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P1_6 Tipler Radiation Shielding

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Abstract

This paper investigates the use of copies of “Physics for Scientists and Engineers” by P. A. Tipler and G. Mosca to attenuate gamma rays. The number of copies of Tipler required to reduce a lethal beam of 100keV gamma rays delivering 8 Gy of radiation to a human being to a “safe” beam of 50 mGy was found to be 5 copies.

Introduction

The textbook *Physics for Scientists and Engineers* by P. A. Tipler and G. Mosca (henceforth referred to as Tipler) has somewhat of a notorious reputation amongst undergraduate physicists at the Department of Physics and Astronomy at the University of Leicester. All first year undergraduates at the department receive a copy of the book, the hardcover 6th edition of which is 1356 pages or 5.1cm thick [1]. A paper by Conlon et al. (2010) discusses the use of Tipler as armour against firearms [2]. In this paper the usefulness of Tipler as radiation shielding against gamma rays is investigated.

Theory

We begin by considering a narrow beam of monochromatic radiation perpendicularly incident upon a flat layer of material. The ratio of the intensity of the beam emerging from the material I to the incident intensity I_0 will be given by a modified form of the Beer-Lambert Law

$$\frac{I}{I_0} = \exp\left[-\left(\frac{\mu}{\rho}\right)x\right] \quad (1)$$

where μ/ρ is the mass attenuation coefficient and x is the area density of the material, given by

$$x = \sigma t$$

where σ is the macroscopic material density and t is the thickness of the material[3]. The mass attenuation coefficient can be determined for a chemical species experimentally but is dependent on the frequency of the incident radiation. However, the mass attenuation coefficient for a mixture or compound (assumed to be or approximated as homogeneous) can be found approximately using

$$\frac{\mu}{\rho} = \sum_i w_i \left(\frac{\mu}{\rho}\right)_i \quad (2),$$

where w_i is the fraction by mass of the ith species in the compound and $(\mu/\rho)_i$ is the mass attenuation coefficient of that species[4].

Let us consider a scenario in which a narrow, monochromatic gamma ray beam of known frequency is incident upon a human being. If we assume any radiation attenuated within the human is absorbed by body tissue and is ionising and therefore harmful, we can find the number of photons absorbed by the human being, given by

$$N_{abs} = N_i\left(1 - \frac{I}{I_0}\right) \quad (3),$$

where N_i is the incident number of photons. It is then trivial to find the energy absorbed by the human being from the incident beam. If we know the amount of energy in the form of ionising radiation that is lethal, we can determine the number of incident photons that will deliver a lethal dose, with the same being true for an arbitrarily limited safe dose. The ratio of numbers of safe to lethal photons is then trivially found.

To determine the thickness of a shield required to attenuate the calculated lethal incident beam of photons to a safe beam of photons, we simply rearrange equation (1) to give

$$t = -\left(\frac{\mu}{\rho}\right)^{-1}\frac{1}{\sigma}\ln\left(\frac{I}{I_0}\right) \quad (4),$$

where in this case I/I_0 is the safe-to-lethal photon number ratio.

Results

We shall consider the number of copies of Tipler required to reduce a lethal beam of 100 keV gamma rays to a "safe" level. We will assume the human the beam is incident upon is 70 kg. A radiation dose of 8 Gy (1 Gy = 1 J/kg) is almost invariably fatal [5], and in this case is equivalent to $3.5\text{x}10^{16}$ photons at 100 keV. The maximum allowable short term dose for emergency workers is 50 mSv (1 Sv = 1 Gy) [6] and in this case is equal to $2.19\text{x}10^{14}$ photons. Assuming a human being is 20cm thick and the beam is passing through soft tissue with a mass attenuation coefficient of $1.69\text{x}10^{-1}$ cm^2/g [7] the value of photons which must be incident upon the human being found using equations (1) and (3) to give a lethal dose is $3.62\text{x}10^{16}$ photons and the safe incident dose is $2.26\text{x}10^{14}$ photons. Therefore, the ratio of intensity emergent from the shielding to that incident upon the shielding required to render the lethal dosage safe is $6.24\text{x}10^{-3}$.

The mass attenuation coefficient of paper can be found using equation (2) by approximating paper to be 100% cellulose by mass. Cellulose is an organic polymer with a unit molecule of $C_6H_{10}O_5$ and a density σ of 1.5 gcm^{-3} [8]. Using the given chemical formula the fractions by mass for each of the constituent chemical species can be found trivially. The mass attenuation coefficients for each species at a given frequency of radiation can then be found from previously published experimental tables and the total mass attenuation coefficient of cellulose for that frequency can then be found. Using species coefficients given in sources [9], [10] and [11] we find the mass attenuation coefficient of cellulose to be 0.162 cm^2/g. Using equation (4), we find the thickness of paper required to attenuate the beam from the lethal incident dose to the safe incident dose to be 20.9cm. The thickness of Tipler as given in the introduction is 5.1cm. This means the minimum number of copies of Tipler required to safely attenuate the dose is 4.09, or 5 rounding up.

Discussion and Conclusion

The mass attenuation coefficient of lead for 100keV photons is 5.55 cm^2/g [12] and lead has a density of 11.3 g/cm^3, meaning the equivalent thickness of lead required to render the lethal beam safe is 0.08 cm, a factor of ≈261 times smaller. However, whilst there may be far more suitable materials for radiation shielding, this paper finds that is certainly feasible to shield oneself using academic textbooks in a pinch.

References

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