this depth for unit flux incident at depth zero[11] *.

Normalized in this manner, values of the flux through the central 5.5° and from 5.5° to 50° are given in Table I.

Table I

Depth (radiation lengths)	1.17 (Pb)	2.52 (Pb)	5.30 (Pb)	0.85 (Cu)
0° to 5.5°	0.891±0.5 percent	0.696±0.5 percent	0.340±0.7 percent	0.863±0.5 percent
5.5° to 50°	0.54	0.85	0.73	
Total neglecting $\theta > 50°$	1.43	1.55	1.07	
Total from Strauch's curve	1.24	1.55	1.00	

The values given for the central flux each represent the results of two or more determinations. The uncertainties quoted for these values are standard deviations based on counting statistics only, but should be the total uncertainties for the relative values. The values of total flux given in the fourth row are taken from Strauch's transition curve in lead for the photons responsible for Cu^{63} (γ, n) Cu^{62}.

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* This value was checked using a 1/4 inch collimator. A three inch square foil was placed in the usual monitor position directly preceding the lead and one was placed directly on the far side where it would intercept all the emerging flux. The value obtained was 1.54 ± .02.

It might be of interest to express the distribution curves in terms of the number of quanta per Mev interval at 17.5 Mev, per steradian, per equivalent quantum* incident at zero shower depth.

For the incident bremsstrahlung spectrum it is known that at 17.5 Mev

$$\frac{dN(E)}{QdE} = 0.0846 \quad \frac{\text{quanta}}{\text{Mev interval} \cdot \text{equivalent quantum}}$$

Then, since the distributions plotted in Figs. 2, 3, 4 and 5 are all as accurately as possible normalized to unit incident flux, we have

$$\frac{dN(17.5\ \text{Mev})}{Qd\Omega dE} = \frac{0.0846\ I\ (\theta)}{} \quad \frac{\text{quanta}}{\text{steradian} \cdot \text{Mev interval} \cdot Q}$$

where I (θ) is the value of the ordinate in the figures.

Angular Distribution at Small Angles

The angular distribution of photons of a given energy is very steep near the shower axis, theoretically the distribution has a 1/θ singularity at the axis. This steepness at small angles is illustrated by the curve in Fig. 6, obtained at the depth of the shower maximum in lead. To get the data at the small angles a geometry different from that using the three inch foils had to be employed. Instead of the usual 1/4 inch collimator, one 1/8 inch in diameter was used. The detectors were 5/32 inch copper discs positioned at various angles on a mount 43 cm from the lead target. At this distance, the diameter of each disc subtended an angle of 0.27°. The monitor was a 5/32 inch disc centered on the beam axis, and the data is plotted taking the intensity averaged over this disc as unity. Data was taken at angles from 1.4° to 6.8° as shown. The larger angle data (previously shown in Fig. 4) was arbitrarily normalized to give a smooth continuation of the curve. The curve shown was drawn to fit the data and is not based on theory.

Theoretical Angular Distribution Curves

Detailed predictions of the angular distribution functions for photons in showers have been given by Eyges and Fernbach[7, 9, 10]. They have calculated the distributions under the following conditions and assumptions:

(a) The pair production cross section is a constant for the energies considered and is taken as the asymptotic value.

(b) The incident photons or electrons which produce the showers are of much larger energies than the photons observed.

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* The number of incident equivalent quanta Q is given by $Q = \frac{U}{E_{max}}$ where U is the total incident energy, E_{max} is the upper limit of the bremsstrahlung.

(c) For treatment of depths other than that of the shower maximum, t_{max}: The photons observed have energies so much greater than the critical energy that ionization losses may be ignored (Approximation A).

(d) The scattering angles are small.

(e) One can uniquely determine the distribution function by a trial and error fitting of a curve to the known moments of the distribution function.

Do these conditions apply to 17.5 Mev photons in a shower produced in lead by incident 322 Mev bremsstrahlung? Condition (a) does not hold well. Near 17.5 Mev the pair production cross section is only 0.4 of the asymptotic cross section. Condition (b) does not hold well for an incident bremsstrahlung spectrum, but not as badly as it might first seem. Because of the multiplication and attenuation processes, the primaries producing the photons deep in the shower medium on the average must have considerably larger energies than the photons observed. Condition (c) obviously does not hold since the critical energy in lead is of the order of 7 Mev; however, it holds much better for lead than for lower Z materials. Condition (d) is worse for high Z materials since the scattering probability varies as Z^2. Nevertheless, for electrons of energies quite a bit larger than 17.5 Mev, the condition holds fairly well. Assumption (e) has been experimentally tested by Eyges and Fernbach and they are confident of the accuracy of their method. The fitting of a distribution to values of its moments does not, however, determine the distribution with accuracy near the origin.

The distribution calculated by Eyges and Fernbach[7] for $1/2\ t_{max}$, t_{max}, amd $2\ t_{max}$ are shown in comparison with the experimental data in Figs. 3, 4, and 5 respectively. Their curves were calculated in terms of the general argument $\frac{E}{E_s}\theta$ (where E_s is the so-called characteristic energy, ~21 Mev), and have been evaluated for E = 17.5 Mev. At $1/2\ t_{max}$ and $2\ t_{max}$, the only available curves are calculated in Approximation A. At the shower maximum, t_{max}, Eyges and Fernbach[9, 10] have calculated, for different photon energies, a series of curves which do take ionization loss into account. Their distribution at t_{max} for $E = 2\epsilon$ (where ϵ = critical energy, ~7 Mev in lead), evaluated for E = 17.5 Mev, is shown as the dotted curve in Fig. 4.

Discussion of Results

The distributions given by Approximation A are observed to give a fair fit at 1/2 t_{max}, but to become very poor with increasing depth, being too flat. This is to be expected since the effect of ionization loss would be to increase the average energy at which the scattering of the electron ancestors of the 17.5 Mev photons occurs. For angles above about 40° the experimental distributions seem to become much flatter, an effect which might be due to neutron backgrounds or to inadequate subtraction of Geiger counting background. The curve for t_{max} which takes ionization loss into account gives a reasonable fit to experiment for intermediate angles.

In general, the agreement in shape of the experimental distributions and the theoretical curves is better than might be expected since the comparison is made under circumstances where the conditions, as listed above, for real confidence in the theory have not been fulfilled.

APPENDIX

Solid Angle Calculation

The geometry of the detector foils used in the study of the angular distribution of photons in showers is shown in Figs. 1 and 7.

Let l = length of foil along circumference (of Fig. 7)

Let n = number of atoms per unit area of foil

Let σ = cross section per atom

Referring to Fig. 7, the solid angle subtended by one atom in the interval dx is σ/r^2, and the total solid angle subtended by atoms in dx is

$$d\Omega = (\sigma/r^2)\ n\ l\ dx$$

In terms of the angle θ:

$$dx = r d\theta/\sin\theta$$

and

$$r = R/\sin\theta$$

Then

$$d\Omega = l\sigma n\ d\theta/R$$

To find the total solid angle subtended by the atoms in a foil we integrate over $d\theta$ and obtain finally:

$$\Omega = l\sigma n\ \Delta\theta/R$$

Then to find the relative photon intensity, we weight the relative activity of a given foil with the factor $R/l\Delta\theta$ since n and o are identical for all foils.

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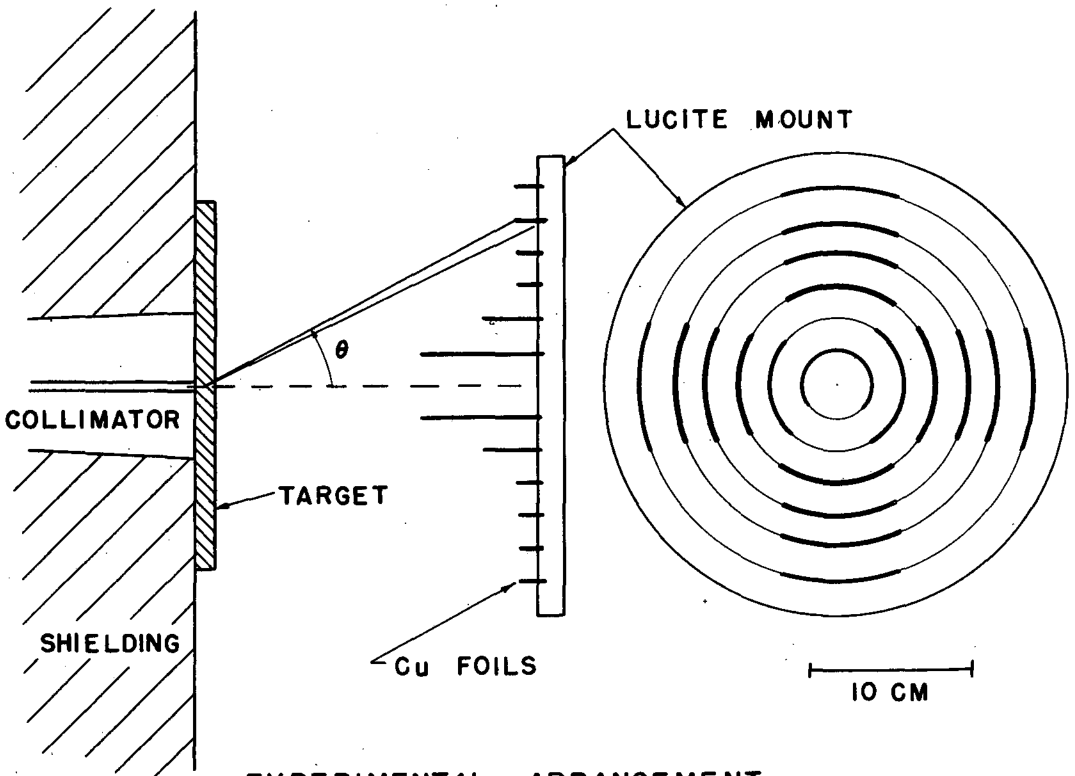
FIGURE CAPTIONS

1. Experimental arrangement for measurement of angular distribution of shower photons.
2. Angular distributions of 17.5 Mev shower photons at various shower depths, 322 Mev bremsstrahlung incident.
3. Angular distribution of 17.5 Mev shower photons at 1.2 radiation lengths depth in lead (mislabeled 1.7 radiation lengths).
4. Angular distribution of 17.5 Mev shower photons at 5.3 radiation lengths depth in lead.
5. Angular distribution of 17.5 Mev shower photons at 2.5 radiation lengths depth in lead.
6. Angular distribution (including small angles) of 17.5 Mev shower photons at 2.5 radiation lengths depth in lead.
7. Geometry of detector foils for measuring angular distribution of shower photons.

Information Division
11/3/52 dm



EXPERIMENTAL ARRANGEMENT

Fig. 1

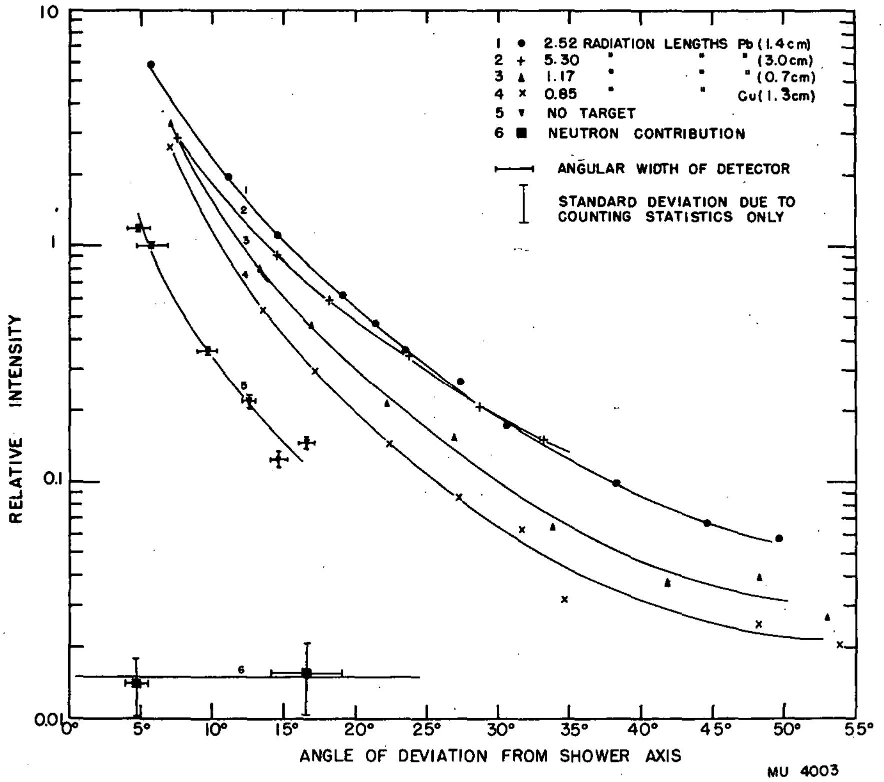

10
1
0.1
0.01
RELATIVE INTENSITY
0°
5°
10°
15°
20°
25°
30°
35°
40°
45°
50°
55°
ANGLE OF DEVIATION FROM SHOWER AXIS
1 ● 2.52 RADIATION LENGTHS Pb (1.4cm)
2 + 5.30 " " " (3.0cm)
3 ▲ 1.17 " " " (0.7cm)
4 × 0.85 " " Cu (1.3cm)
5 ▼ NO TARGET
6 ■ NEUTRON CONTRIBUTION
ANGULAR WIDTH OF DETECTOR
STANDARD DEVIATION DUE TO COUNTING STATISTICS ONLY
1
2
3
4
5
6
MU 4003

Fig. 2

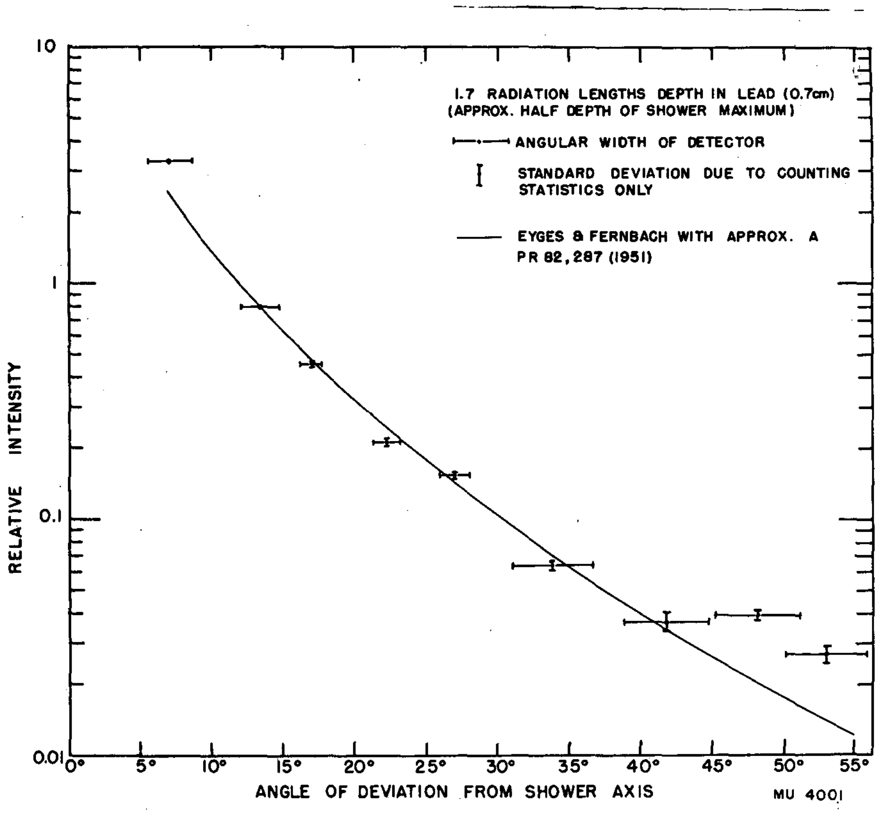

10
1
0.1
0.01
RELATIVE INTENSITY
0°
5°
10°
15°
20°
25°
30°
35°
40°
45°
50°
55°
ANGLE OF DEVIATION FROM SHOWER AXIS
MU 4001
1.7 RADIATION LENGTHS DEPTH IN LEAD (0.7cm)
(APPROX. HALF DEPTH OF SHOWER MAXIMUM)
ANGULAR WIDTH OF DETECTOR
STANDARD DEVIATION DUE TO COUNTING STATISTICS ONLY
EYGES & FERNBACH WITH APPROX. A
PR 82, 287 (1951)

Fig. 3

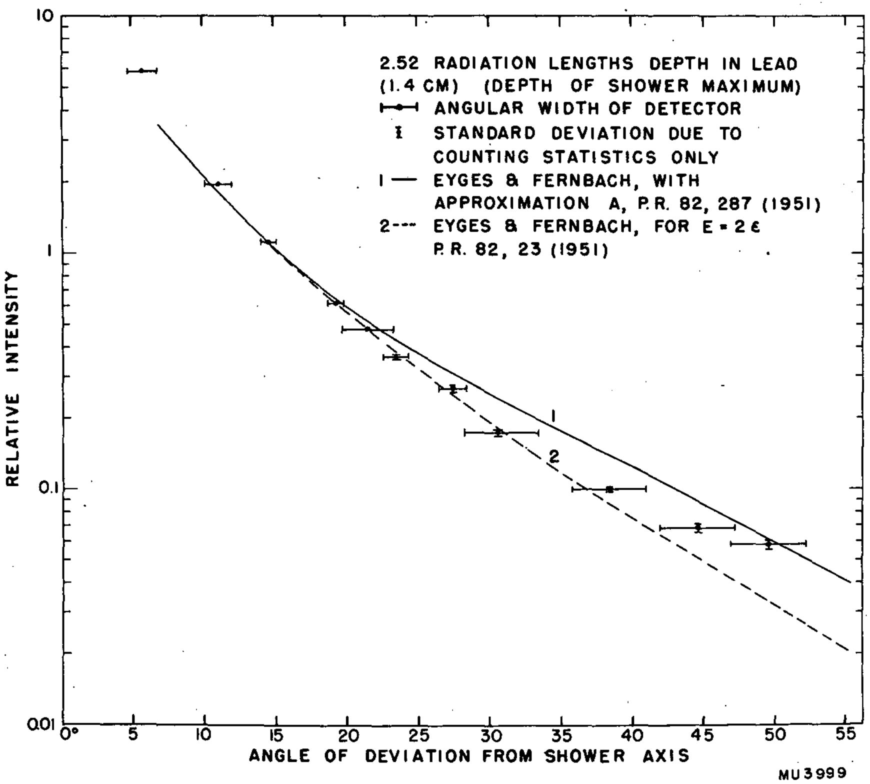

2.52 RADIATION LENGTHS DEPTH IN LEAD
(1.4 CM) (DEPTH OF SHOWER MAXIMUM)
ANGULAR WIDTH OF DETECTOR
STANDARD DEVIATION DUE TO COUNTING STATISTICS ONLY
1 — EYGES & FERNBACH, WITH APPROXIMATION A, P.R. 82, 287 (1951)
2--- EYGES & FERNBACH, FOR E = 2 ε P.R. 82, 23 (1951)
RELATIVE INTENSITY
10
1
0.1
0.01
0°
5
10
15
20
25
30
35
40
45
50
55
ANGLE OF DEVIATION FROM SHOWER AXIS
1
2
MU3999

Fig. 4

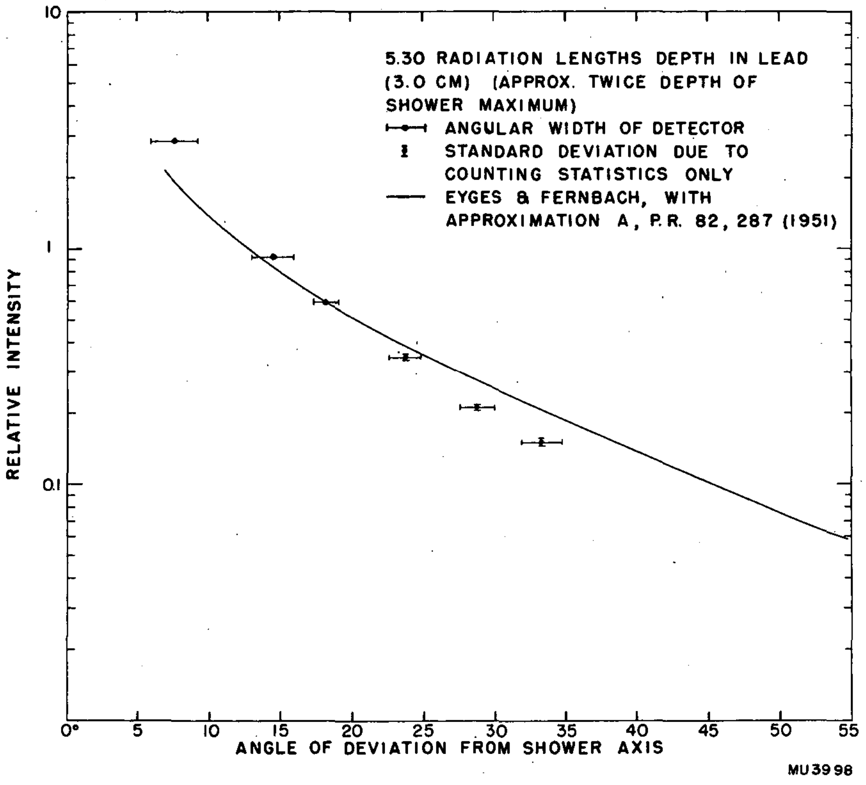

10
1
0.1
RELATIVE INTENSITY
0°
5
10
15
20
25
30
35
40
45
50
55
ANGLE OF DEVIATION FROM SHOWER AXIS
5.30 RADIATION LENGTHS DEPTH IN LEAD (3.0 CM) (APPROX. TWICE DEPTH OF SHOWER MAXIMUM)
ANGULAR WIDTH OF DETECTOR
STANDARD DEVIATION DUE TO COUNTING STATISTICS ONLY
EYGES & FERNBACH, WITH APPROXIMATION A, P.R. 82, 287 (1951)
MU3998

Fig. 5

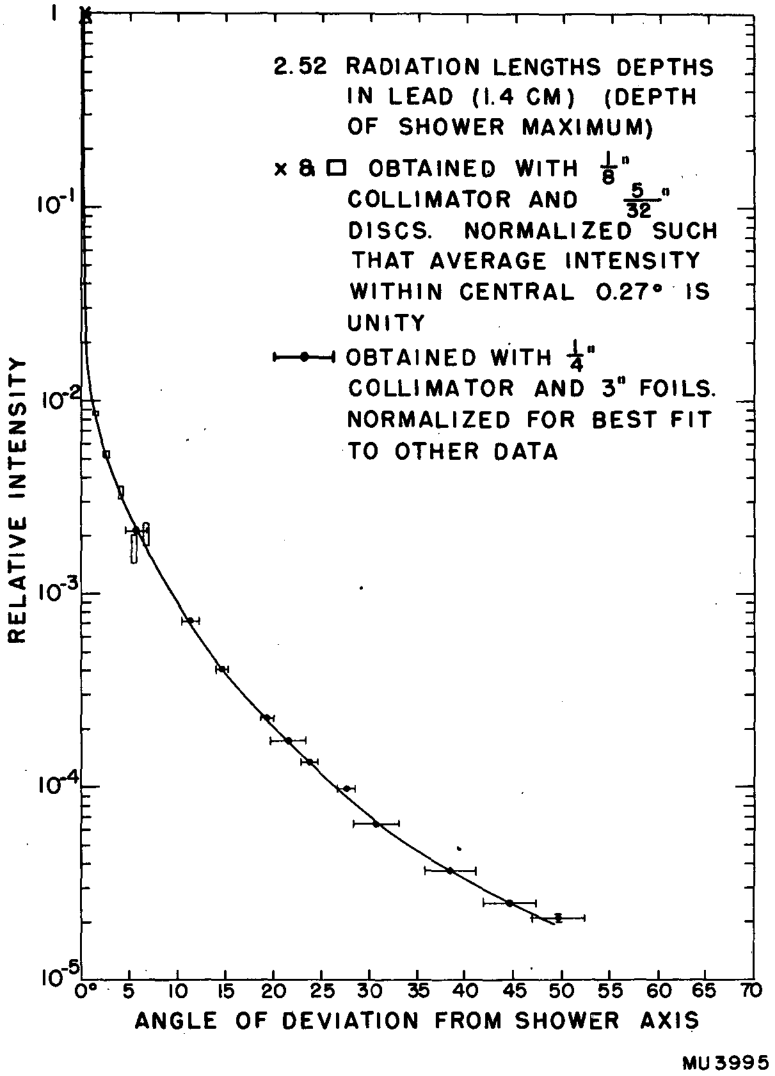

2.52 RADIATION LENGTHS DEPTHS IN LEAD (1.4 CM) (DEPTH OF SHOWER MAXIMUM)
x & □ OBTAINED WITH $\frac{1}{8}$" COLLIMATOR AND $\frac{5}{32}$" DISCS. NORMALIZED SUCH THAT AVERAGE INTENSITY WITHIN CENTRAL 0.27° IS UNITY
OBTAINED WITH $\frac{1}{4}$" COLLIMATOR AND 3" FOILS. NORMALIZED FOR BEST FIT TO OTHER DATA
RELATIVE INTENSITY
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0°
5
10
15
20
25
30
35
40
45
50
55
60
65
70
ANGLE OF DEVIATION FROM SHOWER AXIS
MU3995

Fig. 6

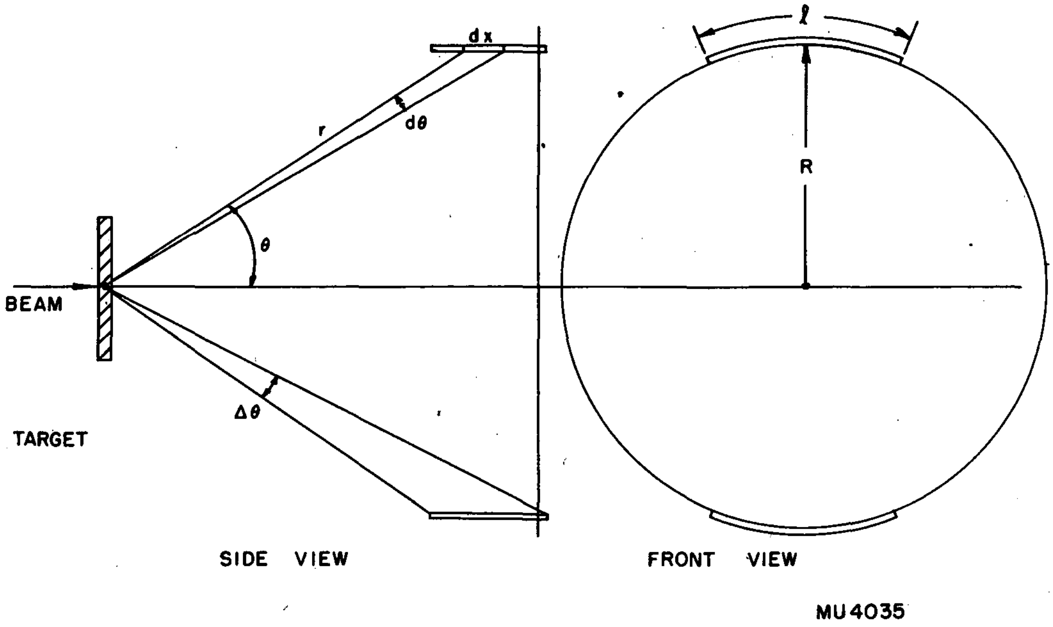


Fig. 7