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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 A major resource for this report is a 1948 unpublished informal report by L. V Spencer which will be quoted here almost in its entirety, since, of all the works cited in the annotated bibliography, it appears to be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, incoherent scattering, polarization effects, radiation transport calculations, bibliography

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1. 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) [1] 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) [2] indicated a weak polarization of the primary X-ray beam, and in 1906 Barkla (06Ba01) [3] 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) [3] results were quickly confirmed by Haga (07Ha01) [4] and others. These were followed by similar-geometry measurements reported in 1924 by Compton and Hagenow (24Co01) [5] 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) [6] 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 Sections 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 (29K101) [7], 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) [8] which will be extensively quoted.

2. 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 (Sections VII), as references : 49Be01, 49Fa01, 49Ka01, 49Sp01, 51Sp01, 52Sp01, 52Sp02 and 59Be01 [9–16]. 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) [17–19]. 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) [11,20], 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 some interest of 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) [20], 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) [20]]. For detected spectrum

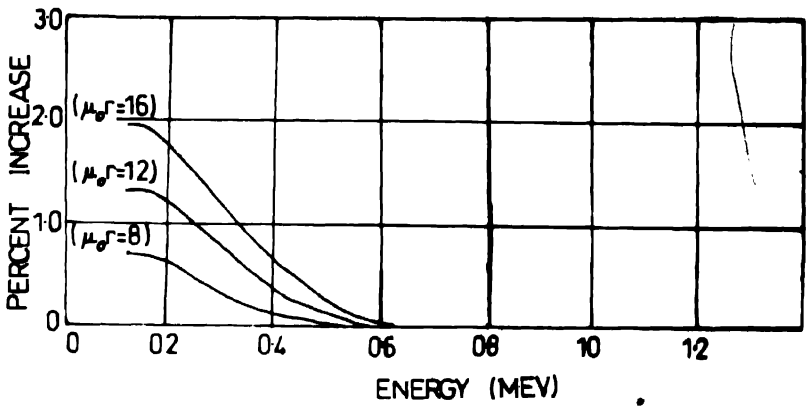

Figure 1. [Figure 3 in Spencer and Wolff (53Sp01) [20]] The percentage increase in the spectral energy density due to polarization. The source energy is $E_0 = 1.277$ MeV. The levelling off at low energies relates to the fact that photon directional distributions become isotropic at low energies

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) [8] for use in his Monte Carlo investigation of polarization effects on multiple Compton scattering.

3. 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) [17,18] 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 maximum contribution of only 10% just below the photoeffect K absorption edge, for high-Z elements. In the current ETRAN version (91Se01) [19], however, coherent scattering is included.

In certain situations, such as in medical diagnostic and industrial flaw-detection x-ray imaging, 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) [21], of which the EGS4 version has been described by Nelson, Hirayama and Rogers (85Ne01) [22] and more recently by Nelson and Namito (90Ne01) [23]. 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) [24] 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) [25,26] 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) [27–29]; Sood *et al* (58So01, 64Si01) [30,31]; Bobel and Passatore (60Bo01) [32]; Williams and McNeill (65Wi01) [33]; Somayajulu *et al* (68So01, 68So02) [34,35]; Molak *et al* (71Mo01) [36]; Dwiggins (83Dw01) [37] and Hanson (86Ha01, 86Ha02) [38,39]; 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.

4. 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) [7] 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_0 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 :

Polarized beam (Klein-Nishina) :

$$I = I_0\left(e^4/m^2c^4r^2\right)\sin^2\theta(1 + \alpha(1 - \cos\Theta))^{-3}\left(1 + \alpha^2(1 - \cos\Theta)^2\right)/$$

$$\left(2\sin^2\theta(1 + \alpha(1 - \cos\Theta))\right) \tag{1}$$

For the case of the unpolarized incident beam, according to Klein and Nishina (29Kl01) [7], in the two places in eq. (1) where the azimuthal dependence factor $\sin^2\theta$ appears, we substitute for this factor its mean value which is 1/2 (1 + $\cos^2\Theta$), giving the more-familiar differential cross section for Compton scattering of an unpolarized (random polarizations) beam :

Unpolarized beam (Klein-Nishina) :

$$I = I_0\left(e^4/2m^2c^4r^2\right)(1+\cos^2\Theta)(1+\alpha(1-\cos\Theta))^{-3}\left(1+\alpha^2(1-\cos\Theta)^2/\right.$$

$$\left.((1+\cos^2\Theta)(1+\alpha(1-\cos\Theta)))\right). \tag{2}$$

For purposes of exploratory calculations at NIST with ETRAN, it may be a sufficient approximation to assume that the first Compton scatter, described by eq. (2), results in 100% plane polarization (as an extreme case) of the first-scattered trajectory, following which eq. (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 eq. (1) which it appears.

If one wishes to go beyond the above rough-approximation external exploratory calculation described above, and admit partial linear polarizations into the model, one can use the following scheme and formulas derived by Spencer (48Sp01) [8], which he adapted to the

Monte Carlo technique (this work of Spencer's is one of the earliest, perhaps even the 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 :

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

For consistency in this report; some of the Spencer (48Sp01) [8] notation in the following account has been changed to that of Klein and Nishina (29Kl01) [7], used in their eqs. (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 Figure 2).

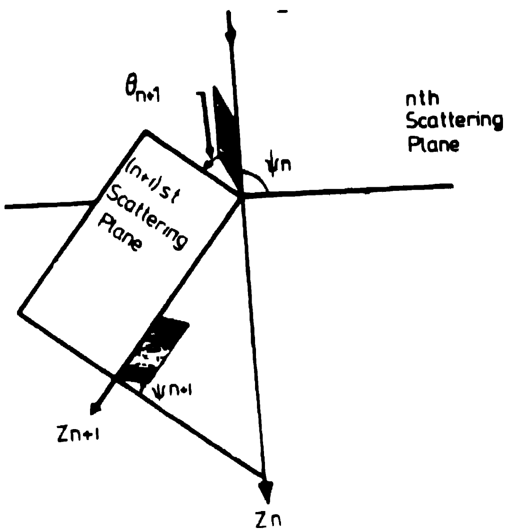

Figure 2. [Figure 1 in Spencer (48Sp01) [8]] Graphical definitions of angular and directional parameters in Spencer expressions

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

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

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 n-th scattered radiation. Using this notation, the following relations hold :

$$\begin{aligned} d\sigma = {} & \left(e^4/m^2c^4r^2\right)\left(1 + \alpha_n\left(1 - \cos\Theta_{n+1}\right)\right)^{-2}\left(1 + \cos^2\Theta_{n+1}\right. \\ & + \alpha_n^2\left(1 - \cos\Theta_{n+1}\right)^2 \times \left(1 + \alpha_n\left(1 - \cos\Theta_{n+1}\right)\right)^{-1} \\ & \left. - P_n \sin^2\Theta_{n+1}\cos\theta_{n+1}\right)\sin\Theta_{n+1} d\Theta_{n+1} d\theta_{n+1}, \end{aligned} \tag{4}$$

$$\begin{aligned} P_{n+1} = {} & \left(\left(-\sin^2\Theta_{n+1} + \left(1 - \cos^2\Theta_{n+1}\right)P_n\cos 2\theta_{n+1}\right)^2\right. \\ & \left. + \left(2\cos\Theta_{n+1}P_n\sin 2\theta_{n+1}\right)^2\right) \times \left(1 + \cos^2\Theta_{n+1} + \alpha_n^2\left(1 - \cos\Theta_{n+1}\right)^2 \Big/\right. \\ & \left.\left(1 + \alpha_n\left(1 - \cos\Theta_{n+1}\right)\right) - \sin^2\Theta_{n+1}P_n\cos 2\theta_{n+1}\right)^{-2}, \end{aligned} \tag{5}$$

$$\begin{aligned} \psi_{n+1} = {} & 1/2\tan^{-1}\left(2\cos\Theta_{n+1}P_n\sin 2\theta_{n+1}\right)\Big/\left(-\sin^2\Theta_{n+1}\right. \\ & \left. + \left(1 + \cos^2\Theta_{n+1}\right)P_n\cos 2\theta_{n+1}\right). \end{aligned} \tag{6}$$

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 eqs. (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, $P_0 = 0$) :

$$\begin{aligned} P_1 = {} & \sin^2\Theta_1\Big/\left(1 + \cos^2\Theta_1 + \alpha_0^2\left(1 - \cos\Theta_1\right)^2\right. \\ & \left.\left(1 + \alpha_0\left(1 - \cos\Theta_1\right)\right)\right). \end{aligned} \tag{7}$$

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 :

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

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

$$+ \alpha_n^2(1 - \cos\Theta_{n+1})^2\Big/\big(1 + \alpha_n(1-\cos\Theta_{n+1})\big)d\theta_{n+1} \qquad (8)$$

Remembering (7), we rewrite this as

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

where

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

$$\big(1 + \alpha_n(1 - \cos\Theta_{n+1})\big)\Big). \qquad (10)$$

Spencer's (48Sp01) [8] graph of $P_1(\Theta_{n+1})$ for various values of α_n is given in Figure 3.

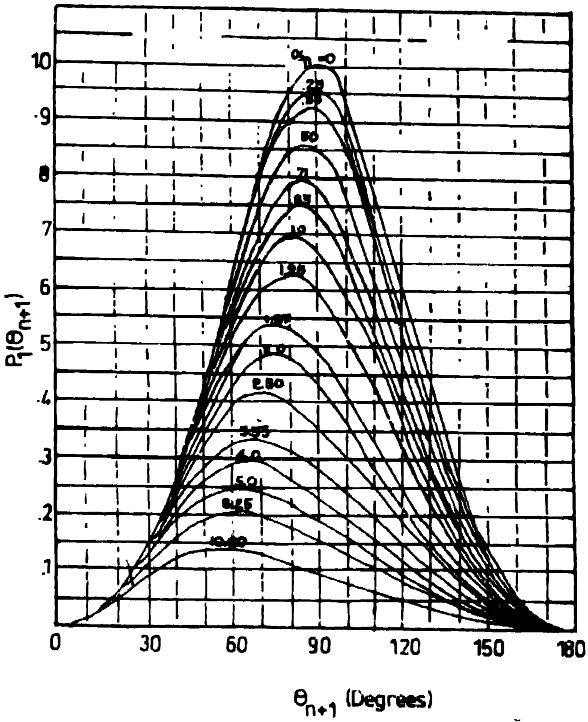

Figure 3. [Figure 2 in Spencer (48Sp01) [8]] Polarizations as a function of scatter angle Θ_{n+1} for photon incident energies α_n from 0 to 10 mc^2.

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 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.

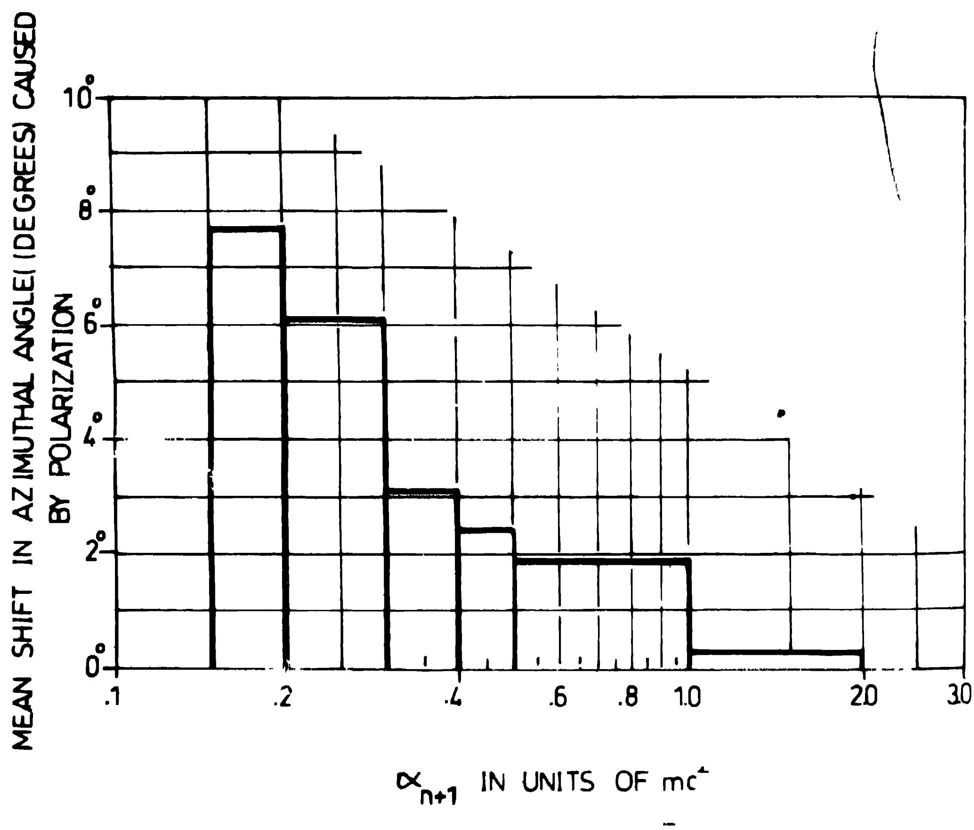

Figure 4. [Figure 3 in Spencer (48Sp01) [8]] Mean change in the azimuthal angle caused by polarization, *vs* energy α_n of the photon after the collision.

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

(Figure 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 (Figure 5). In view of eq. (9), the square of this is also plotted on the same diagram.

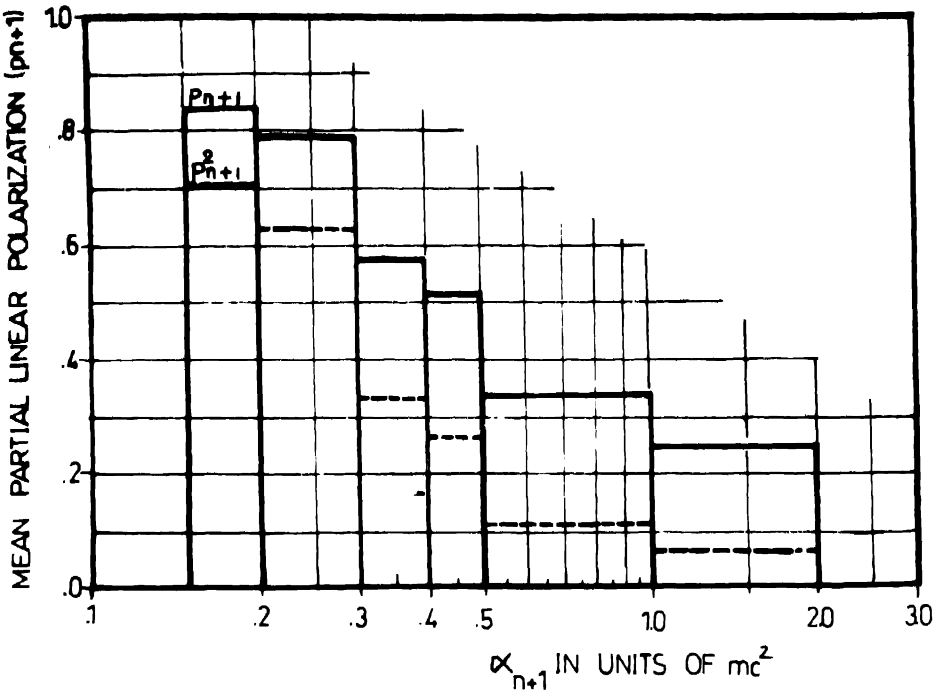

Figure 5. [Figure 4 in Spencer (48Sp01) [8]] Mean polarization (and square of polarization) of the gamma-ray photons as a function of their energy degradation.

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, eq. (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 eq. (5), may result in a sizeable

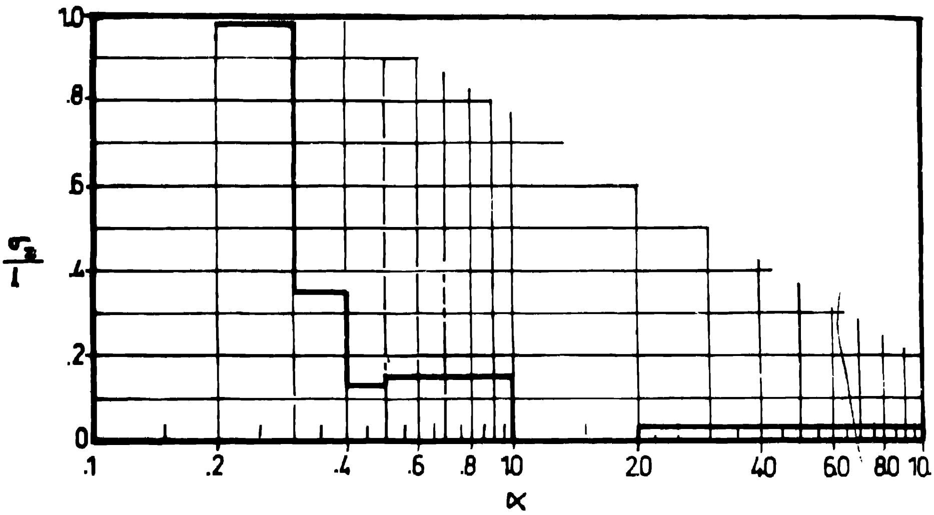

Figure 6. [Figure 5 in Spencer (48Sp01) [8]] The square root of the mean square separation of the z (penetration) component, due to polarization effects, as a function of the degraded energy of the photons.

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 directions of the γ-ray photon, in the sense that further penetration is more or less a diffusion process.

5. 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.

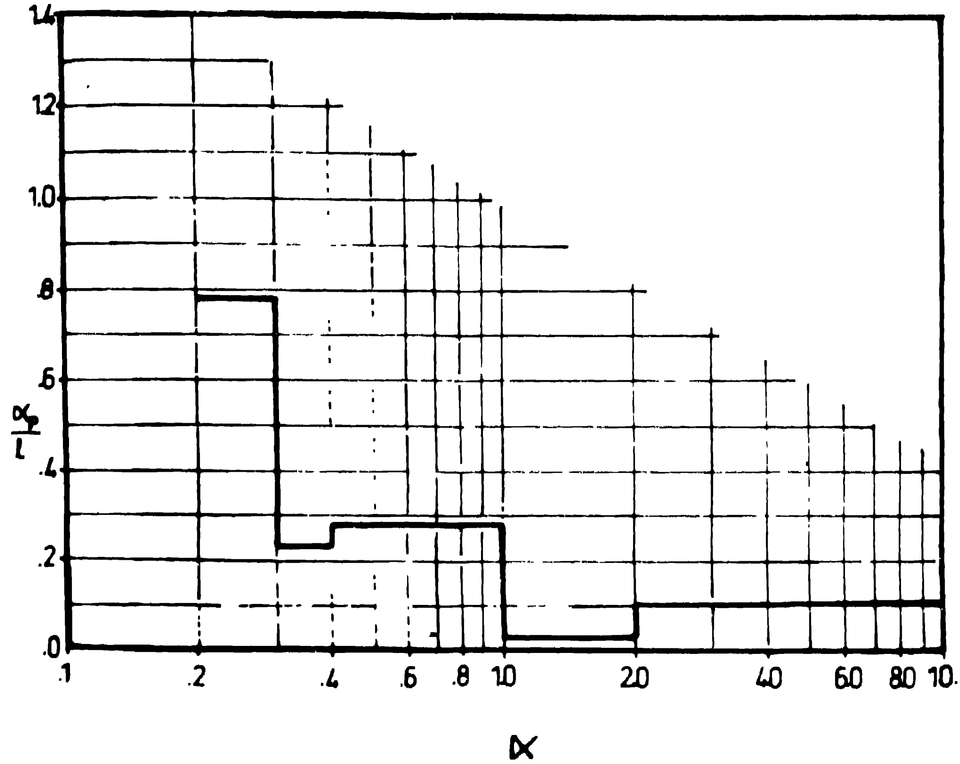

Figure 7. [Figure 6 in Spencer (48Sp01) [8]] The square root of the mean square root of the ρ (lateral displacement) component, due to polarization effects, as a function of the degraded energy of the photons

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) [19] and ITS (92Ha01, 92Ha02) [25,26] 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) [7] 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 eqs. (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 eq. (1), and a companion calculation using eq. (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) [8] provides the necessary expressions, reproduced here in eqs. (4) through (10). These expressions were used by Spencer (48Sp01) [8] 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) [8] except the notation in some cases is changed to be consistent with the Klein-Nishina (29Kl01) [7] 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.

6. Annotated selected 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.)

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