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Bremsstrahlung Polarization Measurements for 1.0-Mev Electrons*†

J. W. MOTZ
National Bureau of Standards, Washington, D. C.
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With 1-Mev electrons incident on thin aluminum and gold targets, bremsstrahlung polarization as a function of photon energy for a 20-degree emission angle has been measured with a polarimeter that depends on the polarization sensitivity of the Compton process. The selection of energy intervals out of the continuous bremsstrahlung spectrum was accomplished by employing the polarimeter as a double crystal Compton spectrometer. The results show a polarization reversal in qualitative agreement with the Born approximation calculations of Gluckstern and Hull. With the gold target, the polarization reversal occurs at a lower photon energy than that predicted by the Born approximation theory. Such a shift in the reversal energy is obtained with the Born approximation theory for a lower initial electron energy.

I. INTRODUCTION

THE dependence of the bremsstrahlung cross section on arbitrary photon polarization has been calculated under the Born approximation by May and Wick,[1] and by Gluckstern, Hull, and Breit.[2] In addition, Gluckstern and Hull[3] have integrated this cross section over the direction of the emerging electron. At nonrelativistic energies, an estimate of the polarization has been made by Kirkpatrick and Wiedmann[4] from the results of the exact Sommerfeld theory.[5]

The important parameters in the bremsstrahlung process that determine the photon polarization are shown in Fig. 1, where E_0 and $\mathbf{p}_0$ are the initial total energy and momentum, respectively, of the electron, k and $\mathbf{k}$ are the energy and momentum of the emitted photon, θ is the angle between $\mathbf{p}_0$ and $\mathbf{k}$, and Z is the atomic number of the target material. In the present experiment, the polarization, P, is defined as:

$$P=\frac{d\sigma_{\perp}(E_0,k,\theta,Z)-d\sigma_{\parallel}(E_0,k,\theta,Z)}{d\sigma_{\perp}+d\sigma_{\parallel}}, \qquad (1)$$

where $d\sigma_{\perp}$ and $d\sigma_{\parallel}$ are the differential bremsstrahlung cross sections integrated over the directions of the emerging electron for photons polarized perpendicular and parallel, respectively, to the plane of emission, i.e., the $\mathbf{p}_0\mathbf{k}$ plane.

Bremsstrahlung polarization has been observed[6] by experimental methods which utilize the polarization sensitivity of (1) the photoelectric process, (2) the Compton process, and (3) the photodisintegration of the deuteron. At nonrelativistic energies, methods (1) and (2) have been used to measure the dependence of the polarization on photon energy for bremsstrahlung emitted at 90 degrees from a thin aluminum target.[7] Method (3) has been used to measure the angular dependence of the polarization of 6±2 Mev photons produced by 24-Mev electrons incident on a thin aluminum target.[8] The low-energy results are not consistent with each other, although the most recent measurement of Kulenkampff *et al.*[7] indicates agreement with the Sommerfeld theory.[5] The high-energy results[8] have shown considerable disagreement with the Born approximation theory.[3] It is apparent that more quanti-

* A summary of this work was reported at the 1956 annual meeting of the American Physical Society [J. Motz, Bull. Am. Phys. Soc. Ser. II, 1, 10 (1956)].

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[1] M. May and G. C. Wick, Phys. Rev. **81**, 628 (1951); M. May, Phys. Rev. **84**, 265 (1951).

[2] Gluckstern, Hull, and Breit, Phys. Rev. **90**, 1026 (1953).

[3] R. L. Gluckstern and M. H. Hull, Jr., Phys. Rev. **90**, 1030 (1953).

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[7] Kulenkampff, Leisegang, and Scheer, Z. Physik **137**, 435 (1954); H. Kulenkampff, Physik. Z. **30**, 514 (1929); D. S. Piston, Phys. Rev. **49**, 275 (1936).

[8] Dudley, Inman, and Kenney, Phys. Rev. **102**, 925 (1956).

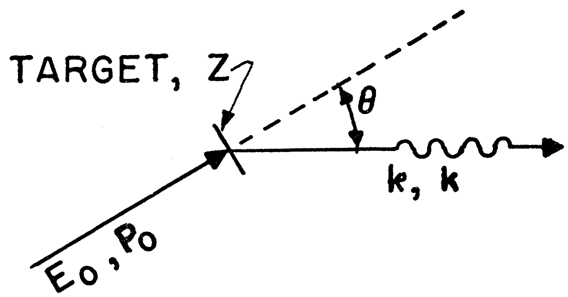

FIG. 1. Parameters that determine the bremsstrahlung polarization. Electrons with initial energy E_0 and momentum $\mathbf{p}_0$, are incident on a thin target with atomic number Z. Photons with energy k and momentum $\mathbf{k}$, are emitted at an angle θ with respect to the incident electron direction. The polarization is defined with respect to the $\mathbf{p}_0\mathbf{k}$ plane.

tative measurements of the above type are needed before an accurate description of the polarization is available.

In the present work, the bremsstrahlung polarization is measured as a function of photon energy by method (2) for thin aluminum and gold targets. A photon emission angle of 20 degrees is selected because it is roughly equal to the angle mc^2/E_0 at which the largest polarization effect is expected.[3] The initial electron energy is 1 Mev, which is in a region where the validity of the Born approximation is questionable. In fact, measurements of the bremsstrahlung cross section summed over polarization for 1-Mev electrons,[9] and of the total pair cross section at energies close to 1 Mev[10] have shown disagreement by about a factor of two with the Born approximation theory. In the face of such differences, it would not be surprising if the polarization behavior in this energy region does not agree in every detail with the predictions of the Born approximation theory.

In the nonrelativistic classical theory, the dependence of the polarization on photon energy is governed by the fact that the polarization vector is in the direction of the electron acceleration. Consequently, there is a polarization reversal in which the high- and low-energy photons tend to be polarized parallel and perpendicular, respectively, to the emission plane $\mathbf{p}_0\mathbf{k}$. As the initial electron energy increases, relativistic effects cause the radiation to have a greater degree of polarization perpendicular to the emission plane. A quantitative description of this behavior according to the Born approximation theory[3] is shown in Fig. 2 for electron energies of 0.5 and 1.0 Mev. The curves were computed for a gold target and a photon emission angle of 20 degrees, and they show that for increasing electron energies in this range, the ratio $k_r/(E_0-mc^2)$ becomes larger, where k_r is the photon energy at which the polarization reversal occurs. It is also seen that 1 Mev is an optimum initial electron energy for the experimental observation of such a reversal, because (a) the reversal occurs about at the midpoint of the photon energies and (b) there is an appreciable polarization both parallel and perpendicular to the plane of emission.

II. POLARIMETER

In the present measurements, the polarimeter must simultaneously perform two functions: (a) it must select photons within a small energy interval out of the continuous bremsstrahlung spectrum, and (b) it must measure the polarization, P, of these photons with respect to the plane of emission, i.e., the $\mathbf{p}_0\mathbf{k}$ plane as shown in Fig. 1. This double demand calls for certain compromises in design, with the result that the polarimeter sacrifices good energy resolution for better polarization sensitivity.

The polarimeter depends on the polarization sensitivity of the Compton process, and consists of two scintillation crystals,[11] an anthracene scatterer and a

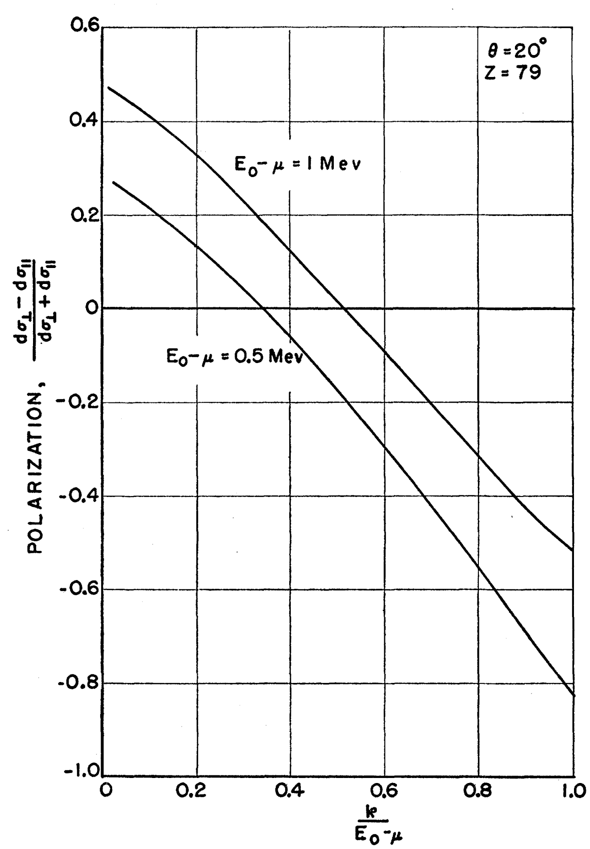

FIG. 2. Dependence of bremsstrahlung polarization on photon energy k, as predicted by the Gluckstern-Hull[3] (Born approximation) theory. The photon emission angle is 20 degrees, the target material is gold, and the initial electron kinetic energies, $(E_0-\mu)$, are 0.5 and 1 Mev.

[9] J. W. Motz, Phys. Rev. **100**, 1560 (1955).
[10] H. I. West, Jr., Phys. Rev. **101**, 915 (1956); T. L. Jenkins, Bull. Am. Phys. Soc. Ser. II, **1**, 167 (1956).

[11] This type of scintillation polarimeter was first used in measurements of the polarization-direction correlation of gamma rays emitted from radioactive sources by F. Metzger and M. Deutsch, Phys. Rev. **78**, 551 (1950).

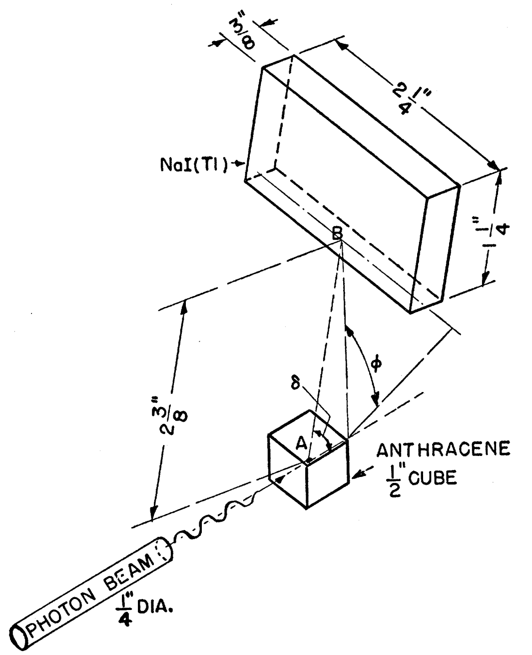

FIG. 3. Polarimeter Geometry. Photons pass from $\frac{1}{4}$-inch diameter collimator to anthracene crystal. The scattering angle δ is fixed at 80 degrees. A and B are the midpoints of the anthracene cube and the face of the NaI(Tl) crystal, respectively. The photon beam axis passes through A, and AB is perpendicular to the face of the NaI(Tl) crystal. Azimuthal settings are given by the angle ϕ, with the bremsstrahlung emission plane defined at $\phi=0$.

NaI(Tl) photon detector, which have their pulse outputs placed in coincidence to permit the selection of Compton events in the anthracene crystal. The size and geometrical arrangement for these crystals is shown in Fig. 3. Photons with energy k are incident on the anthracene crystal and are detected by the NaI(Tl) crystal after being scattered with energy k' into the solid angle $d\Omega$ which is defined in terms of the spread in the scattering angle δ and azimuth ϕ. The polarization sensitivity of this arrangement depends on the asymmetry ratio,

$$R(k)=\int_{\Delta\delta,\Delta\phi} d\tau\left(\phi=\frac{\pi}{2}\right)\Big/\int_{\Delta\delta,\Delta\phi} d\tau(\phi=0), \quad (2)$$

where $d\tau$ is the Klein-Nishina differential cross section averaged over polarizations of the scattered photon for incident x-rays polarized in the bremsstrahlung emission plane ($\phi=0$), and is given by the expression $\frac{1}{2}(e^2k'/mc^2k)^2[k'/k+k/k'-2\sin^2\delta\cos^2\phi]d\Omega$. For a given k and a given crystal separation, R is determined by the parameters δ, $\Delta\delta$, and $\Delta\phi$. Metzger and Deutsch have shown[11] that in the present range of photon energies (0.2−1.0 Mev), a scattering angle, δ, of 80 degrees gives values of R close to the maxima. Also, straightforward integrations of $d\tau$ over a range of solid angles show that to improve the polarimeter efficiency for the high-energy photons (near 1 Mev), $\Delta\phi$ can be increased to 40 degrees without appreciably decreasing R. On the other hand, the spread in $\Delta\delta$ should not exceed 8 degrees in order to satisfy the minimum requirements (shown later) on energy resolution. The above values for δ, $\Delta\delta$, and $\Delta\phi$ are used as the basis for the polarimeter design. As shown in Fig. 3, the polarimeter has reasonably good geometry, in which the incident direction of the photon beam is well defined with a $\frac{1}{4}$-inch diameter collimator and the spread in the scattering volume around the point A is small compared to the crystal separation AB. The solid angle in which scattered photons are detected by the NaI crystal is determined by the length AB and by the area of the crystal face. To allow for possible variations in the detection efficiency near the edges of the crystal face, the effective length of the crystal (along the ϕ direction) is taken to end $\frac{1}{4}$ inch from each edge. The limits of error in R are computed for lengths extending to each edge ($\Delta\phi=50°$) and $\frac{1}{2}$ inch from each edge ($\Delta\phi=30°$). The effect of errors in the width ($\Delta\delta$) of the crystal face on R are small enough to be neglected. The values of R used in the present measurements were computed by carrying through the integrations in Eq. (2) for $\delta=80$ degrees, $\Delta\delta=8$ degrees, and $\Delta\phi=40$ degrees. The results are shown in Fig. 4, where a comparison is made with the maximum values of R (dashed line) that would be obtained if the polarimeter had ideal geometry such that $\Delta\delta$, $\Delta\phi\rightarrow0$. It would have been desirable to check these calculated R values for the polarimeter by measuring the asymmetry ratio with a photon beam having a known polarization, P, such as produced by Compton scattering through a given angle.[11] Such a calibration

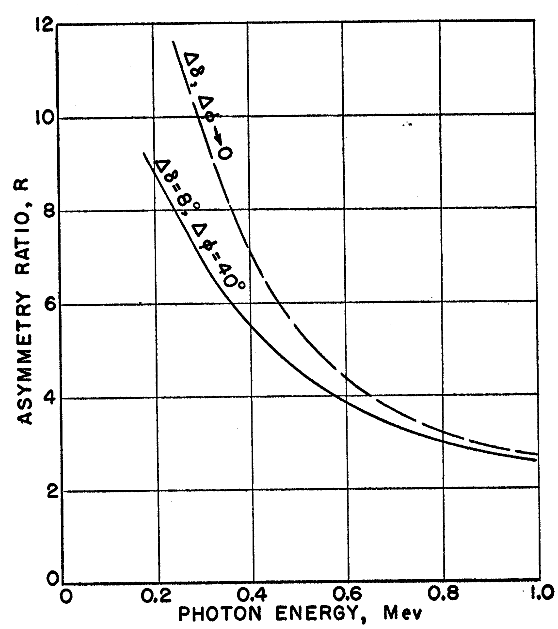

FIG. 4. Dependence of asymmetry ratio, R, on photon energy for geometry used with present polarimeter (solid line) and for ideal geometry (dashed line).

was attempted but was not successful because the solid angles involved are too small to give adequate counting rates. Nevertheless, the large error limits allowed for $\Delta\phi$ (30°,50°) in the computed values of R are more than adequate to include the true R values for the polarimeter.

With the above information about the polarimeter asymmetry ratio R, the partial polarization, P, of an incident beam of photons with energy k can be determined with respect to the bremsstrahlung emission plane for which ϕ is selected to be zero. It has been shown[12] from the results of Compton scattering theory that

$$P(k)=\left(\frac{R(k)+1}{R(k)-1}\right)\left(\frac{1-r}{1+r}\right), \quad (3)$$

where, for a given number of incident photons, r is the measured asymmetry ratio $N(\phi=\pi/2 \text{ or } 3\pi/2)/N(\phi=0 \text{ or } \pi)$, with N representing the number of scattered photons detected by the NaI(Tl) crystal at the azimuths $\pi/2$ or $3\pi/2$, and 0 or π, respectively. Equation (3) indicates that on the basis of the theoretical polarization curve shown in Fig. 2, the *measured* asymmetry ratios should cover a practical range of values extending from approximately 1.5 for 0.95-Mev photons polarized parallel to the emission plane to approximately 0.6 for 0.2-Mev photons polarized perpendicular to the emission plane.

To measure the polarization of photons in an energy interval selected out of the continuous spectrum, the polarimeter was employed as a double-crystal Compton spectrometer.[13] Pulses from the anthracene crystal in a prescribed pulse-height interval passed through a single channel analyzer and were then used to gate the coincidence circuit for the Compton events. In order to obtain satisfactory energy resolution for an average scattering angle, δ, of 80 degrees, it was necessary to limit considerably the spread, $\Delta\delta$, that is defined by the NaI crystal (Fig. 3). For example, with 1-Mev photons scattered at 80 degrees, a value of 8 degrees for $\Delta\delta$ gives an energy spread of approximately 10% for the recoil electrons. Figure 2 indicates that it becomes difficult to measure positive polarizations (parallel to the emission plane) when the photon energy spread begins to exceed 20%. For this reason, the value of $\Delta\delta$ was restricted to 8 degrees. The energy response of the polarimeter was calibrated with the gamma rays from Cs^{137} and Co^{60} sources. The results are shown in Fig. 5, where the response curves have an energy resolution of approximately 20%. The ratio of the pulse heights corresponding to the peaks of the response curves for the 0.66-Mev (Cs^{137}) and 1.33-Mev (Co^{60}) gamma rays agrees very closely with the ratio of the corresponding recoil electron energies expected when the gamma rays are scattered at 80 degrees. This agreement provides a good check for the polarimeter geometry shown in Fig. 3, where the average photon scattering angle, δ, is designated as 80 degrees.

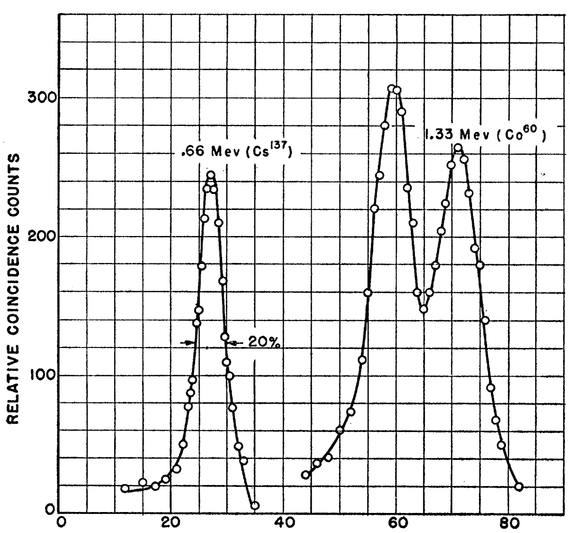

FIG. 5. Energy response curves for polarimeter operated as a double crystal Compton spectrometer. This calibration was made with the gamma rays from Cs^{137} and Co^{60} sources.

[12] See U. Fano, Jr., J. Opt. Soc. Am. **39**, 859 (1949); Phys. Rev. **93**, 121 (1954); also N. R. Steenberg, Canadian J. Phys. **31**, 204 (1953).

III. EXPERIMENTAL PROCEDURE

The experimental arrangement for these measurements is shown in Fig. 6. A $\frac{1}{4}$-inch diameter beam of 1-Mev electrons from the National Bureau of Standards cascade-type accelerator impinges on a thin target with atomic number Z. Photons emitted from the target at an angle θ of 20 degrees pass through a 15-mil aluminum window, a lead filter, and a brass collimator

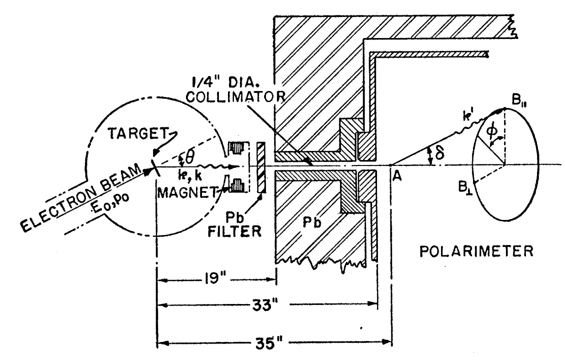

FIG. 6. Experimental arrangement for the polarization measurements. The photon emission angle, θ, is 20 degrees and the polarimeter scattering angle, δ, is 80 degrees. Photons pass from the target through a 15-mil aluminum window and lead filter ($\frac{1}{4}$ inch and $\frac{1}{16}$ inch thick, respectively, for polarization measurements above and below 0.5 Mev). The azimuthal settings for the polarimeter are defined so that $B_{11}(\phi=0)$ is parallel to the bremsstrahlung emission plane, i.e., the $\mathbf{p}_0\mathbf{k}$ plane.

[13] R. Hofstadter and J. McIntyre, Phys. Rev. **78**, 619 (1950).

TABLE I. Polarimeter measurements for an initial electron energy of 1 Mev and a bremsstrahlung emission angle of 20 degrees.

Energy interval (Mev)	Median photon energy (Mev)	Target	Coincidence counts $N_\perp(\phi=\pi/2)$ Total	Chance	True	$N_\parallel(\phi=0)$ Total	Chance	True	Asymmetry ratio $r=\frac{N_\perp(\text{True})}{N_\parallel(\text{True})}$
0.89−1.0	0.94	Au	4400	760	3640	2911	739	2172	1.68 ±0.06
		Al	2159	455	1704	1530	427	1103	1.55 ±0.08
0.80−0.91	0.84	Au	4969	784	4185	3472	780	2692	1.56 ±0.05
		Al	3474	699	2775	2616	677	1939	1.43 ±0.05
0.72−0.80	0.75	Au	4992	693	4299	3568	679	2889	1.49 ±0.04
		Al	1977	334	1643	1543	322	1221	1.35 ±0.06
0.62−0.70	0.65	Au	4894	711	4183	3543	701	2842	1.47 ±0.04
		Al	5878	1081	4797	4832	1077	3755	1.28 ±0.03
0.52−0.58	0.55	Au	4492	588	3904	3701	598	3103	1.26 ±0.03
		Al	3329	570	2759	3032	567	2465	1.12 ±0.04
0.43−0.47	0.44	Au	4248	587	3661	3828	581	3247	1.13 ±0.03
		Al	3695	583	3112	3625	613	3012	1.03 ±0.03
0.33−0.38	0.35	Au	4040	633	3407	4048	628	3420	1.00 ±0.03
		Al	3264	654	2610	3796	658	3138	0.831±0.03
0.21−0.24	0.23	Au	3453	561	2892	3761	545	3216	0.899±0.03
		Al	2771	551	2220	3525	560	2965	0.749±0.03

$\frac{1}{4}$ inch in diameter and 14 inches long. Electrons scattered in the direction of the window are deflected by a permanent magnet, so that the radiation passing through the collimator comes primarily from the target. The lead filter ($\frac{1}{4}$ inch and $\frac{1}{16}$ inch, respectively, for measurements above and below 0.5 Mev) improved the statistical accuracy of the measurements by increasing the number of photons in a given energy interval relative to the total number in the spectrum.

The targets consisted of a 0.43-mg/cm^2 gold foil and a 1.0-mg/cm^2 aluminum foil. Previous measurements[9] of the bremsstrahlung cross section for this electron energy and photon emission angle have indicated that the effects of electron scattering and impurities in these foils can be neglected.

The $\frac{1}{4}$-inch diameter photon beam impinges on the anthracene crystal at A, and the scattered photons are detected by the NaI(Tl) crystal at B (Fig. 3). The pulses from the anthracene crystal are amplified and analyzed before being placed in coincidence with the pulses from the NaI(Tl) crystal. A given photon energy interval is selected by the pulse-height analyzer which was calibrated with the gamma rays from Cs^{137} and Co^{60} (Sec. II). The asymmetry ratio, r, is determined from measurements of the number of coincidence counts, with the NaI(Tl) crystal at the azimuths $B_\parallel(\phi=0 \text{ or } \pi)$ and $B_\perp(\phi=\pi/2 \text{ or } 3\pi/2)$, where $B_\parallel$ defines the bremsstrahlung emission plane, $\mathbf{p}_0\mathbf{k}$. For each azimuthal setting, the number of incident photons is kept constant; this is accomplished by counting the anthracene pulses at the amplifier output for pulse heights greater than 5 kilovolts, and at the pulse height analyzer output for a selected energy interval. Pulses from the amplifier output are limited to counting rates of less than 10^4 counts per second in order to have a negligible pulse pileup. The target currents are of the order of 10^{-5} amp. The resolving time of the coincidence circuit is approximately 5×10^{-7} sec and the coincidence counting rates measured by the polarimeter exceeded 100 counts per minute.

As a check on the operation of the polarimeter, measurements were made of the coincidence counts ratio at the azimuthal settings $\pi/4$ or $5\pi/4$, and $3\pi/4$ or $7\pi/4$, for photon energies in the interval 0.72 to 0.8 Mev. From symmetry arguments, it is to be expected[12] that this ratio should be one. The measured ratio was found to be 0.97±0.05, which indicates that the combined errors due to azimuthal settings and counting statistics were less than 5%

IV. RESULTS AND DISCUSSION

The results of the asymmetry ratio measurements are summarized in Table I. These data are obtained for an initial electron energy of 1 Mev and a photon emission angle of 20 degrees. The energy interval is determined by the window width of the pulse-height analyzer, and the median energy in each interval is calculated for an energy distribution obtained from previous measurements[9] with corrections for absorption in the lead filter (Fig. 6). It is seen that the measured asymmetry ratios, r, show counting rate differences as large as 50% with corresponding standard deviations due to counting statistics of less than 5%.

With the measured asymmetry ratios given in Table I, the bremsstrahlung polarization, P, is determined with the aid of Eq. (3) and is plotted as a function of photon energy in Fig. 7. The limits of error for the

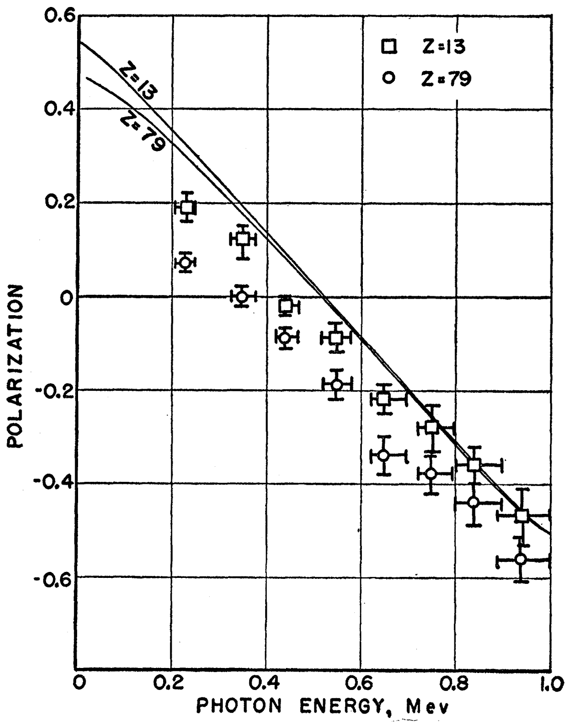

FIG. 7. Dependence of the bremsstrahlung polarization on photon energy for an initial electron kinetic energy of 1 Mev and a photon emission angle of 20 degrees. The solid lines are predicted by the Gluckstern-Hull (Born approximation theory) with approximate corrections for screening in aluminum and gold targets. The error limits for the experimental points include systematic errors due to the uncertainty in the polarimeter asymmetry ratio, R (see Sec. II), and the statistical counting errors. The energy spread for each point is determined by the calibrated window width of the pulse-height analyzer.

experimental points include the systematic errors due to the uncertainty in the polarimeter asymmetry ratio R (Sec. II), as well as the statistical counting errors. The limits of the energy interval are given by the calibrated window width of the pulse height analyzer. The polarization behavior predicted by the Gluckstern-Hull (Born approximation) theory[3] for the parameters used in the measurements (1-Mev electron energy, 20 degrees photon emission angle, and aluminum and gold targets), with approximate corrections for the screening effect of the atomic electrons in the target is shown by the solid lines. The theoretical curves show that the effect of screening is negligible except for very small photon energies.

The results of the measurements shown in Fig. 7 may be summarized as follows:

(a) The bremsstrahlung polarization measured as a function of photon energy shows a reversal with respect to the bremsstrahlung emission plane, which is in qualitative agreement with the predictions of the Gluckstern-Hull theory.[3]

(b) There is a difference in the bremsstrahlung polarization measured for a high-Z target and a low-Z target, which considerably exceeds the difference expected because of screening. The nature of this difference can be described as a shift in the polarization curve with increasing Z, so that the photon energy at which the polarization reversal occurs is smaller than that predicted by the Gluckstern-Hull theory. It is interesting to observe that this shift in the polarization curve as Z increases is similar to the shift shown in Fig. 2 that occurs as the electron energy decreases. In the nonrelativistic region, the exact Sommerfeld theory[4] predicts that the polarization curve depends on the quantity E_0/Z^2. Because 1 Mev is in a transition region extending from the nonrelativistic energies, it is not unreasonable to expect some carry over of this E_0/Z^2 dependence that is not revealed in a Born approximation theory.

Plans are being made to extend these measurements in order to study the angular dependence of the polarization for electron energies in the range from 0.05 Mev up to 1.0 Mev.

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