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Determination of X-ray mass attenuation coefficients using HPGe detector

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ABSTRACT

A detail analysis of a method to determine the mass attenuation coefficient, μ_m, of low energy X-rays employing HPGe X-ray detector and radioactive sources is described. This method incorporates all the suggestions made by Creagh and Hubbell. An optimum distance is set under the broad beam as well as good geometry arrangement. The photon intensity is measured by gating the channel of the spectrometer at FWHM/photo peak. The selection of the absorber foils, optimum counting times are all done after detailed investigations for the μ_m value. The method is studied in detail using aluminum/nickel as an absorber since these are standard reference materials. From these results, we conclude that the "best value" for μ_m can be obtained for those thicknesses which lie in the transmission (T) range $0.5 \geq T \geq 0.02$. The measured values of μ_m for Magnesium, Nickel, Copper, Molybdenum and Tantalum and three biological equivalent materials are compared with standard theoretical values.

1. Introduction

The increasing application of low energy photons in a wide variety of fields necessitates the accurate measurements of the photon attenuation coefficients, μ_m, in various materials at different energies. From the survey of experimental methods (Table 1) the following points have been taken care off while measuring the photon intensity selection for the measurement of mass attenuation coefficients. Even in narrow beam geometrical configuration, the incident photon of energy E get degraded in energy, through small angle scattering and multiple scattering, and reaching the detector. If there were no proper energy discrimination made then they would be counted as 'true' counts having the energy E. The small angle scattering events can be minimized to the optimum level by proper selection of high Z material for the geometrical configuration. In the medium and high energy region multiple scattered photons may enter to the measured photon intensity but this can be avoided by avoiding the low Z material for the geometrical configuration. So some investigators have adopted different methods that could be applied within the limitations of the detector to avoid the small and multiple scattered photons entering into the detector. Some have counted photons that fall under the photo peak instead of counting the total (integral) counts. Some have counted with channels gated at different position of the photo peak and extrapolate the 'width' to zero graphically to obtain μ_m. This μ_m is believed to be 'free' from multiple scattering events. Table 1 gives the list of investigators and the methods employed by them.

In addition to this, Creagh and Hubbell (1987) have suggested that both the incident beam collimator and transmitted beam collimator must be varied to establish that the Laue–Bragg and small angle scattered photons are not counted. Further they have made a through analysis of the problems associated with the measurements of mass attenuation coefficient and laid down certain criteria to be followed in all such measurements. They pointed out that it is important to verify that the Beer–Lambert's is obeyed for the specimen under consideration, then and only then, can the measurements be made at those specimen thicknesses for which counting statistics can be optimized. Best results are obtained, according to them, for those thickness which satisfy $2 \leq \ln(I/I_0) \leq 4$ which corresponds to the transmission range $0.13 \geq T \geq 0.02$. They also recommended an experimental configuration consisting of collimators, samples mounted normal to the incident beam, monochromator and a solid state detector (Si(Li) detector) coupled to multichannel analyzer as the most suitable configuration for the photon energies range from 4 to 50 keV to obtained most reliable results.

Kerur et al. (1991) and Nagabhushan et al. (2004) also thoroughly investigated the problems associated with the moderate energy resolution detector viz., the proportional counter and NaI (Tl), when measuring the mass attenuation coefficient of X-rays. After a detail study they suggested criteria to be adopted in addition to the Creagh and Hubbell condition when moderate energy resolution detectors are used. However, the workable

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Table 1
List of different methods adopted by investigators to measure the X-ray intensity in X-ray attenuation experiments.

Authors	Energy (keV)	Detector	Method	Remarks
Hopkins (1959)	6–40	Proportional counter	Differential and integral Intensity	$Z=13$–50
Betterman et al. (1961)	17.44	NaI (Tl)	Integrated intensity	$Z=13$–29
Alonzo and Grodzins (1965)	5–10	Resonant (Massbauer) detector –		$Z=13$–79
DeMarco and Suortti (1971)	17.44	NaI (Tl)	Area under photopeak	$Z=12$–13
Miller and Greening (1974)	4–25	Proportional counter	Area under photopeak	$Z=7$–18
Lawrence (1977)	8–17	Proportional counter	Area under photopeak	–
Puttaswamy et al. (1979)	5–129	Proportional and thin NaI (Tl)	Channels symmetrically located around the pp	$Z=6$–82
Gerward (1981)	8–19	Si (Li) and monochromator	Energy dispersive method, integrated counts	$Z=14$
Rao et al. (1981)	5–42	Proportional counter	Area under photopeak	$Z=6$–66
Nathuram et al. (1984)	13–59	Proportional counter	Area under pp	$Z=3$–82
Gowda and Powers (1985)	1–8	Proportional counter	Area under pp	$Z=3$
Varier and Unnikrishnan (1986)	7–15	Proportional counter	Area under pp	$Z=13$
Creagh and Hubbell (1987)	8–60	Project IUCr	Various configurations	$Z=14$
Unonius and Suortti (1989)	5–11	Ge	Singular value decomposition	$Z=22$–30
Kerur et al. (1991)	5–10	Proportional counter	FWHM and PP	$Z=13$–82
Chantler et al. (2001)	8–20	Ionization chamber	Extended range technique	$Z=29$
Nagabhushan et al. (2004)	5–10	NaI(TI) X-ray detector	FWHM and PP	$Z=13$–82

range of the proportional counter is 3 to 25 keV and for the NaI(TI) detector is 3 50 keV, but the NaI(Tl) detector energy resolution is very poor compared with proportional counter.

In the present case, we have tried to investigate the problems associated when the high resolution HPGe detector system is used. A detailed investigation has also been done to measure μ_m for pure as well as mixed radiation source viz., ^{55}Fe and ^{57}Co radioactive sources, respectively, by following the conditions of Creagh and Hubbell to meet the basic requirements and in addition a strategy is adopted to minimize the unwanted radiation effects on μ_m value.

The advantage of the configuration involving HPGe X-ray detector is wide energy operational range from 3 to 500 keV and very good energy resolution. As a result of this, the energies of the photons degrade in energy due to small angle scattering and multiple scattering and K_α, K_β line detected by the detector are well resolved, if at all present. Therefore, μ/ρ, value obtained in such configuration is purely corresponding to the respective energies only i.e., K_α K_β and γ-rays.

2. Experimental

The experimental arrangement is shown in Fig. 1. The experimental consists of a mild steel (MS) stand into which two lead holders can be inserted. The upper holder holds both the source and collimator to collimate the incident beam, while lower one holds both the absorber and a collimator to collimate the transmitted beam. Their positions are so fixed that the absorber is at half way between the source and the detector and is placed normal to the beam. A broad beam geometry as well as good geometry setup is adopted for the photon intensity measurement. In case of good geometry arrangement a rigid stand positioned above the detector holds the source, specimen and collimator in place and ensures vertical alignment. And for the broad beam the source is kept at the same distance as except the collimators. Photons from the radioactive source S were collimated by the lead collimator C1 and were incident on the absorber AB placed normal to beam and midway between the source and detector. The photons transmitted passing through the second lead collimator C2 were detected by the HPGe detector.

A pair of lead collimator each of 3.5 cm thick with 6 mm diameter was used to collimator the photon beam. These two collimators are inserted at the middle positions of the collimation stand between source and detector of 10 cm distance. The sample/s is kept exactly at the mid position of the two collimators as shown in Fig. 1. To study the effects of small and multiple scattered photons by the absorber and collimators in a good geometrical arrangement, a pair of collimators of size 6 and 9 mm and broad beam were successively used which found to be about the angle of acceptance at the detector from the source is around 3° and 7° for 6 and 9 mm collimators, respectively. The fluorescence intensity due to collimator, stand and other components was found to be either far from the region of interest or negligible found from the observed spectra.

In present work, ^{55}Fe and ^{57}Co radioactive isotope each of about 740 kBq (20 μCi) strength were used. Both radioactive isotopes were procured from BRIT, Mumbai, India, in the form of standard X-ray source used in this experiment. The variable energy X-ray (VEX) source of 370 MBq (10 mCi) ^{241}Am is used as the primary source of excitation radiation. The 59.65 keV gamma photons from ^{241}Am were incident on the Copper and Rubidium target to produce fluorescent X-rays with characteristic energies of the target. The details of X-ray energies emitted by K_α and K_β from the above sources are given in Table 2 (Kortright, 1986). No noticeable impurities were found in these sources when their photon spectrum was analyzed using an HPGe detector. The inner bremsstrahlung intensity from the sources was found to be negligible compared to the X-ray intensity at the region of interest.

In our experiment, different background levels observed depending on the type of sources used in the experiment. The relative background varies from 10^{-3} to 10^{-1} for sources used in the present investigation; for these the T_{opt}, from the Rose and Shapiro (1948) graph, are found to be 0.12 and 0.20, respectively. Rose and Shapiro also plotted the optimum apportionment of counting times as a function of optimum transmission. From this graph we see that for $T_{opt}=0.12$ the fraction of counting times for incident, transmitted and background intensity, α_0, α_1 and α_2, respectively, are 0.2, 0.62, and 0.18 approximately, and for $T_{opt}=0.25$, $\alpha_0 \sim 0.2$, $\alpha_1 \sim 0.4$, and $\alpha_2 \sim 0.4$. This shows that in both the cases if we adjust time for the transmitted intensity such that the statistical error associated with it is $<1\%$; the same counting time method adopted for background and incident intensity to obtain good statistical accuracy all data measurements. Obviously this depends on the sources strength.

In the present measurement, Good fellow metal foils in the atomic number range from $12<Z<72$ with high purity range from