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X-ray scattering in the shielding of industrial irradiation facilities

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Abstract

When high-energy X-ray photons impinge on thick shields, most of the incident energy is absorbed in the shielding material, but some of it is deflected sideways or backward into the treatment room. This effect is important in facilities that have openings in the shields to allow the passage of products through the irradiation zone or mazes to provide access into this zone for operating personnel. Multiple scattering events in these openings can reduce the energies of the photons and the dose rates of the residual radiation to comply with applicable safety regulations. Basic equations and examples are presented to show how these scattering effects can be evaluated in the designs of new irradiation facilities.

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Keywords: X-rays; X-ray scattering; radiation shielding; industrial irradiation facilities

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1. Introduction

This paper describes a method for calculating the reductions in energy and dose rate of the X-ray photons that are scattered through a maze with multiple corners at the entrance to an electron beam irradiation facility. This procedure is simpler and less precise than the use of complex Monte Carlo programs such as ITS3 Accept, MCNP and GEANT. However, the results obtained by this method can be sufficiently accurate for evaluating the personnel safety to first order of this type of facility.

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The shielding of energetic photons from X-ray sources in irradiation facilities is determined by interactions of X-ray photons with atomic electrons in the shielding materials. Most of the X-ray energy is absorbed in the shield, but some is deflected or scattered back into the treatment room. The energy of the scattered photon is less than the energy of the incident photon because part of the photon's energy is transferred to the recoiling electron. This event decreases the energy of the scattered photon and increases its wavelength accordingly. It also reduces the dose rate of the scattered radiation. This interaction is called the Compton scattering effect. It was named after Arthur Holly Compton. He received the Nobel Prize in 1927 for demonstrating and measuring this effect and deriving the equations to explain it while he was a physics professor at Washington University in Saint Louis, Missouri. His basic equation is useful in calculating the reductions of X-ray energies in a maze with multiple corners (Compton,1923). Note: This paper may not be easy to find because of its age, but his derivation can be found on the internet by using a search program such as Google with the key words "Compton Scattering".

2. Compton Scattering Equation

Compton's analysis showed that each scattering of an energetic X-ray photon by a low-energy atomic electron increases the photon wavelength in meters by the quantity, $\Delta\lambda$, which is given by the following equation:

$$\lambda_f - \lambda_i = \Delta\lambda = (h/(m_0 c))(1 - \cos\theta) \text{ meters} \quad (1)$$

$$\lambda_f = \lambda_i + \Delta\lambda \quad (2)$$

where λ_f is the final wavelength, λ_i is the initial wavelength, $\Delta\lambda$ is the increase in wavelength, h is the Planck constant, 6.626×10^{-34} joule second, m_0 is the rest mass of an electron, 9.109×10^{-31} kg, c is the speed of light in vacuum, 2.998×10^8 m/s, and θ is the scattering angle of the photon. SI units are used except where noted. With a 90 degree scattering angle, the value of $\cos\theta$ is zero and Equation (1) then reduces to the following relation:

$$\Delta\lambda = h/(m_0 c) = h c/(m_0 c^2) \quad (3)$$

$$\Delta\lambda = 6.626 \times 10^{-34} / (9.109 \times 10^{-31} \times 2.998 \times 10^8) \quad (4)$$

$$\Delta\lambda = 2.426 \times 10^{-12} \text{ meters} \quad (5)$$

The value of $\Delta\lambda$ given by Equation (5) is called the Compton wavelength for photon scattering by an electron. This increase in the photon wavelength, and also the related decrease in photon energy, is independent of the incident photon energy, E. To obtain the final photon wavelength, λ_f, $\Delta\lambda$ must be added to the initial wavelength, λ_i, which can be obtained from E by using a rearrangement of the Planck-Einstein relation (Weinberg, S. (2013).

$$E = h f = h c / \lambda \quad (6)$$

$$\lambda = h c / E \quad (7)$$

The quantity E is the photon energy in joules (watt seconds), h is the Planck constant in joule seconds, f is the electromagnetic frequency of the photon in hertz (cycles per second), c is the velocity of light in meters per second and λ is the photon wavelength in meters.

The energy of the Compton wavelength, $\Delta\lambda$, can be obtained by substituting $\Delta\lambda$ for λ in Equation (6) as follows:

$$E = h c / \Delta\lambda \quad (8)$$

$$E = 6.626 \times 10^{-34} \times 2.998 \times 10^8 / (2.426 \times 10^{-12}) \quad (9)$$

$$E = 8.188 \times 10^{-14} \text{ joules} \quad (10)$$

The photon energy, E, in electron volts, eV, can be obtained by dividing the energy in joules by the electronic charge, e, which is 1.602×10^{-19} coulombs. Therefore:

$$E = 8.188 \times 10^{-14} / 1.602 \times 10^{-19} = 0.511 \text{ MeV} \quad (11)$$

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