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Determination of effective atomic numbers, effective electrons numbers, total atomic cross-sections and buildup factor of some compounds for different radiation sources

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HIGHLIGHTS

- The photon interaction parameters have been measured for some chemical compounds.
- The effective atomic numbers (Z_{eff}) depends on the range of atomic numbers of elements in the compound.
- The buildup factor increased with the increasing collimator diameter.
- The effective atomic numbers (Z_{eff}) value depends on the photon energy and buildup factor.

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ABSTRACT

The photon interaction parameters such as mass attenuation coefficient, effective atomic number, effective electron density, buildup factor have been measured for $Fe(NO_3)_3$, V_4O_2, $NaCO_3 \cdot H_2O$, $C_6H_5FeO_7 \cdot H_2O$ and CuCl compounds using ^{137}Ba, ^{157}Gd and ^{241}Am γ-rays sources in stable geometry. The mass attenuation coefficients have been determined experimentally via Energy Dispersive X-ray Fluorescence Spectroscopy (EDXRF) system and theoretically by using WinXCom computer program. Then, effective atomic numbers, Z_{eff}, and electron densities, N_{eff}, have been calculated by using the mass attenuation coefficients. The obtained values of effective atomic numbers have been compared with the ones calculated according to a different approach proposed by Hine and the calculated ones from theory. Also, photon buildup factors were obtained by changing collimator diameters in the different photon energies. We observed that the buildup factor increased as the collimator diameter increased for all sources used.

1. Introduction

In recent years, the study of photon matter interaction parameters such as mass attenuation coefficient, effective atomic number, effective electron density, buildup factor and photon interaction cross-section in compounds (or materials) have attained significant increasing use of radioactive sources in gamma-ray fluorescence studies, medicine, radiation physics and chemistry, industrial applications and agriculture etc. Also, the dependence of photon interaction upon atomic number Z has many applications in radiation studies and other fields involving radiation matter interaction. Thus, the knowledge of these parameters is absolutely necessary. These parameters have determined for Fe $(NO_3)_3$, V_4O_2, $NaCO_3 \cdot H_2O$, $C_6H_5FeO_7 \cdot H_2O$ and CuCl compounds in this study.

Because radiation used in the many areas is dangerous for living, it is important to eliminate the effects of primary and secondary radiation in shielding technology. The photon forwarding in the material exposes many scattering (Compton scatter and Photoelectric effect, e.g.) and the secondary radiations occur as a result of the scattering. The precise determination of the radiation rate depends on the correct measurement of total absorbed photon for studies involving radiation in nuclear areas and dosimeter. Calculations of the energy absorbed in a medium include not only the additive of the uncollided photons from the source, but also include the additive from collided and secondary photons. The energy absorption buildup factor is the product of the Compton Scattering known as the ratio of the total energy absorbed due to uncollided, collided, and secondary photons to the energy absorbed due to only uncollided photons (Overcamp, 2009). There are many studies on the effective atomic number and the buildup

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factors in the literature (Brar and Mudahar, 1995; Sharma et al., 2012; Singh et al., 2003; Manohara et al., 2010; İçelli et al., 2013). Shimizu et al. (2004) calculated the ratio of buildup factor depending different thickness and energy for some elements. Variations of buildup factor with absorber thickness were reviewed for different values of scatter acceptance angle (Changing the diameter of collimator) in high volume fly ash concrete and water by Singh et al. (2008).

The mass attenuation coefficient (μ/ρ) is the parameter which evaluates probability of interaction of photon with the matter and is measured in cm^2/g. It is the essential parameter to provide many other photon interaction parameters such as atomic cross-section, electronic cross-section, equivalent and buildup factor, electron density, effective atomic numbers etc. In this direction, one of the first studies on the mass absorption coefficient was made for 32 elements Z = 1to90 and the photon energy range between 30 eV and 2.5 MeV by Allen (1935). In later years, measurements of (μ/ρ) values are made for different energy ranges and Z atomic numbers (Brown, 1966; Biggs and Lighthill, 1971; Veigele, 1973). Mass attenuation coefficients of some compounds and mixtures of dosimetric in the energy range 1 keV–20 MeV were determined by Hubbell (1982). Berger and Hubbell (1987) developed a computer program that calculates theoretically attenuation coefficients for any element, compound or mixture. Then Gerward et al. (2001, 2004) improved the program and its name as WinXCom. It can calculate attenuation coefficients of elements, compounds and mixtures atomic numbers from 1 to 100 and energy of up to 100 GeV.

The atomic numbers of compounds, alloys and composite materials, as in the pure elements cannot represented by a single number in the different energy regions. This number for compounds, alloys or mixtures is named as the "effective atomic number", Z_{eff}, and it varies with the photon energy. This concept has been introduced for the very first time by Hine (1952). Effective electron density, N_{eff}, is a measurement the number of electrons per unit mass of the interacting substance. The increase in the electron density increases the chances of photon interactions. Literature is rich of experimental as well as theoretical studies regarding effective atomic number and electron density in which radiation sources of X- and/or gamma-rays are used (El-Kateb et al., 2000; Gowda et al., 2004; Manjunathaguru and Umesh, 2006; Kaewkhao et al., 2008; Cevik et al., 2008; Manohara et al., 2008, 2009; Han and Demir, 2009; Sidhu et al., 2012; Elmahroug et al., 2015).

In present study, mass attenuation coefficient, effective atomic number, effective electron density, buildup factor of $Fe(NO_3)_3$, V_4O_2, $NaCO_3 \cdot H_2O$, $C_6H_5FeO_7 \cdot H_2O$ and CuCl compounds have been determined experimentally for different radiation sources emitting photons of different energy. These parameters (except for buildup factor) of the compounds have been calculated for the same energies. Also we have investigated change of buildup factor with increasing photon interaction in material for different sources. Chemical compounds used in the study are especially useful in the manufacture of some special steels, analytical chemistry, glass production, as a wetting elements in brick-making and applications related of humidity indicator.

2. Theoretical formulation

2.1. Mass attenuation coefficient

The mass attenuation coefficient is a measurement of scattering or absorption of incident light depending on the chemical properties of the material, per unit mass. If the intensity of the incoming radiation on materials is known, the mass attenuation coefficient is a useful parameter for finding the radiation leaving from the materials. This process is described by the following equation:

$$I = I_0 e^{-\mu x} = I_0 e^{-\left(\frac{\mu}{\rho}\right)t} \tag{1}$$

where I_0 is the original intensity of the beam ; I is the intensity of the beam after attenuation into the substance; μ/ρ is the mass attenuation coefficient (cm^2/g) and t is sample mass thickness (g/cm^2) (the mass per unit area). If I and I_0 are the measured count rates in detector respectively with and without the absorber of thickness x (cm) of the absorber, the linear attenuation coefficients (μ) (and consequently the mass attenuation coefficients) can be extracted by Lambert-Beer Law:

$$\mu = \frac{1}{x}\ln\left(\frac{I_0}{I}\right) \tag{2}$$

The same experimental procedure (and condition) was repeated for different radiation sources to determine the mass attenuation coefficients. After determining the mass attenuation coefficients of compounds experimentally, it has been obtained theoretically by using WinXCom computer program. The experimental and theoretical values of the mass attenuation coefficients of compounds have been used to determine the total atomic cross-section, σ_a.

2.2. Effective atomic number (Z_{eff})

The atomic numbers of chemical compounds or mixtures cannot be represented by a single number for all energies as in the elements. So the effective atomic number, Z_{eff}, is the term used for composite samples. It can be obtained by using of the atomic number of each elements and the total atomic cross-section. The total atomic cross-section (σ_a) is given by the following formula;

$$\sigma_a = \frac{(\mu/\rho)_{comp}}{N_A \sum_i w_i/A_i}(barns/atom) \tag{3}$$

where $(\mu/\rho)_{comp}$ is the mass attenuation coefficient of the compound, N_A is the Avogadro constant, w_i is the fraction by weight of the element i, and A_i is the atomic weight of the ith element. After determining the total atomic cross-sections of compound experimentally, it has been obtained theoretically by using WinXCom computer program. The experimental and theoretical values of the total atomic cross-section, σ_a, of compounds have been used to determine the effective atomic number, Z_{eff}. The total atomic cross-section values of samples were interpolated in the total atomic cross-section values of elements generated from WinXCom (Gerward et al., 2004) at the selected energy to calculate the effective atomic number (Z_{eff}) using the following logarithmic interpolation formula (Singh et al., 2007):

$$Z_{eff} = \frac{Z_1(log\sigma_2 - log\sigma) + Z_2(log\sigma - log\sigma_1)}{log\sigma_2 - log\sigma_1} \tag{4}$$

where σ_1 and σ_2 are the atomic cross-sections (barns/atom) in between which the atomic cross-section σ of the material lies and Z_1 and Z_2 are atomic numbers of the elements corresponding to the cross-sections σ_1 and σ_2, respectively.

The mean atomic number $(\bar{Z})$ has been suggested by Müller (1954) and Lloyd (1987).

$$\bar{Z} = \sum_{i=1}^{n} w_i Z_i \tag{5}$$

Another approach of effective atomic number (Z_{eff}) put forward by Hine is as follows.