Total Attenuation Coefficients for 5- to 11-MeV Photons*

R. H. Barlett† and D. J. Donahue‡
Pennsylvania State University, University Park, Pennsylvania
(Received 31 August 1964)

Monoenergetic neutron-capture gamma rays have been used to measure gamma-ray attenuation coefficients of beryllium, aluminum, copper, tin, and lead at energies of 5.435, 6.405, 7.725, and 10.833 MeV. These coefficients have been obtained with uncertainties of from 0.3 to 0.5%. Results are in reasonable agreement with calculated coefficients. Analysis of the results shows that, in the energy range studied, if Compton scattering can be calculated from the Klein-Nishina formula without radiative corrections, pair production in the Coulomb field of an electron is best predicted by the theory of Borsellino.

I. INTRODUCTION

GAMMA-RAY attenuation measurements of beryllium, aluminum, copper, tin, and lead have been made at four photon energies between 5 and 11 MeV. From these measurements, attenuation coefficients have been obtained with precisions of 0.5% or better. In this energy range approximately 99% of the attenuation occurs by Compton scattering and pair production in the field of the nucleus. In low-Z elements a small but measurable contribution arises from pair production in the Coulomb field of the electron. After subtracting a small photoelectric contribution from the results for lead and tin, and a photonuclear contribution from beryllium, tin and lead, our measurements were analyzed in terms of the Compton scattering and the two pair production processes. In this energy range a comparison of experiment with theories for pair production in an electron field can be instructive since different theoretical predictions differ by as much as a factor of six.

The gamma rays used in this experiment resulted from thermal neutron capture by different materials placed near the core of the Pennsylvania State University reactor. The spectra of these neutron-capture gamma rays from many elements have been studied and compiled by different authors.[1,2] Generally, the photon energies are greater than those of gamma rays from radioactive isotopes, and less than the maximum energy of bremsstrahlung beams usually used in attenuation measurements.

In the energy interval from 5- to 11-MeV total attenuation-coefficient measurements have previously been made at 6.13 MeV by Paul[3] and Colgate[4] and at 5.13 and 10.3 MeV by Rosenblum *et al.*[5]

II. EXPERIMENTAL PROCEDURE

The experimental arrangement used is shown in Fig. 1. Neutrons from the reactor passed through a bismuth filter and were captured in the gamma-ray source. The purpose of the bismuth was to reduce the background in the experimental area produced by gamma rays from the reactor core. The materials used as gamma-ray sources, and the energies of the gamma rays from these sources which were used in the measurements, were sulfur (5.435 MeV), sodium (NaOH, 6.405 MeV), aluminum (7.725 MeV) and nitrogen (melamine, 10.833 MeV). Gamma rays produced in the source passed through four feet of water, which was used to remove neutrons from the beam, and were collimated into a slightly divergent beam which was $\frac{3}{8}$ in. in diameter at the position of the absorbers. The photon beam was further collimated between the absorber and detector to reduce the number of gamma rays which reached the detector after multiple scattering in the absorber and experimental apparatus. The detector was a 4-in.-diam by 6-in.-long NaI(Tl) crystal coupled to a photomultiplier and 128-channel analyzer. The spectrum produced by monoenergetic gamma rays in the energy range of this experiment consisted of a full-energy peak and a one-escape peak of approximately equal magnitude, plus a low-energy tail.

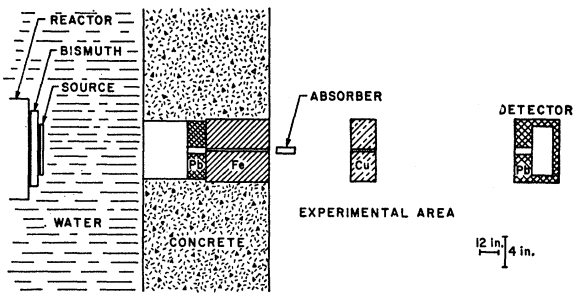

FIG. 1. Schematic drawing of experimental arrangement.

* This work was supported in part by the U. S. Atomic Energy Commission, and is from the Ph.D. thesis of R. H. Barlett.
† Present address: Lawrence Radiation Laboratory, Livermore, California.
‡ Present address: Department of Physics, University of Arizona, Tucson, Arizona.
[1] G. A. Bartholomew and L. A. Higgs, Atomic Energy of Canada Limited, No. 669, Chalk River, Ontario, Canada, 1958 (unpublished).
[2] L. V. Groshev, V. W. Lutsenko, A. M. Demidov, and V. I. Pelekhov, *Atlas of Gamma Rays from Radiative Capture of Thermal Neutrons* (Pergamon Press, Inc., New York, 1959).
[3] R. S. Paul, Phys. Rev. **96**, 1563 (1954).
[4] S. A. Colgate, Phys. Rev. **87**, 592 (1952).
[5] E. S. Rosenblum, E. F. Shrader, and R. M. Warner, Jr., Phys. Rev. **88**, 612 (1952).

The absorbers were $\frac{3}{4}$-in.-diam rods with lengths of approximately two mean free paths. To measure an attenuation coefficient the intensity of the γ-ray beam was measured with and without the absorber in place. This process was repeated from six to twelve times for each absorber at each gamma-ray energy. The attenuation coefficient for a given absorber at a given energy was obtained from the average of these several measurements, and the standard deviation of the average was deduced from the spread of the individual measurements about this average. Extensive tests showed that the variation of the intensity of the incident beam during any particular measurement was small enough so that it did not affect the measurement.

The decrease in intensity of gamma rays at the detector which resulted when an absorber was placed in the beam caused a change in the gain and resolution of the detector system. To minimize the effect of these changes, intensity measurements were made by summing the counts recorded in the 0.511-MeV energy interval between the maximum of the full-energy peak and the maximum of the one-escape peak. The limits of this interval could be located to within one-twentieth of a channel, and uncertainties introduced into intensity measurements because of errors in locating this interval were negligible since its limits were in channels of nearly equal counting rates. Further, since the interval includes the halves, except for tails, of two symmetrical peaks, the effect of resolution changes was largely circumvented. A small error was introduced into the attenuation-coefficient measurements by the change in resolution of the spectrometer, because the counting interval did not include the tails of peaks. However, if it is assumed that the peaks have a Gaussian shape, this error is less than 0.1% of the coefficients.

The effect of resolution changes on a measurement of an attenuation coefficient was investigated by measuring the attenuation coefficient as a function of the counting interval used for intensity measurements. The high-energy limit of the interval was fixed at the maximum of the full-energy peak, and the width of the interval was varied from a few hundred kilovolts to about 1 MeV. The results of this investigation are shown in Fig. 2. For intervals between about 300 keV and 1 MeV the variation of the attenuation coefficients from that for a 0.511-MeV interval is less than 0.3%. Whenever the standard deviation of an attenuation coefficient determined from a statistical analysis of several independent measurements is less than 0.3%, the uncertainty quoted with the attenuation coefficient is taken to be equal to the 0.3% variation observed for different counting-interval widths. Measured attenuation coefficients, and the errors assigned to them are listed in Table I.

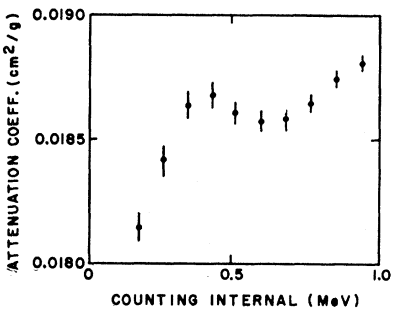

FIG. 2. Attenuation coefficient for beryllium at 7.725 MeV as a function of energy interval used in measurement of beam intensities.

Also listed in Table I are corrections which were applied to the measured attenuation coefficients in order to convert them to electronic attenuation coefficients. These are discussed briefly below.

(a) *Air displacement.* When an absorber is removed from the gamma-ray beam, a column of air replaces it. Corrections for air attenuation were made using tabulated theoretical values from NBS circular 583.[6]

(b) *Background.* When measurements were made with 5.435-MeV gamma rays from a sulfur source, it was necessary to correct for contributions to the intensity measurements from higher energy gamma rays emitted by the sulfur source, and from 7.725-MeV gamma rays produced by capture in aluminum in the reactor core and in structural material. A similar correction for the 7.725-MeV gamma rays was necessary when measurements were made with the 6.405-MeV gamma rays from sodium.

(c) *Impurities.* All absorbers were checked for impurities.[7] The only significant correction which was necessary was for oxygen content in the beryllium. The oxygen content was measured at three positions along the length of the beryllium absorber. The average content was found to be 2% by weight and appropriate corrections were applied.

(d) *Nuclear absorption.* Photonuclear cross sections were assumed to be given by photoneutron cross sections, which were subtracted directly from measured cross sections. With one exception the photoneutron cross sections listed in Table I are measured ones, and have been taken from several sources.[8] For tin at 10.8 MeV it was necessary to estimate the cross section from the known photoneutron thresholds for the different tin isotopes, and from the general shape of photoneutron cross sections near threshold.

(e) *Other corrections.* The possibility was investigated that corrections should be made for Compton scattering of gamma rays into the detector by the 4-ft-thick water filter, the collimators, or the absorbers.

[6] G. W. Grodstein, Natl. Bur. Std. Circ. (U.S.) 583 (1957).

[7] Spectrochemical analysis of the absorbers to determine their impurity content was done by Spectrochemical Laboratories, Inc., Pittsburgh, Pennsylvania.

[8] Values for beryllium are from H. Goldstein, *Fundamental Aspects of Reactor Shielding* (Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, 1959), p. 57; values for the heavy elements at 10.8 MeV are from R. Montalbetti, L. Katz, and J. Goldemberg, Phys. Rev. **91**, 659 (1953), and for the heavy elements at 7.7 MeV from L. Green, Physics Department, The Pennsylvania State University, University Park, Pennsylvania (private communication).

TABLE I. Total gamma-ray attenuation coefficients.

Photon energy (MeV)	Absorber	Measured attenuation coefficient cm²/g	Uncertainty, ±%	Corrections: Air displacement, 10^{-5} cm²/g	Background, 10^{-3} cm²/g	Impurities, 10^{-4} cm²/g	Photonuclear cross section 10^{-3} cm²/g	Corrected electronic attenuation coefficient cm²/g	Uncertainty, ±%
5.435	Be	0.02236	0.3	+0.99	+0.25±0.05	−0.89±0.22	0.07±0.004	0.02246	0.4
	Al	0.02751	0.3	0.68	+0.19±0.04	−0.03		0.02770	0.3
	Cu	0.03124	0.3	0.21	+0.04±0.01			0.03128	0.3
	Sn	0.03542	0.3	0.25	−0.06±0.02			0.03536	0.3
	Pb	0.04288	0.3	0.16	−0.10±0.02			0.04278	0.3
6.405	Be	0.02058	0.3	0.92	+0.09±0.03	−0.82±0.20	0.08±0.004	0.02052	0.4
	Al	0.02613	0.3	0.63	+0.06±0.02	−0.03		0.02619	0.3
	Cu	0.03087	0.3	0.19	+0.05			0.03092	0.3
	Sn	0.03591	0.3	0.23	−0.03			0.03588	0.3
	Pb	0.04405	0.3	0.15	−0.06			0.04399	0.3
7.725	Be	0.01864	0.3	0.85		−0.75±0.19	0.09±0.005	0.01848	0.3
	Al	0.02468	0.3	0.58		−0.05		0.02469	0.3
	Cu	0.03054	0.3	0.18				0.03054	0.3
	Sn	0.03701	0.3	0.22			0.01±0.003	0.03700	0.3
	Pb	0.04622	0.3	0.14			0.04±0.012	0.04618	0.3
10.833	Be	0.01565	0.5	0.75		−0.78±0.15	0.10±0.005	0.01548	0.5
	Al	0.02273	0.5	0.51		−0.07		0.02273	0.5
	Cu	0.03089	0.5	0.16		−0.03	0.12±0.01	0.03077	0.5
	Sn	0.03930	0.5	0.19			0.40±0.12	0.03890	0.6
	Pb	0.05118	0.5	0.12		+0.10	0.87±0.09	0.05032	0.5

Calculations similar to those of Tarrant as described by Davisson and Evans[9] were performed. These calculations showed that for the geometry of this experiment, such corrections were negligible.

III. RESULTS AND DISCUSSION

The corrected electronic attenuation coefficients are listed in Table I and plotted in Fig. 3. Also shown in Fig. 3 are the measurements of Colgate[4] and Rosenblum.[5] The curves in the figure represent the calculations of Grodstein,[6] which have been adjusted to fit the results of Paul[3] at 6.13 MeV.

The methods used by Grodstein[6] to obtain the calculated curves in Fig. 3 are described briefly. Compton scattering is computed from the Klein-Nishina equation with a correction for the fact that the scattering electrons are bound. No attempt is made to consider second-order Compton scattering processes. Pair production in the Coulomb field of a nucleus is calculated from the equation

$$\sigma_{pp}=\sigma_B-\Delta\sigma_c+a^2(\ln\epsilon/\epsilon).$$

σ_B is the cross section calculated using the Born approximation,[10] with corrections for screening by bound electrons. $\Delta\sigma_c$ is a Coulomb correction term computed by Davies, Bethe, and Maximon[11] for high-energy photons. The term $a^2(\ln\epsilon/\epsilon)$ where $a=Z/137$, is included by Davies, Bethe, and Maximon to make the Coulomb correction term more nearly correct for low-energy photons. In her calculations Grodstein allows the term a to be a parameter which is adjusted to fit the experimental results of Paul[3] at 6.13 MeV and the calculations of Jaeger and Hulme[12] at energies near threshold.

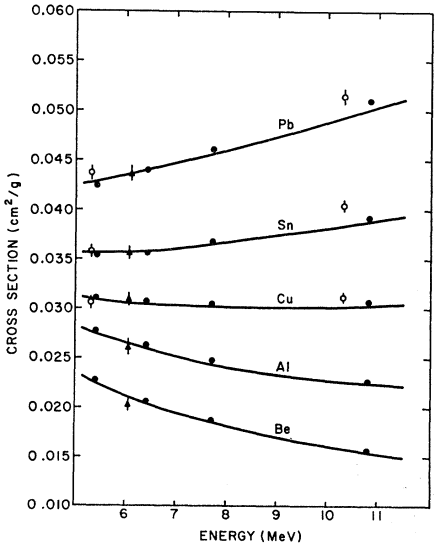

FIG. 3. Total electronic attenuation coefficients. Present measurements are represented by solid circles, measurements of Colgate (Ref. 4) by solid triangles and of Rosenblum *et al.* (Ref. 5) by open circles. Solid curves are calculated, and have been normalized at 6.13 MeV to the measurements of Paul (Ref. 3).

[9] C. M. Davisson and R. D. Evans, Rev. Mod. Phys. **24**, 79 (1952).

[10] H. A. Bethe and W. Heitler, Proc. Roy. Soc. (London) **A146**, 83 (1934).

[11] H. Davies, H. A. Bethe, and L. C. Maximon, Phys. Rev. **93**, 788 (1954).

[12] J. C. Jaeger and H. R. Hulme, Proc. Roy. Soc. (London) **A153**, 443 (1936).

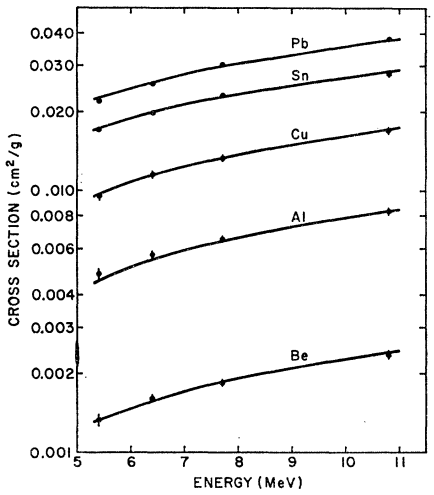

FIG. 4. Cross sections for pair production in the nuclear Coulomb field. Solid curves are semiempirical calculations of Grodstein (Ref. 6).

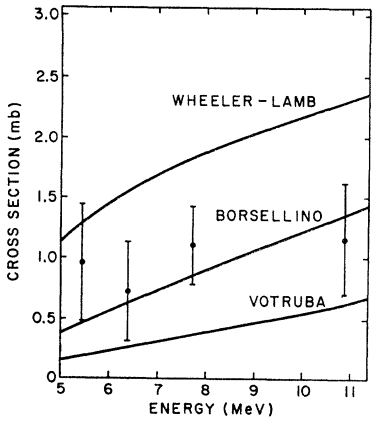

FIG. 5. Cross sections for pair production in the field of an electron. Theoretical curves were taken from Ref. 14.

Finally, for pair production in the field of an electron, Grodstein uses the calculations of Votruba. Other methods which can be used for calculating this cross section are discussed by Joseph and Rohrlich.[13]

The agreement between our experimental results and the calculations cited are within Grodstein's estimated uncertainty of 3% for the calculated cross sections. However, because of a systematic difference of approximately 1% between experiment and calculations for the low-Z elements, a further analysis of our results was attempted. The total electronic attenuation coefficients for beryllium and aluminum were set equal to

$$\sigma_t = K_1 Z + K_2 Z^2.$$

The Z-dependent term is a constant times the number of electrons per atom, and is the cross section per atom for the Compton scattering plus pair production in the Coulomb field of the electron. The Z^2-dependent term represents the cross section for pair production in the Coulomb field of the nucleus as predicted by the calculation of Bethe-Heitler using Born approximation. Corrections to Born approximation resulting in terms not proportional to Z^2, and for screening are small for these low-Z elements at the photon energies used in this experiment.

The two equations, one for beryllium and one for aluminum, were solved simultaneously for K_1 and K_2. From K_2 the nuclear pair cross sections for beryllium and aluminum were obtained. The nuclear pair cross sections for the heavier elements were obtained by subtracting $K_1 Z$ plus a small photoelectric contribution from the measured total electronic cross section. The nuclear pair cross sections are illustrated in Fig. 4. The curves are from the semiempirical calculations of Grodstein. The systematic difference between experiment and theory for the total cross section cannot readily be attributed to the theoretical nuclear pair cross section because of the good agreement between experiment and theory. A 10% increase in the pair cross section for beryllium would be required for a 1% increase in the total cross section. Also, because of Z^2 dependence of this cross section, an adjustment to fit experimental data for both beryllium and aluminum would not be possible.

Instead, the difference can be attributed to an increased electronic pair cross section or to higher order Compton processes. If it is assumed that the Compton cross section is given by the Klein-Nishina law to within a few tenths of a percent, then subtraction of this component from the Z-dependent term obtained above for beryllium and aluminum gives the cross section for pair production in the Coulomb field of the electron shown in Fig. 5. The error flags are standard deviations, calculated using the measured standard deviations of the total cross sections for beryllium and aluminum. The curves for electron-field pair production were taken from a paper by Wyckoff and Koch.[14] As can be seen, results agree best with calculations of Borsellino. However, it should be emphasized that the conclusion that Borsellino's equation for the cross section for pair production in the Coulomb field of an electron best fits the experimental data could be completely invalidated if second-order corrections of the order of 1/137 of the first order cross section were required with the Klein-Nishina equation.

[13] J. Joseph and F. Rohrlich, Rev. Mod. Phys. **36**, 354 (1958).

[14] J. M. Wyckoff and H. W. Koch, Phys. Rev. **117**, 1261 (1960).