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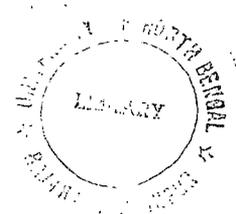
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Measurements of Gamma-Ray Attenuation Coefficients

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(Received 25 October 1972; revised manuscript received 17 January 1973)

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 measurements²⁻¹⁴ 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

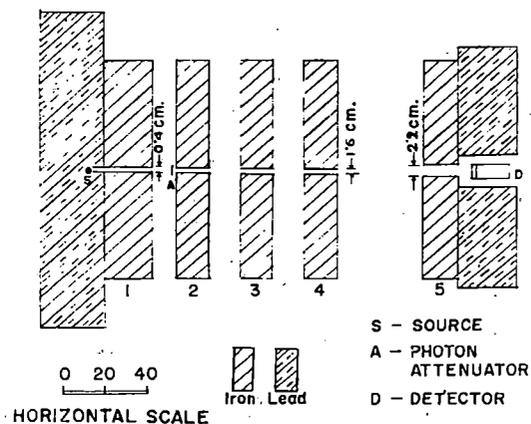
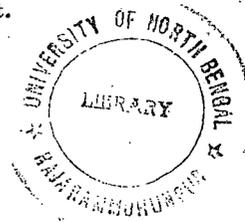


FIG. 1. Schematic diagram of the experimental arrangement.



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 Al₂O₃, 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/cm² of a sample was determined with an accuracy better than 0.05% from a number of observations. The sample thicknesses from about 5 g/cm² to a maximum of about 34 g/cm² 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 cm²/g. (In parentheses is given the uncertainty in the last one or two places.)

| Element | Z | γ -ray energy (MeV) | | | | | |
|---------|----|----------------------------|-----------|-----------|-----------|-----------|-----------|
| | | 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) | | 0.0562(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 <i>et al.</i> (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 attenua-

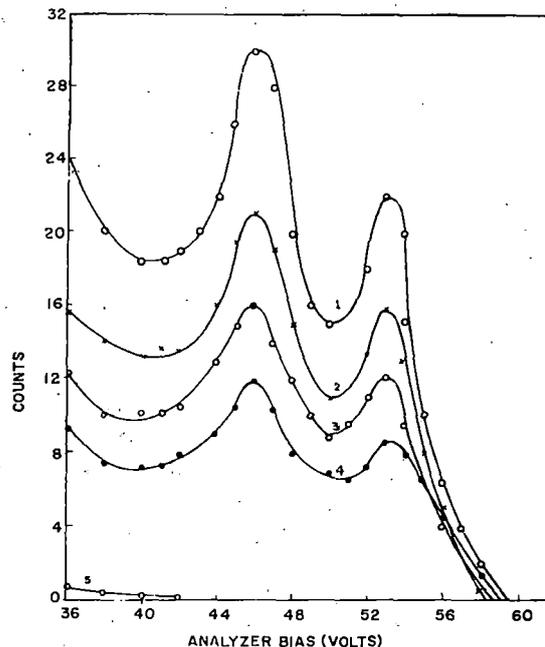


FIG. 2. Pulse-height spectra of Co^{60} photons observed with the experimental arrangement. Curve 1 (counts in units of 10^3 in 15 sec): direct spectrum; curves 2-4 (counts in units of 10^3 in 1 min): spectra with increasing thicknesses of mercury attenuator; curve 5 (counts in units of 10^3 in 1 min):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

tion 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.

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}_μ 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}_μ^b |
|--------|--------------|---|--------|---|-----------|------------------------------------|-----------------|
| S | 1.115 | 5.329 | 1.3803 | 0.0605 | 3 | 0.0605 | 1 |
| | | 7.106 | 1.5377 | 0.0605 | 2 | | |
| | | 9.682 | 1.7964 | 0.0605 | 2 | | |
| | | 12.96 | 2.1906 | 0.0605 | 2 | | |
| Ge | 1.115 | 9.613 | 1.6966 | 0.0550 | 4 | 0.0549 | 2 |
| | | 20.60 | 3.0639 | 0.0548 | 4 | | |
| | | 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 | | |

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

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

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's¹⁷⁻¹⁹ 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) detec-

tion 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 Sc⁴⁶ and Co⁶⁰ 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.

ACKNOWLEDGMENTS

The authors would like to express their thanks to Professor S. N. Sen, Head of the Department of Physics, and Professor P. C. Mukherjee, Vice Chancellor of the North Bengal University, for providing the facilities to carry out these measurements and the award of a NBU Research Fellowship to B. Goswami. P. Tamang and S. Chowdhury are thanked for their assistance.

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MEASUREMENTS OF GAMMA-RAY ATTENUATION COEFFICIENTS OF ORGANIC SCINTILLATORS

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Received 5 September 1972

Total gamma-ray mass attenuation coefficients have been measured for fifteen organic scintillators at seven energies of

gamma-rays from radioactive sources. Experimental errors in the measurements are less than 1%.

1. Introduction

The initial results of total gamma-ray attenuation coefficient measurements were reported in a previous paper¹). The complete results of measurements are given for fifteen organic scintillators at seven energies of gamma-rays from radioactive sources ¹³³Ba(0.36 MeV), ¹³⁷Cs(0.662 MeV), ⁴⁶Sc(0.89 and 1.12 MeV), ⁶⁵Zn(1.11 MeV) and ⁶⁰Co(1.17 MeV and 1.33 MeV). To eliminate the small angle scattering corrections to the measured attenuation coefficients, both the incident beam of photons and the photon beam transmitted by the scintillator sample were collimated to a high degree by a system of cast iron collimators between the source and the sample, and the sample and the detector of incident and attenuated photon beam. The solid angle of the collimating system between the source and the sample was 1×10^{-4} sr and that between the sample and the detector was 1×10^{-5} sr.

2. Method and measurements

Measurements were done by the standard method of determining the transmission ratio of the absorber placed in the path of the collimated incident beam of photons. A NaI(Tl) scintillation detector coupled to a conventional single channel analyzer system was employed for counting. The counting times were fixed by the source strength and the condition that the statistical error to the measured attenuation coefficients would be within 0.1-1%. Scintillation grade samples were used for measurements. Liquid samples were contained in thin walled perspex containers. The effect of attenuation of photons in the container material was taken into account in the measurements. The

thickness in g/cm² of the sample was determined from the appropriate internal dimension of the container and the measured density of the sample. For each sample and energy, measurements were made at three sample thicknesses selected such that the resolution of the detector system remained almost the same for all the three thicknesses. At each sample thickness in the range 8-18 g/cm², counts with and without the sample in the container were taken repeatedly to obtain a mean transmission ratio. The total attenuation coefficient was calculated from the measured sample thickness and the mean transmission ratio. Measurements at three thicknesses gave consistent values from which a mean attenuation coefficient was obtained. For a particular sample and photon energy, measurements were repeated at three different solid angles of the collimating system between the sample and the detector. The measured values of attenuation coefficients at these angles are fairly constant. The measured total attenuation coefficients are given in table 1. The errors in the measured results shown are standard deviations. The sample thickness was measured very accurately to minimise any error due to any deviation in thickness. The effect of small angle scattering of photons to the detector was made negligible for small solid angles used in our measurements. The error in the measured result due to this effect was found to be less than 0.1%. There was no other known source of error in the measurements.

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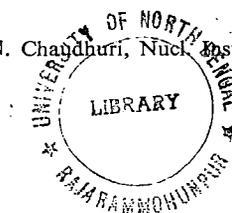


TABLE I
Measured total mass attenuation coefficients in cm²/g.

| Absorber | Gamma-ray energy | | | | | | |
|----------------------|-------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| | 0.36 MeV | 0.662 MeV | 0.89 MeV | 1.11 MeV | 1.12 MeV | 1.17 MeV | 1.33 MeV |
| Toluene | 0.10757 ± 0.00032 | 0.08372 ± 0.00068 | 0.073142 ± 0.000031 | 0.065321 ± 0.000061 | 0.065300 ± 0.000060 | 0.064082 ± 0.000070 | 0.059813 ± 0.000051 |
| O-xylene | 0.10830 ± 0.00034 | 0.08437 ± 0.00080 | 0.073498 ± 0.000031 | 0.065728 ± 0.000063 | 0.065529 ± 0.000058 | 0.064246 ± 0.000056 | 0.060922 ± 0.000059 |
| Benzene | 0.10649 ± 0.00034 | 0.08264 ± 0.00067 | 0.072489 ± 0.000031 | 0.064629 ± 0.000060 | 0.064588 ± 0.000063 | 0.063486 ± 0.000051 | 0.059302 ± 0.000059 |
| P-cymene | 0.10964 ± 0.00033 | 0.08523 ± 0.00071 | 0.074310 ± 0.000032 | 0.066312 ± 0.000061 | 0.066429 ± 0.000064 | 0.065037 ± 0.000056 | 0.060653 ± 0.000064 |
| Cyclo hexane | 0.11322 ± 0.00036 | 0.08785 ± 0.00071 | 0.076779 ± 0.000030 | 0.068644 ± 0.000054 | 0.068589 ± 0.000052 | 0.067310 ± 0.000062 | 0.062878 ± 0.000059 |
| Decalin | 0.11161 ± 0.00033 | 0.08685 ± 0.00071 | 0.075999 ± 0.000031 | 0.068004 ± 0.000064 | 0.067928 ± 0.000072 | 0.066646 ± 0.000059 | 0.062503 ± 0.000062 |
| Liquid paraffin | 0.11360 ± 0.00034 | 0.08878 ± 0.00070 | 0.077214 ± 0.000032 | 0.068994 ± 0.000063 | 0.067998 ± 0.000074 | 0.067760 ± 0.000061 | 0.062972 ± 0.000064 |
| Anisole | 0.10631 ± 0.00031 | 0.08231 ± 0.00069 | 0.072211 ± 0.000032 | 0.064800 ± 0.000062 | 0.064601 ± 0.000072 | 0.063236 ± 0.000057 | 0.058884 ± 0.000059 |
| Mesitylene | 0.10878 ± 0.00030 | 0.08496 ± 0.00068 | 0.073998 ± 0.000032 | 0.066430 ± 0.000060 | 0.066259 ± 0.000073 | 0.064836 ± 0.000053 | 0.060589 ± 0.000060 |
| Ethyl benzene | 0.10835 ± 0.00032 | 0.08423 ± 0.00069 | 0.073669 ± 0.000039 | 0.065884 ± 0.000052 | 0.065688 ± 0.000076 | 0.064534 ± 0.000055 | 0.060140 ± 0.000059 |
| Dioxane | 0.10780 ± 0.00032 | 0.08341 ± 0.00075 | 0.073322 ± 0.000038 | 0.065857 ± 0.000050 | 0.065598 ± 0.000071 | 0.064181 ± 0.000057 | 0.059796 ± 0.000061 |
| Butyl benzene | 0.10924 ± 0.00034 | 0.08503 ± 0.00059 | 0.074447 ± 0.000034 | 0.06583 ± 0.000045 | 0.066449 ± 0.000072 | 0.065070 ± 0.000055 | 0.060683 ± 0.000061 |
| Cumene | | | 0.073894 ± 0.000032 | 0.066034 ± 0.000049 | 0.065978 ± 0.000071 | 0.064734 ± 0.000062 | 0.060424 ± 0.000064 |
| P-xylene | | | 0.073882 ± 0.000038 | 0.065830 ± 0.000052 | 0.065540 ± 0.000080 | 0.064309 ± 0.000064 | 0.060219 ± 0.000069 |
| Plastic scintillator | | 0.085233 ± 0.000064 | 0.074498 ± 0.000062 | 0.062009 ± 0.000060 | 0.066028 ± 0.000061 | 0.062183 ± 0.000060 | 0.060098 ± 0.000060 |

MEASUREMENTS OF GAMMA-RAY MASS ATTENUATION COEFFICIENTS OF ORGANIC SCINTILLATORS

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Received 8 December 1970

Preliminary results of gamma-ray attenuation measurements in organic scintillators are given. Total mass attenuation coefficients of a number of the most important organic scintillators for gamma-rays from ^{133}Ba , ^{137}Cs , ^{60}Co and ^{65}Zn have been determined in narrow-beam experiments. Theoretical mass attenuation

coefficients are computed by interpolation from the atomic cross-section data of Grodstein. Satisfactory agreement is obtained between the experimentally determined mass attenuation coefficients and the computed values.

1. Introduction

With the increasing application of organic liquid and solid scintillators in scientific and industrial research, it has become important to know their gamma-ray attenuation coefficients. No extensive measurement of these coefficients appears to have been published.

In the present investigation accurate measurements of the mass attenuation coefficients of a number of important organic scintillators have been undertaken for various gamma-ray energies. This report gives the data so far obtained from gamma-ray transmission experiments in the narrow beam geometry.

Since the primary interaction process in an organic solution scintillation system corresponds to the transfer of energy from the incident radiation to the excitation energy of the molecules of the main component (solvent) measurements have been made on the solvents of the different liquid solution scintillation systems. The concentrations of the solutes in solution scintillation systems are normally so small that the direct excitation of the solute molecules in the primary interaction process may be neglected.

2. Experimental arrangement

The geometric design of the arrangement employed for total attenuation measurements is similar to one used by Davisson and Evans¹). In the modified geometry of the collimated arrangement used in the present investigation, no photon which results from a single act of scattering in the absorber at a scattering angle greater than 1° would reach the detector, a $2.5\text{ cm} \times 2.5\text{ cm}$ NaI(Tl) scintillator mounted on a 6199 photomultiplier. The shielding for the source and the detector, and the collimators were made of lead. The openings in the collimator system were adjusted to the geometry of the arrangement.

2.1. MATERIALS AND MEASUREMENTS

An absorption experiment was performed by observing the transmission ratio of the absorber placed half way between the source and the detector. The detector system to record the pulses from the photomultiplier consisted of a non-overloading linear amplifier, a single-channel pulse height analyser and a decade scaler. The resolution of the whole system was about 9% for ^{137}Cs photons (0.662 MeV).

For measurement with a particular gamma-ray energy, the pulse-height distribution for the direct beam was first taken. The pulse-height analyser was then set such that the window nearly covered the photopeak at its half maximum. Counts with and without the sample were alternately taken with a statistical accuracy of the order of about 1%.

The four different types of sources (sealed) ^{137}Cs (0.662 MeV), ^{60}Co (1.33 and 1.17 MeV), ^{65}Zn (1.1 MeV) and ^{133}Ba (0.079 and 0.30 MeV) were used in these experiments.

Measurements were made on plastic scintillator and scintillation grade solvents of the important liquid scintillator solutions. Liquid samples were contained in a thin walled glass container (wall thickness about 1 mm). For each measurement, the transmission ratio of an absorber was determined for thickness upto 2-3 half-thicknesses of the absorber.

As a check of the accuracy of the measured data, the mass attenuation of carbon was also measured. For carbon, the previous measurements in the same energy range agree within statistical accuracy with the theoretically predicted attenuation coefficients.

3. Results

If the attenuation of gamma-rays in a chemical compound is assumed to depend only on the sum of the total cross sections for all the atoms in the com-

TABLE I
Measured total mass attenuation coefficients in cm²/g compared with the computed values.

| Absorber | Gamma-ray energy | | | | | |
|----------------------|------------------|------------------|---|------------------|------------------|--|
| | 0.079 MeV | 0.30 MeV | 0.662 MeV | 1.11 MeV | 1.17 MeV | 1.33 MeV |
| Carbon | | | | | | |
| Expt. | | 0.107 ± 0.0003 | 0.0779 ± 0.0011 (0.0770 ± 0.0001) ^a | | 0.0590 ± 0.00016 | 0.055 ± 0.00019 (0.055 ± 0.0001) ^a |
| Theor. | | 0.107 | 0.0772 | | 0.0590 | 0.055 |
| Toluene | | | | | | |
| Expt. | 0.1707 ± 0.0098 | 0.1156 ± 0.00038 | 0.0826 ± 0.0004 | 0.0663 ± 0.0026 | 0.0642 ± 0.00018 | 0.0597 ± 0.00022 |
| Theor. | 0.1740 | 0.1162 | 0.0836 | 0.0660 | 0.0642 | 0.0597 |
| O Xylene | | | | | | |
| Expt. | 0.1738 ± 0.0101 | 0.1160 ± 0.00037 | 0.0840 ± 0.00004 | 0.0671 ± 0.0026 | 0.0646 ± 0.00018 | 0.0608 ± 0.00022 |
| Theor. | 0.1751 | 0.1170 | 0.0841 | 0.0662 | 0.0645 | 0.0601 |
| Benzene | | | | | | |
| Expt. | 0.1701 ± 0.0099 | 0.1156 ± 0.00038 | 0.0838 ± 0.0004 | 0.0663 ± 0.0033 | 0.0636 ± 0.00018 | 0.0592 ± 0.00022 |
| Theor. | 0.1725 | 0.1151 | 0.0828 | 0.0652 | 0.0635 | 0.0592 |
| P Cymene | | | | | | |
| Expt. | 0.1770 ± 0.0102 | 0.1184 ± 0.00041 | 0.0846 ± 0.0004 | 0.0555 ± 0.00026 | 0.0546 ± 0.00015 | 0.0506 ± 0.00019 |
| Theor. | 0.1766 | 0.1180 | 0.0849 | 0.0554 | 0.0540 | 0.0504 |
| Cyclohexane | | | | | | |
| Expt. | 0.1873 ± 0.0107 | 0.1237 ± 0.00039 | 0.0896 ± 0.0004 | 0.0692 ± 0.0032 | 0.0675 ± 0.00019 | 0.0621 ± 0.00022 |
| Theor. | 0.1824 | 0.1221 | 0.0879 | 0.0692 | 0.0673 | 0.0628 |
| Decalin | | | | | | |
| Expt. | 0.1809 ± 0.0107 | 0.1207 ± 0.00039 | 0.0874 ± 0.0004 | 0.0671 ± 0.0033 | 0.0665 ± 0.00019 | 0.0626 ± 0.00024 |
| Theor. | 0.1805 | 0.1209 | 0.0869 | 0.0684 | 0.0666 | 0.0621 |
| Liquid paraffin | | | | | | |
| Expt. | 0.1789 ± 0.0688 | 0.1227 ± 0.00039 | 0.0883 ± 0.0004 | 0.0697 ± 0.0035 | 0.0677 ± 0.00019 | 0.0631 ± 0.00023 |
| Theor. | 0.1832 - 0.1834 | 0.1227 - 0.1228 | 0.0883 - 0.0884 | 0.0695 - 0.0696 | 0.0676 - 0.0677 | 0.0631 - 0.0632 |
| Anisole | | | | | | |
| Expt. | 0.1747 ± 0.0099 | 0.1150 ± 0.00038 | 0.0844 ± 0.0004 | 0.0616 ± 0.0030 | 0.0585 ± 0.00017 | 0.0549 ± 0.00022 |
| Theor. | 0.1773 | 0.1148 | 0.0827 | 0.0606 | 0.0588 | 0.0549 |
| Plastic scintillator | | | | | | |
| Expt. | | | 0.0816 ± 0.0022 | | | |
| Theor. | | | 0.0834 | | | |

^a The results reported by Colgate.

pound, then its mass attenuation coefficient is given by the average of the appropriately weighted mass attenuation coefficients of the constituent elements.

The mass attenuation coefficients of the elements H, C, and O which constitute the materials investigated were first determined using their total atomic cross sections at each gamma-ray energy. The atomic cross sections were obtained from the cross section data given by Grodstein²⁾ by interpolation. The overall mass attenuation coefficients of the materials thus determined are given in table 1, for comparison with the values obtained in the present experiments. The carbon data at 0.662 MeV of Colgate³⁾ is included in the table for comparison with our data for carbon. The errors quoted in the table are r.m.s. statistical errors.

It can be seen that the measured values agree, within the combined errors of experiment and the possible errors in the computation by graphical interpolation, with the theoretical values.

A complete account of this investigation will be communicated in future.

Our thanks are due to Prof. S. N. Sen, Head of the Department of Physics, University of North Bengal for providing facilities of work at the University.

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