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Determination of mass attenuation coefficients and effective atomic numbers for compounds of the 3d transition elements

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HIGHLIGHTS

- The mass attenuation coefficient depends on photon energy and chemical content.
- The effective atomic number depends on photon energy and chemical content.
- The mass attenuation coefficient decreases with increasing photon energy.
- The experimental and theoretical results are consistent with each other.

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ABSTRACT

In this study, we aimed to determine mass attenuation coefficient (μ_m) and effective atomic number (Z_{eff}) for some compounds of the 3d transition elements such as CoO, CoF_2, CoF_3, Cr_2O_3, CrF_2, CrF_3, FeO, Fe_2O_3, MnO_2, TiO_2, V_2O_3, VF_3, V_2O_5, VF_4 and ZnO at 19.63 and 22.10 keV photon energies by using an HPGe detector with a resolution of 182 eV at 5.9 keV. The experimental results of μ_m are compared with the theoretical results. Also, effective atomic numbers of compounds of the 3d transition elements have been determined by using experimental and theoretical mass attenuation coefficients. The agreement of measured values of effective atomic numbers with theoretical calculations is quite satisfactory.

1. Introduction

The photon attenuation is a mechanism that interacting with the matter of gamma or x-rays and has an importance characterized the penetration and diffusion of x-and gamma rays in multi element materials. The photon attenuation coefficients are required in nuclear science, engineering, industry, medicine and agriculture (Knoll, 2000). Mass attenuation coefficient is a measure of the average number of interactions between incident photons and matter that occur in a given mass per unit area thickness of the substance under investigation (Jackson and Hawkes, 1981; Kerur et al., 1991). Effective atomic number is a number to characterize the composite material and this number provides conclusive information about the complex medium when gamma radiation beam is incident on it (Hine, 1952).

We have investigated compounds of the 3d transition elements for benefits of technology, biomedical, space, and automotive usage (an alloying agent in steel, non-ferrous metals, dental filling, electroplated protective coating, fuel cell electrodes etc.). Mass attenuation coefficients and effective atomic numbers are very important for understanding physical properties of 3d elements, compounds, metals and their alloys have played an important role in the development of modern technology.

Various studies were carried out about the calculation of these atomic parameters through theoretical and experimental methods in the 2000 s. Han and Demir (2009a,b,c) determined the mass attenuation coefficients, effective atomic and electron numbers for Cr, Fe and Ni alloys at different photon energies. Mass attenuation coefficients, effective atomic and electron numbers of Ti and Ni alloys are investigated by Han and Demir (2009a,b,c). Han and Demir (2009a,b,c) studied the effective atomic numbers, electron densities from mass attenuation coefficients in Ti_xCo_{1-x} and Co_xCu_{1-x} alloys. Han et al. (2012) measured effective atomic numbers at 22.1, 25.0, 59.5 and 88.0 keV incident photon energies for Ti, Cr, Fe, Co, Ni and Cu metals with a new semi-empirical approach.

Akkurt (2007) has made effective atomic numbers for Fe-Mn alloy using transmission experiment. Sidhu et al. (2012) determined mass attenuation coefficients, effective atomic numbers

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and electron densities for some low Z compounds of dosimetry interest at 59.54 keV incident photon energy. Limkitjaroenporna et al. (2013) measured mass attenuation coefficients and effective atomic numbers for Inconel 738 alloy for different energies obtained from Compton scattering. Mohammed et al. (2012) studied mass attenuation coefficients for $Ni_{100-x}Al_x$, $Zn_{100-x}Al_x$ and mixtures with different weight ratios. Singh et al. (2014) determined effective atomic numbers using different methods for some low Z materials. Kaewkhao and Limsuwan (2010) studied mass attenuation coefficients and effective atomic numbers in phosphate glass containing Bi_2O_3, PbO and BaO at 662 keV. Küçük et al. (2013) measured mass attenuation coefficients, effective atomic numbers and effective electron densities for some polymers. Trunova et al. (2015) measured x-ray mass attenuation coefficients in biological (mussel and oyster tissues, blood, hair, liver, and cabbage leaves) and geological samples (baikal sludge, soil, and alaskite granite) in the energy range of 7–12 keV. Elmahroug et al. (2015) determined total mass attenuation coefficients, effective atomic numbers and electron densities for different shielding materials. Akman et al. (2015) studied effective atomic numbers, electron densities from mass attenuation coefficients near the K edge in some samarium compounds ($SmCl_36H_2O$, $Sm(NO_3)_36H_2O$ and $Sm(SO_4)_3$.) Al-Masri et al. (2013) measured mass attenuation coefficients of soil and sediment samples using gamma energies from 46.5 to 1332 keV. İçelli et al. (2011) determined total mass attenuation coefficients and effective atomic numbers for concentrated colemanite and Emet colemanite clay. Kore and Pawar (2014) measured mass attenuation coefficient, effective atomic number and electron density of some amino acids. Önder et al. (2012) determined mass attenuation coefficient, effective atomic number and electron density of some thermoluminescent dosimetric compounds.

In the present work, we aimed to determine mass attenuation coefficient and effective atomic number for some compounds of the 3d transition elements such as CoO, CoF_2, CoF_3, Cr_2O_3, CrF_2, CrF_3, FeO, Fe_2O_3, MnO_2, TiO_2, V_2O_3, VF_3, V_2O_5, VF_4 and ZnO at 19.63 and 22.10 photon energies by using an HPGe detector with a resolution of 182 eV at 5.9 keV in a transmission geometry. The experimental results are compared with theoretical mass attenuation coefficients and effective atomic numbers. The agreement of measured values with theoretical calculations is quite satisfactory.

2. Materials and methods

A narrow beam of mono-energetic photons with incident intensity I_0, penetrating a layer of material with mass thickness t (the mass per unit area) and density ρ emerges with intensity I given by the exponential attenuation law

$$I = I_0 \exp[-\mu_m t] \tag{1}$$

where I/I_0 is the transmission fraction T. Mass attenuation coefficient μ_m is defined

$$\mu_m = \frac{\mu}{\rho} \tag{2}$$

where μ is the linear attenuation coefficients and varies with the density of the absorber, even if the absorber is the same. The theoretical μ_m values for present samples were obtained by WinXCom program (Berger and Hubbell, 1987/1999). Effective atomic number Z_{eff} is given by

$$Z_{eff} = \frac{\sum_i n_i A_i (\mu/\rho)_i}{\sum_i n_i A_i / Z_i (\mu/\rho)_i} \tag{3}$$

where Z_i and A_i are the atomic number and the atomic mass of the ith element present in a molecule, respectively.

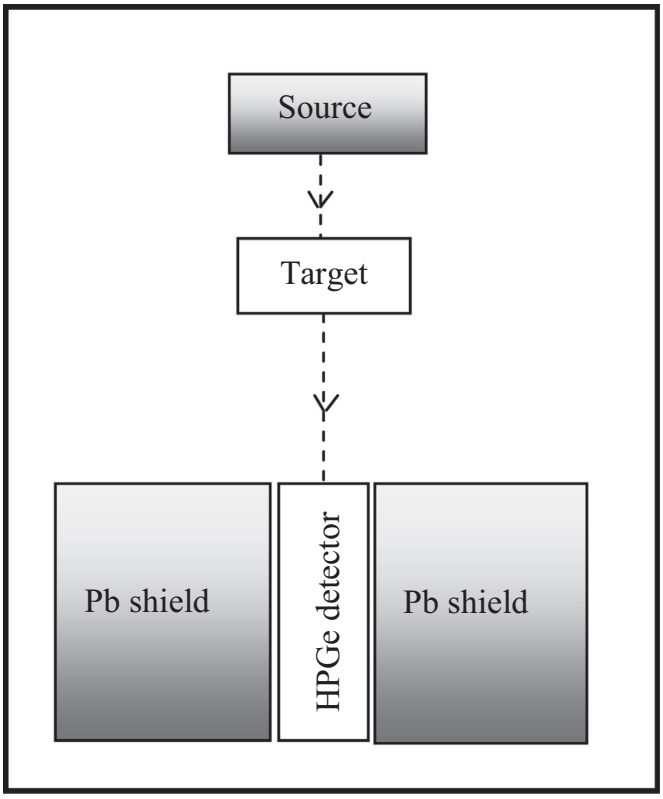

Fig. 1. Experimental setup.

The maximum errors in the measurement of mass attenuation coefficient were calculated from errors in intensities I_0 (without sample), I (with sample) and densities using the following relation

$$\Delta(\mu_m) = \Delta(\mu/\rho) = \frac{1}{\rho t}\left\{\left(\frac{\Delta I_0}{I_0}\right)^2 + \left(\frac{\Delta I}{I}\right)^2 + \left[\ln\left(\frac{I_0}{I}\right)\right]^2\left[\left(\frac{\Delta\rho}{\rho}\right)^2 + \left(\frac{\Delta t}{t}\right)^2\right]\right\}^{1/2} \tag{4}$$

The experimental setup used in the present study is shown in Fig. 1. The source-sample and sample-detector distance was set to 45 mm and 55 mm, respectively. The transmission range is $0.5 \geq T \geq 0.02$ for the HPGe detectors. The samples of thickness ranging from 0.120 to 0.243 g/cm^2 were prepared in the form of 0.65 mm radius cylindrical pellets by pressing in a hand-operated hydraulic press. In order to irradiate the compounds, a variable energy x-ray source from Amersham (AMC.2084) was used. This source contains a sealed ceramic primary source (Am-241 of intensity 10 mCi) that excites characteristic x-rays from six different targets (Cu, Rb, Mo, Ag, Ba and Tb) in turn. In this study, the used energies were 19.63 and 22.10 keV that the weighted averages of Kα and Kβ energies of Ag and Mo secondary targets, respectively. Photon intensities were measured using a DSG planar HPGe detector. The detector has a diameter of 16 mm, a length of 10 mm, a beryllium window of 0.12 mm, active area of 200 mm^2 and a resolution of 182 eV at 5.9 keV. The applied bias voltage to the detector is −1500 V. In this work, the studied compounds were CoO, CoF_2, CoF_3, Cr_2O_3, CrF_2, CrF_3, Fe_2O_3, FeO, MnO_2, TiO_2, V_2O_3, VF_3, V_2O_5, VF_4 and ZnO. The spectra were recorded using by a Canberra (AccuSpec) PC-based multichannel analyzer card. The time constant of the Ortec model 472 amplifier was set to 6 μs, ensuring optimum detector performance as specified by manufacturers. Operating parameters of the system are governed and controlled by the computer program Genie-2000. The pulse height spectra of