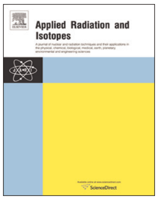
Applied Radiation and Isotopes 105 (2015) 11–14

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso



Finite and infinite system gamma ray buildup factor calculations with detailed physics

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HIGHLIGHTS

- Gamma ray buildup factors have been generated both for finite and infinite ordinary water systems.
- The importance of detailed physics calculations is emphasized for low energy gamma rays.
- Results of finite and infinite calculations are compared.

ARTICLE INFO

Article history:
Received 25 September 2013
Received in revised form
14 April 2015
Accepted 17 July 2015
Available online 20 July 2015

Keywords:
Buildup factor
Buildup
Radiation shielding
Coherent scattering
Monte Carlo method
MCNP

ABSTRACT

Examination of physical interactions of photons in materials is a significant subject for buildup factor studies. In most of the buildup calculations, by default, coherent (Rayleigh) scattering is ignored and the Compton scattering is modeled by free-electron Klein–Nishina formula with "simple physics" treatment. In this work, photon buildup factors are calculated for many different cases including "detailed physics" by taking into account coherent and bound-electron Compton scatterings with the Monte Carlo code, MCNP5, and the results are compared with the literature values. They are computed for point isotropic photon sources up to depths of 20 mean free paths and at the three photon energies most widely used (0.06, 0.6 and 6 MeV). Calculations are made for both finite and infinite homogeneous ordinary water media. It is concluded that Coherent scattering is very dominant at low energies and for deep penetrations and assumed physical approximation (simple/detailed, finite/infinite) is the critical point for determining shielding material dimensions. After all, it can be stated that all parametric assumptions should be clearly given and indicated in the tabulation of photon buildup factors.

1. Introduction

Shielding design calculations are carried out in order to protect the biological tissues and also the materials from the hazards of ionizing radiation. However, interaction of photons in the shielding medium occurs in a complex manner producing new (secondary) and scattered photons with different energy and directions. Hence, physicists and engineers should make some corrections to their calculations considering these secondary and scattered radiations. For this purpose, "the buildup factor" is used as a multiplier to the uncollided fraction of the incident photon beam response in the detecting material after passing the shielding. The response (or the physical quantity of interest) can be number and energy flux density, absorbed dose in water and tissue or exposure.

It is of prime importance, yet not the general case in the literature, to state explicitly which quantity of interest is used in the calculations. In addition, since the buildup factors are traditionally given for infinite medium calculations in the literature (Goldstein and Wilkins, 1954; Chibani, 2001; Harima et al., 1991; Hirayama, 1995), their utilization is not suitable for shields of finite thickness. In most of the studies, calculations of the interactions of photons within the medium are performed by using "simple physics" treatment in which coherent scattering is ignored and the Compton scattering is modeled using free-electron Klein–Nishina formula. In addition, no assumptions about the geometry of the system and the physical interaction mechanisms are given in the buildup factor calculations in some studies (Sardari et al., 2009, 2011). All these factors undoubtedly introduce errors to dose calculations depending on the type and thickness of the material and energy of the photon source.

In this work, the main goal is to show the importance of using the proper definition of buildup factor in dose calculations. For this

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http://dx.doi.org/10.1016/j.apradiso.2015.07.019

purpose, number and energy flux density, water and tissue equivalent absorbed dose and exposure point isotropic buildup factors are generated for three typical energies in both finite and infinite ordinary water media up to 20 mean free paths (mfps) using the Monte Carlo code MCNP5 (X-5 Monte Carlo Team, 2003). Then, in order to see the effects of ignoring some physical mechanisms, "detailed physics" buildup calculations including coherent scattering and form factors to account for the bound-electron Compton scattering are included. All calculations are analyzed in detail and compared with the published standard (ANSI/ANS-6.4.3, 1991) in the literature. Literature standard (ANSI/ANS-6.4.3, 1991) has been withdrawn in 2001, but revision of the standard (Ryman et al., 2008) is in progress for updating. Meanwhile, using the ANSI/ANS-6.4.3 (1991) standard is proper for low- and medium-Z materials, where possible discrepancies are expected to be small.

2. Methods

2.1. Definition of buildup factors

Buildup factor data are conventionally presented as a function of the shielding thickness in mfp lengths which is calculated as the total linear attenuation coefficient of the shielding medium for the initial energy of photons multiplied by the thickness in centimeters as

$$mfp = \mu_{tot} R \tag{1}$$

The total linear attenuation coefficient can be written as the sum of contributions from the primary photon interactions:

$$\mu_{tot} = \mu_{pe} + \mu_{coh} + \mu_{incoh} + \mu_{pair} + \mu_{pn} \tag{2}$$

where μ_{pe} is the atomic photoelectric effect coefficient, μ_{coh} and μ_{incoh} are the coherent (Rayleigh) and the incoherent (Compton) scattering coefficients, respectively, μ_{pair} is the coefficient for electron–positron production and μ_{pn} is the photonuclear coefficient.

For a fixed value of mfp, the physical dimension of the shielding may vary according to the physical assumptions in the calculation of total attenuation coefficient. In most buildup factor calculations, it is assumed that photons are scattered by free electrons, and coherent (Rayleigh) scattering is not considered.

When the binding energy of electrons is included in the calculations by multiplying the Klein–Nishina free electron distribution by an appropriate scattering function, the scattering is called incoherent scattering. The energy of an incoherently scattered photon is calculated from the sampled scattering angle. If available, this energy is modified to account for the momentum of the bound electron. The interaction is named coherent scattering when a photon is scattered by an atom and its energy is not changed substantially. Form factors are used with the proper distribution to account for Coherent scattering.

The photon buildup factor is a correction multiplier for the Compton scattering into the detector. Buildup factor can be defined in a number of ways for each physical quantity of interest. In this work, three definitions are presented using the notation in Kase and Nelson (1978) as follows:

Normal Flux Density Buildup Factor:

$$B(r) = \frac{\int \phi(r, E)\, \mathrm{d}E}{\int \phi_0(r, E)\, \mathrm{d}E} \tag{3}$$

is the ratio of the actual flux of photons of all energies to the flux of uncollided photons beyond a shield.

Energy Flux Density Buildup Factor:

$$B_E(r) = \frac{\int I(r, E)\, \mathrm{d}E}{\int I_0(r, E)\, \mathrm{d}E} \tag{4}$$

is the ratio of the actual energy flux to the energy flux of the unscattered beam.

Exposure Dose Buildup Factor is given by the following expression:

$$B_{d,material}(r) = \frac{\int \frac{\mu_{en,material}(E)}{\rho} I(r, E)\, \mathrm{d}E}{\int \frac{\mu_{en,material}(E)}{\rho} I_0(r, E)\, \mathrm{d}E} \tag{5}$$

where ϕ_0 and ϕ are the uncollided and total number flux densities, respectively, I_0 and I are the uncollided and total energy flux densities, respectively, $\mu_{en}(E)/\rho$ is the mass energy absorption coefficient of the related material. Here, B_x notation will be used when the related material is *air* and will be called as 'exposure buildup factor'.

2.2. Monte Carlo approach

Experimental methods can be used to calculate the buildup factor. However, since the interaction cross sections of photons with various materials can be obtained accurately and also with the development of sophisticated machines, simulation methods are mostly utilized. Photon transport in water is simulated with MCNP5 in this work. It is a general-purpose, continuous-energy, generalized-geometry Monte Carlo transport code. The user can instruct MCNP5 to make various tallies such as photon flux across any set of surfaces. In infinite medium calculations, for a mono-energetic point source in a spherical geometry, surface tallies are placed at six different points up to 20 mfps in a 100-mfp infinite homogeneous system and the photon fluxes are taken at each surface point. On the other hand, a single geometrical model is constructed and individual runs are made for each detection point (e.g., a 2 mfps sphere for buildup calculation at 2 mfps and a 4 mfps sphere for buildup calculation at 4 mfps) and then the flux at the outer surface is used to calculate the related buildup factor value in finite medium buildup computations. In both procedures, the outside medium is assumed to be vacuum.

The total attenuation coefficients with the simple and detailed physics approaches are used to determine the mfps individually. In order to compute the thickness values for the related mfp lengths for the surfaces in MCNP5 for water shielding, the total attenuation coefficients are hand-calculated from the ENDF/B-VI.8 data library derived from EPDL97 (Cullen et al., 1997). It would be compatible with MCNP5 as the code uses that photon library to simulate the interactions. The cross-section data of each material and the mass energy absorption coefficients of air affect the exposure buildup factors. The same database must be used to check the computational method by comparing the results from different calculation methods. The unscattered photon fluxes are found using 'FT' and 'FU' tallies which discriminate particles by collisions. The mass energy absorption coefficients of liquid water, ICRU-44 Soft Tissue and air are taken from the compilation of Hubbell and Seltzer (2004).

Many particle (10 million) histories and particle splitting techniques are utilized for variance reduction. In particle splitting method, a particle is split into many particles each having less weight in order to compensate for an increase in number when it arrives at the point of interest (Hirayama, 1995). All calculations are performed using Intel® Xeon® CPU E3110 @ 3.00 GHz processor with eight cores.