Gamma-Ray Absorption Coefficients at 6.13 Mev

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Narrow-beam geometry attenuation measurements have been made with 6.13-Mev gamma rays which follow the beta decay of N^{16} using a NaI scintillation spectrometer detector. The measured absorption coefficients in cm^2/g are: 0.0244 (C), 0.0264 (Al), 0.0309 (Cu), 0.0359 (Sn), 0.0359 (Cd), 0.0436 (Pb), 0.0459 (U), 0.0284 (H_2O), 0.0350 (NaI). The statistical standard deviations range from 0.2 percent to 0.4 percent. These results are in good agreement with previous experimental work in those cases for which earlier data exist. "Experimental" pair-production cross sections are derived from the data and compared with the calculated values from the Born approximation to the Bethe-Heitler theory. A discrepancy of 7 to 8 percent is observed for high atomic number elements (Pb and U).

I. INTRODUCTION

EXPERIMENTAL gamma-ray absorption coefficients, with a statistical accuracy of ± 2 percent, have been reported by Colgate[1] for gamma rays of 6.13-Mev energy obtained from the $F^{19}(p,\alpha)O^{16*}\gamma O^{16}$ reaction. The narrow-beam geometry measurements reported here had been initiated prior to the publication of Colgate's work and were subsequently completed to provide an independent measurement with a statistical accuracy of ± 0.2 percent to ± 0.4 percent, to include several additional elements of interest, and to furnish some information needed for planning attenuation experiments in poor geometry with 6.1-Mev gamma rays. The reduced statistical uncertainties were realized by using a high specific activity source of nitrogen-16 produced by irradiating water in a high neutron flux, and by using, for the detector, a NaI scintillation spectrometer biased to accept only the N^{16} gamma rays. Results of these measurements are compared with those of Colgate and with theoretical predictions.

II. APPARATUS

The 6.13-Mev[2] gamma rays were obtained from the $O^{16}(n,p)N^{16}\beta O^{16*}\gamma O^{16}$ reaction in water passed through a high flux nuclear reactor. Since N^{16} has a 7.3-second half-life, the detector viewed a continuously flowing source. Water entered the central tube of a co-axial cylindrical source chamber as shown in Fig. 1. A flow-meter with electrical trip limits monitored the water flow rate.

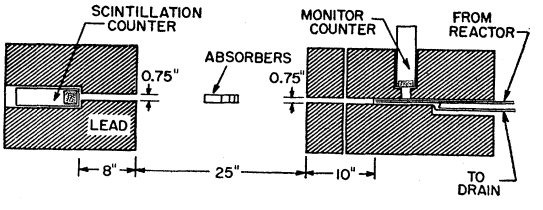

FIG. 1. Schematic diagram of counting geometry.

The collimated geometry arrangement shown in Fig. 1 was used for all measurements. The solid angles were made as small as possible consistent with maintaining reasonable counting rates to reduce the magnitude of the scattering corrections. Large amounts of lead shielding were required around the detector to reduce the background from other sources of high energy gamma radiation and to eliminate scattering into the detector from the room. The absorber samples were centered in the beam by Lucite holders. There was no detectable scattering into the detector by the sample supports.

The primary detector was a scintillation counter using a 2-in. diameter by 2-in. thick NaI(Tl) crystal mounted on a DuMont 6292 photomultiplier tube. This counter only had a resolution of 17 percent for the Cs^{137} 0.66-Mev photopeak but this was adequate to bias out lower energy gammas in the source. The electronic portion of the spectrometer consisted of a conventional *A*-1 linear amplifier, differential and integral discriminators, and scalers. Drifts in the gain of the spectrometer were negligible during the three to five hours required to complete a run with any one absorber material. As shown in the spectrum in Fig. 2, gamma rays of energies lower than 6.1 Mev were present in the source due to the $O^{18}(n,\gamma)O^{19}$ reaction, neutron activation of impurities in the water, and

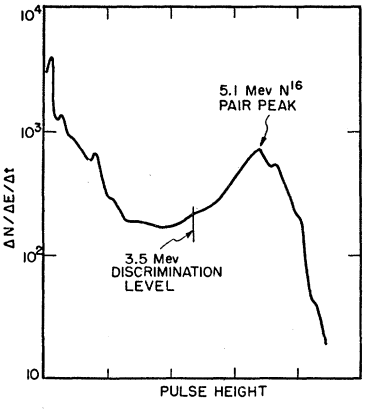

FIG. 2. Scintillation spectrum from N^{16} source.

* Operated for the U. S. Atomic Energy Commission by the General Electric Company.
[1] S. A. Colgate, Phys. Rev. **87**, 592 (1952).
[2] Millar, Bartholomew, and Kinsey, Phys. Rev. **81**, 150 (1951).

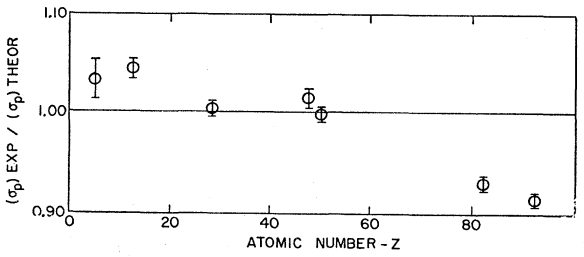

FIG. 3. Ratio of the "experimental" pair-production cross section to the theoretical cross section obtained from the Born approximation to the Bethe-Heitler theory.

annihilation quanta. Preliminary experiments established that these were not detectable and that an optimum count-to-background ratio was obtained for the 6.13-Mev gammas with an integral discriminator setting at 3.5 Mev. As discussed later a small theoretical correction was applied for the presence in the beam of the 7.1-Mev gamma which is present in about eight percent[2] of the O^{16*} decay events.

In the initial measurements, the beam intensity was monitored by a second scintillation spectrometer for variations in source strength which could result from reactor flux level changes or small water flow rate changes. It was found, however, that these changes were negligible during any one run and better statistical accuracy could be obtained by taking periodic zero absorber and background counts with the main detector.

The density of the absorbers was determined to better than 0.10 percent by weight and volume measurements. High purity materials were used and the purities were also checked spectroscopically. No corrections for impurities were required for any of the materials. The aluminum, copper, cadmium, and tin absorbers were 1.0 inch diameter cylinders of varying lengths. The lead and uranium cylinders were about 1.25 inches and the carbon (graphite) 1.4 inches in diameter. The water was contained in 1.2-inch diameter glass cells with thin parallel aluminum windows. Two sodium-iodide crystals of 1.5-inch diameter and 1.0- and 2.0-inch lengths were used. These were contained in thin polyethylene bags during the measurement. The handbook density of 3.667 g/cm² was used for the sodium-iodide calculations.

III. EXPERIMENTAL PROCEDURE

Transmission ratios suitably corrected for background counts were obtained for a series of absorber thicknesses for each element. The background was determined by (*i*) diverting the water flow from the source chamber, and (*ii*) placing absorbers with transmissions of less than 10^{-6} in the beam. Both methods gave identical results within the counting statistics. The counting periods with the absorber in and out of the beam were chosen to give a standard deviation in the final value of the absorption coefficient of less than 0.5 percent. The background counting rate was about 2 percent of the unattenuated beam counting rate. In all cases true exponential absorption was observed over the range of attenuations measured.

IV. EXPERIMENTAL RESULTS

Two small theoretically calculated corrections were applied to the experimental data. The first (Δ_c) corrected for the small-angle Compton scattering received at the detector. This was determined by a method similar to that described by Davisson and Evans[3] who show that for small angles the amount of scattered radiation reaching the detector is independent of the photon energy and proportional to the solid angle of the scattering cone being considered. This procedure is valid in this experiment since the maximum scattering angles were from 2° to 3°. These Compton scattering corrections to the measured transmissions

TABLE I. Absorption measurements with 6.13-Mev gamma rays.

Absorber	τ_m (cm²/g)	τ_c (cm²/g)	$a\mu$ (cm²/atom) Corrected	$a\mu$ (cm²/atom) Experimental by Colgate (in units of 10^{-24} cm²/atom)	$a\mu$ (cm²/atom)[a] Theoretical
Carbon $Z=6$	0.0241±0.23%	0.0244±0.23%	0.487±0.23%	0.491±2%	0.4823
Aluminum $Z=13$	0.0262±0.20%	0.0264±0.20%	1.184±0.20%	1.17 ±2%	1.167
Copper $Z=29$	0.0307±0.19%	0.0309±0.19%	3.255±0.19%	3.27 ±2%	3.237
Cadmium $Z=48$	0.0359±0.32%	0.0359±0.32%	6.708±0.32%		
Tin $Z=50$	0.0359±0.16%	0.0359±0.17%	7.079±0.17%	7.07 ±2%	7.057
Lead $Z=82$	0.0436±0.43%	0.0436±0.43%	14.99 ±0.43%	15.1 ±2%	15.51
Uranium $Z=92$	0.0459±0.23%	0.0459±0.24%	18.14 ±0.24%	18.2 ±2%	
Water	0.0281±0.30%	0.0284±0.30%			
Sodium-Iodide	0.0348±0.41%	0.0350±0.41%			

[a] Values given directly or derived from data given by C. Davisson and R. D. Evans, Revs. Modern Phys. **24**, 79 (1952).

[3] C. M. Davisson and R. D. Evans, Revs. Modern Phys. **24**, 79 (1952).

TABLE II. Calculation of (σ_p)exp (in units of 10^{-24} cm²/atom).

Element	C(6)	Al(13)	Cu(29)	Cd(48)	Sn(50)	Pb(82)	U(92)
$_a\mu$ Experimental	0.487	1.184	3.255	6.708	7.079	14.99	18.14
$\sigma_{Compton}$	0.433	0.938	2.092	3.464	3.608	5.92	6.64
σ_{photo}			0.004	0.047	0.058	0.54	0.93
$\sigma_{pair\ electron\ field}$	0.003	0.007	0.016	0.026	0.027	0.04	0.05
(σ_{pair})exp	0.051 ±0.011	0.239 ±0.002	1.143 ±0.006	3.171 ±0.022	3.386 ±0.012	8.49 ±0.06	10.52 ±0.04
(σ_{pair})theor	0.0495	0.229	1.141	3.125	3.391	9.12	11.48

range from less than 0.1 percent to 0.2 percent for the largest absorber thickness with carbon. In evaluating the statistical accuracy of the final absorption coefficient, an uncertainty of ±20 percent was assigned to the small Compton corrections.

Bremsstrahlung below 3.5 Mev and annihilation quanta which are produced in the absorber were experimentally eliminated by biasing the detector at 3.5 Mev. Rayleigh scattering is negligible in this experiment.

A second small correction was calculated for the presence in the beam of the 7.10-Mev gamma from O^{16}. The ratio of the intensity of the 7.10-Mev gamma to the 6.13-Mev gamma (η_7/η_6) is given as 0.08 by Millar *et al.* The correction was determined as a factor f given by

$$f=e^{-\mu_6 X}\frac{\epsilon_6\eta_6+\epsilon_7\eta_7}{\epsilon_6\eta_6 e^{-\mu_6 X}+\epsilon_7\eta_7 e^{-\mu_7 X}},$$

where μ_6 and μ_7 are the theoretical[3] absorption coefficients for a particular material for 6.13 and 7.10 Mev, respectively, ϵ_6 and ϵ_7 are the respective detector efficiencies for the two energies, and X is absorber thickness. The values of f were all within the range from 9.985 to 1.013 and were assigned an uncertainty of ±20 percent of $|1-f|$.

The final corrected transmission ratio, T_c, for a particular absorber thickness was determined from the measured transmission, T_m, as follows:

$$T_c=f(T_m-\Delta_c).$$

Values of the absorption coefficient τ in cm²/g were determined by weighted least squares fit of the T_m's and T_c's for each material to the equation $T=e^{-\tau X}$. The standard deviation associated with each as-measured coefficient τ_m and corrected coefficient τ_c were determined. τ_m, τ_c and their standard deviations are listed in Table I together with the atomic absorption coefficient

$$_a\mu(\text{cm}^2/\text{atom})=A\tau_c/N$$

where A is the atomic weight and N Avogradro's number.

Table I also lists the experimental values of $_a\mu$ determined by Colgate and those calculated theoretically by Davisson and Evans. The values from this measurement agree well within the statistical limits with those of Colgate. Disagreement with the theoretical values increases with increasing atomic number. This is expected since the pair cross section becomes a successively larger fraction of the total cross section with increasing Z and the Born approximation to the Bethe-Heitler theory of pair-production has been shown to be inadequate.[2,4,5]

An experimental pair-production cross section $[(\sigma_p)_{\text{exp}}]$ may be obtained by subtracting from the experimental $_a\mu$ calculated Compton, photoelectric and electronic pair-production cross sections as shown in Table II. The tabulated values as well as the theoretical Bethe-Heitler pair-production cross section $[(\sigma_p)_{\text{theor}}]$ are derived from reference 3. Figure 3 shows the ratio $(\sigma_p)_{\text{exp}}/(\sigma_p)_{\text{theor}}$ plotted *versus* atomic number. At 6.13 Mev the discrepancy is only appreciable for high Z where σ_p is more than half of $_a\mu$. The empirical correction to the Bethe-Heitler pair cross section as derived by Davies-Bethe-Maximon[6] for Pb yields a value of 8.95 barns which is in somewhat better agreement with the experimental value.

[4] Rosenblum, Shrader, and Warner, Phys. Rev. **88**, 612 (1952).
[5] D. R. Corson and A. O. Hanson, Ann. Revs. Nuclear Sci. **3**, 67 (1953).
[6] Davies, Bethe, and Maximon, Phys. Rev. **93**, 792 (1954).