PHYSICAL REVIEW A VOLUME 8, NUMBER 6 DECEMBER 1973

Gamma-Ray Attenuation Coefficient Measurements

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(Received 5 June 1973)

In an earlier paper, published by the authors elsewhere, it was shown that for 661.6-keV γ rays the measurements of γ-ray attenuation coefficients would greatly improve if one uses the counting sequence of Conner *et al.* together with a new criterion $\mu t < 1$, where μ is the γ-ray attenuation coefficient and t is the thickness of the sample. In this paper the authors report results which establish the above criterion for 84-keV γ rays also. Using the above method the total γ-ray attenuation coefficients have been measured in carbon, aluminum, copper, tin, and lead at γ-ray energies of 84, 129, 145.41, 279.12, 322, and 411.8 keV.

I. INTRODUCTION

In an earlier paper,[1] the authors reported the investigations of the effect of sample thickness on narrow-beam-collimated geometry and on measured attenuation coefficients at 661.6-keV γ-ray energy. The results indicated that the γ-ray attenuation coefficients would improve if one follows the counting sequence of Conner *et al.*[2] together with the criterion $\mu t < 1$, where μ is the γ-ray attenuation coefficient and t is the thickness of the sample. This paper presents similar investigations at 84-keV γ-ray energy. Further, the γ-ray attenuation coefficients have been measured in carbon, aluminum, copper, tin, and lead at γ-ray energies of 84, 129, 145.41, 279.12, 322, and 411.8 keV using the above criterion.

II. EXPERIMENTAL

The experimental setup used in the present investigation is the same as that described by the authors earlier.[1] The radio isotopes 50-mCi ^{198}Au (411.8 keV), 50-mCi ^{51}Cr (322 keV), 50-mCi ^{203}Hg (279.12 keV), 80-mCi ^{141}Ce (145.41 keV), 80-mCi ^{191}Os (129 keV), and 150-mCi ^{170}Tm (84 keV) in the form of radiographic capsules (supplied by the Isotope Division, Bhabha Atomic Research Centre, Bombay, India) have been used as γ-ray sources.

The samples of carbon, aluminum, copper, tin, and lead were in the form of circular cylinders and foils with diameters of 1.5 cm. The foils were fabricated in rolling mills. A typical sample from the rolling mill had an area of several cm^2. From this, a circular foil of a uniformly thick portion of the sample having a diameter of 1.5 cm was trimmed. The area and mass of this sample were then measured, and its average thickness in g/cm^2 was calculated. The cylinders were machined and the uniformity of the thickness of these machined samples was usually better than 0.1%. The sample was then mounted in a Perspex holder which permitted it to be positioned normal to the direct beam. A specimen from each batch of material used for preparing the sample was subjected to chemical analysis for the purpose of determining percentage of purity. The purity of the samples was found to be better than 99.6%.

The photopeaks of 84-keV photons were recorded with and without samples of different thicknesses. A sufficient number of counts were recorded so that counting statistics contributed less than 1% error. From the photopeaks, percentage resolutions were calculated.

For each of these thicknesses t, γ-ray attenuation coefficients μ were determined by following the counting sequence of Conner *et al.*[2] and the corresponding μt values were calculated. An 8-keV "counting window" around the photopeak was selected in the single-channel analyzer of the spectrometer to register the pulses in the scaler. A sufficient number of counts were recorded so that counting statistics contributed less than 0.3% error. The background counts were taken by placing a 15-cm-long lead cylinder of 1.5-cm diameter in the sample position.

III. RESULTS AND DISCUSSION

A. Criterion $\mu t < 1$

In the present investigation the values of percentage resolutions and γ-ray attenuation coefficients are found to change with the sample thickness. This dependence is illustrated as a function of μt for the elements of lowest and highest atomic numbers in Figs. 1(a) and 1(b). The representative photopeaks of 84-keV photons (normalized to the same peak value) are displayed in Fig. 2 for a few μt values of lead. From Figs. 1(a), 1(b), and 2, it is seen that for values of $\mu t < 1$, the percentage resolution of the detecting system and the γ-ray attenuation coefficient remain fairly constant; for

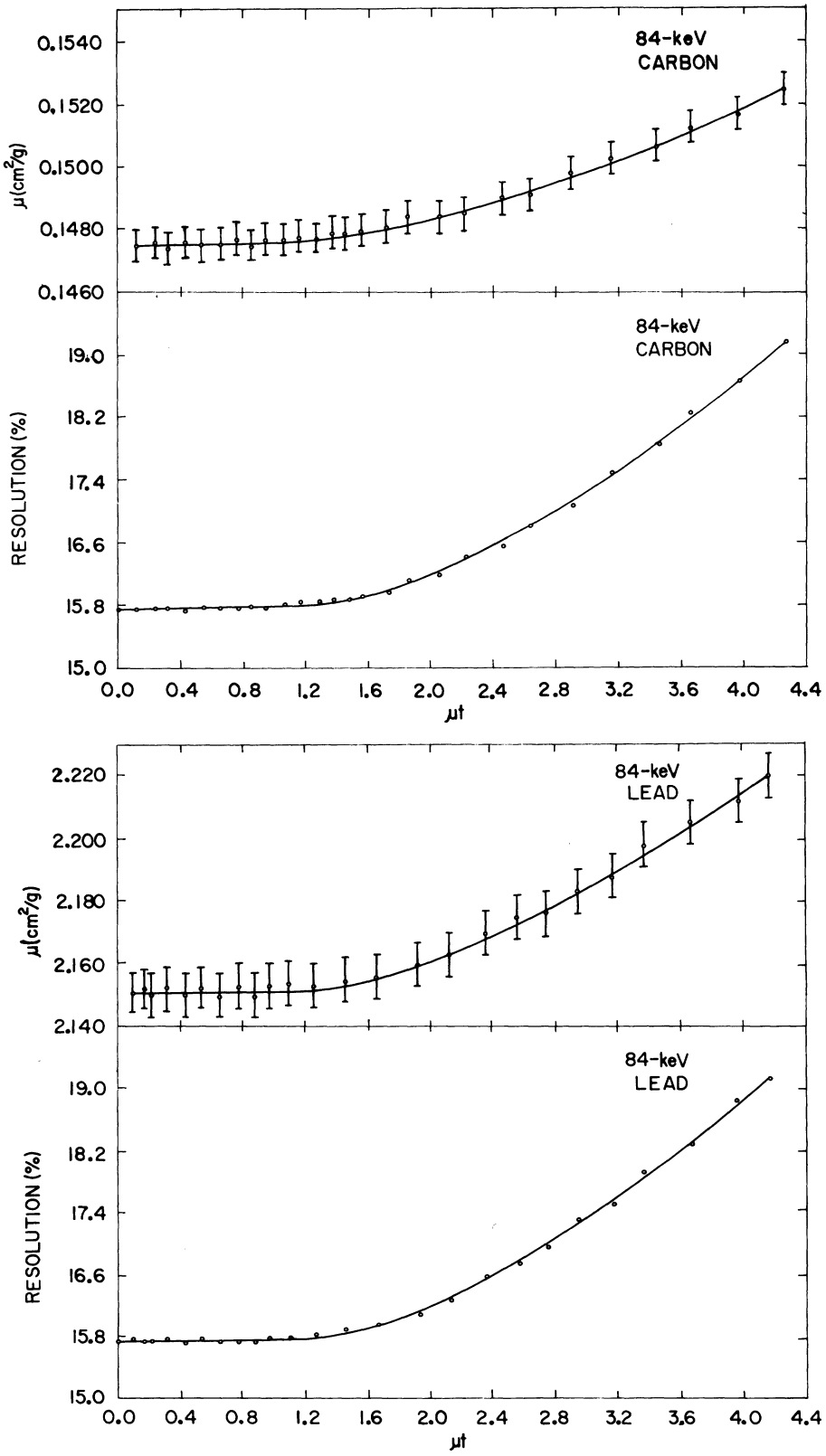

FIG. 1. Detector resolution (%) and γ-ray attenuation coefficient as a function of μt.

values of $\mu t > 1$, the percentage resolutions and the γ-ray attenuation coefficients increase significantly. These investigations were not carried out beyond $\mu t \approx 4.2$ because long counting times are required with the source used.

It can be seen from Fig. 2 that the left-hand side of the photopeak gets broadened as μt increases beyond 1. Since the instrumental variables[3] which can contribute to the observed width of a photopeak are minimized and kept constant throughout the experiment, the peak broadening towards the left-hand side is attributed to the increase in the number of energy degraded photons owing to multiple scattering reaching the detector. This is the reason for the resolution of the spectrometer becoming poorer (increase in "resolution %") as μt increases beyond 1.

Under conditions of good geometry the spectrum of photons arriving at the detector is the same as the radiation spectrum of the source. For large sample thicknesses, the multiple scattering becomes large and γ rays reaching the detector will have a continuous spectrum from zero to the source energy. Due to multiple scattering, more quanta will enter the detector than in measurements under conditions of good geometry. Though the number of photons reaching the detector would increase as t increases, it is expected that in our counting mode there would be a decrease in the number of photons owing to poorer resolution. The apparent increase in μ may be attributed to the fact that the number of photons detected is smaller than the expected in the absence of multiple scattering.

The present investigations together with the results reported earlier[1] indicate that the narrow-beam-collimated geometry condition is preserved and the effect of multiple scattering is greatly reduced for values of $\mu t < 1$ in the energy range of 84–661.6 keV.

B. μ from the Usual Transmission Method

A representative graph of fractional transmissions determined in the above investigations for calculating the values of μ for different thicknesses of lead is shown in Fig. 3. Here all the points lie on the straight line and one would expect that no multiple scattering exists as t increases in the present geometrical setup. The value of μ is found to be 2.196 ± 0.007 cm^2/g from the slope of the above line determined by the method of least squares. The value of μ determined using the criterion $\mu t < 1$ is 2.151 ± 0.007 cm^2/g. The higher value of the attenuation coefficient determined by transmission method may be attributed to multiple scattering. The fact that all the points lie on the straight line indicates that the multiple scattering is a small effect and could be revealed by the method adopted in this experiment.

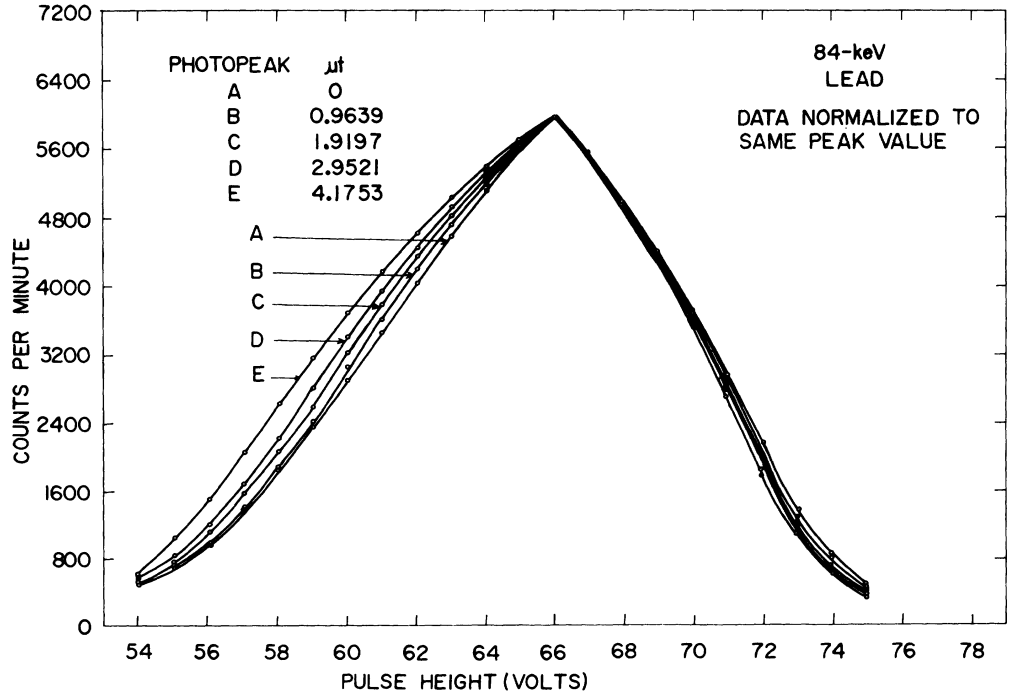

FIG. 2. Photopeaks normalized to same peak value for a few values of μt.

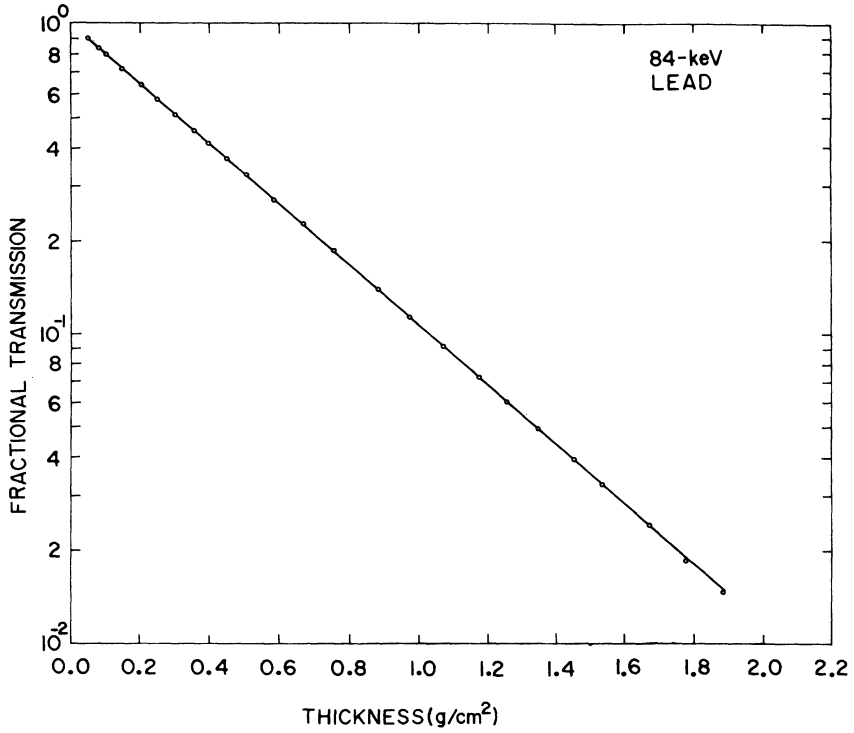

FIG. 3. Fractional transmission as a function of thickness.

C. γ-Ray Attenuation Coefficients

The studies indicate that the criterion $\mu t < 1$ holds good at 84- and 661.6-keV γ-ray energies for the materials under investigation. This implies that the same criterion holds good for the γ rays whose energies lie in the above range. Therefore, γ-ray attenuation coefficients are determined by following the counting sequence of Conner *et al.*[2] choosing the sample thicknesses such that $\mu t = 0.2$ to 0.4 at 84-, 129-, 145.41-, 279.12-, 322-, and 411.8-keV γ-ray energies in carbon, aluminum, copper, tin, and lead. For the short half-life source ^{198}Au, the data recording cycle was adjusted so that a linear decay correction was sufficiently accurate over the period of a single sequence. The values of attenuation coefficients measured in this experiment are given in Table I.

It can be seen from Table I that the present values are in general agreement with the results of Conner *et al.*[2] except in a few cases. This, we believe is due to the following reason. The sample thicknesses selected by Conner *et al.* to have good counting statistics were such that $0.1 < I/I_0 < 0.4$, where I is the transmitted intensity and I_0 is the incident beam intensity. This corresponds to μt values of 2.30 to 0.92, respectively. Therefore, it is obvious that not all sample thicknesses satisfy the criterion $\mu t < 1$. Incidentally, the counting statistics would greatly improve if the sample thickness is chosen such that $\mu t < 1$.

IV. ERRORS

The contribution due to coherent scattering was calculated using differential scattering cross section data of Brown[4] to interpolate at small angles

TABLE I. γ-ray attenuation coefficients (cm²/g).

Energy (keV)	Carbon	Aluminum	Copper	Tin	Lead
84	0.1475 ± 0.0005	0.1812 ± 0.0006	0.6702 ± 0.0021	2.602 ± 0.009	2.151 ± 0.007
129	0.1363 ± 0.0004	0.1402 ± 0.0005	0.2822 ± 0.0009	0.8593 ± 0.0028	2.887 ± 0.009
145.41	0.1321 ± 0.0004	0.1365 ± 0.0004	0.2293 ± 0.0008	0.6469 ± 0.0022	2.126 ± 0.007
279.12	0.1080 ± 0.0004	0.1048 ± 0.0003	0.1164 ± 0.0004	0.1770 ± 0.0007	0.4629 ± 0.0018
322	0.1029 ± 0.0003	0.0996 ± 0.0003	0.1045 ± 0.0004	0.1458 ± 0.0006	0.3353 ± 0.0014
411.8	0.094 15 ± 0.000 28	0.09050 ± 0.000 30	0.09122 ± 0.000 31	0.1095 ± 0.0003	0.2134 ± 0.0006

and found to be less than 0.04% on the measured attenuation coefficients. The number of Compton-scattered photons from the absorber reaching the detector was estimated[5] and found to be negligible.

The errors in the mass absorption coefficients due to nonuniformity in the thickness of the material were calculated using the relation given by Carter *et al.*[6] This correction was found to be less than 0.05% on the measured attenuation coefficients.

The source ^{198}Au emits two γ rays of higher energy than the 411.8-keV γ ray used in the measurements. These γ rays are emitted at 676 (1%) and 1088 keV (0.2%). It is possible that the Compton-scattered photons in the NaI(Tl) crystal due to higher-energy γ rays are detected at the photopeak energy of the principal γ ray. The correction[2] was applied for the two higher-energy γ rays by ^{198}Au source for all elements and was found to be negligible. Impurity corrections[2] were applied and found to be within 0.005% on the measured attenuation coefficients.

The statistical uncertainties in the measured values of μ are within 0.4% and these are the errors given in Table I.

V. CONCLUSION

In performing the experiments described in Secs. I–IV, the purpose was to investigate the effect of sample thickness on the narrow-beam-collimated geometry condition and on the measured attenuation coefficients. The investigations indicate that the multiple scattering is a small effect and could be minimized largely if the thickness of the sample chosen is such that $\mu t < 1$ (i.e., less than one mean free path). The results also show that the counting sequence adopted by Conner *et al.*[2] together with our criterion $\mu t < 1$, would improve the measured attenuation coefficients. However, it will be interesting to investigate whether the same criterion holds good for all the γ-ray energies.

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