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Fig.4. Ratio of pseudo exposure buildup factors with coherent scattering and with Compton scattering while taking into account the binding effect and Doppler broadening applying linear polarization for both coherent and incoherent scattering to the true ones without coherent and free electron scattering at a 10-mfp penetration depth as a function of the photon energy for water, iron, and lead.

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EFFECTS OF LINEAR POLARIZATION AND DOPPLER BROADENING ON THE EXPOSURE BUILDUP FACTORS OF LOW-ENERGY GAMMA RAYS

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ABSTRACT

The effects of including linear polarization and Doppler broadening in a calculation of the exposure buildup factors for plane normal gamma-ray sources have been investigated by using an improved electron gamma shower Monte Carlo code, EGS4, for water, iron, and lead in the 40- to 250-keV range for penetration depths of up to 16 mfp. The "pseudo" exposure buildup factors were calculated in order to determine these effects combined with the effects of coherent and/or incoherent scattering.

The pseudo exposure buildup factor increases upon including linear polarization and decreases upon including Doppler broadening. The degree of each effect varies with the atomic number of the material. The effect of linear polarization is large for materials of small atomic number; that of the Doppler broadening is large for materials of medium and large atomic number.

I. INTRODUCTION

The effects of including coherent scattering and the binding effect for Compton scattering (incoherent scattering) in a calculation of the exposure buildup factors for plane normal gamma-ray sources had been investigated¹ by one of the authors, and are cited in ANSI/ANS-6.4.3,² a new buildup factor compilation. In the investigation discussed in the reference 1, however, the incoherent scattering cross section, including the binding correction, were applied for only the total cross section. The angular distribution of incoherent scattering is also affected by the binding effect and must be taken into account. This was studied by Angelopoulos et al.³ for only water. Doppler broadening upon incoherent scattering is also supposed to contribute to

the buildup factors of low-energy photons. Moreover, linear polarization at coherent and incoherent scattering may affect photon transport in the medium.

The object of the present study was to investigate the effect of linear polarization at both coherent and incoherent and incoherent scattering, including the angular distribution and Doppler broadening upon exposure buildup factors in the 40- to 250-keV range for typical shielding materials, such as water, iron and lead. The gamma-ray sources considered were plane normal to the material. The exposure buildup factor is based on the energy absorption response of air; that is, exposure is assumed to be equivalent to the absorbed dose in air, as measured by a nonperturbing detector.

II. DEFINITION OF THE BUILDUP FACTOR

Buildup factor data are customarily presented as a function of the distance measured in the mean-free-paths. The mean-free-path, in turn, can vary for a given linear distance (e.g., in centimeters) or mass per unit area thickness, depending on how the mass attenuation coefficient is defined, e.g., with or without coherent scattering, and also whether or not electron binding for Compton scattering is taken into account. The mean-free-path in the new standard data is for no coherent scattering and without considering any electron binding effect for Compton scattering. It would be desirable to determine the size of the error due to neglect of various reactions in the transport calculations at the same distance. For this purpose, a "pseudo" exposure buildup factor (defined in reference 1) was used (definition 2). Various pseudo exposure buildup factors used in this paper are expressed as follows:

$$B'_{coh}(free, aKN) = D_{coh}(free, aKN : x) / D_0 \exp(-\mu_t x), \quad (1)$$

$$B'^{LP}_{coh}(free, aKN) = D'^{LP}_{coh}(free, aKN : x) / D_0 \exp(-\mu_t x), \quad (2)$$

$$B'_{wc}(bound, aKN) = D_{wc}(bound, aKN : x) / D_0 \exp(-\mu_t x), \quad (3)$$

$$B'_{wc}(bound, incoh) = D_{wc}(bound, incoh : x) / D_0 \exp(-\mu_t x), \quad (4)$$

$$B'_{wc}(bound, incoh, DB) = D_{wc}(bound, incoh, DB : x) / D_0 \exp(-\mu_t x), \quad (5)$$

$$B'^{LP}_{coh}(bound, incoh, DB) = D'^{LP}_{coh}(bound, incoh, DB : x) / D_0 \exp(-\mu_t x), \quad (6)$$

where

coh: with coherent scattering both for total scattering and angular distribution,

wc: without coherent scattering,

free: free-electron Compton scattering cross section for total Compton scattering,

bound: incoherent scattering cross section for total Compton scattering,

aKN: angular distribution based on the free-electron Klein-Nishina cross section for Compton scattering,

incoh: angular distribution including the binding effect for Compton scattering,

DB: include Doppler broadening for Compton scattering,

LP: include linear polarization in the scattering,

B': pseudo exposure buildup factor,

D: exposure at x centimeters,

D_t: exposure for source photon,

μ_t : linear attenuation coefficient with free electron Compton scattering and without coherent scattering (cm^{-1}).

Therefore, $B'_{coh}(bound, incoh, DB)$ is the pseudo exposure buildup factor with coherent scattering and with Compton scattering, while taking account of the binding effect and Doppler broadening, applying linear polarization both for coherent and incoherent scattering. Using the same notation, the standard exposure buildup factor can be expressed as

$$B_{wc}(free, aKN) = D_{wc}(free, aKN : x) / D_0 \exp(-\mu_t x). \quad (7)$$

The treatment of each phenomenon of coherent and Compton scattering on each exposure and pseudo exposure buildup factors are summarized in Table I.

III. METHOD OF CALCULATION

For simulating photon transport in the medium, a general electromagnetic radiation transport code, Electron Gamma Shower Version 4 (EGS4),⁴ was used. The EGS4 calculations were made in one-dimensional plane. The data up to 16 mfp were estimated from calculations for a 18-mfp-thick semi-infinite plane. The linear attenuation coefficient without coherent scattering and without considering any electron binding effect for Compton scattering was used to determine the mean-free-path. Table II gives the linear attenuation coefficients with and without coherent scattering and considering the electron binding effect for Compton scattering at the source energies and the material densities used in the calculation. Linear polarization and Doppler broadening were implemented into the EGS4 system by the authors^{5,6} and applied to this work.

In the EGS4 calculation, the exposure was obtained from the photon flux and the energy transfer coefficient of air. The pseudo exposure buildup factor was calculated by dividing the exposure calculated by EGS4 by the exposure of the analytically calculated unscattered photons, which was calculated using the linear attenuation coefficient without coherent scattering and without considering the electron binding effect for Compton scattering. An exponential transform and next event surface crossing techniques are used to obtain sufficient statistics at deep penetration.

The photoelectric reaction and coherent scattering cross section were taken from a compilation by Storm and Israel.⁷ The mass energy transfer coefficients of air were taken from Hubbell's compilation.⁸

IV. RESULTS AND DISCUSSION

The ratios of the various pseudo exposure buildup factors to the true one without coherent and free electron Compton scattering, $B_{wc}(free, aKN)$, for water, iron, and lead at 40, 60, 100 and 200 keV are given in Figs. 1, 2 and 3, respectively. These figures clearly show each effect on the pseudo exposure buildup factors and their energy and Z dependence.

The pseudo exposure buildup factor increases with the inclusion of the electron binding correction to Compton scattering for the total cross section; its increasing rate is decreased upon including the angular distribution based on the incoherent scattering function due to suppression of scattering in the forward direction. This tendency is remarkable for water and is larger for lower energy photons. In the case of iron and lead, the same tendency is smaller than that for water, and the effect is larger for higher energy photons. Compton-scattered photon energy is broadened by a

pre-collision motion of electron, i.e., Doppler broadening. The inclusion of this Doppler broadening changes the photon energy after Compton scattering at a fixed angle. The degree of broadening is larger for high-Z material. The effect to a pseudo exposure buildup depends on the change in the total and the scattering cross section in the expanded energy region. In the case of water, the effect of Doppler broadening is very small at all energies due to the small broadening. Except for the case of iron at 40 keV, the inclusion of Doppler broadening decreases the pseudo exposure buildup factor.

The effect of coherent scattering, which decreases the pseudo exposure buildup factor, and is remarkable for a high-Z material, is slightly recovered by including linear polarization. For deep penetrations, the inclusion of polarization effects in a calculation increases the predicted photon flux, due to favoring of coplanar scattering. This effect occurs only when a photon is scattered several times in the medium and, therefore, can be seen in water only.

As the net effect, the inclusion of angular distribution and doppler broadening at incoherent scattering and that of linear polarization for both coherent and incoherent scattering decreases the rate of any overestimated or underestimated tendency due to including incoherent and coherent scattering in the total cross section, respectively. The energy dependence of the net effect at 10 mfp is shown in Fig. 4. In the case of water, the net effect increases the pseudo exposure buildup factors, except at 40 keV; its rate is less than 7% for all of the energy region considered. The net effect always has a decreasing tendency in the case of lead, and is most remarkable just below the K-edge, because the contribution of coherent scattering is maximum at that energy. In the case of iron, the pseudo exposure buildup factor increases with an increase of the photon energy, except at 40 keV.

V. SUMMARY

The pseudo exposure buildup factors with linearly polarization for both incoherent and coherent scattering and Doppler broadening at incoherent scattering in water, iron, and lead were calculated for plane normally incident sources of 40 to 250 keV. The pseudo exposure buildup factors obtained give correction factors to the standard data, i.e., $B_{coh}^{LP}(bound, incoh, DB)/B_{inc}(free, aKN)$.

The present study reveals that linearly polarization and Doppler broadening also affect the pseudo exposure buildup factor. The inclusion of angular distribution and Doppler broadening at incoherent scattering decreases the pseudo exposure buildup factor, and that

of linear polarization increases it. The effect of Doppler broadening is remarkable for iron and lead and that of linearly polarization is seen only for water in the energy region studied.

All calculations were performed using HITACHI's Unix workstations (3050RX) at the Data Handling Center of National Laboratory for High Energy Physics (KEK).

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Table I
Treatment of coherent and Compton scattering in
exposure and pseudo exposure buildup factor

	Coherent scattering			Compton scattering			
	total	angular	LP	total	angular	DB	LP
$B_{wc}(free, aKN)$	×	×	×	<i>free</i>	<i>aKN</i>	×	×
$B'_{coh}(free, aKN)$	○	○	×	<i>free</i>	<i>aKN</i>	×	×
$B'^{LP}_{coh}(free, aKN)$	○	○	○	<i>free</i>	<i>aKN</i>	×	○
$B'_{wc}(bound, aKN)$	×	×	×	<i>bound</i>	<i>aKN</i>	×	×
$B'_{wc}(bound, incoh)$	×	×	×	<i>bound</i>	<i>incoh</i>	×	×
$B'_{wc}(bound, incoh, DB)$	×	×	×	<i>bound</i>	<i>incoh</i>	○	×
$B'^{LP}_{coh}(bound, incoh, DB)$	○	○	○	<i>bound</i>	<i>incoh</i>	○	○

Table II
Linear Attenuation Coefficients and Material Densities

E (keV)	Water			Iron			Lead		
	(g/cm^3)								
	1.0			7.86			11.34		
	Linear Attenuation Coefficient (cm^{-1})								
	μ_t	$\mu_{t,b}$	$\mu_{tc,b}$	μ_t	$\mu_{t,b}$	$\mu_{tc,b}$	μ_t	$\mu_{t,b}$	$\mu_{tc,b}$
40.0	0.248	0.237	0.266	27.0	26.8	28.2	151.	150.	161.
60.0	0.197	0.192	0.206	8.81	8.68	9.40	51.0	50.6	56.1
80.0	0.179	0.175	0.183	4.31	4.22	4.65	23.8	23.6	26.9
100.0	0.168	0.165	0.170	2.67	2.60	2.89	60.7	60.5	62.7
150.0	0.149	0.148	0.150	1.43	1.39	1.53	21.9	21.8	22.8
200.0	0.136	0.135	0.137	1.09	1.06	1.14	10.7	10.7	11.3
250.0	0.126	0.126	0.127	0.928	0.912	0.962	6.38	6.32	6.71

- μ_t : Linear attenuation coefficient using a free electron Compton scattering cross section without coherent scattering.
- $\mu_{t,b}$: Linear attenuation coefficient using a bound electron Compton scattering cross section without coherent scattering.
- $\mu_{tc,b}$: Linear attenuation coefficient using a bound electron Compton scattering cross section with coherent scattering.

Fig.1. Ratio of various pseudo exposure buildup factors to the true ones without coherent and free electron scattering for water at 40, 60, 100, and 200 keV.

Fig.2. Ratio of various pseudo exposure buildup factors to the true ones without coherent and free electron scattering for iron at 40, 60, 100, and 200 keV.

Fig.3. Ratio of various pseudo exposure buildup factors to the true ones without coherent and free electron scattering for lead at 40, 60, 100, and 200 keV.