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Gamma rays' shielding parameters for some Pb-Cu binary alloys

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ABSTRACT

Binary alloys of xPb-(1-x)Cu where x varies from 0.1 to 0.9 with the increment of 0.1 were prepared. The physical properties and gamma rays' shielding parameters in terms of density (ρ), attenuation coefficient (μ_m), mean free path (mfp), half value thickness (HVT), tenth value thickness (TVT), effective atomic number (Z_{eff}), effective electron number (N_e), radiation protection efficiency (RPE) and exposure buildup factor (EBF) were studied for the prepared alloys. Using narrow beam geometry, transmitted photon spectra were recorded with the help of GAMMARAD5 (scintillator detector of NaI(Tl) crystal dimensions 3″ × 3″ having resolution of 6.5% at 662 keV) and radioactive isotopes of Na^{22} (511 keV), Cs^{137} (662 keV) and Mn^{54} (835 keV). These recorded spectra were analysed to compute μ_m values; which were further used to compute mfp, HVT, TVT, Z_{eff}, N_e (in energy region 1 keV–100 GeV) and EBF (in energy region 15 keV–15 MeV). Good agreement has been observed between the experimentally measured and theoretically generated results. The shielding parameters for the alloy samples were analysed on the basis of chemical composition, energy and penetration thickness.

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1. Introduction

The use of radioactive isotopes especially gamma – sources has been increased exponentially since its invention. These radioisotopes become an essential tool in different fields' viz. medicine, industry, agriculture and space exploration etc. Besides numerous applications of these sources, the exposure for longer duration of these highly energetic and penetrating photon beam can be harmful to living cells/tissues/organs as well as surrounding environment. Hence, to protect the human beings from harmful biological effects of these radiations, some shielding materials such as lead, steel and concrete were suggested; which must possess higher atomic number and higher density. Radiation physicists and nuclear engineers are always in a search of materials with better radiation absorption properties. So, radiation interaction (especially gamma rays; due to large penetration powers) with materials and comparative studies of radiation shielding parameters among proposed and existing shielding materials becomes fascinating field of research.

The shielding effectiveness of materials can be examined on the basis of different parameters which includes mass attenuation coefficient (μ_m), mean free path (mfp), half value thickness (HVT), tenth value thickness (TVT), effective atomic number (Z_{eff}), effective electron number (N_e) and exposure buildup factor (EBF). Extensive work has been carried out to visualize the scope of various types of materials as gamma rays shielding material. Enormous work has been reported relevant to investigations of μ_m values in various types of materials [1,2,3,4,5]. Gerward et al. [6] reported the mass attenuation coefficient software package in windows version which is known as 'WinXCom'. Recently, Kaur et al. [7] reported optimum thickness for experimentally measuring mass attenuation coefficients for some alloys. Further, penetration thickness of material can be expressed in terms of various parameters viz. mean free path (mfp), half value thickness (HVT) and tenth value thickness (TVT). These are important factors in normalizing the thickness for comparing two or more materials. Kaur et al. [8] and Kaur et al. [9] reported mfp values for some concretes and heavy metal oxide glasses, respectively. Akkas [10] reported HVL

Abbreviations: Pb, Lead element; Cu, Copper element; ρ, Density (g/cc); μ_m, Mass attenuation coefficient (cm^2/g); mfp, Mean free path (cm); HVT, Half value thickness (cm); TVT, Tenth value thickness (cm); Z_{eff}, Effective atomic number; N_e, Effective electron number; RPE, Radiation protection efficiency; GP, Geometric Progression; EBF, Exposure buildup factor; NaI(Tl), Sodium iodide thalium activated; keV, Kilo electron volt; MeV, Mega electron volt; GeV, Gega electron volt; Na^{22}, Sodium radioactive isotope with mass No. 22; Cs^{137}, Caesium radioactive isotope with mass No. 137; Mn^{54}, Manganese radioactive isotope with mass No. 54; Co^{57}, Cobalt radioactive isotope with mass No. 57; Co^{60}, Cobalt radioactive isotope with mass No. 60; Fcc, face centred cubic; ΔZ, Difference in atomic numbers.

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and TVL thicknesses for five types of concretes using a collimated beam of gamma rays from ^{60}Co source.

Effective atomic number (Z_{eff}) has been used as a tool to visualize the interaction of photon with multi-elemental material on the basis of atomic number. Different researchers had investigated Z_{eff} values for different type of materials: for alloys by El-Kateb et al. [11]; different types of materials by Manohara et al. [12]; for some solvents by Singh et al. [13]; for organic acids by Singh et al. [14]; for borate glasses and alloys by [15,16] and for Li_2O-B_2O_3 glasses by Kumar [17].

Radiation protection efficiency (RPE) measures the efficiency of the shielding material in terms of ratio of difference among incident beam from the monochromatic source on the detector (without any medium) and attenuated beam (due to the presence of shielding material between the source and the detector) to the attenuate beam. It is usually represented in percentage. Recently, Kumar [17] reported radiation protection efficiency for some glass samples.

Exposure buildup factor (EBF) not only extends the validity of Lambert Beer law but also helps in estimating the effectiveness of the shielding material. The methods mostly used for obtaining buildup factor values viz. geometric-progression (GP) fitting method: Harima et al. [19], ANS/ANSI 6.4.3 [20] and Harima [18], invariant embedding method: Shimizu [21], Shimizu et al. [22], iterative method: Suteau and Chiron [23]; Monte Carlo method: Sardari et al. [24], Icelli et al. [25] etc. EBF were reported mostly for low-Z compounds and mixture: polymers [26], human tissues [27], amino acids, fatty acids, carbohydrates [28], concretes [8], ceramics [29], boron compounds[25], bismuth borosilicate glasses [30], basalt rocks [31]and very less work has been reported for high Z materials: heavy metal oxide glasses, which includes PbO-Bi_2O_3-B_2O_3, PbO-B_2O_3, Bi_2O_3-B_2O_3 [32], Pb-Sn binary alloys [33], Tellurite glasses with different forming oxides [34].

Lead (with atomic size of 1.75 A°) forms face centred cubic (fcc) lattice with 12 co-ordination number with copper (with atomic size of 1.28 A°) as reported by Hofmann [35]. Since, there is large difference ($\Delta Z = 53$) among the atomic number of constituent elements: Cu ($Z = 29$) and Pb ($Z = 82$); an attempt has been made to systematically study the effect of concentration of lead on various shielding parameters. Hence nine samples of x Pb – (1-x) Cu were prepared, where x varies from 0.1 to 0.9 with the increment of 0.1. These samples were further used to experimentally measure and compute various shielding parameters: μ_m, mfp, HVT, TVT, Z_{eff}, N_e and RPE. The study has been extended for computing the EBF values for the same binary alloys in the energy region of 15 keV – 15 MeV and up to the penetration depth of 40 mfp.

2. Experimental details

Binary alloys studied in the present work have been prepared using metallic powders of Cu (purity of 99.7%) and Pb (purity of 99.0%) procured from Himedia, India. The metallic powders of Cu and Pb were weighed using digital balance (least count 0.001 g) and mixed in different proportions using pestle and mortar. The mixture was put in a die set of inner diameter 1.2 cm and the uniformly mixed metallic powder was placed under a fixed pressure of 9 ton to prepare pellets using KBr press. The different compositions and physical properties of alloys which are prepared in the form of pellets were listed in Table 1. It has been observed that pellet thickness of Pb-Cu samples decreases; whereas density of the samples increases with the increase in the concentration of Pb.

The experimental setup used for recording transmitted photon spectra to compute μ_m values of the prepared binary alloys has been shown in Fig. 1. Transmitted photon spectra were recorded using compact and portable GAMMARAD5 (3″ × 3″ sodium iodide-thallium activated scintillator detector, procured from AMPTEC Inc., USA; coupled with inbuilt multi-channel analyser and digital pulse processor), which was connected to laptop using USB cable for controlling the inputs (voltage, gain, coarse, pulse shape time etc.), storing the spectra for record and analysing. The detector and source were kept fixed at the distance of 10 cm from the sample holder (which was kept hollow at the centre with inner diameter of 1.2 cm). To minimize the gamma rays exposure, the lead housing with sufficient thickness was used to keep the gamma rays sources. The filter and collimator were made up of aluminium to minimize the background and Pb X-rays; these are rectangular in shape with cylindrical aperture of 0.4 cm. The well collimated photon beam has been obtained using these collimators. The centre of source housing, sample holder, collimators and the detector were aligned in a straight line using laser light. Whole experimental setup was placed at the centre of the room at the height of 40 cm from the floor, to avoid scattering from the walls and the floor. Before starting the experiment, the detector was calibration using different reference sources ^{57}Co, ^{22}Na, ^{137}Cs, ^{54}Mn and ^{60}Co procured from BRIT, India.

After calibration of the detector, the transmitted photon spectra were recorded for ^{22}Na without any sample (I_0) and after placing different alloy samples of thickness 'x' (provided in Table 1 for all alloy samples) one by one respectively in the sample holder (I_t). All the transmitted photon spectra were recorded for 600 s time period; so as to have more than 10,000 counts at the photopeak with sample (I_t) and without sample (I_0); thereby limiting the statistical error to be less than 1%. The process of recording the transmitted photon spectra for each sample was repeated thrice and average of the three recordings were used in computing the mass attenuation coefficient using Lambert Beer law given by:

$$I_t = I_0 e^{-(\mu/\rho)\cdot(\rho x)} \tag{1}$$

Similar process was used to record and analyse the transmitted photon spectra of ^{137}Cs and ^{54}Mn for all prepared alloys. The uncertainty in measuring mass attenuation coefficient can be computed using the expression:

Table 1
Physical properties of prepared alloys.

Sample	Chemical Composition (in weight percentage)	Mass of the prepared alloy (g)	Thickness of the prepared alloy (cm)	Density of the prepared alloy (g/cm^3)
Pb10Cu90	Pb:10%, Cu:90%	4.805	0.59	7.170
Pb20Cu80	Pb:20%,Cu:80%	4.995	0.60	7.340
Pb30Cu70	Pb:30%, Cu:70%	4.990	0.59	7.440
Pb40Cu60	Pb:40%, Cu:60%	4.970	0.59	7.490
Pb50Cu50	Pb:50%, Cu:50%	4.985	0.58	7.570
Pb60Cu40	Pb:60%, Cu:40%	4.910	0.54	7.980
Pb70Cu30	Pb:70%, Cu:30%	4.970	0.50	8.780
Pb80Cu20	Pb:80%, Cu:20%	4.980	0.48	9.212
Pb90Cu10	Pb:90%, Cu:10%	4.940	0.47	9.250

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