Measurements of Gamma-Ray Attenuation Coefficients

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Measurements have been made to determine γ-ray attenuation coefficients very accurately by using an extremely-narrow–collimated-beam transmission method which effectively excluded corrections due to small-angle and multiple scattering of photons. The measured mass attenuation coefficients with maximum errors less than 3% for 34 elements in the range from hydrogen to lead are given.

I. INTRODUCTION

Extensive measurements have been made to determine γ-ray attenuation coefficients for various elements and photon energies. The results of earlier measurements have been compiled by Davisson and Evans.[1] A survey of these and other relevant measurements[2–14] reported up to 1969 shows that in many of these measurements the experimental results for the same elements at the same energies are somewhat inconsistent. In some of these measurements appreciable discrepancies between the experimental and theoretical values were observed. In view of this situation a series of accurate and consistent measurements of γ-ray mass attenuation coefficients was undertaken by us. The results of these measurements covering 34 elements from hydrogen to lead at six photon energies took a long time to obtain, owing to considerable delay in obtaining some of the requisite materials and radioactive γ-ray sources. Satisfactory accuracy in the present measurements has been achieved by eliminating corrections due to small-angle scattering of photons to the detector. A possible effect due to multiply scattered photons from thick attenuators on the measurements has been minimized to a great extent by using extremely-narrow-beam collimation and selected attenuator thicknesses.

II. EXPERIMENTAL ARRANGEMENT

The experimental arrangement used in our measurements is shown in Fig. 1. An improvement has been achieved by a high degree of collimation of the photon beam from the source to the detector. The source was placed in a 10-cm-deep conical bore in a lead block. The minimum thickness of lead shielding at the side and the back of the source was 20 cm. Collimator No. 1 is a 23-cm-thick iron block having a collimating bore of exit aperture 0.4 cm. The collimation of the beam after the attenuator was provided by collimator Nos. 2–5 of total thickness 60 cm of iron. The collimator shields prevent photons scattered in the air and the shield materials from reaching the detector. The collimators were mounted on a rigid bench of iron. These could be moved so that measurements at two or more geometries could be carried out after minor changes of the collimator apertures. In measurements carried out with the sample at 40 cm from the source, the solid angle of the collimating system between the attenuator and the detector was 10.7×10^{-6} sr. In this geometry the maximum angle of scattering from the attenuator to the detector was 24′. The detector, a 2.5-cm NaI(Tl) scintillator, was shielded by 20 cm of lead. The detector was coupled to a conventional system of photomultiplier, amplifiers, single-channel analyzer, and a scaler with a preset timer.

III. MATERIALS AND MEASUREMENTS

The measurements were made using 140-mCi Zn^{65} (1.115 MeV), 130-mCi Sc^{46} (0.889 and 1.120 MeV), 100-mCi Co^{60} (1.173 and 1.332 MeV), and 20-mCi Cs^{137} (0.662 MeV) for 49 materials. The sample materials were at least 99.99% pure. Elements which were not available in their elemental solid, powder, or liquid form were studied in the form of their oxides, halides, sulphates, and carbonates. Most of these were oxides. Boron and nitrogen were in the form of boron carbide and

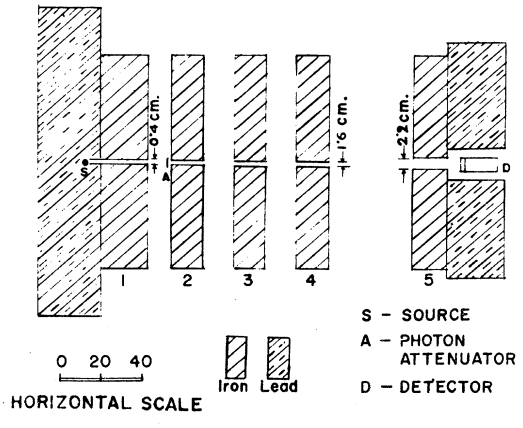

FIG. 1. Schematic diagram of the experimental arrangement.

boron nitride. All these compounds were in the form of powder. Eleven scintillation-grade hydrocarbons in liquid form were studied to derive mean attenuation coefficients for hydrogen using the measured value of the attenuation coefficient of carbon. The mass attenuation of a compound was taken to be equal to the average of the mass attenuation coefficients of the constituent elements, weighted in proportion to the abundance of each element by weight. The mean attenuation coefficient of oxygen was derived from the measurements on Zn and ZnO, Al, and Al_2O_3, scintillation-grade toluene and anisole, ethyl alcohol, and ethane diol. A similar procedure was adopted to obtain mass attenuation coefficients of elements from measurements on their compounds.

Powder and liquid samples were taken in very thin (~1 mm) perspex containers of internal diameter ~1 cm. To ensure uniform packing of a powder sample, the container was placed on a constant shaker. Thickness in g/cm^2 of a sample was determined with an accuracy better than 0.05% from a number of observations. The sample thicknesses from about 5 g/cm^2 to a maximum of about 34 g/cm^2 used in the measurements were fixed in test experiments performed under the condition that the full width at half-maximum of the γ-ray photopeak with the attenuator is almost the same as that without the attenuator in position. In this way the effect due to multiple scattering from the sample to the detector was made negligible.

Measurements were carried out under steady conditions of the detector system; no drift of the photopeak was detected over at least 12 h. When

TABLE I. Measured total mass attenuation coefficients in cm^2/g. (In parentheses is given the uncertainty in the last one or two places.)

		γ-ray energy (MeV)					
Element	Z	0.662	0.889	1.115	1.120	1.173	1.332
H	1	0.153(2)	0.134(1)	0.121(1)	0.120(1)	0.120(1)	0.110(1)
Li	3	0.0659(8)	0.0592(2)	0.0534(2)	0.0522(2)	0.0509(2)	0.0489(2)
B	5	0.0703(8)	0.0624(2)	0.0568(2)	0.0562(2)	0.0536(2)	0.0508(2)
C	6	0.0771(6)	0.0673(1)	0.0601(1)	0.0603(1)	0.0585(1)	0.0551(1)
N	7	0.0782(9)	0.0674(3)	0.0605(3)	0.0603(3)	0.0588(3)	0.0552(3)
O	8	0.0780(12)	0.0675(2)	0.0604(2)	0.0602(2)	0.0589(2)	0.0551(2)
F	9	0.0742(8)	0.0650(2)	0.0608(2)	0.0582(2)	0.0560(2)	0.0520(2)
Na	11	0.0735(7)	0.0652(3)	0.0572(3)	0.0571(3)	0.0560(3)	0.0530(3)
Mg	12	0.0762(8)	0.0659(3)	0.0597(3)	0.0590(3)	0.0577(3)	0.0536(3)
Al	13	0.0744(14)	0.0647(2)	0.0583(2)	0.0576(2)	0.0567(2)	0.0531(2)
Si	14	0.0776(12)	0.0673(3)	0.0604(2)	0.0602(2)	0.0589(2)	0.0551(2)
S	16	0.0783(6)	0.0680(1)	0.0605(1)	0.0598(1)	0.0592(1)	0.0555(1)
K	19	0.0768(8)	0.0659(2)	0.0586(2)	0.0589(2)	0.0576(2)	0.0540(2)
Ca	20	0.0781(14)	0.0677(3)	0.0601(3)	0.0601(3)	0.0595(3)	0.0559(3)
Ti	22	0.0716(13)	0.0624(3)	0.0556(3)	0.0555(3)	0.0546(3)	0.0509(3)
Fe	26	0.0731(4)	0.0635(1)	0.0568(1)	0.0571(1)	0.0557(1)	0.0521(1)
Zn	30	0.0730(6)	0.0630(1)	0.0561(1)	0.0562(1)	0.0548(1)	0.0511(1)
Ge	32	0.0723(4)	0.0614(1)		0.0552(1)	0.0532(1)	0.0495(1)
As	33	0.0708(18)	0.0607(3)	0.0543(3)	0.0539(3)	0.0529(3)	0.0492(3)
Br	35	0.0710(6)	0.0605(1)	0.0539(1)	0.0537(1)	0.0528(1)	0.0494(1)
Rb	37	0.0704(13)	0.0603(3)	0.0534(3)	0.0532(3)	0.0520(3)	0.0489(3)
Mo	42	0.0734(13)	0.0618(3)	0.0549(3)	0.0548(3)	0.0535(3)	0.0501(3)
I	53	0.0772(4)	0.0630(1)	0.0543(1)	0.0543(1)	0.0526(1)	0.0499(1)
Cs	55	0.0775(6)	0.0627(2)	0.0542(2)	0.0541(2)	0.0530(2)	0.0494(2)
Ba	56	0.0771(8)	0.0622(2)	0.0536(2)	0.0535(2)	0.0521(2)	0.0489(2)
La	57	0.0784(13)	0.0630(2)	0.0542(3)	0.0541(3)	0.0527(3)	0.0493(3)
Ce	58	0.0798(13)	0.0639(2)	0.0550(3)	0.0548(3)	0.0534(3)	0.0499(3)
Nd	60	0.0824(13)	0.0656(2)	0.0561(3)	0.0560(3)	0.0547(3)	0.0520(3)
Sm	62	0.0838(13)	0.0659(2)	0.0562(3)	0.0561(3)	0.0547(3)	0.0507(3)
Gd	64	0.0850(13)	0.0663(2)	0.0563(3)	0.0562(3)	0.0551(3)	0.0508(3)
Dy	66	0.0871(13)	0.0672(3)	0.0570(3)	0.0569(3)	0.0560(3)	0.0513(3)
Yb	70	0.0922(13)	0.0695(3)	0.0585(3)	0.0583(3)	0.0566(3)	0.0527(3)
Hg	80	0.1061(1)	0.0771(1)	0.0630(1)	0.0624(1)	0.0600(1)	0.0550(1)
Pb	82	0.1072(1)	0.0784(1)	0.0640(1)	0.0640(1)	0.0615(1)	0.0557(1)

TABLE II. Measured mass attenuation coefficients in cm^2/g of germanium for three different angles between the attenuator and detector. (In parentheses is given the uncertainty in the last place.)

Solid angle (sr)	γ-ray energy 1.173 (MeV)	1.332 (MeV)
10.7×10^{-6}	0.0531(1)	0.0495(2)
13.3×10^{-6}	0.0530(1)	0.0493(2)
19.5×10^{-6}	0.0532(2)	0.0495(2)

measuring with a particular γ-ray energy, the detector bias was set such that the window covered the photopeak above half-maximum. Counting times from 30 min to 6 h were used to obtain a statistical accuracy in the range 0.1–0.3%. The background counts with the source and the attenuator in position and a 20-cm-long lead stopper placed in the beam between the collimators No. 4 and 5, and the same with the source taken away, were observed. The difference between these two count rates of the background was very small. For measurement with each sample and energy, counts

TABLE III. Measured mass attenuation coefficients in cm^2/g of mercury at varying thickness.

Thickness (g/cm^2)	γ-ray energy (MeV) 0.889	1.115	1.120	1.173	1.332
29.12	0.0771(1)	0.0630(1)	0.0624(1)	0.0600(1)	0.0550(1)
33.86	0.0770(1)	0.0630(1)	0.0624(1)	0.0600(1)	0.0551(1)

without the container, with the empty container, and with the sample in the container were taken. The background was recorded before and after each measurement. The source counts with and without the empty container were almost the same. The source counts with the empty container were taken as the intensity of the incident beam. At each sample thickness counts with and without the sample were repeated a number of times for aligned and slightly different misaligned positions of the attenuator in the incident beam to minimize error due to slight point-to-point variation in sample thickness. The mass attenuation coefficient was calculated from the measured sample thickness and mean transmission ratio. The mean

TABLE IV. Comparison of measured and theoretically expected values of total attenuation coefficients (cm^2/g) for some elements. (In parentheses is given the uncertainty in the last one or two places.)

Element	Energy (MeV)	Present measurement	Conner *et al.* (Ref. 15)	Colgate (Ref. 2)	Davisson and Evans (Ref. 1)	Theor. value
C	0.662	0.0771(6)	0.07713(36)	0.0770(1)		0.0767
	1.115	0.0601(1)	0.06043(27)			0.0609
	1.332	0.0551(1)		0.0550(1)		0.0551
Mg	0.662	0.0762(8)	0.07653(44)			0.0764
	1.115	0.0597(3)	0.06023(23)			0.0596
Al	0.662	0.0744(4)	0.07436(25)	0.0742(1)		0.0746
	1.115	0.0583(2)	0.05807(45)		0.0578(8)	0.0582
	1.332	0.0531(2)		0.0532(1)		0.0532
S	0.662	0.0783(6)	0.07822(43)			0.0776
	1.115	0.0605(1)	0.06079(20)			0.0607
Ti	0.662	0.0716(13)	0.07130(23)			0.0718
	1.115	0.0556(3)	0.05590(29)			0.0560
Fe	0.662	0.0731(6)	0.07258(22)			0.0735
	1.115	0.0568(1)	0.05610(18)			0.0569
Zn	0.662	0.0730(6)	0.07296(30)			0.0730
	1.115	0.0561(1)	0.05606(21)			0.0562
Mo	0.662	0.0734(13)	0.07304(24)			0.0738
	1.115	0.0549(3)	0.05467(21)			0.0550
La	0.662	0.0784(13)	0.07796(22)			0.0783
	1.115	0.0542(3)	0.05398(26)			0.0548
Gd	0.662	0.0850(13)	0.08317(33)			0.0845
	1.115	0.0563(3)	0.05619(25)			0.0567
Pb	0.662	0.1072(1)	0.1074(5)	0.1072(2)		0.1083
	1.115	0.0640(1)	0.06324(32)		0.0626(5)	0.0638
	1.332	0.0557(1)		0.0553(1)		0.0558

value of the mass attenuation coefficient was calculated from measurements repeated for two to three different thicknesses of the same sample. For some samples and energies, measurements were made at three different solid angles of the collimating system between the attenuator and the detector to study the effect of the geometry of the experimental arrangement on the contribution of small-angle scattering.

IV. EXPERIMENTAL RESULTS

The measured mass attenuation coefficients are given in Table I. Most of the results are from measurements made at the attenuator-to-detector solid angle of 13.3×10^{-6} sr. Few measurements have been made at a solid angle of 10.7×10^{-6} sr. The experimental results given in Table II for germanium with Co^{60} source are consistent, showing that the effect of small-angle scattering of the photon on the measured attenuation coefficient is not observed in the geometry employed. Theoretical estimates show that the contribution of both coherent and incoherent scattering at small scattering angles (20′–24′) to the measured attenuation coefficients is less than 0.01%. Consequently no scattering correction to our data is necessary. Error due to multiply scattered photons from the attenuator was minimized by very narrow collimation of the transmitted beam of photons and by measuring transmission for relatively small sample thicknesses selected in test experiments. The observed Co^{60} pulse-height spectra for the direct and attenuated radiation through varying thicknesses of mercury are shown in Fig. 2. The attenuation coefficients at 1.173 and 1.332 MeV in Table III are the values obtained from measurements under conditions represented by spectral shapes 2 and 3. The results are the same within statistical error.

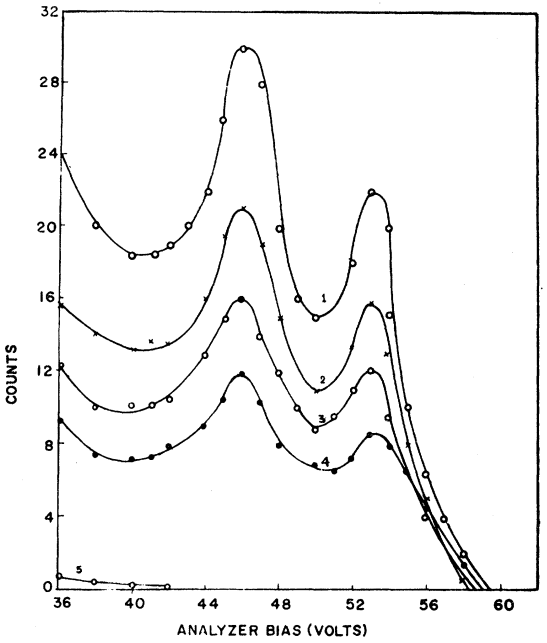

FIG. 2. Pulse-height spectra of Co^{60} photons observed with the experimental arrangement. Curve 1 (counts in units of 10^3 in 15 sec): direct spectrum; curves 2–4 (counts in units of 10^3 in 1 min): spectra with increasing thicknesses of mercury attenuator; curve 5 (counts in units of 10^3 in 1 min): background spectrum.

TABLE V. Typical procedure for obtaining the results and the corresponding errors. [R is the ratio of the transmitted γ-ray beam intensity to the incident beam intensity. The total attenuation coefficient is taken to be given by $\mu=\ln(1/R)/x$; x is the average sample thickness; R is the mean transmission ratio. The standard deviation S_μ is computed by considering standard deviation S_R in R and S_x in x. $\bar{S}_\mu$ is the standard deviation of the mean value. Only the first significant figure in the fourth decimal place in the errors is shown.]

Sample	Energy (MeV)	Average sample thickness (g/cm^2)	$1/R$	$\mu=\ln(1/R)/x$ (cm^2/g)	S_μ [a]	Average μ (cm^2/g)	$\bar{S}_\mu$ [b]
S	1.115	5.329	1.3803	0.0605	3		
		7.106	1.5377	0.0605	2	0.0605	1
		9.682	1.7964	0.0605	2		
		12.96	2.1906	0.0605	2		
Ge	1.115	9.613	1.6966	0.0550	4		
		20.60	3.0639	0.0548	4	0.0549	2
		25.68	4.0829	0.0548	4		
Hg	1.115	29.12	6.2542	0.0630	1	0.0630	1
		33.86	8.4412	0.0630	1		

[a] $S_\mu^2=\left(\frac{\partial\mu}{\partial R}\right)^2 S_R^2+\left(\frac{\partial\mu}{\partial x}\right)^2 S_x^2$.

[b] $\bar{S}_\mu^2=(1/n)^2S_{\mu,1}^2+(1/n)^2S_{\mu,2}^2+\cdots+(1/n)^2\,S_{\mu,n}^2$.

V. COMPARISON WITH PREVIOUS WORK AND RECENT THEORETICAL RESULTS

We have already referred to most of the previous measurements relevant to the present work. In Table IV a comparison of data is given for some elements and energies which are common among the measurements by Conner *et al.*,[15] Colgate,[2] and Davisson and Evans.[1] The values of attenuation coefficients expected theoretically were computed by combining the cross sections of scattering, photoelectric absorption, and, above 1.02 MeV, pair-production effect. The coherent-scattering cross sections were derived by interpolation of the tabulated data of Storm and Israel,[16] which are based on Cromer's[17–19] form factor. The incoherent-scattering cross sections have been obtained from the tabulated data of Veigele *et al.*,[20] who calculated these using an incoherent-scattering function given by Cromer. The photoelectric cross sections for complete atoms were obtained from the tabulated theoretical data of Schmickley and Pratt.[21] The cross sections for pair production were obtained from the theoretical data computed by Øverbo.[22,23] The agreement of the measured and theoretical results is seen to be satisfactory.

VI. ERRORS OF EXPERIMENTAL DATA

The typical procedure of obtaining the results and the corresponding errors is shown in Table V. The validity of exponential attenuation in the data is evident.

The systematic errors taken into consideration arise from the following sources: (i) detection of some background photons scattered by the neighboring materials other than the attenuator, (ii) detection of photons scattered by the attenuator at very small angles, (iii) change of primary photon energy owing to Compton scattering in the γ-ray source itself, (iv) experimental limitation of complete discrimination between two γ rays in the case of Sc^{46} and Co^{60} sources, and (v) count loss in the detection system. As already discussed, the corrections of errors due to (i) and (ii) have been effectively excluded in the present measurements. The effect of (iii) was found to be negligible for small γ-ray sources used in the measurements. The magnitude of the average correction factor [due to (iv)] to the measured results is about 0.5% for low- and intermediate-Z elements and of the order of 0.8% for high-Z elements. For a maximum of about 1% count loss in our measurements, the error to the results is negligible. In measurements where powder and liquid samples had to be used, the effect of scattering of the primary photons by the thin container is similar to that of self-scattering by the source. The uncertainty due to this is assumed to be relatively small. The errors to the results derived from measurements on compounds are quadratically composed of errors from separate measurements involved in the process.

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