Effect of finite absorber dimensions on γ-ray attenuation measurements

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Using ^{137}Cs γ rays, the effect of finite absorber dimensions on attenuation measurements has been studied. Copper and mercury targets were used. Absorber dimensions up to five mean free paths were used. A correlated effect was observed in the measurements due to absorber thickness and its dimensions in the transverse directions. The values of the attenuation coefficients for copper and mercury have also been determined.

I. INTRODUCTION

One of the important requirements in experiments on γ-ray attenuation is that of narrow-beam geometry.[1] Such a geometry ensures that the "in scattering" of the incident γ rays is reduced to a minimum. This is essential, because only those γ rays which are transmitted through the absorber without undergoing any interaction should be detected. However, even with a narrow-beam geometry, if the thickness x of the absorber is greater than one mean free path, multiple scattering could affect the measured value of the attenuation coefficient (μ). Gopal and Sanjeevaiah[2,3] have demonstrated the effect of multiple scattering for μx varying up to 4.2 for 84- and 661.6-keV γ rays using carbon and lead absorbers. In their experiments, carried out with a sodium iodide detector, they observed a deterioration of the resolution of the detector as the absorber thickness increases above $1/\mu$, with a simultaneous increase in the value of the measured attenuation coefficient. Kane, Basavaraju, and Varier,[4] using a high-resolution Ge(Li) detector, however, could not observe a measurable effect up to $\mu x = 3$ for 1.116-MeV γ rays and a lead absorber.

An important factor which has not been considered in the previous studies is the dimensions of the absorber in directions perpendicular to the incident γ-ray beam. These transverse dimensions would also be expected to have some effect, through the multiple-scattering process, on the measured value of μ. In the previous experiments, the transverse dimensions were possibly less than or around one mean free path, and their effect could not have been seen at all. The present measurements were undertaken to study the effect of the transverse dimensions on measured attenuation coefficients using 661.6-keV γ rays and a mercury absorber. The absorber thickness dependence was reinvestigated using copper and mercury absorbers.

II. EXPERIMENTAL DETAILS

The 661.6-keV γ rays for the present measurements were obtained from a 1-mCi ^{137}Cs source supplied by the Bhabha Atomic Research Centre, Bombay. The copper absorbers were in the form of sheets of the dimensions $5 \times 5 \times 0.1$ cm^3. The mercury absorber was obviously in liquid form. It was taken in a beaker. In this case the thickness was varied by filling the beaker up to different heights (see below). The height of the mercury surface was measured by using a traveling microscope. The transverse dimensions (t) of the copper absorber were such that $\mu t = 1.7$. For mercury, transverse dimensions with μt varying from 2.3 to 5.44 were used. Variation of the transverse dimensions was effected by using beakers which had diameters of 3.3, 4.5, 6.3, and 7.9 cm and capacities of 50, 100, 250, and 500 cm^3, respectively. The absorbers were 99.9% pure.

The experimental arrangement is shown in Fig. 1. Vertical geometry was used for easiness of absorber thickness variation in the case of mercury. The collimators and shielding were of lead. The use of the collimators ensured a narrow-beam geometry with a maximum in-scattering angle of 0.64°.

A $2 \times 1\frac{1}{2}$-in.^{2} sodium-iodide detector was used for the

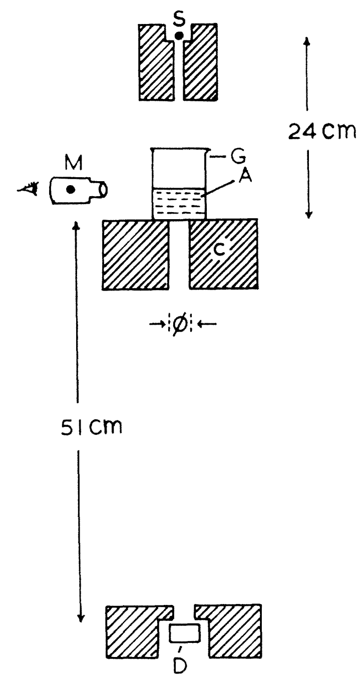

FIG. 1. Experimental arrangement for ^{137}Cs γ-ray attenuation measurements with copper and mercury absorbers.

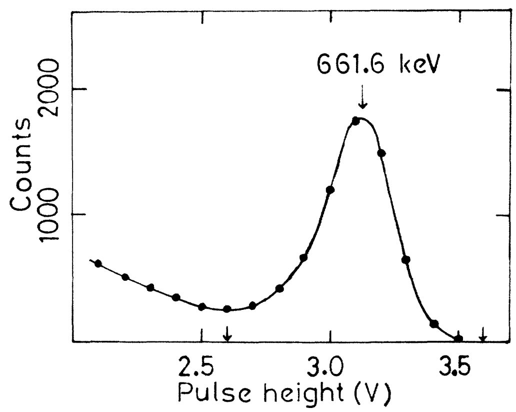

FIG. 2. Pulse-height spectrum of ^{137}Cs γ rays obtained with a $2\times1\frac{1}{2}$-in.^{2} NaI(Tl) detector and a SCA. The arrows on the x axis show the window setting used.

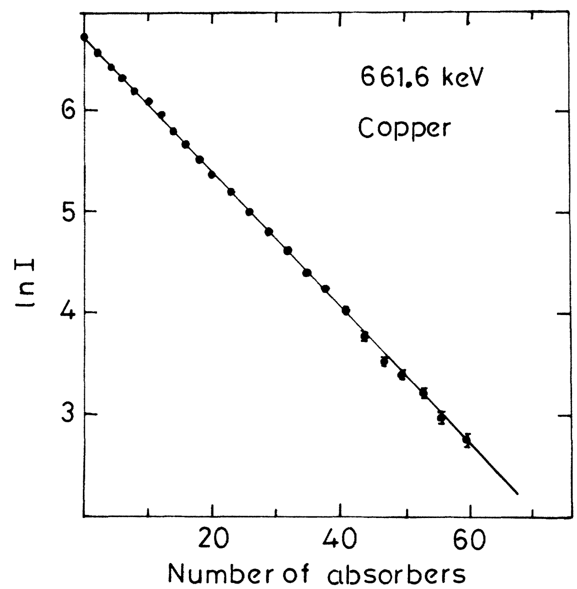

FIG. 3. Attenuation curve for the copper absorber. The copper absorber thickness is 0.926 g/cm^2 per sheet. The error bars shown are the statistical errors. For the initial few points, the errors are less than or equal to the size of the points.

measurements. The detector pulses were amplified by a suitable amplifier and fed to a single-channel analyzer (SCA) and scaler. The spectrum of 661.6-keV γ rays taken with the SCA is shown in Fig. 2. The arrows show the window setting of the SCA used in the measurements. The spectrum in the photopeak region was monitored periodically. It was found that there was no appreciable drift in the position of the peak during the measurements.

The background was measured by inserting a 15-cm-long lead block in the path of the direct γ-ray beam. Background measurement was also repeated at regular intervals. The total counts in the photopeak were taken for sufficient time periods to obtain statistical accuracy of better than 1% without any absorber and with accuracies ranging from 1% for the smallest absorber thickness used to about 6% for the largest thickness used. The net transmitted γ intensity I was determined for each absorber thickness x after background substraction.

III. RESULTS AND DISCUSSION

Plots of $\ln I$ versus x for copper and for mercury are given in Figs. 3 and 4, respectively. For mercury, plots for four values of the transverse dimension t are given.

It is seen from Fig. 3 that for copper, all the points for the transmitted intensities for absorber thicknesses up to $\mu x = 4.0$ lie on a straight line (which incidentally is a least-squares fit to the data points). The data, therefore, do not reveal any noticeable effect due to multiple scattering. The transverse dimension in this case corresponds to $\mu t = 1.6$. Thus, one can conclude that for $\mu t = 1.6$, there is no multiple scattering effect revealed in the present data up to absorber thicknesses $\mu x = 4.0$.

The situation is similar for the mercury absorber for the smallest transverse dimension used ($\mu t = 2.3$), as can be seen from Fig. 4, curve I. The experimental points lie on the least-squares-fitted straight line. Therefore, in this case also, there are no appreciable effects due to multiple scattering up to $\mu x = 4$.

However, the data for the transverse dimensions with $\mu t > 2.3$ do not follow the linear variation with absorber thickness (curves II, III, and IV in Fig. 4). The experimental points lie above the expected linear curve for larger values of μx. The deviations from the straight-line behavior start showing up at μx values of 4.2, 3.9, and 3.1, respectively, for $\mu t = 3.3$, 4.4, and 5.5 and increase

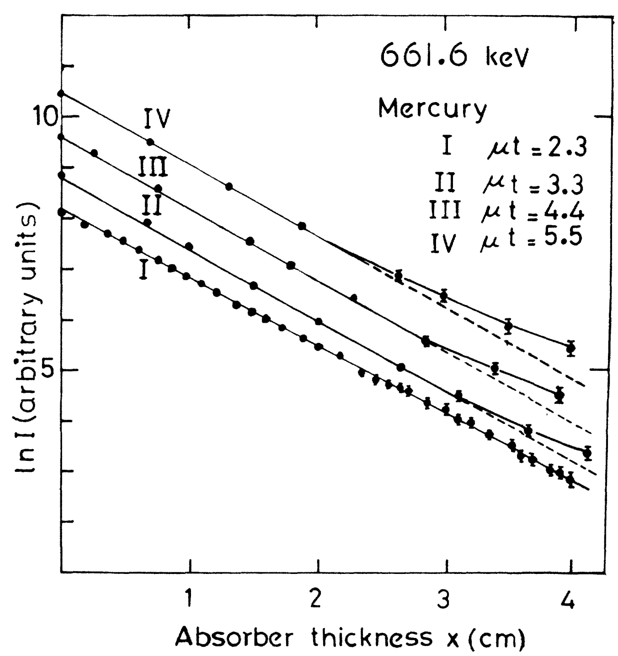

FIG. 4. Attenuation curves for the mercury absorber, for various values of μt. The solid line for $\mu t = 2.3$ (curve I) is the least-squares fit through the experimental points. For other μt values, the solid lines are just visual fits. The dashed extensions of these solid lines show the expected linear variation. Wherever the statistical errors are greater than the size of the points, they are indicated by the error bars.

TABLE I. Attenuation coefficients for 661.6-keV γ rays in copper.

Authors	μ (cm^2/g) Experiment	Theory
Gopal and Sanjeevaiah[a]	0.072 76±0.000 22	
Umesh *et al.*[b]	0.072 99±0.002 09	
Conner *et al.*[c]	0.072 85±0.000 38	
Present value	0.071 92±0.000 23	
McMaster *et al.*[d]		0.072 23

[a]Reference 2.
[b]Reference 6.
[c]Reference 7.
[d]Reference 5.

with the absorber thickness. Also, the deviations are larger for the larger transverse dimensions. These effects could most probably be attributed to the multiple-scattering process.

Attenuation coefficients have been calculated for various absorber thicknesses. The observed linear variation of $\ln I$ with x for copper and for mercury at $\mu t = 2.3$ shows that μ should be a constant with x in these cases. The average values for the coefficients obtained are $0.071\,92 \pm 0.000\,23$ cm^2/g for copper and 0.1028 ± 0.0007 cm^2/g for mercury. The corresponding theoretical values, calculated using the interpolation formulas suggested by McMaster *et al.*[5] are 0.072 23 cm^2/g and 0.1056 cm^2/g. The experimental value for copper agrees quite well with the theoretical value. In the case of mercury, the agreement is fairly good.

To the best of our knowledge, there are no earlier reported measurements for mercury at 661.6 keV. In the case of copper, the present value is compared with some previous results in Table I. There is good agreement of the present result with the previous ones.

The values of the attenuation coefficients for mercury in the case of $\mu t = 3.3$, 4.4, and 5.5 decrease with increasing values of μx. As an example, the case of $\mu t = 5.5$ is shown in Fig. 5, where the solid line is given as visual fit through the experimental values. μ is seen to decrease by almost 12% as μx increases from 1 to 5.5. The corresponding decrease in μ for $\mu t = 3.3$ and 4.4 are, respectively, about 6% and 8%. This decrease in the value of μ as μx increases is also attributable to multiple scattering.

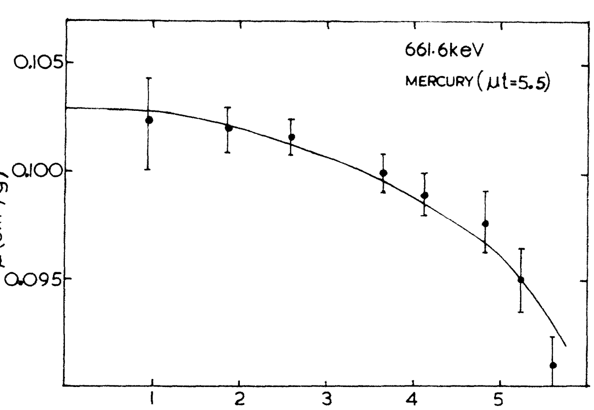

FIG. 5. Variation of μ of mercury with μx for $\mu t = 5.5$.

Multiple scattering is expected to depend on some power of the thickness of the absorber. The data for $\mu t = 3.3$, 4.4, and 5.5 were analyzed to obtain the form of this dependence. The observed transmitted intensities (I) were assumed to obey the following equation

$$I = I_0 e^{-\mu x} + I_0 k(t) x^n , \tag{1}$$

where I_0 is the incident intensity and $k(t)$ characterizes the extent of the multiple-scattering process and obviously depends on t, as revealed by the experimental data. From (1) it follows that

$$Y = \ln[(I/I_0 e^{-\mu x}) - 1] - \mu x = \ln k + n \ln x . \tag{2}$$

The value of the logarithm on the left side of the above equation was calculated from Fig. 4 for various values of x. Here μ is the average value of the attenuation coefficient, calculated using all the data points which do not show multiple-scattering effects.

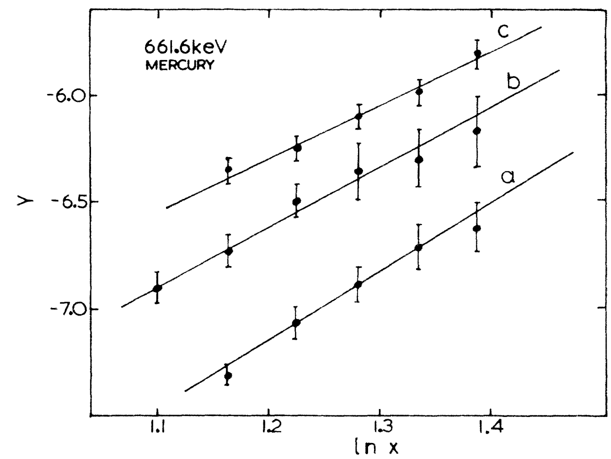

FIG. 6. Least-squares fits through the values of the quantity $Y = \ln[(I/I_0 e^{-\mu x}) - I] - \mu x$ plotted as a function of $\ln x$. (a) $\mu t = 5.5$, (b) $\mu t = 4.4$, (c) $\mu t = 3.3$. Y is obtained from the curves in Fig. 4.

Plots of Y versus $\ln x$ are given in Fig. 6, for the three values of μt. The solid lines are the least-squares fits to the experimental points. The values of n and $\ln k$ are given in Table II.

It can be seen from Table II that both n and k depend on μt. It was found that $k(t)$ is proportional to t^m where $m = 2.57$. The average value of n (from Table II) is 2.66 ± 0.33. Thus, the dependence of the multiple-scattering effect on x and t is more or less similar. This result, coupled with the fact that for $\mu t < 2.3$, the effect is

TABLE II. Parameters characterizing the effect of multiple scattering.

μt	n	$\ln k$
3.3	2.87 ± 0.82	$-(10.58 \pm 1.05)$
4.4	2.69 ± 0.44	$-(9.85 \pm 0.52)$
5.5	2.43 ± 0.33	$-(9.20 \pm 0.41)$

negligible, suggests that there is a correlation between the effects due to the two quantities x and t.

IV. CONCLUSIONS

It has been shown that for small transverse dimensions of the absorber, the multiple-scattering effect is negligible even for absorber thicknesses up to about 4 mean free paths. For larger transverse dimensions, multiple-scattering effects are important and could affect the measured value of the attenuation coefficient for absorber thicknesses above 1 mean free path. Therefore the thickness and transverse dimension effects seem to be correlated. Hence the criterion that $\mu x < 1$ should be satisfied for both the thickness and the transverse dimensions is justified.

The observed multiple-scattering effects are found to obey a t^m dependence on the absorber dimensions, where $m \simeq 2.6$. The values of the attenuation coefficients, determined with the criteria $\mu x < 1$ and $\mu t < 1$, agree quite well with the theoretical values.

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