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Polarization Effects in Coherent and Incoherent Photon Scattering: Survey of Measurements and Theory Relevant to Radiation Transport Calculations

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POLARIZATION EFFECTS IN COHERENT AND INCOHERENT PHOTON SCATTERING: SURVEY OF MEASUREMENTS AND THEORY RELEVANT TO RADIATION TRANSPORT CALCULATIONS

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ABSTRACT

This report reviews available information on polarization effects arising when photons in the x-ray and gamma-ray energy regime undergo coherent (Rayleigh) scattering and incoherent (Compton) scattering by atomic electrons. In addition to descriptions and discussions of these effects, including estimates of their magnitudes as they apply to radiation transport calculations, an annotated bibliography 1905-1991 of 102 selected works is provided, with particularly relevant works for the purpose of this report flagged with asterisks (*). A major resource for this report is a 1948 unpublished informal report by L.V. Spencer which will be quoted here almost in its entirety, since, of all the works cited in the annotated bibliography, it appears to be the only one which explicitly and directly addresses the purpose of this report. Hence this valuable material should be re-introduced into the available and current literature.

KEYWORDS: coherent scattering; gamma rays; incoherent scattering; photon; polarization; radiation transport calculations; x-ray.

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I. INTRODUCTION: DEFINITIONS, HISTORY

The observations of polarization effects on scattering of electromagnetic radiation (photons) most familiar to us are likely in the visible-light portion of the electromagnetic spectrum, via polaroid sunglasses or rotatable polarizing filters on through-the-lens cameras. The aligned fibrous polarizing film on these optical devices preferentially passes photons whose electric vector is similarly aligned. This can have the desirable effect, particularly when the scatter angle is near 90°, of suppressing specular reflections off shiny objects illuminated by the sun, also of suppressing single-scattered photons from the sun-illuminated atmosphere, which in the camera-filter example results in a pleasing deeper-blue sky in the photograph.

The basic mechanism in the scattering process for preferentially aligning the scattered photon plane of polarization, in the case of a single electron being the scattering target, is the "ringing," or acceleration, of the electron, perpendicular to the incident photon beam direction, in the plane of the photon's electric-vector. The "rung" electron oscillates as an harmonic oscillator. This "rung" electron then re-emits a photon (the scattered photon), whose electric vector is preferentially in the plane of the incident photon's electric vector.

If the primary beam consists of photons with random polarizations, i.e. is said to be "unpolarized," the first scatter intensity will also exhibit a random azimuthal directional dependence, or azimuthal isotropy. However, a second scatter will be strongly azimuthally dependent, with preference for the tertiary photon to be coplanar with the incident and first-scatter photon paths, and suppression in non-coplanar directions. Although this is a rather simplified picture of a complex process, with the complexities treated at great length in the appended annotated selected bibliography (Section VI.), it can be seen that multiple (sequential) scattering from successive single electrons, as in Compton events, tend to coplanar, in a plane perpendicular to the polarization (electric vector direction plane) of the particular incident-beam photon initiating the chain of scatter events.

In Roentgen's 1895 "discovery" paper (1895Ro01) he conjectured that his newly-revealed radiation (now called "x rays") might be ultraviolet light, in which case it should meet a list of four criteria including: "It cannot be polarized by any ordinary polarizing media." However, in the years following, several attempts were made to find polarization effects in x rays, as the notions of electromagnetic radiation were still in the early stages of development, with the "ether" still a popular medium for its propagation. In 1905 Barkla's scattering measurements (05Ba01) indicated a weak polarization of the primary x-ray beam, and in 1906 Barkla (06Ba01) added a second carbon-block scatterer to his experimental arrangement. The tertiary scattered beam indeed exhibited large azimuthal variations in intensity as recorded in a detector rotated around the second carbon-block scatterer in a plane perpendicular to the direction of the secondary (first-scattered) x-ray beam. This confirmed the plane-polarization of the scattered x-ray beam, and hence the kinship of x rays to visible and to ultraviolet light, despite Roentgen's above criterion in his conjecture.

Barkla's (06Ba01) results were quickly confirmed by Haga (07Ha01) and others. These were followed by similar-geometry measurements reported in 1924 by Compton and Hagenow (24Co01) whose observations included not only 100%

polarization in the 90° first-scattered beam, but also the modified (lowered energy) component of the scattered beam. This energy modification is a major characteristic of the photon interaction process soon to become well-known as "Compton scattering." Further measurements extended the range of primary photon energies into the "hard x-ray" region, including the 1936 work of Rodgers (36Ro01) who studied the polarization of 90° Compton scattering of 80 to 800 kV primary x rays. Other measurements of the polarization of scattered radiation, and extensive theoretical treatments, are listed in the annotated bibliography in Section VI.

Hence the polarization of scattered x-ray photons, and the effect of this polarization on subsequent scatters, at least for the Compton scattering process, is well documented. The equations, particularly those of Klein and Nishina (29Kl01), for quantitatively including, at least roughly, polarization effects in radiation transport calculations, will be taken up in more detail in Section IV. Also included in Section IV are the detailed mathematical prescriptions in the seminal Monte Carlo treatment by Spencer (48Sp01) which will be extensively quoted.

II. EFFECTS OF POLARIZATION IN TRANSPORT CALCULATIONS

The National Bureau of Standards / National Institute of Standards and Technology Radiation Theory Group (now, under S.M. Seltzer, part of the Radiation Interactions and Dosimetry Group, B.M. Coursey, Group Leader, in the Ionizing Radiation Division, R.S. Caswell, Division Chief, also functioning as the NIST/OSRD Photon and Charged Particle Data Center) has a distinguished and productive history, going back to the 1940's, as the national and international center for radiation transport calculations and associated data. A sampling of this authoritative intellectual productivity, initially under the inspiring guidance of U. Fano, later under L.V. Spencer, then M.J. Berger, and now under S.M. Seltzer, is included the Additional Text References (Section VII), as references: 49Be01, 49Fa01, 49Ka01, 49Sp01, 51Sp01, 52Sp01, 52Sp02 and 59Be01. The current focus of the current NIST Radiation Theory Group efforts, particularly the ETRAN Monte Carlo codes developed by Berger and Seltzer, and their applications, is described in more-recent works by Seltzer (88Se01, 88Se02, 91Se01). Also, included in the Annotated Selected Bibliography (Section VI) because of its treatment of Compton scattering polarization, is an extensive and detailed review article by Fano, Spencer and Berger (59Fa02) summarizing the radiation transport results and insights, up through 1959, from this remarkably talented Radiation Theory Group.

With the exception of two papers by Spencer (48Sp01, 53Sp01), radiation transport calculations including the effects of polarization on radiation scattering processes appear to be non-existent. In recent transport calculations, mostly by the Monte Carlo technique, polarization effects on the differential (in angle) scattering cross sections have been universally ignored. Hence it is of some interest to investigate or find reference to the magnitude of the error introduced into present transport calculation results by omission of polarization effects, to see if it would be worth-while to try to include such effects in future calculations.

The 1953 work by Spencer (53Sp01), employing the Stokes parameters but based on radiation diffusion theory rather than the Monte Carlo technique now universally used, indicates that for penetration depths ranging from 8 to 16 mean free paths, for a photon source energy of 1.277 MeV, one might expect an enhancement in spectral energy density due to polarization, for depth-spectra photons of energies 200 keV or less, ranging from roughly 1% to 2%, as seen in Figure 1 [Figure 3 in (53Sp01)]. For detected spectrum photons of energies 600 keV up to the source energy (1.277 MeV), at penetration depths 8 to 16 mean free paths, Spencer's calculations predict zero enhancement in the spectral energy density due to inclusion of polarization effects in the calculations.

The material in Section IV (Polarization Effects in Incoherent (Compton) Scattering) is an attempt to provide sufficient information, based mainly on that given in 1948 by Spencer (48Sp01) for use in his Monte Carlo investigation of polarization effects on multiple Compton scattering.

III. POLARIZATION EFFECTS IN COHERENT (RAYLEIGH) SCATTERING

Until recently, transport calculations using the Monte Carlo technique, including the widely-used ETRAN codes of Seltzer and Berger (88Se01, 88Se02), have ignored coherent (Rayleigh) scattering. The reasons for ignoring coherent scattering are that the scattered-photon energy is unchanged from that of the primary photon, the angular distribution at high photon energies is strongly forward-peaked, and its contribution to the total photon interaction cross section is small, reaching its maximum contribution of only 10% just below the photoeffect K absorption edge, for high-Z elements. In the current ETRAN version (91Se01), however, coherent scattering is included.

In certain situations, such as in medical diagnostic and industrial flaw-detection x-ray imaging, as pointed out by Johns and Yaffe (83Jo01), coherent scattering can have a significant effect on the image sharpness, as their single-scatter calculations show that coherently scattered photons diverge sufficiently from the primary ray to degrade image contrast, and that they account for a significant fraction of the total scattered energy fluence at the image receptor.

In addition to the NBS/NIST ETRAN codes of Seltzer and Berger, another system of radiation transport codes, EGS, has been developed at SLAC by Ford and Nelson (78Fo01), of which the EGS4 version has been described by Nelson, Hirayama and Rogers (85Ne01) and more recently by Nelson and Namito (90Ne01). Although polarization effects are still excluded from this code system, EGS4 does include coherent scattering as an option. This option of EGS4 was used by Rogers and Bielajew (90Ro01) to calculate narrow-beam and broad-beam central-axis depth dose for 30-keV photons incident on water, for penetration depths up to 27 mean free paths. Their results indicated that the narrow-beam geometry is much more sensitive to the inclusion of coherent scattering than is the broad-beam geometry. In either case, the with-and-without coherent scattering differences were found to be substantial. At 4 mean free paths, inclusion of coherent scattering decreases the broad-beam result by only 0.7%, but decreases the narrow-beam result by 20%, and at 18 mean free paths these decreases are 19% and 105%, respectively. The ITS (Integrated TIGER Series) coupled electron/photon Monte Carlo transport code by Halbleib et al (92Ha01, 92Ha02) also now includes coherent scattering, incorporating ETRAN for its physics.

The remarks here on polarization effects for the coherent scattering photon interaction process will be limited to pointing out the authors and references in the Annotated Bibliography who have treated, either theoretically or experimentally, polarization effects in coherent scattering: Brini, Fuschini, et al (58Br01, 59Br01, 60Fu01); Sood et al (58So01, 64Si01); Bobel and Passatore (60Bo01); Williams and McNeill (65Wi01); Somayajulu et al (68So01, 68So02); Molak et al (71Mo01); Dwiggins (83Dw01); and Hanson (86Ha01, 86Ha02), with the main thrust of each of these papers indicated in the annotation appended to the reference.

The above listed references indeed present evidence of polarization effects in coherent scattering, and resulting azimuthal asymmetries, but not as clearly, uniformly and explicitly as in the case of Compton scattering, which is generally used as the polarizer or polarization analyzer (polarimeter) in the coherent scattering experiments. Interpretation and implementation of the information in these papers for treating polarization effects in coherent scattering in transport calculations would considerably exceed the scope and intended effort of this report; however, the above references could form the basis of a further interesting and useful study.

IV. POLARIZATION EFFECTS IN INCOHERENT (COMPTON) SCATTERING

For polarization effects in Compton scattering, we can go back to the classic expressions of Klein and Nishina (29Kl01) for Compton scattering of a polarized (polarizations aligned in one azimuthal direction) and an unpolarized (random polarization directions) beam of photons of energy α in mc^2 units, where m is the mass of an electron and c is the speed of light. Letting I_o be the intensity of the incident beam and I the intensity of the scattered beam, Θ be the deflection angle of the scattered beam (photon) from the incident beam direction, θ be the azimuthal angle of the scattered photon direction from the electric vector (polarization plane) of the incident photon (the normal to the plane containing the incident and scattered photons), and r be the classical electron radius, we have, for a polarized incident beam,

<u>Polarized beam (Klein-Nishina):</u>

$$I = I_o(e^4/m^2c^4r^2)\sin^2\theta(1 + \alpha(1 - \cos\Theta))^{-3}(1 + \alpha^2(1 - \cos\Theta)^2/$$
$$(2\sin^2\theta(1 + \alpha(1 - \cos\Theta)))). \qquad (1)$$

For the case of the unpolarized incident beam, according to Klein and Nishina (29Kl01), in the two places in eqn. (1) where the azimuthal dependence factor $\sin^2\theta$ appears, we substitute for this factor its mean value which is $\frac{1}{2}(1 + \cos^2\Theta)$, giving the more-familiar differential cross section for Compton scattering of an unpolarized (random polarizations) beam:

<u>Unpolarized beam (Klein-Nishina):</u>

$$I = I_o(e^4/2m^2c^4r^2)(1 + \cos^2\Theta)(1 + \alpha(1 - \cos\Theta))^{-3}(1 + \alpha^2(1 - \cos\Theta)^2/$$
$$((1 + \cos^2\Theta)(1 + \alpha(1 - \cos\Theta)))). \qquad (2)$$

For purposes of exploratory calculations at NIST with ETRAN, it may be a sufficient approximation to assume that the first Compton scatter, described by eqn.(2), results in 100% plane polarization (as an extreme case) of the first-scattered trajectory, following which equation (1) is used, inserting the random selections of the azimuthal angle θ (with respect to the normal to the plane containing the previous two photon directions) into the azimuthal dependence factor $\sin^2\theta$ in the two places in eqn. (1) in which it appears.

If one wishes to go beyond the above rough-approximation extremal exploratory calculation described above, and admit partial linear polarizations into the model, one can use the following scheme and formulas derived by Spencer (48Sp01), which he adapted to the Monte Carlo technique (this work of Spencer's is one of the earliest, perhaps even <u>the</u> earliest application of the Monte Carlo method, at least in radiation transport) for polarization of multiply scattered gamma rays, here quoted directly from his unpublished work:

<u>Spencer method and formulas for polarization of multiply (Compton-) scattered gamma rays:</u>

For consistency in this report, some of the Spencer (48Sp01) notation in the following account has been changed to that of Klein and Nishina (29Kl01), used in their equations (1) and (2), above:

Θ (this report; K.-N.) = θ (Spencer)

θ (this report; K.-N.) = ϕ Spencer)

α (this report; K.-N.) = γ (Spencer)

SPENCER FORMULAE:

We want to consider a beam of gamma rays which has been Compton scattered n times. All photons in this beam have undergone precisely the same history of previous scatterings. We shall call the axes of propagation of the beam after it has been scattered n and (n + 1) times z_n and z_{n+1}. The plane containing z_n and z_{n+1} will be called the (n + 1)st plane of scattering. (See Fig. 2.)

In general, the beam will have a partial linear polarization after having been scattered. We use the index $0 < P_n < 1$ to represent the degree of partial linear polarization which arises after n scatterings. P_n is defined as

$$P_n = \frac{P_{para} - P_{perp}}{P_{para} + P_{perp}} \tag{3}$$

where P_{para} and P_{perp} are the fractions of parallel and perpendicular photons, respectively.

It can be shown that if there is no elliptical polarization prior to scattering there will be none afterwards; therefore, if we start with an unpolarized beam, we need only consider linear polarization at later times. The angles which the planes of partial polarization of the scattered beam make with the planes of scattering will be ψ_n, ψ_{n+1}, while θ_{n+1} will be the angle which the (n + 1)st plane of scattering makes with the plane of polarization of the nth scattered radiation. Using this notation, the following relations hold:

$$d\sigma = (e^4/m^2c^4r^2)(1 + \alpha_n(1 - \cos\Theta_{n+1}))^{-2}(1 + \cos^2\Theta_{n+1} + \alpha_n{}^2(1 - \cos\Theta_{n+1})^2$$

$$\times (1 + \alpha_n(1 - \cos\Theta_{n+1}))^{-1} - P_n\sin^2\Theta_{n+1}\cos\theta_{n+1})\sin\Theta_{n+1}d\Theta_{n+1}d\theta_{n+1} \tag{4}$$

$$P_{n+1} = ((-\sin^2\Theta_{n+1} + (1 - \cos^2\Theta_{n+1})P_n\cos 2\theta_{n+1})^2 + (2\cos\Theta_{n+1}P_n\sin 2\theta_{n+1})^2)$$

$$\times\ (1 + \cos^2\Theta_{n+1} + \alpha_n{}^2(1 - \cos\Theta_{n+1})^2/(1+ \alpha_n(1 - \cos\Theta_{n+1}))$$

$$- \sin^2\Theta_{n+1}P_n\cos 2\theta_{n+1})^{-2} \qquad (5)$$

$$\psi_{n+1} = \tfrac{1}{2}\tan^{-1}(2\cos\Theta_{n+1}P_n\sin 2\theta_{n+1})/(-\sin^2\Theta_{n+1} + (1 + \cos^2\Theta_{n+1})P_n\cos 2\theta_{n+1}) \qquad (6)$$

Here, $d\sigma$ is the differential scattering cross-section , α_n, α_{n+1}, in units of mc^2, represent the energy of the incident and scattered photon, respectively, and Θ and θ are as defined by Klein and Nishina in their equations (1) and (2) above.

In the case of the first scattered beam, we have (since we assume that the initial polarization of the beam is natural (unpolarized), that is, $P_o = 0$):

$$P_1 = \sin^2\Theta_1/(1 + \cos^2\Theta_1 + \alpha_o{}^2(1 - \cos\Theta_1)^2/(1 + \alpha_o(1 - \cos\Theta_1)). \qquad (7)$$

Now, given P_n, α_n, and Θ_{n+1}, what is the probability $pr(\theta_{n+1})d\theta_{n+1}$ that a single photon in this beam will be scattered with an azimuthal angle between θ_{n+1} and $\theta_{n+1} + d\theta_{n+1}$? This is easily obtained:

$$pr(\theta_{n+1})d\theta_{n+1} = d\sigma/\int_{\theta=0}^{\theta=2\pi} d\sigma =$$

$$= (1/2\pi)(1 - \sin^2\Theta_{n+1}P_n\cos^2\theta_{n+1}/(1 + \cos^2\Theta_{n+1} + \alpha_n{}^2(1 - \cos\Theta_{n+1})^2$$

$$/(1 + \alpha_n(1 - \cos\Theta_{n+1}))d\theta_{n+1} \qquad (8)$$

Remembering (7), we rewrite this as

$$pr(\theta_{n+1})d\theta_{n+1} = (1/2\pi)(1 - P_1(\Theta_{n+1})P_n\cos 2\theta_{n+1})d\theta_{n+1} \qquad (9)$$

Where

$$P_1(\Theta_{n+1}) = \sin^2\Theta_{n+1}/(1 + \cos^2\Theta_{n+1} + \alpha_n{}^2(1 - \cos\Theta_{n+1})^2/(1 + \alpha_n(1 - \cos\Theta_{n+1})) \qquad (10)$$

Spencer's (48Sp01) graph of $P_1(\Theta_{n+1})$ for various values of α_n is given in Fig. 3.

SPENCER'S THEORETICAL EXPERIMENT AND DISCUSSION:

Examination of (9) shows that the polarization may be neglected as long as the factor $P_1(\Theta_{n+1})$ is small compared to 1. This will certainly be the case for $\alpha > 10$. To get some indication of the photon energies at which polarization effects occur, a series of 20 photon case histories was studied by means of the so-called "Monte Carlo" method. In each case history the photon had an energy of $\alpha_0 = 10$ to begin with. Path lengths, deflection angles, and azimuthal angles were chosen by random numbers in accordance with the laws of Compton scattering. For comparison, a second set of 20 case histories was calculated, identical with the first set except that the azimuthal angles were chosen to be those which would have occurred in the first set had polarization not been taken into account. In general, the corresponding angles in the two sets differed slightly.

The effect of polarization was studied in three different ways:

1. A histogram was made showing the mean change in the azimuthal angle caused by polarization, plotted against the energy of the photon after the collision had occurred (Fig. 4). Although there were only 20 case histories, there was a total of around 150 collisions. This gave the histogram significance.

2. A second histogram was made showing the mean polarization of the gamma ray photons as a function of their energy degradation (Fig. 5). In view of eqn. (9), the square of this is also plotted on the same diagram.

3. A study was made of the cumulative effect of polarization in order to determine whether it is possible for the effects of polarization to build up even though the polarization remains small. In this study the actual separation in space of the polarizable and unpolarizable photons was determined and its z and ρ components studied (The z component represents the penetration and the ρ component the sidewise dispersion.). In Figures 6 and 7 these components of the square root of the mean square separation are plotted in units of the classical mean free path ℓ against the degraded energy of the photons.

The first two of these graphs (Figures 4 and 5) show clearly that the polarization increases from near zero for $\alpha > 1$ to above 0.8 for energies $\alpha < 0.2$. The effect upon the azimuthal angle is dependent upon the square of the polarization rather than the polarization itself. It might be considered surprising at first that it is possible to reach such high values of the mean polarization as occur at low energies. However, eqn. (9) shows that if a certain amount of polarization exists, azimuthal angles θ_{n+1} near 0° and 180° have a diminished probability These are just the angles which, according to eqn. (5), may result in a sizeable decrease in the polarization. The azimuthal angles which preserve or tend to increase the polarization are made more probable by the existence of some polarization. The process tends to "feed on itself," so to speak.

Figures 6 and 7 show that the cumulative effect of polarization over an average of 4 to 5 collisions occurring in the degradation to $\alpha = 0.5$ results in a change of position of around 0.3 in the ρ direction and 0.15 in the z direction. This is to be compared with an average total z of about 7.5.

It will be seen that for $\alpha < 0.3$, the polarizable and non-polarizable photons go their separate ways. An examination of polarization effects in this low energy region by Monte Carlo would require a much larger number of case histories and has not been attempted (in this 1948 work, prior to the advent of electronic computers). At these low energies there is little "memory of the original direction of the γ-ray photon, in the sense that further penetration is more or less a diffusion process.

V. SUMMARY AND DISCUSSION

The effects of polarization arising from photon (x-ray, gamma-ray, bremsstrahlung) coherent (Rayleigh) and incoherent (Compton) scattering, to which the transport of radiation through materials might be sensitive, are reviewed, and an extensive annotated bibliography, extending from 1905 to 1991, is presented.

At present it does not appear practical to try to include coherent (Rayleigh) scattering polarization effects in transport calculations, although these effects may be significant in some circumstances, and such effects could be the basis for a future useful study, when coherent scattering becomes more routinely included in transport calculations. Present ETRAN (91Se01) and ITS (92Ha01, 92Ha02) radiation transport codes include coherent scattering, and the EGS4 code system includes coherent scattering as an option. Although the coherent scattering polarization effects do not appear to be theoretically defined in mathematical expressions amenable to ready inclusion in Monte Carlo or other radiation transport calculational techniques, 13 papers from the Annotated Bibliography are singled out for mention as a starting point for such an enterprise.

For incoherent (Compton) scattering, the situation is much improved, since the original theoretical understanding and mathematical quantification of the Compton effect by Klein and Nishina (29Kl01) included expressions for the differential cross section for this process for both polarized and unpolarized incident beams of photon radiation. These expressions are reproduced in this report as equations (1) and (2), and presumably can be used directly in an exploratory pair of comparison Monte Carlo calculations, using the same set of case histories, one of which would include the azimuthal asymmetries of the scattered photon intensities from the polarization effects included in equation (1), and a companion calculation using equation (2) which assumes azimuthal isotropy of the scattered photon directional intensities.

For a more refined calculation of polarization effects from Compton scattering in multiple-scattering radiation transport computations, including partial polarizations of the scattered photons, the 1948 unpublished work of Spencer (48Sp01) provides the necessary expressions, reproduced here in equations (4) through (10). These expressions were used by Spencer (48Sp01) in hand-computed Monte Carlo calculation of 20 case histories, in which the same 20 histories (identical input of random numbers) were computed with and without polarization effects included. The results of this comparison computation, by Spencer, are shown in Figures 2 through 7, reproduced from his report (48Sp01) except the notation in some cases is changed to be consistent with the Klein-Nishina (29Kl01) original expressions.

With modern high-speed computers, the Spencer expressions could likely be included in current transport calculations for exploratory examination of the effects of polarization from Compton scattering for a large number of geometries and situations. If these effects are sufficiently large, these expressions could presumable be included routinely in ETRAN, EGS4, ITS and other radiation transport code systems.

VI. ANNOTATED BIBLIOGRAPHY OF PHOTON POLARIZATION AND OF POLARIZATION EFFECTS IN COHERENT AND INCOHERENT SCATTERING: MEASUREMENTS AND THEORY

(References preceded by an asterisk (*) contain formulas and/or data particularly relevant to the purpose of this report. The remaining references are of more marginal relevance, but are included for their information on the general physics of photon polarization.)

05Ba01 Barkla, C.G., Polarized Rontgen Radiation, Phil. Trans. Roy. Soc. London A 204, 467-479 (1905).
[Meas.: observation of slight polarization of x-ray of primary x-ray beam using carbon block scatterer; results inconclusive.]

06Ba01 Barkla. C.G., Polarization in Secondary Rontgen Radiation, Proc. Roy. Soc. London A 77, 247-255 (1906).
[Meas.: observation of significant polarization of first-scattered x-ray beam by addition of second-scatter carbon block; rotation of detector around second-scatter block, in plane normal to first-scatter beam direction, to measure azimuthal variations in intensity of tertiary (second-scattered) beam.]

07Ha01 Haga, H., Uber die Polarisation der Rontgenstrahlen und der Sekundarstrahlen, Annalen der Physik 23, 439-444 (1907).
[Meas.: repeated Barkla (06Ba01) experiment; in addition to carbon for first-scatter target ("polarizer"), also substituted Al, Cu and Pb; for second-scatter target ("analyzer") used both carbon and copper; found primary x-ray beam to have no polarization.]

24Co01 Compton, A.H. and Hagenow, C.F., A Measurement of the Polarization of Secondary X-Rays, J. Opt. Soc. Am. and Rev. Sci. Instr. 8, 487-491 (1924).
[Meas.: using 90° twice-scattered 50 keV x rays.]

29Kl01 *Klein, O. and Nishina, Y., Uber die Streuung von Strahlung durch freie Elektronen nach der neuen relativistischen Quantendynamik von Dirac, Z. Physik 52, 853-868 (1929).
[Theor.: expressions given for differential-in-angle Compton scattering cross sections for plane-polarized photons, and for unpolarized photons, incident on free electrons. The expressions differ only in that for polarized incident photons a factor $\sin^2\theta$, which appears in two places, where θ is the angle between the observation direction and plane of the incident photon electric vector, is replaced, for unpolarized (random polarization) incident photons, by its mean value which is $(1+\cos^2\Theta)/2$, where Θ is the Compton-scatter deflection angle.]

29Ni01 *Nishina, Y., Die Polarisation der Comptonstreuung nach der Diracschen Theorie des Elektrons, Z. Physik 52, 869-877 (1929).

[Theor.: polarization of tertiary Compton scattered photons; both linear and elliptical polarization.]

36Co01 *Compton, A.H. and Allison, S.K., X-Rays in Theory and Experiment (Van Nostrand 1935), particularly p. 18-19, 93-95, 119-121, 236-237, 249-250.
[Review: nature of x-ray polarization, and polarized-photon scattering interactions.]

36Fr01 Franz, W., Rayleighsche Streuung harter Strahlung an schweren Atomen, Z. Physik 98, 314-320 (1936).
[Theor.: formulas, some numerical results for Pb for coherent scattering off Dirac electron, Thomas-Fermi atom; departures from Klein-Nishina values of the order of 1%.]

36Ro01 Rodgers, E., Polarization of Hard X-Rays, Phys. Rev. 50, 875-878 (1936).
[Meas.: polarization of 80 to 800 keV x rays after two 90° scatters.]

47Ch01 Chandrasekhar, S., On the Radiative Equilibrium of a Stellar Atmosphere. XV., Astroph. J. 105, 424-440 (1947).
[Theor.: general equations of transfer of radiation in a scattering atmosphere, allowing for partial elliptic polarization of the radiation field, are formulated, using Stokes parametric representation.]

48Sp01 *Spencer, L.V., Polarization of Multiply Scattered Gamma Rays, Interim Report on NBS Contract with the U.S. Office of Naval Research (Diffusion of Radiation) (1948) (unpublished).
[Theor.: very early application of Monte Carlo; major resource paper addressing the purpose of this report. Formulas, some results presented.]

48Wi01 *Wightman, A., Note on Polarization Effects in Compton Scattering, Phys. Rev. 74, 1813-1817 (1948).
[Theor.: matrix presentation of polarization vectors in Compton scattering.]

49Fa01 *Fano, U., Remarks on the Classical and Quantum-Mechanical Treatment of Partial Polarization, J. Opt. Soc. Am. 39, 859-863 (1949).
[Theor.: use of Stokes parameters for representing degree of polarization.]

50Ch01 Chandrasekhar, S., Radiative Transfer (Oxford, Clarendon Press 1950), Ch.1 (The Equations of Transfer), particularly Sec. 15 (The Representation of Polarized Light).
[Theor.: treats elliptically polarized beams, the Stokes parameters for arbitrarily polarized light, the law of transformation of the Stokes parameters for a rotation of the axes.]

50Me01 Metzger, F. and Deutsch, M., A Study of the Polarization-Direction Correlation of Successive Gamma-Ray Quanta, Phys. Rev. 78, 551-558 (1950).
[Meas.: application of Compton polarimeter to study of nuclear disintegration gamma-ray polarization correlations.]

51Ma01 May, M. and Wick, G.C., On the Production of Polarized High Energy X-Rays, Phys. Rev. 81, 628 (1951).
[Theor.: polarized bremsstrahlung production prediction expression.]

51WI01 Wick, G.C., Detection of Gamma-Ray Polarization by Pair Production, Phys. Rev. 81, 467-468 (1951).
[Theor.: pair production sensitivity to polarization of incident quanta.]

52Ho01 *Hoover, J.I., Faust, W.R. and Dohne, C.F., Polarization of Scattered Quanta, Phys. Rev. 85, 58-59 (1952).
[Meas.: first Compton scatter angle varied; second scatter at 90°.]

53Sp01 *Spencer, L.V. and Wolff, C., Penetration and Diffusion of Hard X-Rays: Polarization Effects, Phys. Rev. 90, 510-514 (1953).
[Theor.: this and ref. 48Sp01 are the major resource references of this report. Explanation and use of the Stokes parameters combined with the diffusion equation, for Compton scattering. For deep penetrations, inclusion of polarization effects in calculation increases the predicted radiation flux, due to favoring of coplanar scatterings. Numerical results are presented for penetrations of 8, 12 and 16 mean free paths, indicating enhancements of as much as 2% for the lower-energy components of the transmitted spectrum.]

54Br01 Brenner, S., Brown, G.E. and Woodward, J.B., The Coherent Scattering of Gamma-Rays by K Electrons in Heavy Atoms. II. The Scattering of 0.32 mc^2 Gamma-Rays in Mercury, Proc. Roy. Soc. London A 227, 59-72 (1954).
[Theor.: coherent scattering cross sections for arbitrary angle, arbitrary initial and final polarizations.]

54Mc01 *McMaster, W.H., Polarization and the Stokes Parameters, Am. J. Phys. 22, 351-362 (1954).
[Theor.: matrix formulation for photon polarization, including single and successive Compton scatters.]

56Br01 Brown, G.E. and Mayers, D.F., The Coherent Scattering of Gamma-Rays by K Electrons in Heavy Atoms. III. The Scattering of 0.64 mc^2 Gamma-Rays in Mercury, Proc. Roy. Soc. London A 234, 387-390 (1956).
[Theor.: coherent scattering; amplitudes for scattering of 330 keV gamma rays with and without polarization change.]

57Br01 Brown, G.E. and Mayers, D.F., The Coherent Scattering of Gamma-Rays by K Electrons in Heavy Atoms. IV. The Scattering of 1.28 and 2.56 mc^2 Gamma-Rays in Mercury, Proc. Roy. Soc. London A 242, 89-95 (1957).
[Theor.: coherent scattering of .65, 1.31 MeV gamma rays; form factor amplitudes are a poor representation when there is no polarization change; a better representation when there is a polarization change.]

58Br01 *Brini, D., Fuschini, E., Peli, L. and Veronesi, P., Elastic Scattering of Polarized Photons, Nuovo Cim. 7, 877-890 (1958).
[Meas.: Compton first scatter, Rayleigh secondary scatterer on Hg, 320 keV gammas.]

58Ol01 Olsen, H. and Maximon, L.C., Electron and Photon Polarization in Bremsstrahlung and Pair Production, Phys. Rev. 110, 589-590 (1958). [Theor.: effect of Coulomb correction on polarization part of the bremsstrahlung and pair production cross sections; the effect is of the same order as the unpolarized part of the cross section.]

58Sc01 Schopper, H., Measurement of Circular Polarization of Gamma-Rays, Nucl. Instr. Meth. 3, 158-176 (1958). [Survey of methods for detection of circular polarization of photons.]

58So01 *Sood, B.S., Polarization of 0.411, 0.662 and 1.25 MeV Gamma-Rays Elastically Scattered by Lead, Proc. Roy. Soc. London A 247, 375-380 (1958). [Meas.: coherent scattering of .411, .662 and 1.25 MeV gammas through two 90° scatters.]

59Br01 *Brini, D., Fuschini, E., Murty, D.S.R. and Veronesi, P., Rayleigh Scattering of Polarized Photons, Nuovo Cimento 11, 533-545 (1959). [Meas.: Co-60 gammas first Compton scattered at 50° for polarized beam, then coherently scattered from Hg at 65°, 90° and 110°; results agree better with theory of Brown and Mayers (56Br01, 57Br01) than with that of Franz (36Fr01).]

59Fa01 *Fagg, L.W. and Hanna, S.S., Polarization Measurements on Nuclear Gamma Rays, Rev. Mod. Phys. 31, 711-758 (1959). [Review: meas. and theor.; applications to detection of polarized nuclear gamma rays; 204 references.]

59Fa02 *Fano, U., Spencer, L.V. and Berger, M.J., Penetration and Diffusion of X Rays, in S. Flugge, Ed., Encyclopedia of Physics 38/2 (Springer Verlag 1959), P. 671-673, 679-680, 696-699. [Theor: prescriptions for use of Stokes parametric representation of polarization for inclusion in transport equation computations; mention of second Compton scatter direction favoring coplanarity with previous two photon directions, tending to enhance flux at deep penetrations.]

59Ol01 Olsen, H. and Maximon, L.C., Photon and Electron Polarization in High-Energy Bremsstrahlung and Pair Production with Screening, Phys. Rev. 114, 887-904 (1959). [Theor.: cross sections for high energy bremsstrahlung and pair production for arbitrary photon and electron polarization.]

60Bo01 *Bobel, G. and Passatore, G., On the Polarization of Photons Elastically Scattered by Mercury Atoms, Nuovo Cim. 15, 979-982 (1960). [Theor.: coherent scattering; use of Stokes parameters in treating polarization in Rayleigh and Thompson scattering.]

60Fr01 Frolov, G.V., Polarization Phenomena in the Compton Effect, Zh. Eksp. Teor. Fiz. 39, 1829-1836 (1960); Engl. transl. in Sov. Phys. JETP 12, 1277-1281 (1961) [Theor.: expressions for all coefficients characterizing polarization effects in Compton scattering are derived; application of results to computation of Compton recoil electron polarization.]

60Fu01 Fuschini, E., Murty, D.S.R. and Veronesi, P., Polarization Effects in the Elastic Scattering of Photons, Nuovo Cim. 15, 847-849 (1960). [Meas.: coherent scattering of 1.25 MeV primary gamma rays; second scatter Compton for analyzer.]

60Mc01 McMaster, W.H., Polarization Phenomena for Positron Annihilation-in-Flight, Nuovo Cim. 17, 395-414 (1960). [Theor.: matrix representation of polarization for use with Stokes parameters, for treating the electron-positron annihilation process.]

61Ma01 Manuzio, G. and Vitale, S., Elastic Scattering of 1.25 MeV Gamma Rays by Lead, Nuovo Cim. 20, 638-647 (1961). [Meas.: coherent scattering; first angle varied 45° to 105°.]

61Mc01 *McMaster, W.H., Matrix Representation of Polarization, Rev. Mod. Phys. 33, 8-28 (1961). [Theor.: major review of photon polarization; matrix manipulation of Stokes parameters; Compton scattering of unpolarized and polarized photons; bremsstrahlung, pair production and photoeffect polarization effects also treated; 41 references.]

61Mi01 Miller, S.C. and Wilcox, R.M., Left-Right Asymmetry in Compton Scattering by Transversely Polarized Electrons, Phys. Rev. 124, 637-639 (1961). [Theor.: effect of a radiative correction on left-right asymmetry in Compton scattering of unpolarized photons by polarized electrons.]

62Ma01 Maximon, L.C. and Olsen, H., Measurement of Linear Photon Polarization by Pair Production, Phys. Rev. 126, 310-319 (1962). [Theor.: calculation of cross section for pair production by linearly polarized high energy photons.]

62St01 Standing, K.G. and Jovanovich, J.V., The Elastic Scattering of Co-60 Gamma Rays, Can. J. Phys. 40, 622-653 (1962). [Meas.: coherent scattering of 1.25 MeV gamma rays 12° to 150°; polarization not measured here, discussed only.]

63Co01 Cole, H., Polarization of X-Rays, in G.L. Clark, ed., The Encyclopedia of X-Rays and Gamma Rays (Reinhold, 1963), p. 774-776. [Review: concise description of scattering of polarized x rays, in vector notation.]

63Hu01 Huber, H., Galster, S. and Schopper, H., The Influence of Multiple Scattering on the Measurement of the Circular Polarization of Gamma-Rays, Nucl. Instr. Meth. 21, 338-344 (1963). [Meas.: Compton scattering from magnetized Fe for circular polarization.]

64Si01 Singh, M., Anand, S. and Sood, B.S., Influence of Incoherent Scattering on the Polarization of Elastic Scattering of Gamma-Rays, Curr. Sci. 33, 239-240 (1964). [Meas.: coherent scattering of 662 keV gamma rays at 64° from Pb.]

65An01 *Anand, S., Singh, M. and Sood, B.S., Effects of L-Shell Electrons on the Polarization of Elastic Scattering of Gamma Rays, Curr. Sci. 34, 45 (1965).
[Meas.: coherent scattering of .280, .662 and 1.25 MeV gamma rays from L-shell electrons of Pb at 64° to 120°; per cent polarization measured and results listed.]

65Si01 *Singh, M., Anand, S. and Sood, B.S., Azimuthal Variation of Compton Scattering of Polarized Gamma Rays, Nucl. Phys. 62, 267-272 (1965).
[Meas.: Compton scattering on Cu 64° - 120°, .280, .662 and 1.25 MeV primary gamma rays; second scatterer-detector in coincidence with final scattered-radiation detector; results consistent with Klein-Nishina azimuthal dependence.]

65Wi01 *Williams, R.A. and McNeill, K.G., Polarization of Elastically Scattered 1.33-MeV Photons, Can. J. Phys. 43, 1078-1087 (1965).
[Meas.: coherent scattering of 1.33 MeV gamma rays on Pb; Compton polarimeter; L-shell contribution to Compton scattering assessed; results agree better with Brown and Mayers (57Br01) than with Manuzio and Vitale (61Ma01).]

67Ha01 *Hamilton, M.C. and McIntyre, J.A., Measurement of the Polarization of the Gamma Rays Inelastically Scattered in Lead, M.S. Thesis (Hamilton), Texas A&M Univ.(1967).
[Meas.: Compton scattering of 1.25 MeV gamma rays 90° on Pb; low-Z Compton polarimeter.]

68Ol01 Olsen, H., Ch. 4: Polarization Effects in Scattering and Radiation Processes, p. 106-122, in Olsen, H.: Applications of Quantum Electrodynamics, in G. Hohler, ed., Springer Tracts in Modern Physics, Vol. 44 (Springer-Verlag 1968).
[Theor.: discussions of photon polarization, polarization tensor, Stokes parameters, polarization correlations.]

68So01 Somayajulu, D.R.S., Rama Rao, J. and Lakshminarayana, V., Polarization of Elastically Scattered Gamma Rays, Nuovo Cim. 54, 281-292 (1968).
[Meas.: coherent scattering of 662 keV gamma rays 45° to 105° on Pb; Compton polarimeter; coincidence detectors both coplanar and orthogonal with plane of first scatter.]

68So02 Somayajulu, D.R.S. and Lakshminarayana, V., Rayleigh Scattering of Polarized Photons, J. Phys. A 1, 228-235 (1968).
[Meas.: Compton scattering of 662 keV gamma rays in Al for polarized source; coherent scattering 45° to 105° in Pb.]

69Ew01 Ewan, G.T.,Andersson, G.I., Bartholomew, G.A. and Litherland, A.E., Gamma-Ray Polarization Measurements with a Single Ge(Li) Detector, Phys. Lett. B 29, 352-354 (1969).
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69Ho01 Honzatko, J. and Kajfosz, J., Linear Polarization Measurements by Ge(Li) Detector, Czech. J. Phys. B 19, 1281-1289 (1969).
[Meas.: polarized gammas from Co-60; Compton polarimeter; asymmetry expression.]

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[Meas.: gamma polarimeter for cascade nuclear gammas; .847, 1.368, 1.779, 4.43 MeV gammas.]

71Al01 Alexandropoulos, N.G., Parks, S.H. and Kuriyama, M., Polarization of the X-Ray Compton-Raman Radiation, Phys. Lett. A 35, 369-370 (1971).
[Meas.: Compton scatter from Li at 90°; Ge second scatterer; peak and integrated intensities as a function of azimuthal angle.]

71Bo01 Bock, P., Theory of Polarization Phenomena in Compton Scattering by Electrons, Nucl. Phys. A 177, 289-306 (1971).
[Theor.: polarization coefficients in terms of spin-density matrices.]

71Lo01 Logan, B.A., Detection of the Plane of Polarization of 121 keV Linearly Polarized Photons, Can. J. Phys. 49, 2612-2614 (1971).
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71Mo01 *Molak, B., Ilakovac, K. and Ljubicic, A., Z Dependence of Linear Polarization in Elastic Scattering, Fizika 3, 239-246 (1971).
[Meas.: coherent scattering of 662 keV gamma rays at 90° in Sn, Sm, Hf, Pb and U; degree of linear polarization decreases with increasing Z.]

72Mi01 Milton, K.A., Tsai, W.-y. and DeRaad, L.L., Compton Scattering. I. Spectral Forms for the Invariant Amplitudes to Order e^4, Phys. Rev. D 6, 1411-1427 (1972).
[Theor.: information required to calculate radiative corrections to polarized electron-photon scattering experiments.]

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[Theor.: differential cross section for polarized electron-photon scattering.]

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[Theor.: bremsstrahlung can be used as an analyzer of polarization transmission from electrons to photons, or as a source of polarized photons.]

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[Theor.:pair production can be used as a transmitter of polarization from photons to positrons, or as an analyzer of polarized photons.]

75Ke01 Kel'ner, S.R., Kotov, Yu.D. and Logunov, V.M., Methods of Measuring Linear Polarization of Gamma Quanta, Yad. Fiz. 21, 604-609 (1975); Engl. transl. in Sov. J. Nucl. Phys. 21, 313-315 (1975).
[Theor.: azimuthal asymmetry of secondary particle emission; results can be used for experimental determination of degree of linear polarization of photons.]

76Ew01 Ewald, H. and Franz, W., Scattering of a Polarized Photon by a Polarized Electron, Z. Naturforsch. A 31, 808-814 (1976).
[Theor.: scattering of polarized photons by polarized free electrons calculated in covariant form.]

77Ev01 Evans, K.D., Leigh, B. and Lewis, M., The Absolute Determination of the Reflection Integral of Bragg X-Ray Analyser Crystals. Two-Reflection Methods, X-Ray Spectrom. 6, 132-139 (1977).
[Meas.: polarization ratios for double-crystal spectrometer.]

77Si01 Simon, T. and Daniel, H., Measurement of the Spin Dependence of Rayleigh Scattering, Phys. Rev. A 15, 1015-1022 (1977).
[Meas.: circularly polarized 129 keV gamma rays from Os-191 source in a magnetized Fe-Co alloy; Rayleigh scattering spin dependence has same sign as that for spin-dependent Compton scattering.]

78Ha01 Hart, M., X-Ray Polarization Phenomena, Phil. Mag. B 38, 41-56 (1978).
[Meas.: channel-cut Ge crystal x-ray polarimeter; doubly Bragg reflecting; at 8.0 keV.]

79Le01 *Le Page, Y., Gabe, E.J. and Calvert, L.D., X-Ray Beam Polarization Measurements, J. Appl. Cryst. 12, 25-26 (1979).
[Meas.: polarization ratio measured for Mo K-alpha and Cu K-alpha x rays using graphite monochromator and detector rotated around beam-direction axis; simple $\cos^2\theta$ expression included for azimuthal intensity dependence of diffracted beam.]

80Fl01 Flack, H.D. and Vincent, M.G., On the Polarization Factor for Crystal-Monochromated X-Radiation. III. A Weighting Scheme for Products, Acta Cryst. A 36, 620-624 (1980).
[Theor.: minimum-variance weighting scheme for determining polarization ratio of x rays reflected from a monochromator.]

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[Theor.: relation between the degree of perfection of a crystal monochromator and x-ray polarization factor.]

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Polarization Ratio for Crystal Monochromators, Acta Cryst. A 36, 614-620 (1980).
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82Br01 Brummer, O., Eisenschmidt, Ch. and Hoche, H.R., Generation and Proof of Elliptically Polarized X-Rays, Z. Naturforsch. A 37, 524-527 (1982).
[Meas.: tertiary scattering and diffraction by Ge, Si, and Ge successive scatterers.]

82La01 Lawrence, J.L., The Reflectivity of a Pyrolytic Graphite Monochromator, Acta Cryst. A 38, 859-863 (1982).
[Meas.: the efficiency of scattering of the parallel components of polarization is less than that for the perpendicular components, which undergo multiple scattering within the crystal.]

82Vi01 *Vincent, M.G., The Polarization Factor for a Repeatedly Reflected X-Ray Beam: Special Cases, Acta Cryst. A 38, 510-512 (1982).
[Theor.: expressions for polarization factors following arbitrary number of successive reflections.]

83Ch01 *Christoffersson, J.-O. and Mattson, S., Polarized X-Rays in XRF-Analysis for Improved in vivo Detectability of Cadmium in Man, Phys. Med. Biol. 28, 1135-1144 (1983).
[Meas.: polarimeter; 90° Compton scatter of 150 kV x rays off PMMA target; application to determining Cd in human kidney; useful simple formulas presented.]

83Dw01 *Dwiggins, C.W., General Calculation of the Polarization Factor for Multiple Coherent Scattering ring of Unpolarized and Plane-Polarized X-Rays, Acta Cryst. A 39, 773-777 (1983).
[Theor.: polarization factors resulting from a series of scattering events; repeated matrix multiplication using McMaster (54Mc01, 61Mc010) formalism.]

83La01 *Lawrence, J.L., Polarization Ratios for Repeatedly Reflected X-Ray Beams, Acta Cryst. A 39, 753-755 (1983).
[Theor.: polarization effects in double-crystal spectrometers; comparison with earlier Lawrence (82La01) measurement.]

84Br01 Brummer, O., Eisenschmidt, Ch. and Hoche, H.R., Polarization Phenomena of X-Rays in the Bragg Case, Acta Cryst. A 40, 394-398 (1984).
[Meas.: polarization in crystal diffraction; tertiary scattering.]

84Le01 Leubner, C. and Metzler, H.P., Frequency Distribution and Total-Cross Section of Synchro-Compton Radiation in a Linearly Polarized Plane Vacuum Wave of Arbitrary Intensity, Astron. Astrophys. 131, 329-332 (1984).
[Theor.: cross-section for inducing synchro-Compton radiation by a linearly polarized plane vacuum wave of arbitrary intensity; applications in astrophysics.]

84Ma01 Materlik, G. and Suortti, P., Measurement of the Polarization of X-Rays from a Synchrotron Source, J. Appl. Cryst. 17, 7-12 (1984).

[Meas.: x-ray components polarized in the orbital plane and perpendicular to this plane are separated by measuring a reflection 90° to the vertical and horizontal planes, respectively.]

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[Theor.: the averaged perturbed electric field within the crystal is shown to cause the polarization rotation of the x rays passing through the crystal.]

84Xu01 Xu, Z.-x., Polarized-Photon Structure Function and Asymmetry in Photon Photoproduction Process, Phys. Rev. D 30, 1440-1446 (1984).
[Theor.: helicity difference of the photon structure function; cross section and asymmetries in photon photoproduction due to Compton scattering; applications in high-energy particle physics.]

86Ha01 *Hanson, A.L., The Polarization of X-Rays Scattered into 90°, Nucl. Instr. Meth. A 249, 515-521 (1986).
[Theor.: Compton 90° scatter polarization; solid angle integrations.]

86Ha02 Hanson, A.L., Further Comments on the Integrated Incoherent Scattering Cross Sections for Polarized X-Rays, Nucl. Instr. Meth. A 249, 522-529 (1986).
[Theor.: Rayleigh and Compton polarimeter for synchrotron x rays.]

86Ha03 *Hanson, A.L., The Calculation of Scattering Cross Sections for Polarized X-Rays, Nucl. Instr. Meth. A 243, 583-598 (1986).
[Theor.: coherent and incoherent scattering of polarized x rays; integration over detector solid angles.]

86Ka01 Kane, P.P., Kissel, L., Pratt, R.H. and Roy, S.C., Elastic Scattering of Gamma-Rays and X-Rays by Atoms, Phys. Rep. 140, 75-159 (1986).
[Theor.: in Section 2.2.1, pages 85-88, formulas given for parallel and perpendicular polarization amplitudes for Thomson and Rayleigh scattering with inclusions of atomic form factor.]

88Ha01 Hanson, A.L., The Calculation of Coherent and Incoherent Scattering Cross Sections for Polarized X-Rays into an Arbitrarily Placed Circular Aperture, Nucl. Instr. Meth. A 264, 471-483 (1988).
[Theor.: Rayleigh and Compton scattering of polarized x rays; integration over circular apertures.]

88Ha02 *Hanson, A.L., An Easy and Accurate Approximation to the Integrated Compton Cross Section for the Scattering of Polarized X-Rays into an Arbitrarily Circular Aperture, Nucl. Instr. Meth. A 264, 484-487 (1988).
[Theor.: polarized x rays; Compton scattering; solid angle integrations using Thomson scattering approximation.]

88Ha03 Hanson, A.L., Errors Associated with the Measurement of Scattered Polarized X-Rays, Nucl. Instr. Meth. A 264, 488-496 (1988).
[Theor.: solid angle integrations; Compton scattering; example of 15 keV x rays with different degrees of polarization (0 to 100%) in C.]

89Al01 Alexandrov, Yu.M., Vinogradov, A.V., Zorev, N.N., Kozhevnikov, I.V., Kondratenko, V.V., Koshevoi, M.O., Murashova, V.A., Rupasov, A.A., Fedorenko, A.I., Shikanov, A.S. and Yakimenko, M.N., Study of Polarization Properties of Multilayer X-Ray Mirrors, Nucl. Instr, Meth. A 282, 551-552 (1989).
[Meas.: soft x-ray mirrors; polarization properties for synchrotron light.]

89Gi01 Gibbs, D., Blume, M., Harshman, D.R. and McWhan, D.B., Polarization Analysis of Magnetic X-Ray Scattering, Rev. Sci. Instr. 6, 1655-1660 (1989).
[Meas.: Ho target; C polarimeter analyzer; 7.847 keV x rays.]

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89Ma01 Maximon, L.C., Scattering of Polarized Photons by Protons, Phys. Rev. C 39, 347-351 (1989).
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[Meas.: Compton profile measurements using circularly polarized 60 keV x rays.]

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[Meas.: spin-dependent absorption spectroscopy with circularly polarized synchrotron radiation.]

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[Meas.: application of polarized x rays in an XRF system, to measure Pb in bone; simple expressions for scattering cross sections for unpolarized and polarized x rays given, based on the Klein-Nishina formulation.]

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[Theor.: integration of polarized x-ray coherent and incoherent scattering over a circular aperture, from a rectangular source.]

90Sc01 Scofield, J.H., Angular Distribution of Photoelectrons from Polarized X-Rays, Physica Scripta 41, 59-62 (1990).
[Theor.: photoelectron ejection angular dependence for incident polarized x rays; sample numerical results given as Legendre coefficients for 3 keV polarized x rays incident on Ne, Cu, Ba and Au, for each subshell of atomic electrons.]

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[Meas.: Stokes parameters for 5 to 80 eV polarized synchrotron light; triple reflection polarimeter.]

VII. ADDITIONAL TEXT REFERENCES

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59Be01 Berger, M.J., Hubbell, J.H. and Reingold, I.H., Contribution of Annihilation Radiation to the Gamma-Ray Flux in Lead, Phys. Rev. 113, 857-862 (1959).

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85Ne01 Nelson, W.R., Hirayama, H. and Rogers, D.W.O., The EGS4 Code System, Report SLAC-265 (1985).

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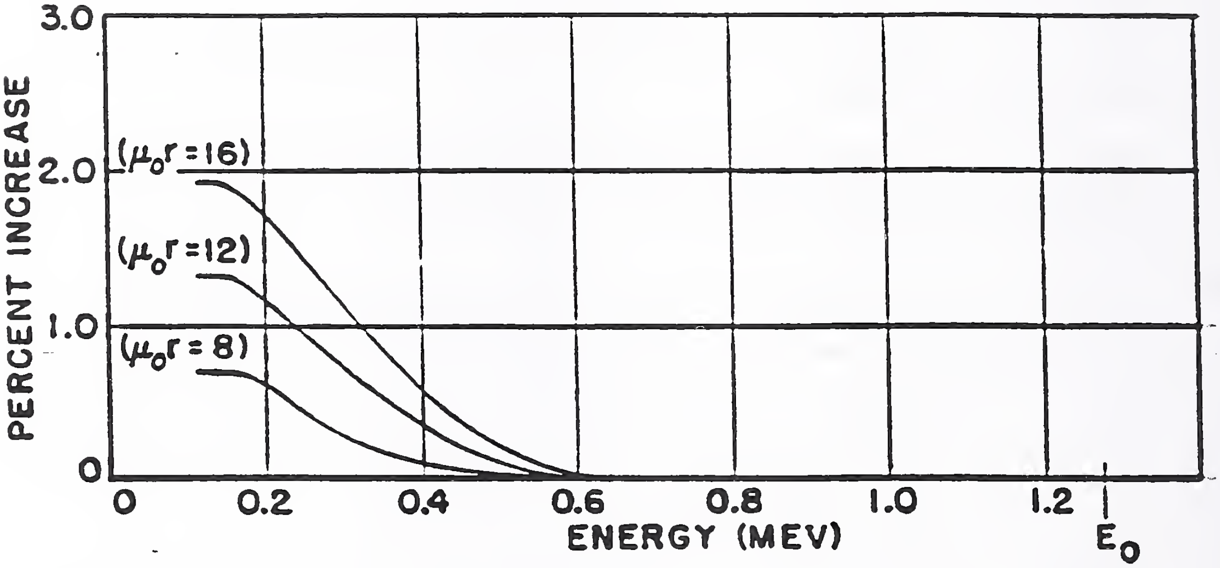

Figure 1. [Figure 3 in Spencer (53Sp01)] The percentage increase in the spectral energy density due to polarization. The source energy is E_0 = 1.277 MeV. The leveling off at low energies relates to the fact that photon directional distributions become isotropic at low energies.

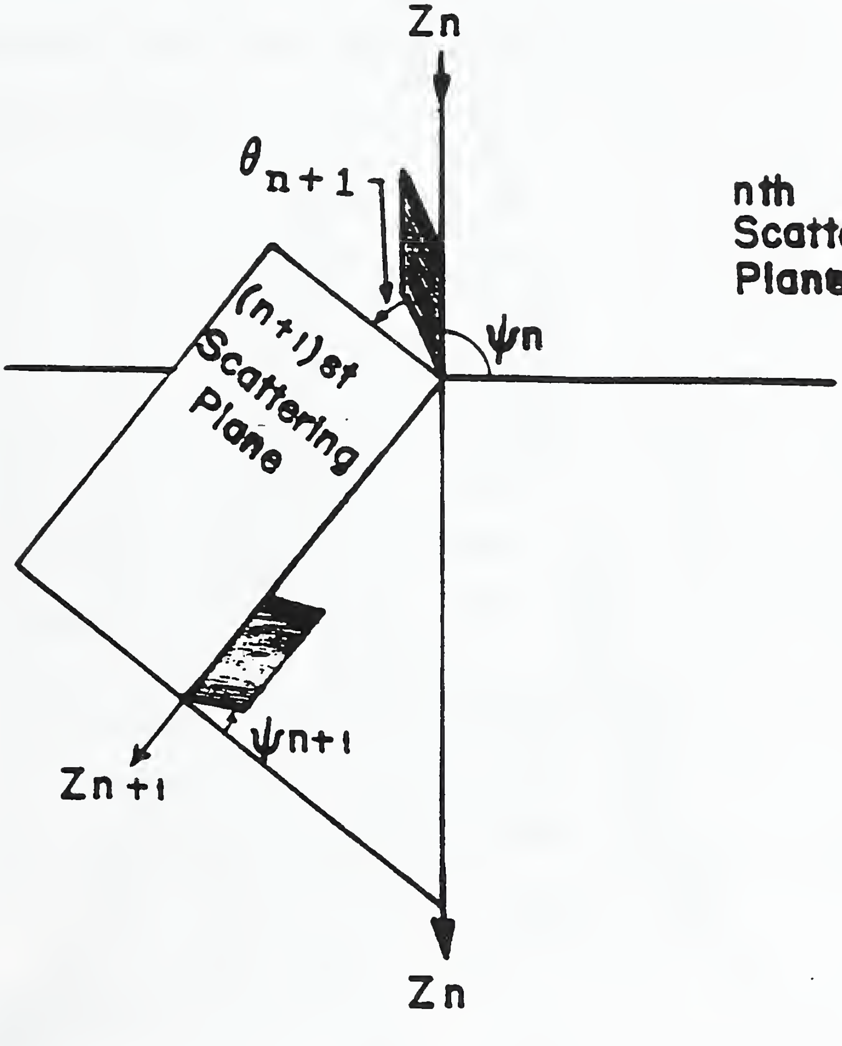

Figure 2. [Figure 1 in Spencer (48Sp01)] Graphical definitions of angular and directional parameters in Spencer expressions.

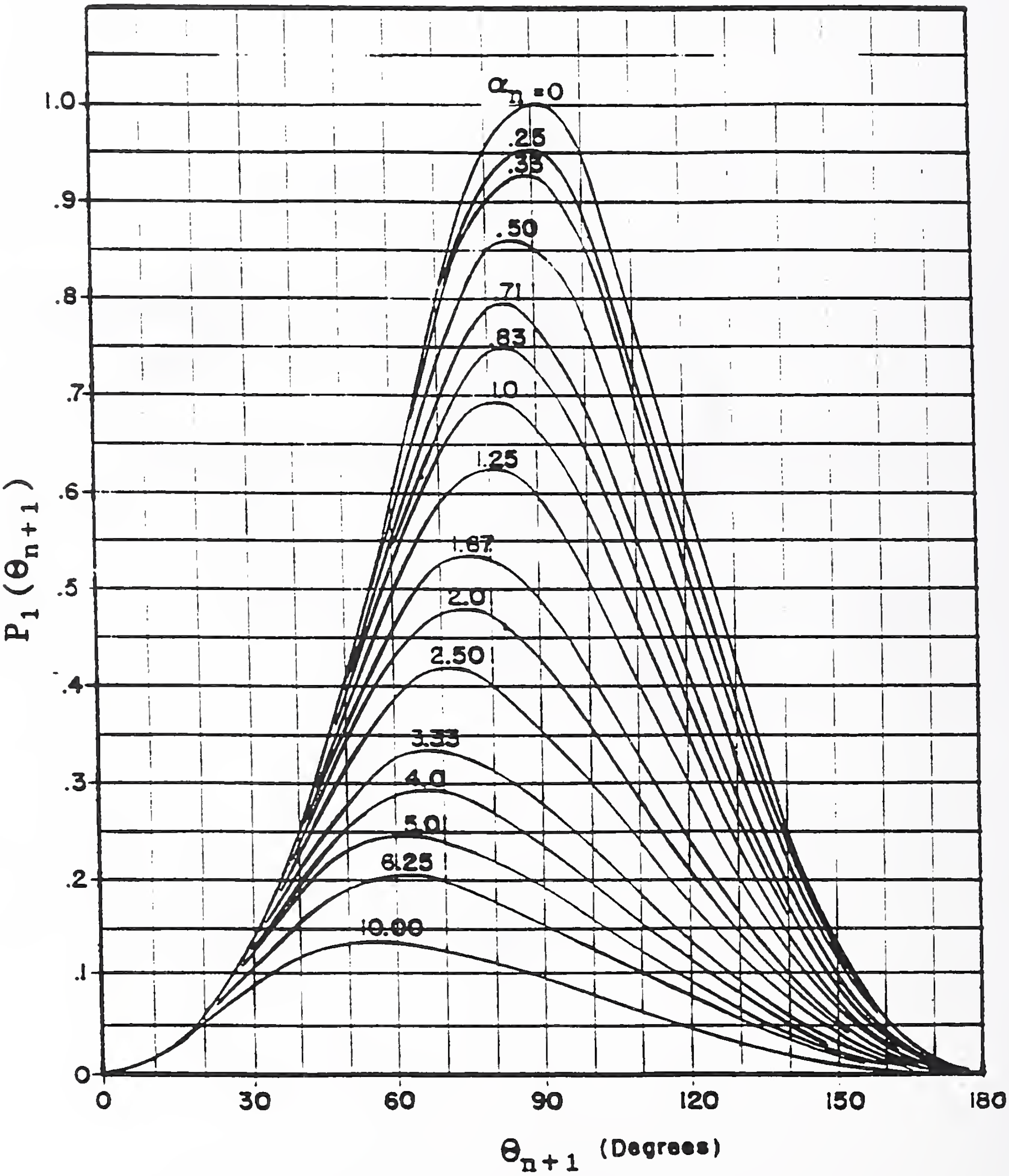

Figure 3. [Figure 2 in Spencer (48Sp01)] Polarizations as a function of scatter angle Θ_{n+1} for photon incident energies α_n from 0 to 10 mc^2.

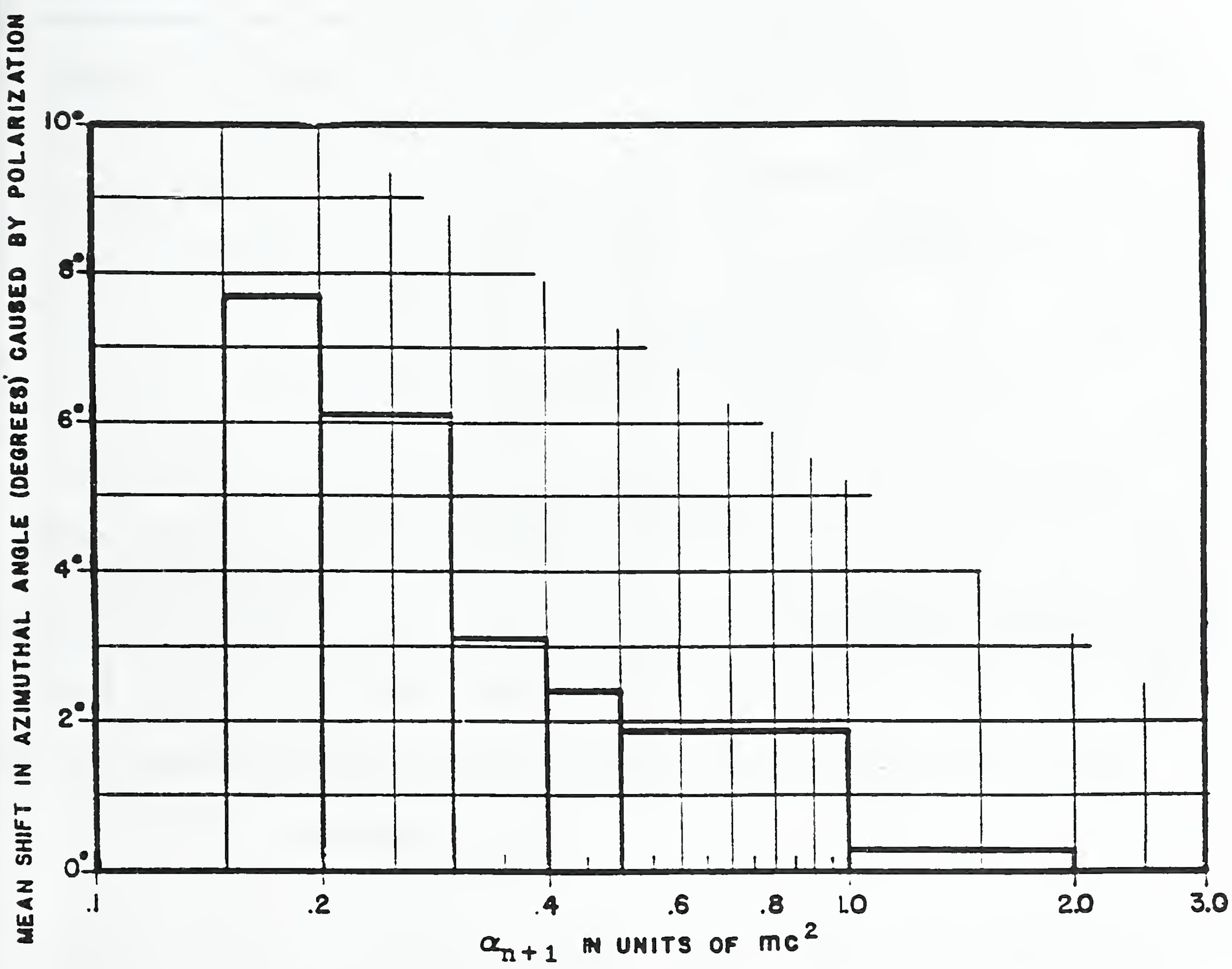

Figure 4. [Figure 3 in Spencer (48Sp01)] Mean change in the azimuthal angle caused by polarization, vs. energy α_n of the photon after the collision.

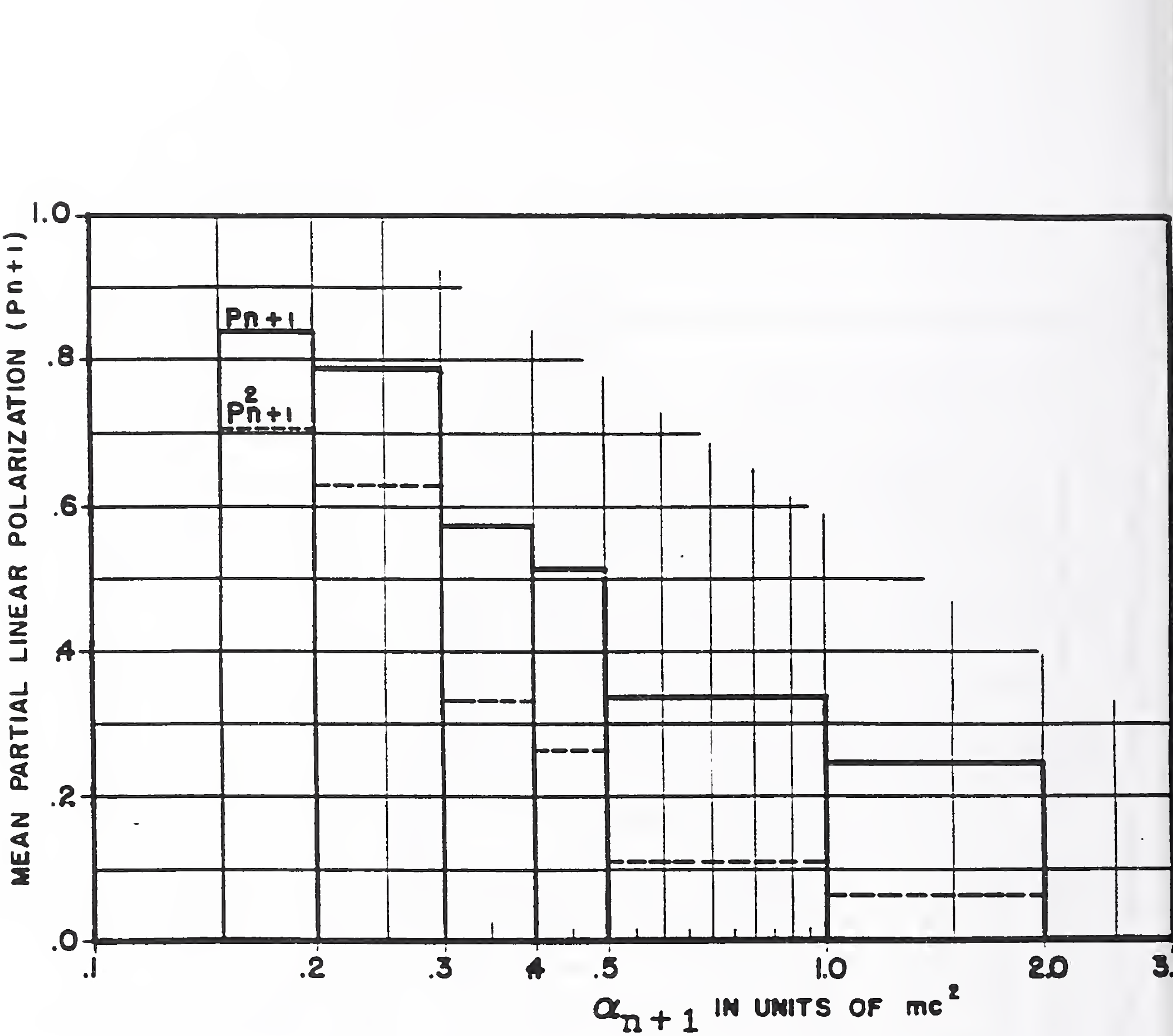

Figure 5. [Figure 4 in Spencer (48Sp01)] Mean polarization (and square of polarization) of the gamma-ray photons as a function of their energy degradation.

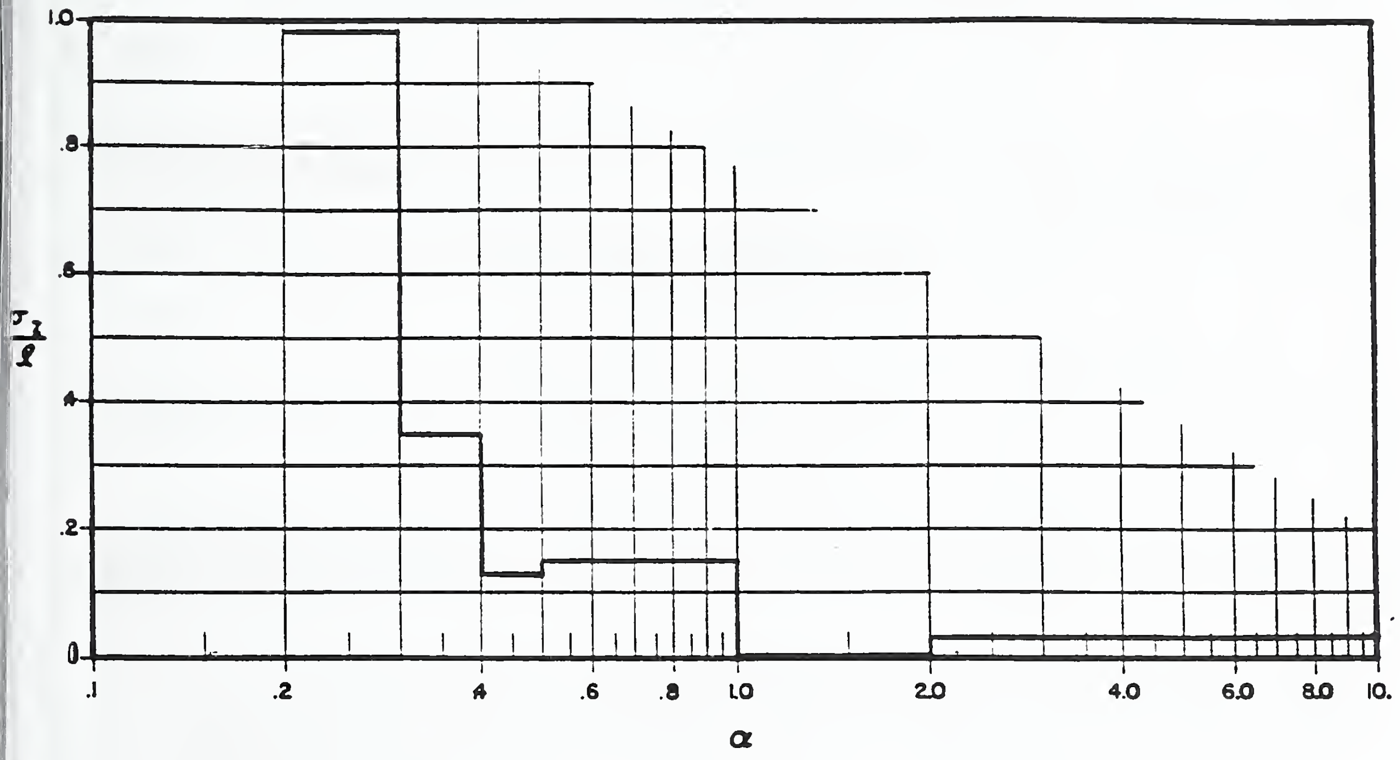

Figure 6. [Figure 5 in Spencer (48Sp01)] The square root of the mean square separation of the z (penetration) component, due to polarization effects, as a function of the degraded energy of the photons.

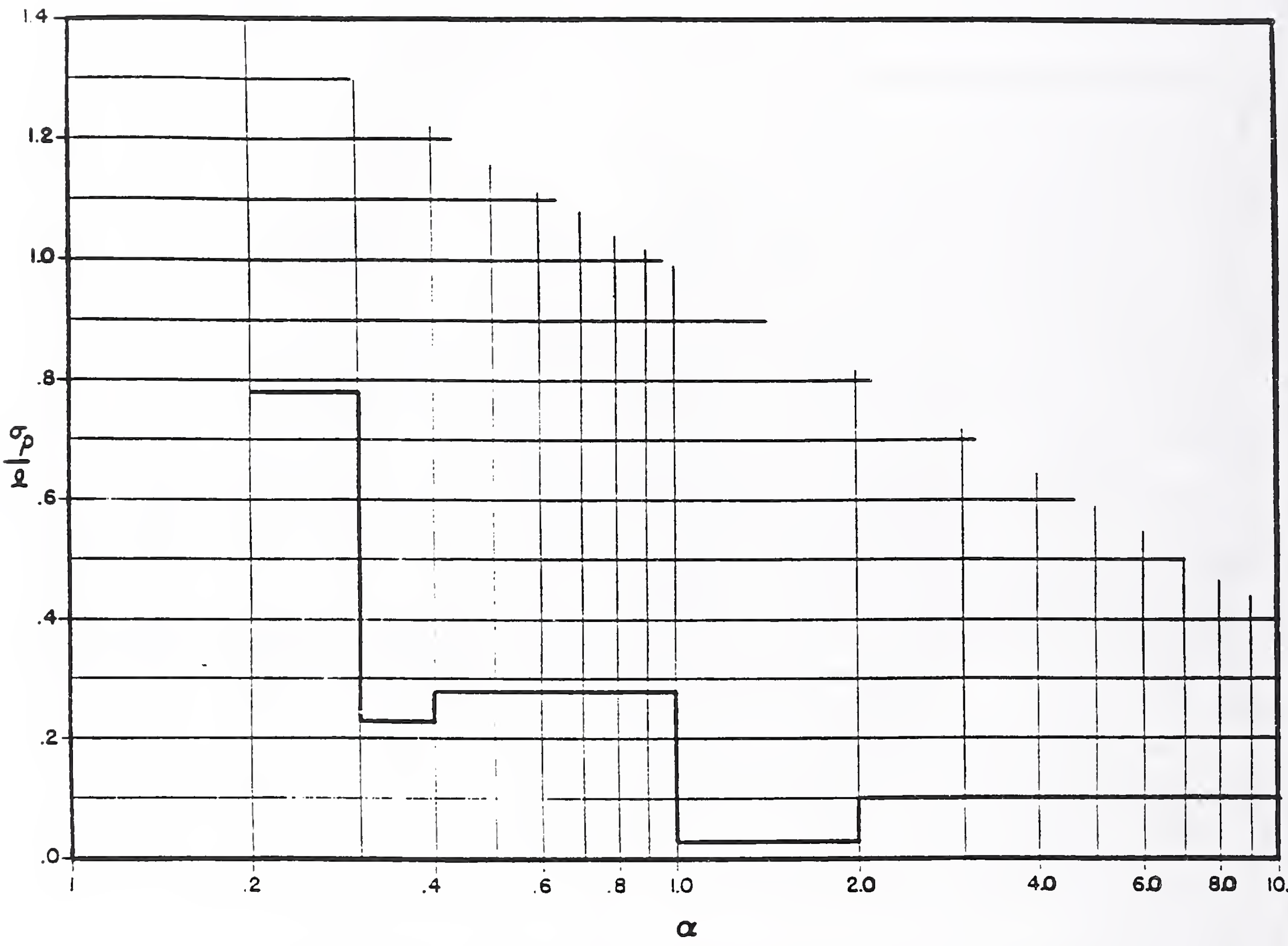

Figure 7. [Figure 6 in Spencer (48Sp01)] The square root of the mean square root of the ρ (lateral displacement) component, due to polarization effects, as a function of the degraded energy of the photons.

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11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

This report reviews available information on polarization effects arising when photons in the x-ray and gamma-ray energy regime undergo coherent (Rayleigh) scattering and incoherent (Compton) scattering by atomic electrons. In addition to descriptions and discussions of these effects, including estimates of their magnitudes as they apply to radiation transport calculations, an annotated bibliography 1905-1991 of 102 selected works is provided, with particularly relevant works for the purpose of this report flagged with asterisks (*). A major resource for this report is a 1948 unpublished informal report by L.V. Spencer which will be quoted here almost in its entirety, since, of all the works cited in the annotated bibliography, it appears to be the only one which explicitly and directly addresses the purpose of this report, hence this valuable material should be re-introduced into the available and current literature.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)
coherent scattering; gamma rays; incoherent scattering; photon; polarization; radiation transport calculations; x-ray

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