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Measurement of absorbed dose rate of gamma radiation for lead compounds

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ABSTRACT

An attempt has been made to estimate the absorbed dose rate using both theoretical and measured mass energy attenuation coefficient of gamma for the lead compounds such as $PbNO_3$, $PbCl_2$, PbO_2 and PbO using various gamma sources such as ^{22}Na (511, 1274), ^{137}Cs (661.6), ^{54}Mn (835) and ^{60}Co (1173, 1332 keV).

1. Introduction

The mass attenuation coefficient, $[\mu/\rho]_c$, describes the exponential attenuation of gamma photons within the compound, mass energy attenuation coefficient, $[\mu_{en}/\rho]_c$, measures the quantity of energy deposited within the mass of a compound and absorbed dose rate, dD/dt, defines the quantity of energy deposited per unit mass per unit time within the mass of a compound when a mono energetic narrow beam of a gamma radiation incident on the given compound. Hence, these three quantities have become prerequisites for both radiation dosimetry [1] and selection of compounds as radiation shielding materials used in design of spacecraft [2]. The suffix "c" signifies for compound. The tabulated values of mass energy attenuation coefficient of Seltzer and Hubbell [3] estimated for elements and few compounds based on theoretical calculations are considered to be the most reliable set of data among those available in the literature. However the evaluation of $[\mu_{en}/\rho]_c$ for other compounds based on the method suggested by Seltzer [4] is quite tedious, as it needs to make use of several expressions and various parameters such as average fraction of photon energy transferred to the kinetic energy of the charged particles, average kinetic energy of secondary charged particles produced in various interactions, mass energy transfer coefficient, etc. Manjunathaguru and Umesh [1] have tabulated $[\mu_{en}/\rho]_c$ for few selected H-, C-, N-, O-based compounds of biological interest for which the atomic number of elements is in the range 2–40, using a simple empirical second order polynomial relation. In the present study, we have made an attempt to write an empirical second order polynomial relation for both $[\mu/\rho]_c$ and $[\mu_{en}/\rho]_c$ in terms of energy E for lead compounds similar to the one suggested by them [1]. We have (i) evaluated the two numerical coefficients that appeared in both these expressions, (ii) established a relation between $[\mu_{en}/\rho]_c$ and $[\mu/\rho]_c$ and (iii) estimated $[\mu_{en}/\rho]_c$ from the knowledge of the measured and theoretical $[\mu/\rho]_c$ using the given relation. We have then estimated dD/dt from the knowledge of the known theoretical and measured $[\mu_{en}/\rho]_c$ values.

2. Present study

2.1. Mass attenuation coefficient

2.1.1. Experimental method

We have followed a narrow geometry experimental setup used in our previous work [5]. It is shown in Fig. 1. We have used a NaI(Tl) crystal detector ($3.8 \times 3.8\,cm^2$) mounted on a photomultiplier tube housed in a lead chamber with a sophisticated PC based 16 k MCA for a detection purpose, gamma sources such as ^{22}Na (511, 1274), ^{137}Cs (661.6), ^{54}Mn (835) and ^{60}Co (1173, 1332 keV) and $PbNO_3$, $PbCl_2$, PbO_2 and PbO as target compounds. The given compound in a powder form is filled in circular perspex holder of 1 cm diameter and a standard thickness of 1 cm. The compound was directly attached to the opening of the lead shield in which the source was placed. The integral intensities, I_0 and I of the beam before and after passing through the compound were measured for sufficient time. $[\mu/\rho]_c$ of the compound has been estimated using the relation

$$[\mu/\rho]_c = (1/t\rho)\ln(I_0/I)$$

where t and ρ are the thickness and density of the compound, respectively.

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2.1.2. Theoretical method

The theoretical $[\mu/\rho]_c$ has been estimated for the given compound and energy using the following mixture rule:

$$[\mu/\rho]_c = \sum_i \omega_i [\mu/\rho]_i \quad (1)$$

where $[\mu/\rho]_i$ is the mass attenuation coefficient (tabulated data of various constituent elements are available in Ref. [3]) and ω_i is the weight fraction of the ith element present in a molecule of the given compound respectively.

2.2. Mass energy attenuation coefficient

2.2.1. Experimental method

We have considered the following empirical second order polynomial relations similar to the one suggested by the author [1]:

$$\ln[\mu/\rho]_c = \sum_{i=0}^{2} n_i (\ln E)^i \quad (2)$$

$$\ln[\mu_{en}/\rho]_c = \sum_{i=0}^{2} m_i (\ln E)^i \quad (3)$$

n_i and m_i are the numerical coefficients that were evaluated using the known theoretical $[\mu/\rho]_c$ and $[\mu_{en}/\rho]_c$ of the various lead compounds in the energy range 400–1500 keV. These evaluated coefficients are shown in Table 1. The theoretical $[\mu_{en}/\rho]_c$ has been estimated similar to the one estimated for theoretical $[\mu/\rho]_c$, using the above mixture rule and the known values of $[\mu_{en}/\rho]_i$ of various constituent elements of the given compound. After substitution of these n_i and m_i, the above expressions reduce into the following forms:

$$[\mu/\rho]_c = 3.1071 \times 10^9 E^{[-6.24308 + 0.38974(\ln E)]} \quad (4)$$

$$[\mu_{en}/\rho]_c = 3.1847 \times 10^{11} E^{[-7.7393 + 0.49494(\ln E)]} \quad (5)$$

To verify the correctness of these two relations, we compared the estimated results obtained from the above two expressions with the values estimated from the mixture rule for several other lead based compounds, in the energy range 400–1500 keV. There was a good agreement between these two results. This confirms the correctness and simplicity of the above two empirical relations. Combining the expressions (4) and (5), the following expression was obtained:

$$[\mu_{en}/\rho]_c = [\mu/\rho]_c 102.497 \times E^{[0.1052 \ln E - 1.49622]} \quad (6)$$

Hence the experimental $[\mu_{en}/\rho]_c$ has been estimated by substituting the measured values of $[\mu/\rho]_c$ of the given lead compounds in the expression (6).

2.2.2. Theoretical method

The theoretical $[\mu_{en}/\rho]_c$ has been estimated by substituting the known theoretical values of $[\mu/\rho]_c$ of lead compounds in expression (6). These values were compared with the values

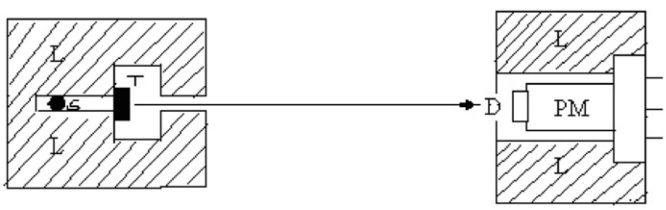

Fig. 1. Experimental setup.

Table 1
Estimated values of numerical coefficients.

n_i			m_i		
n_0	n_1	n_2	m_0	m_1	m_2
21.85697	−6.24308	0.38974	26.4868	−7.7393	0.49494

Table 2
Data of $(\mu/\rho)_c$, $(\mu_{en}/\rho)_c$ in cm²/g and (dD/dt) in μG/hr.

Energy (keV)	$PbNO_3$		$PbCl_2$		PbO_2		PbO	
	1	2	1	2	1	2	1	2
511	0.1350	0.1405	0.1350	0.1463	0.1400	0.1469	0.1460	0.1518
	0.0733	0.0761	0.0733	0.0741	0.0761	0.0816	0.0793	0.0857
	1.25E−05	7.05E−06	1.25E−05	6.86E−06	1.30E−05	7.56E−06	1.35E−05	7.94E−06
661.6	0.1000	0.1051	0.1000	0.1070	0.1070	0.1083	0.1020	0.1118
	0.0521	0.0761	0.0521	0.0527	0.0558	0.0567	0.0532	0.0588
	1.20E−05	6.46E−06	1.20E−05	6.33E−06	1.28E−05	6.80E−06	1.22E−05	7.06E−06
835	0.0806	0.0858	0.0801	0.0801	0.0830	0.0834	0.0831	0.0850
	0.0410	0.0409	0.0407	0.0402	0.0423	0.0423	0.0423	0.0435
	1.22E−05	6.20E−06	1.21E−05	6.10E−06	1.26E−05	6.41E−06	1.26E−05	6.59E−06
1173	0.0608	0.0615	0.06010	0.0617	0.0608	0.0624	0.0619	0.0623
	0.0304	0.0307	0.0301	0.0303	0.0305	0.0310	0.0310	0.0315
	1.29E−05	6.54E−06	1.28E−05	6.45E−06	1.29E−05	6.61E−06	1.32E−05	6.70E−06
1274	0.0574	0.0574	0.0569	0.0578	0.0570	0.0578	0.0574	0.0582
	0.0304	0.0291	0.0285	0.0288	0.0285	0.0294	0.0288	0.0297
	1.33E−05	6.75E−06	1.32E−05	6.66E−06	1.32E−05	6.80E−06	1.33E−05	6.87E−06
1332	0.0560	0.0568	0.0550	0.0565	0.0580	0.0565	0.0560	0.0561
	0.0281	0.0280	0.0276	0.0277	0.0291	0.0282	0.0281	0.0284
	1.35E−05	6.78E−06	1.33E−05	6.70E−06	1.40E−05	6.81E−06	1.35E−05	6.87E−06

1—experimental; 2—theoretical.

obtained from the mixture rule and from the knowledge of the tabulated data of mass energy attenuation coefficients of constituent elements [3] of the given lead compound. Both the results were found to agree with each other.

2.3. Dose rate

The dose rate, dD/dt, delivered to the compound at various gamma energies has been estimated, using the following relations:

$$dD/dt = 5.7672 \times 10^{-4} \Phi_E [\mu_{en}/\rho]_c \text{ in the unit of } \mu\text{Gy/hr} \quad (7)$$

Here,

$$\Phi_E = [(dN/dt) e^{-\mu_a r} / 4\pi r^2]$$

where Φ_E and dN/dt are the energy flux (MeV/m^{2}s) and activity of the gamma source, respectively, f the emitted gamma photons per decay, μ_a the attenuation coefficient of air (m^{-1}) and r the distance of the detector from the point source in the presence of the compound.

The measured and theoretical dose rates have been estimated by substituting the measured and theoretical $[\mu_{en}/\rho]_c$ in the expression (7).

3. Results and discussion

The estimated values of $[\mu/\rho]_c$, $[\mu_{en}/\rho]_c$ and dD/dt in the energy range 511–1332 keV for lead compounds are shown in Table 2. These values were found to decrease with the increase in energy. The measured and theoretical values agree with each other for a given energy. The error occurred in measurement of $[\mu/\rho]_c$ was estimated to be 2–3%, which arises due to counting statistics and peak area determination. It is expected that these data are useful in selection of materials used for shielding of gamma radiation.

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