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The Absorption of Gamma-Radiation*

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Absorption coefficients for gamma-radiation ranging from 0.32 to 2.8 Mev penetrating various elements ranging from low to high Z were measured. A geometry was employed which yielded results whose accuracy was limited only by statistics and background corrections. The source, absorbers of area just sufficient to completely intercept all detected gamma-rays, and a Geiger tube were suspended outdoors about 25 feet above the ground. The results are in excellent agreement with theoretical predictions.

THE large number of wide variety of radioisotopes which have become available to the physical laboratory in the past few years through the facilities of the Atomic Energy Commission have made it possible to investigate further the validity of the modern theories of the interaction of gamma-radiation with matter. Of the various experimental techniques which lend themselves to this work, that of measurement of absorption coefficients is probably the simplest in application and interpretation, though somewhat limited in the degree of accuracy attainable. A number of investigators[1] have utilized absorption measurements for this purpose, obtaining in general good agreement with the predictions of theory. It is the purpose of the present work to extend these measurements over a wider range of gamma-ray energy and for absorbers of widely differing atomic number, employing a technique calculated to reach a higher degree of accuracy by reducing to a minimum the effects of the geometry and environment of the measuring apparatus.

Three processes are primarily responsible for the attenuation of a beam of gamma-radiation when it penetrates matter: the Compton effect, the photoelectric effect and, for quantum energies above 1.02 Mev, pair creation. Applying the methods of Dirac's electron and radiation theories, a number of physicists[2] have developed the theories of these effects, the results and predictions of which are now well known.[3] It is possible, however, that other processes such as multiple Compton scattering[4] and pair creation in the fields of the atomic electrons[5] may account for some slight additional observable attenuation. Further, with sufficiently accurate measurements, one might hope to find small deviations from the theory of Klein and Nishina as a result of the effect of nuclear binding of the orbital electrons.[6]

APPARATUS

The nature of the absorbing and scattering processes for gamma-rays makes stringent demands on geometry if the errors in the measured values of the coefficients are to be kept small.

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[6] H. Casimir, Helv. Phys. Acta. **6**, 287 (1933); W. Franz, Zeits. f. Physik **90**, 623 (1934); G. Wentzel, Zeits. f. Physik **43**, 1 and 779 (1927); F. Bloch, Phys. Rev. **46**, 674 (1934).

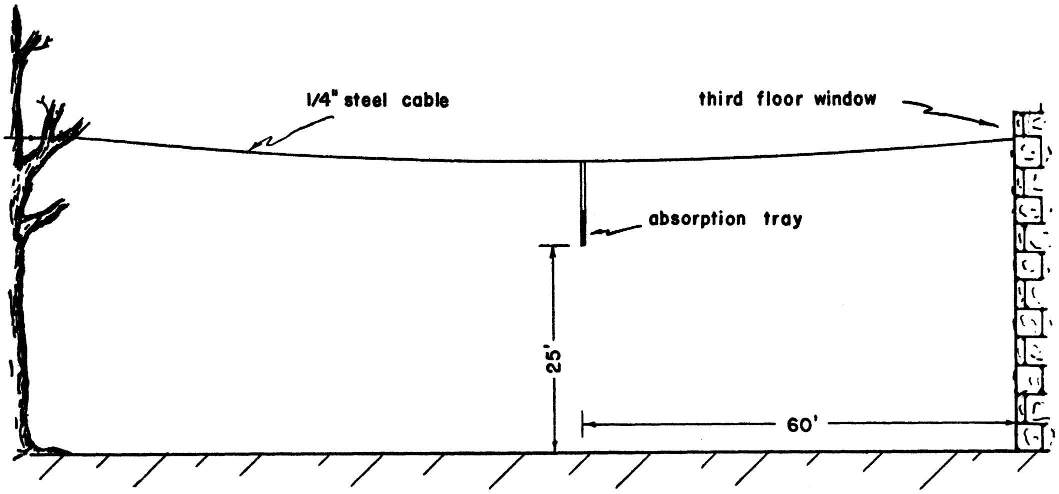

FIG. 1. The out-of-doors suspension employed.

The definition of the absorption coefficient assumes that a given photon will penetrate the full thickness of the absorber unchanged or it will encounter only one absorbing or scattering event, after which no particles which leave the scene of the event are detected in the envelope of the primary beam. Thus, a second or third scattering of the degraded photon which causes it to reach the detector represents a systematic error in the measurements. Furthermore, the beam is assumed to be composed of monoenergetic gamma-quanta which are traveling in parallel paths. An experimental geometry is thus demanded which includes a source of monoenergetic gamma-radiation traveling in a small well-collimated beam, an absorber which is just sufficiently wide to cover the solid angle defined at the source by the detector, and high efficiency gamma-ray detector whose characteristics are invariant to any environmental changes.

TABLE I. Linear absorption coefficients measured in the present work. The values in parentheses are the corresponding theoretical values. The coefficients are listed against the corresponding emitters and the effective gamma-ray energy. Units are cm^{-1}.

Source	Gamma-energy (Mev)	Pb	Sn	Cu	Al	C
Cr-51	0.32		1.05 (1.04)	0.937 (0.928)	0.292 (0.280)	0.170 (0.170)
Cs-137	0.65	1.26 (1.27)	0.521 (0.513)	0.617 (0.622)	0.195 (0.197)	0.128 (0.123)
Zn-65	1.11	0.724 (0.712)	0.372 (0.360)	0.478 (0.475)	0.155 (0.152)	0.091 (0.086)
Sb-124	1.72	0.533 (0.538)	0.302 (0.290)	0.371 (0.392)		0.0742 (0.071)
Na-24 (from 5 to 12 cm Pb)	2.30	0.473 (0.479)	0.266 (0.264)			0.0599 (0.060)

In order to approach this idealized geometry, an essentially bare source with small absorbers and a small Geiger tube, all mounted on a light aluminum frame suspended out of doors and as far from massive objects as possible, was employed (Fig. 1). A $\frac{1}{4}$-inch steel cable was run from a hand winch anchored in a third-floor laboratory to a tree about 130 feet distant from the building. An "absorption tray" was suspended from the cable and about 6 feet below it by two nickel wires and Lucite insulators approximately 60 feet from the building. The tray, 2 inches by 4 inches in cross section and 28 inches long, was made of $\frac{1}{16}$-inch aluminum sheet and carried the source, absorbers and Geiger tube as illustrated in Fig. 2.

The gamma-ray source for each measurement was enclosed in a light aluminum tube. As measurements were made throughout the year, the Geiger tube was designed to meet extremes of weather. Alcohol-argon fillings were useless below temperatures of 40°F, but ethyl ether-argon and ethylene-argon fillings were excellent for all-weather counting. The weatherproof Geiger tube is illustrated in Fig. 3. The tube was connected directly to a 100-foot co-axial lead of $11\mu\mu$f capacity per foot. The lead was hung from the steel cable and connected to a guard cathode follower and scaling circuit and a high-voltage supply located near the winch. The cathode follower neutralized the effect of the long lead very satisfactorily without seriously interfering with the shielding. The only pick-up disturbances noted were caused by near-by lightning discharges. The absorption tray was lowered to ground level by paying out cable from the winch when absorber changes were required.

BACKGROUND EFFECTS

One serious limitation on the accuracy of absorption measurements is the comparative magnitude of background and transmitted radiation (i.e., "signal-to-noise" ratio). A study of the apparatus was, therefore, made as follows: background measurements were taken with no source in the tray and both with and without 20 cm of lead absorber in position, a count being taken for every two feet of altitude from ground level to the maximum height of 25 feet. It was found that background thus measured was the normal cosmic-ray intensity and was not a function of height, nor was it affected by the presence of absorber in the tray. The background *versus* height measurements were then repeated with a 3 mc antimony-124 source and 20 cm of lead absorber in the tray. With this arrangement the background was quite high at ground level and dropped rapidly with increasing height, reaching a constant value of about four times natural background at about 12 feet above the ground. Doubling the mass of the aluminum tray by fastening $\frac{1}{16}$-inch aluminum sheets to it raised this excess or "induced" background by only $\frac{1}{2}$ percent. Only the ground and the air could then account for the induced background.

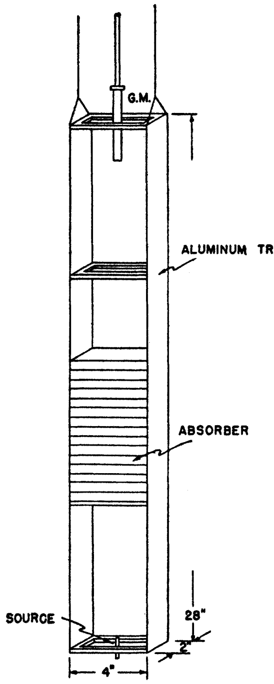

FIG. 2. The absorption tray. The construction afforded adequate rigidity to prevent relative movement of the Geiger tube and the source as the weight of absorber was increased. When the activity of the source was large, the Geiger tube was employed in the position shown. For extremely weak sources, the tube was rotated 90° so that in a broadside position, the increased counting rate with no increase in background could be utilized. A test was made for changes in measured absorption coefficient for absorbers of area half that shown and with the tube in the vertical position. No detectable change was found, indicating that the absorbers used were sufficiently small.

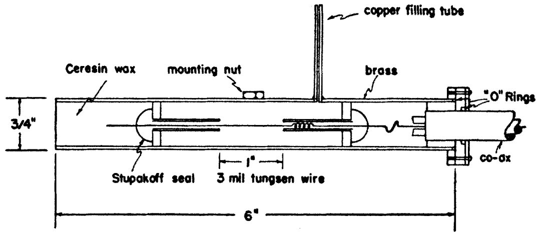

FIG. 3. The weatherproof Geiger tube. The filling of 30 percent ethylene—70 percent argon proved very satisfactory, yielding a tube of high stability, long plateau and no temperature dependence.

A lead cap 2-inches thick was made which fitted over the top of the Geiger tube and shielded the tube from the greater part of the solid angle around it while leaving the active region of the tube largely exposed to the ground. With the source and lead absorbers now in place and with the apparatus 25 feet above the ground, the induced background fell to 5 percent of the natural background, indicating that the air was responsible for the back scattering. As the simple geometry described in the last section was designed to eliminate scattering of transmitted photons by matter near the Geiger tube, the intensity of which would vary with absorber thickness, the lead cap was removed for the absorption measurements. A theoretical study of the scattering of gamma-radiation by the atmosphere was made by Dr. H. Primakoff of this department with the result that the induced background could be assigned to air scattering (Fig. 4).

ABSORPTION MEASUREMENTS

A number of radioisotopes which were available from the Oak Ridge Laboratory were purchased so that as wide a range of monochromatic gamma-ray energy as possible could be tested. In addition, antimony-124 and sodium-24 sources were obtained from the Washington University cyclotron. In several cases it was not possible to obtain monochromatic radiation, but it was possible to use sources which either emitted gamma-lines close together or quite far apart. A study of these complex spectra revealed that when the lines were quite close together, the measurements should yield a coefficient which should be characteristic of gamma-radiation possessing the mean energy of the spectrum. On the other hand, when the lines were well separated, the line possessing the highest absorption coefficient should effectively disappear from the transmitted radiation for relatively small absorber thickness, leaving a quite usable intensity of the higher energy radiation for further measurement. In the case of the radiation from sodium-24, the lines cannot be resolved as above nor are they close enough together to appear monochromatic. The resulting absorption coefficient measured would then be a function of the absorber thickness. The data are usable, however, when taken over only 6 to 10 cm of, say, lead absorber for which range the deviation from a pure exponential absorption caused by the complex character of the spectrum was less than experimental error. Matching this portion of the absorption curve to a synthetic curve constructed by assigning theoretical coefficients to the known lines in the spectrum and adding the resultant curves is a valid test of the theory at this energy. Whenever possible, sources possessing long half-lives relative to the time required for a complete absorption coefficient determination were chosen. The gamma-spectra of the sources were analyzed by the various beta-spectrograph groups in the laboratory whenever

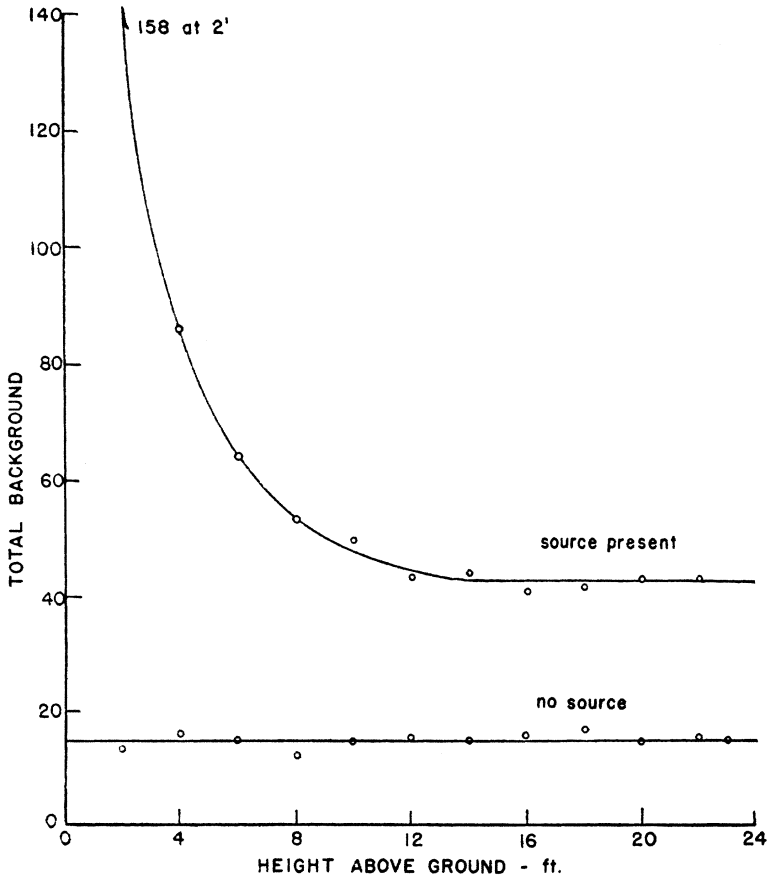

FIG. 4. Background *versus* height of the absorption tray above ground. The statistical deviation for each point is approximately 5 percent.

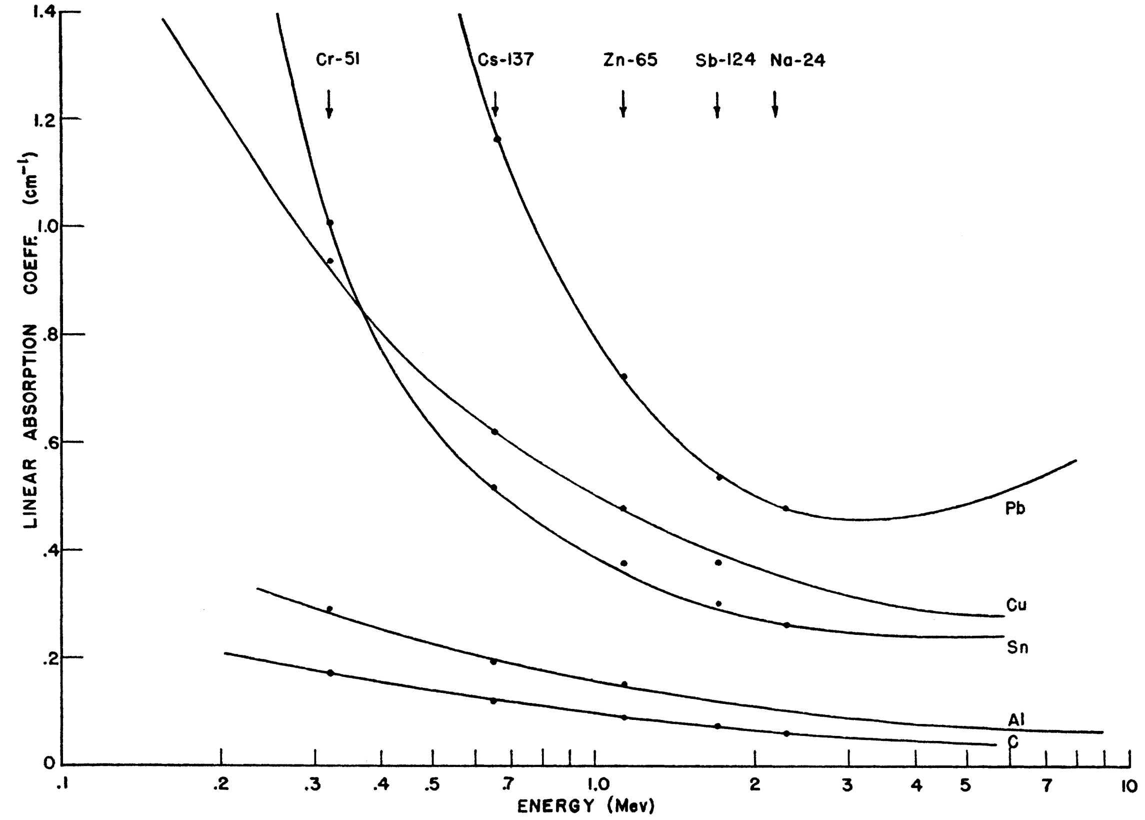

FIG. 5. The points are the results of the present measurements and the lines are the predictions of theory. The line for carbon was calculated for graphite of density 1.59 g/cm^3.

there was doubt as to their true composition. A chemical purification of the radioisotopes was also carried out where indicated.

All counts taken were sufficiently large so that standard deviation was less than one percent. Corrections were made for the effect of Geiger tube insensitive time and, where necessary, for decay of the source during measurement. Attenuation of the gamma-beam by absorber was carried to a point no farther than ten times the total (natural plus induced) background.

RESULTS

Absorption coefficients thus measured are listed in Table I along with theoretically predicted values. Figure 5 is a plot of the predictions of theory (solid lines) on which the experimental values are placed. It is seen that within the experimental error the values are in excellent agreement with theoretical ones from low to high Z and over the energy range covered. No evidence could be found for observable secondary attenuating effects such as double Compton scattering.

ACKNOWLEDGMENTS

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