Absorption of 5.3-Mev, 10.3-Mev, and 17.6-Mev Gamma-Rays*

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Gamma-ray absorption cross sections have been measured for Cu, Sn, Pb, and U at each of the gamma-ray energies, 5.3-Mev, 10.3-Mev, and 17.6-Mev. Betatron radiation collimated to give "good" geometry is used for the transmission measurements. The energy sensitive detector used is a 180° homogeneous magnetic field pair spectrometer with crystal-and-photomultiplier detectors. The measured cross sections in units of barns per atom are at 5.3 Mev, 3.244 (Cu), 7.05 (Sn), 15.07 (Pb), and 18.43 (U); at 10.3 Mev, 3.285 (Cu), 7.95 (Sn), 17.83 (Pb), and 21.73 (U); and at 17.6 Mev, 3.688 (Cu), 9.22 (Sn), 20.47 (Pb), and 25.32 (U). The statistical errors range from 0.5 percent to 1.5 percent.

The pair cross sections are inferred by subtracting the best-known values of the cross sections for the Compton, nuclear, and photoelectric effects from the total cross section. The ratio of this pair cross section to the value calculated from the Bethe-Heitler theory is given as a function of energy. The present results give the transition of this ratio which is greater than unity for low energy gamma-rays to a value less than unity at extremely high gamma-ray energies.

I. INTRODUCTION

RECENT experimental data on gamma-ray absorption coefficients[1–5] from 11 to 280 Mev indicate that the Bethe-Heitler[6] calculation for the contribution due to pair production is in error for elements of high atomic number, being about 10 percent too high for lead and slightly higher for uranium, probably due to failure of the Born approximation. Within the accuracy of these experiments, the error appears to be independent of the energy.

No accurate experimental determination of absorption coefficients appears to have been made below 11 Mev and above the energy of conveniently obtainable natural gamma-rays.[7] Agreement of experimentally determined absorption coefficients with theoretical values has been good below 2.5 Mev. However, the contribution of the coefficient in this region becomes small and vanishes at 1.02 Mev, so that a relatively large percentage error in the theoretically determined value of this component may be undetected in the total coefficient.

In contrast to the high energy case, the exact calculation by Hulme and Jaeger[8] of the pair production cross section near threshold for elements of high atomic number indicates that the value of this cross section calculated from the Bethe-Heitler theory will be too low. The observations of Hahn *et al.*[9] on pair production at 2.0 Mev show this to be the case. The 5- to 17.6-Mev region has been chosen for this investigation because it is in this energy region that the pair cross section must go from the low energy case to the high energy case. For reasons discussed later in this paper, we have not yet found it practicable to measure the absorption coefficients below 5 Mev. The present paper gives results at 5.3 Mev, 10.3 Mev, and 17.6 Mev for four elements, copper ($Z=29$), tin ($Z=50$), lead ($Z=82$), and uranium ($Z=92$).

The method used for determining the total absorption cross section for gamma-rays is similar to that used by previous investigators[3,4] using the bremsstrahlung spectrum from an electron accelerator, differing, however, in that the measurements were not restricted to gamma-ray energies in the region of the maximum energy in the spectrum. The energy sensitive detector is a pair spectrometer of the type first used by Walker and McDaniel,[10] with the modification of replacing the Geiger counters with stilbene scintillation detectors. This modification makes possible higher counting rates without bothersome accidental coincidence background which unfortunately is enhanced in pulsed type accelerators. The source of the radiation used is the Case field-biased, flux-forced betatron.

The geometry and energy resolution of the detector insure that the effect of measuring the degraded radiation produced when an absorber is introduced is small enough to be neglected. It is estimated that for the present experimental arrangement the reduction in cross section from this cause is less than 0.1 percent in every case.

III. EXPERIMENTAL ARRANGEMENT

The arrangement of equipment is shown schematically in Fig. 1, which is drawn approximately to scale.

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[1] G. D. Adams, Phys. Rev. **74**, 1707 (1948); conclusions modified by Walker (reference 2).
[2] R. L. Walker, Phys. Rev. **76**, 527 (1949).
[3] J. L. Lawson, Phys. Rev. **75**, 443 (1949).
[4] DeWire, Ashkin, and Beach, Phys. Rev. **82**, 447 (1951).
[5] A. I. Berman, Phys. Rev. **85**, 774 (1952).
[6] H. Bethe and W. Heitler, Proc. Roy. Soc. (London) **146**, 83 (1934).
[7] For a summary of results obtained at all energies prior to about June 1949, see W. S. Snyder and J. L. Powell, AEC Report, AECD-2739 (1949) (unpublished). For a more recent review, see C. M. Davisson and R. D. Evans, Revs. Modern Phys. **24**, 79 (1952).
[8] H. R. Hulme and J. C. Jaeger, Proc. Roy. Soc. (London) **153**, 443 (1936).
[9] Hahn, Baldinger, and Huber, Helv. Phys. Acta **24**, 324 (1951).
[10] R. L. Walker and B. D. McDaniel, Phys. Rev. **74**, 315 (1948).

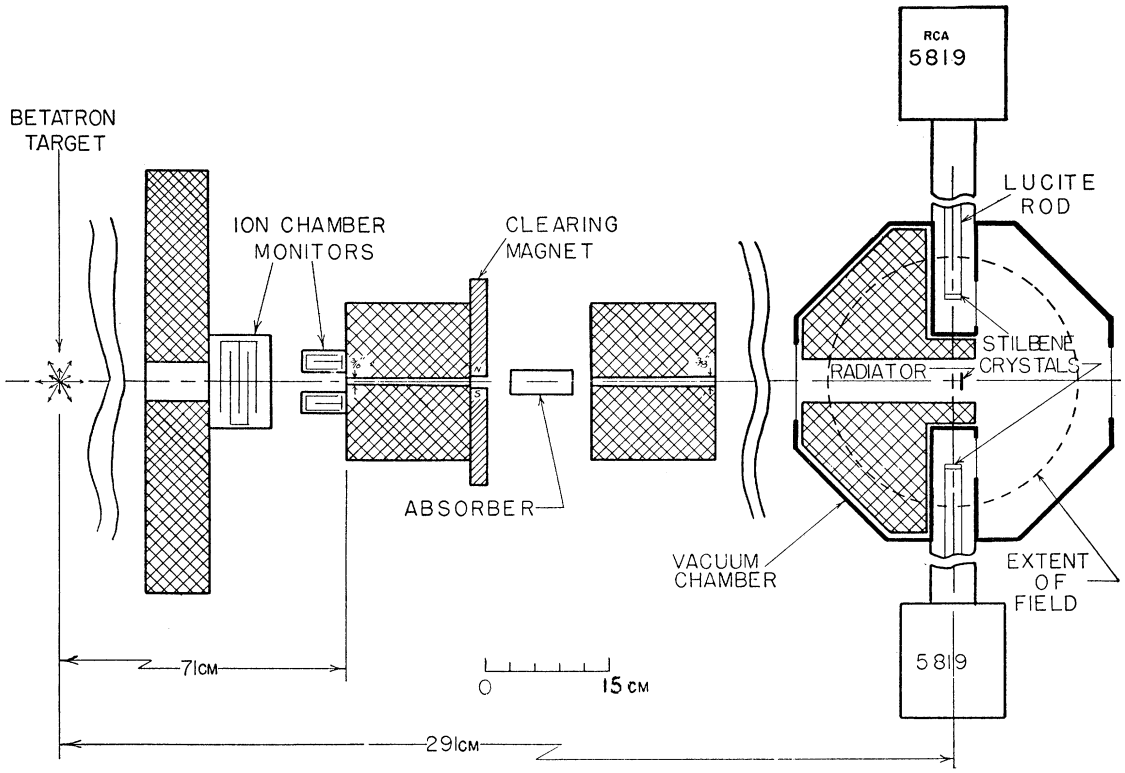

FIG. 1. Experimental arrangement for making gamma-ray transmission measurements at various energies.

A block diagram of the electrical equipment is shown in Fig. 2.

The Case betatron, used as the source of radiation and operated with orbit self-expansion, gives a gamma-ray output consisting of 180 pulses per second, each 150–250 μsec long.[11] A peak energy of 12 to 14 Mev was used for the measurements at 5.3 and 10.3 Mev and a peak energy of 20 Mev for the measurements at 17.6 Mev.

The thin-walled transmission ion chamber is used by the betatron operator for instantaneous monitoring of the beam while the annular thick-walled chamber is used to obtain a continual chart record of the beam intensity.

The lead collimator consists of two sections, each 6 inches thick, separated by 6 inches. The circular hole in the two section collimator tapers from $\frac{3}{16}$ in. to $\frac{3}{8}$ in. in diameter. The apex of the cone defined by this hole is thus 45 cm in front of the collimator. However, the collimator is located about 70 cm from the betatron target, because of clearance requirements. The collimator limits the beam to a cone of about 0.3° half-angle.[12]

The absorber is mounted between the halves of the collimator, in such a manner that it can be moved by remote control in and out of the beam. The maximum angle through which betatron gamma-rays that are incident on the absorber can be scattered by Compton recoil and still fall on the detector is less than 1°.

The energy-sensitive, gamma-ray detector is a 180° magnetic pair spectrometer. The pole pieces are 12 in. in diameter with a gap of $1\frac{5}{8}$ in. The magnetic field is uniform within ± 0.5 percent out to 0.8 pole radius. The magnet is energized by a voltage stabilized *MG* set, resulting in an output current which does not vary more than a fraction of one percent over the running time. The current is monitored visually and corrected manually if necessary. The magnet exhibits no notice-

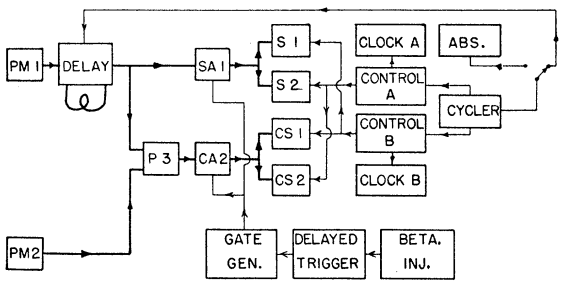

FIG. 2. Block diagram of cycling and recording system for transmission measurements. Either absorber or electrical delay may be cycled to obtain transmission ratio or accidental coincidences.

[11] E. C. Gregg, Jr., Rev. Sci. Instr. **22**, 176 (1951).

[12] Although experiments by J. Robson of this laboratory indicate that charged particles do not get through a small collimating hole which is centered on the betatron target, the clearing magnet shown was inserted as an added precaution. It consists of a magnetron magnet with suitably modified pole faces and flux path.

able hysteresis over the current range used, and the field strength was found to vary linearly with magnetizing current. Therefore, the magnet was calibrated by the proton-resonance technique at one value of the current, and the magnet current then used as the measure of field strength.

Radiators are strips of lead foil about 2 cm wide. One-mil foils have been used, but at 5 Mev, it has been necessary to use a 4-mil foil to get the desired counting rate.

Detectors are two stilbene crystals, each approximately 6 mm wide, 30 mm high, and 15 mm deep. Center-to-center separation is 20 cm. Crystals are mounted on the ends of Lucite rods of the same cross section. One-mil aluminum foil covers all open faces of the crystals to improve the light-gathering properties of the system. A space of one cm was left between the stilbene crystal and the Lucite rod to avoid the scattering of electrons and positrons from the rod into the crystal. The crystals and rods are inserted into reentrant ports in the vacuum chamber; windows in these ports are two thicknesses of one-mil aluminum foil, as are the entrance and exit windows for the betatron beam. Approximate distance from foil to crystal is 1.7 cm.

The Lucite rods butt up against RCA 5819 photomultipliers, which are mounted so that the long axis of the dynodes is horizontal, to minimize defocusing effects due to fringing fields. This precaution is probably unnecessary, as the photomultipliers are shielded electrostatically and magnetically by iron cylinders with walls $\frac{7}{32}$ in. thick; this is sufficient to eliminate difficulties due to fringing fields, under the conditions of this experiment.

Signals from the photomultipliers are fed through cathode followers to a coaxial line, shaped by 1.0-meter lengths of RG8U cable terminated by resistances of 5 ohms, and then into a fast coincidence circuit (P3) which has been described elsewhere.[13] The resolving time of this arrangement is about 5×10^{-9} sec, although it is somewhat dependent on the voltage applied to the photomultiplier tubes and on the discrimination level used in the coincidence amplifier (CA 2). Single pulses from photomultiplier No. 1 can be obtained with an amplifier (SA 1). No use is made of the singles counting rate other than as a check on the system.

The singles and coincidence amplifiers include voltage discriminators whose outputs are gated to give no signal except during a 200-μsec interval, including the betatron pulse. The gating arrangement is shown in Fig. 2, and is adjusted by displaying the betatron x-ray pulse (obtained from a 931-A photomultiplier exposed to the beam) on an oscilloscope along with the gate pulse. The gate can then be varied in time and length so as to bracket the x-ray pulse.

The output pulses from the amplifiers are recorded on scalers S1, S2, CS1, and CS2. These scalers can be made to record or not as desired by an appropriate electrical signal from the cycling mechanism described in the following section on experimental procedure.

The energy calibration and resolution of the pair spectrometer has been calculated taking into account the 180° focusing properties, the natural angular spread in pair particles and the scattering in the radiator, windows, etc. The energy resolution is 5 percent at 17.6, 6 percent at 10.3 Mev, and 9 percent at 5.3 Mev.[14]

III. EXPERIMENTAL PROCEDURE

Preliminary experiments indicated that, when the betatron is in operation and with the shielding shown in Fig. 1, almost all singles counts coming from sources other than the spectrometer radiator consist of pulses small compared to wanted pulses.[15] The former can be eliminated almost entirely at a given photomultiplier high voltage setting by suitable adjustment of the discriminator levels of the amplifiers. Then, with any of the following variations from normal operating conditions, singles counting rates are quite low and coincidence counting rates are essentially zero: (1) beam on, but blocked from radiator by 16 in. of lead; (2) no radiator; (3) magnetic field off.

An approximate pulse-height distribution was obtained of counts originated from the radiator. The results indicate that the differential pulse-height distribution is nearly rectangular, neglecting noise.

When operating with a radiator in place accidental coincidence rates are determined by inserting 10 meters of RG8U cable in the signal lead from one photomultiplier (see Fig. 2). Apparently accidental coincidences are of three types: (1) Rate proportional to square of beam intensity—from accidental coincidences due to random nature of singles caused by events at the radiator; (2) rate proportional to beam intensity; (3) rate nearly independent of beam intensity, but zero with beam blocked from the radiator.

It was found impractical to take the time necessary to separate these types of background. For operation at 10 Mev and at 17.6 Mev, it was found sufficient to decrease the sensitivity of the detection system, so that the background with no absorber averages a few percent, of the coincidence rate. Under these circumstances, the desired statistical accuracy in absorption coefficient can be obtained, even with a background whose statistics are quite poor.

[13] E. F. Shrader, Rev. Sci. Instr. **21**, 883 (1950).

[14] For more complete discussion of factors affecting resolution and energy calibration see E. S. Rosenblum, AEC Report AECU-1825 (unpublished).

[15] In the course of another experiment, it was found that the total integrated light output per unit volume caused by betatron x-rays incident on Lucite rods is less than 8 percent of that with a scintillation crystal in the beam. This light output from the Lucite, furthermore, must consist of individual pulses which are far smaller than pulses from electrons. Therefore, in an experiment such as the present one, in which discrimination against small pulses is employed, contributions from scintillations in the Lucite should be entirely negligible.

At 5.3 Mev, for various reasons the background rate is higher and more time must be devoted to background measurements. At this energy, the number of pairs per quantum is about half that at 10 Mev, and angular spread of pair particles is practically doubled, as is the angular scattering of electrons in a given radiator. This angular spread causes a much lower detection efficiency in a 180° focusing system. For these reasons, operation below 5 Mev is impractical.

Because of fluctuations in betatron beam intensity and possible drifts in the sensitivity of the detection system, a cycling mechanism is employed. It has a 60-sec cycle during which the following steps occur: (1) 3 sec—all clocks and scalers off—absorber moved out of beam; (2) 10 sec—clock B and scalers S1 and CS1 activated, counting singles and coincidences with absorber out of beam; (3) 3 sec—all clocks and scalers off—absorber moved into beam; (4) 44 sec—clock A and scalers S2 and CS2 activated, counting singles and coincidences with absorber in beam; (5) Repeat step 1.

The ratio of running time with absorber in the beam to that with absorber out of the beam was selected, together with absorbers whose transmission is about 10 percent, to give a desired accuracy in absorption coefficients in a minimum running time.[16] As shown by Rose and Shapiro, a rather large variation in time ratio and/or transmission can be allowed, as long as both are near optimum values, without a large increase in running time.

IV. ABSORPTION RUNS

A typical run lasts from one to four hours, with the absorber, clocks, and scalers cycled automatically, as described above. Every ten cycles (ten minutes), the scaler readings are recorded, and the clock time noted on the continuous chart of the betatron output. This record is later examined, and all intervals rejected in which the betatron intensity varied significantly during the interval.

Accidental background determinations are made at various times, in ten-cycle runs with delay in one signal lead throughout the interval and with the absorber cycled in the normal manner. This background data, normalized for running time and beam intensity, is used to correct the transmission data.

The absorbers used were copper, tin, lead, and uranium. The copper used was highly pure electrical bus rod. The tin absorber was cast from chemically pure mossy tin. The lead was obtained from the National Lead Company, Cleveland, Ohio and the uranium was obtained on loan from the AEC.[17] The purity of all materials is greater than 99.9 percent based on information furnished by the suppliers.

[16] M. E. Rose and M. M. Shapiro, Phys. Rev. **74**, 1853 (1948).

[17] The authors wish to thank the Research Service Division of the Chicago Operations Office, USAEC for making available the uranium and for arranging for it to be machined to a form suitable for our measurements.

TABLE I. Experimental cross sections.

Absorber element	Thickness (cm)	Density (g/cm³)	Absorption coeff. (cm^{-1})	Absorption cross section (10^{-24} cm²)
		(a) 5.3-Mev gamma-rays		
Cu	8.638	8.898	0.2735±0.0027	3.244±0.032
Sn	8.365	7.275	0.260 ±0.004	7.05 ±0.10
Pb	4.742	11.34	0.497 ±0.005	15.07 ±0.15
U	2.056	18.70	0.872 ±0.009	18.43 ±0.18
		(b) 10.3-Mev gamma-rays		
Cu	8.638	8.898	0.2770±0.0025	3.285±0.030
Sn	8.365	7.275	0.2933±0.0029	7.95 ±0.079
Pb	3.983	11.34	0.599 ±0.007	
Pb	3.005	11.34	0.581 ±0.005	
Pb (Av)			0.588 ±0.006	17.83 ±0.18
U	2.506	18.70	1.026 ±0.004	
U	3.005	18.70	1.040 ±0.010	
U (Av)			1.028 ±0.004	21.73 ±0.11
		(c) 17.6-Mev gamma-rays		
Cu	7.817	8.878	0.3103±0.0034	3.688±0.040
Sn	8.365	7.275	0.3404±0.0034	9.222±0.092
Pb	3.005	11.34	0.6750±0.0068	20.47 ±0.21
U	2.000	18.70	1.198 ±0.012	25.32 ±0.25

V. EXPERIMENTAL RESULTS

The results of transmission measurements made on the four absorbers at each of three gamma-ray energies is given in Table I. The densities listed for the absorbers are from measurements made in our laboratory and in each case are within a few tenths of one percent of the theoretical density. Both the absorption coefficient in cm^{-1} and the total cross section per atom are given. The energies at which the measurements were made were to a certain extent arbitrary with, however, the object of comparing directly our results with those of Walkers[2] at 17.6 Mev. The considerations entering into the energy calibration of the pair spectrometer are given in reference 14. Two thicknesses of the lead and uranium absorbers were measured at 10.3 Mev to check the internal consistency of the measurements.

VI. THEORETICAL ABSORPTION COEFFICIENTS

The important contributions to the absorption coefficients are the photoelectric effect, the Compton effect, and pair production both in the field of the nucleus and the electrons. The photonuclear contributions are estimated on the basis of our present best knowledge of these processes.

These contributions to the cross sections for the four elements at three energies are tabulated in Table II. The photoelectric cross section has been calculated by formula due to Hall.[18]

A factor of 5/4 is included to take account of the fact that the K electrons contribute about 80 percent of the total coefficient.[19]

The Compton cross section per atom is given by the

[18] H. Hall, Phys. Rev. **45**, 620 (1934). The equation used here is the one valid for higher energies ($\gamma \gg 1$).

[19] W. Heitler, *Quantum Theory of Radiation* (Oxford University Press, London, 1944), p. 127.

TABLE II. Theoretical cross sections.

Element	Photoelectric cross section (10^{-24} cm^2)	Compton cross section (10^{-24} cm^2)	Pair-production (nucleus screened) (10^{-24} cm^2)	Pair production (electrons) (10^{-24} cm^{-2})	Photonuclear (10^{-24} cm^2)	Total cross section (10^{-24} cm^2)
			(a) 5.3-Mev gamma-rays			
Cu	0.0042	2.2822	0.9717	0.0115	$\simeq 0$	3.2696
Sn	0.054	3.935	2.880	0.020	$\simeq 0$	6.889
Pb	0.515	6.453	7.714	0.033	$\simeq 0$	14.715
U	0.862	7.240	9.690	0.037	$\simeq 0$	17.829
			(b) 10.3-Mev gamma-rays			
Cu	0.002	1.447	1.787	0.034	<0.01	3.275
Sn	0.029	2.495	5.268	0.059	0.10 ± 0.07	7.951
Pb	0.279	4.093	14.07	0.096	0.25 ± 0.10	18.79
U	0.469	4.592	17.64	0.108	0.34 ± 0.07	23.15
			(c) 17.6-Mev gamma-rays			
Cu	0.0013	0.9691	2.496	0.059	0.14 ± 0.03	3.665
Sn	0.0174	1.6708	7.347	0.102	0.38 ± 0.07	9.517
Pb	0.168	2.7402	19.53	0.167	0.50 ± 0.10	23.11
U	0.281	3.074	24.51	0.187	0.56 ± 0.12	28.61

Klein-Nishina formula for the cross section per electron,[20] multiplied by Z.

The pair cross section has been calculated by the method described by Walker,[2] using an approximate formula due to Hough[21] modified to include a screening correction and pair production in the field of an electron.

Borsellino's values are used for the electronic pair production factor and are 0.32 at 5 Mev, 0.55 at 10 Mev, and 0.68 at 17.6 Mev.[22]

The screening corrections to the nuclear pair cross section are given in Table III.

In estimating the contribution to the total cross section due to nuclear absorption, one must rely on extremely incomplete experimental data and theory. Our best knowledge of the magnitude of the nuclear absorption is at 17 Mev, where the various gamma-ray processes have been studied using the Li gamma-rays. The neutron yield at this energy for Sn, Pb, and U relative to Cu has been measured by Walker, McDaniel, and Stearns.[23] The ratios are 3.3, 4.5, and 9.0 for Sn, Pb, and U, respectively. Heidman and Bethe[24] have calculated the neutron multiplicity per gamma-ray absorbed for a number of elements including Cu and U, and an estimate can be made for Sn and Pb. Knowing the relative neutron yields and multiplicity, we can calculate the total nuclear cross section for gamma-ray capture for Sn, Pb, and U if we know the (γ, n) cross section for Cu.[25] The $Cu^{63}(\gamma, n)Cu^{62}$ cross section has been measured by a number of investigators. Using the Li gamma-rays, Wäffler and Hirzel[26] give for this cross section $\sigma = 1.2 \pm 0.12 \times 10^{-25}$ cm^2, while Walker, *et al.*[23] give a much lower value of $\sigma = 0.55 \pm 0.12 \times 10^{-25}$ cm^2. From bremsstrahlung activation, Johns *et al.*[27] have measured this cross section as $\sigma = 1.1 \times 10^{-25}$ cm^2 at 17.5 Mev. Measurements made by Krohn and one of the authors (EFS),[28] of the Cu^{63} cross section relative to the deuteron photodisintegration cross section, give a value at 17.5 Mev of $\sigma = 1.0 \pm 0.1 \times 10^{-25}$ cm^2. Johns *et al.*[27] have also measured the $Cu^{65}(\gamma, n)Cu^{64}$ cross section at 17.5 Mev and find a value approximately 1.5 times as large as the $Cu^{63}(\gamma, n)Cu^{62}$ cross section at the same energy. Using a value of $\sigma = 1.0 \times 10^{-25}$ cm^2 for the $Cu^{63}(\gamma, n)Cu^{62}$ reaction, the total gamma-ray nuclear capture cross section for Cu, Sn, Pb, and U have been calculated and listed in Table II(c). A possible error of ± 20 percent has been allowed in these values.

At 5.3 Mev only (γ, γ) processes are possible, with cross sections of at most a few millibarns, so their contribution to the total gamma-ray absorption cross section has been neglected.

At 10.3 Mev, however, other processes are possible, of which however only (γ, n) and fission reactions can make appreciable contributions to the total cross section. From the $Cu^{65}(\gamma, n)Cu^{64}$ cross section as a function of gamma-ray energy as determined by Johns *et al.*,[27] we can make an estimate that the Cu nuclear cross section at 10.3 Mev will be less than 10 percent of its value at 17.6 Mev. Ogle and McElhinney[29] have measured the relative photofission cross section as a function of energy. Their cross section at 10.3 Mev is approximately 0.6 that at 17.6 Mev. We will assume approximately the same ratio for Pb, while for Sn we can use the curve for Sb published by Johns *et al.*[27] The assumed ratios for Sn and Pb are 0.3 and 0.5, respectively, with large allowance for errors. The resulting nuclear cross sections at 10.3 Mev are listed in Table II(b).

VII. DISCUSSION OF RESULTS

Our experimental values of the total gamma-ray absorption cross section per atom for Cu, Sn, Pb, and U at gamma-ray energies of 5.3, 10.3, and 17.6 Mev are listed in Table I. At 10.3 Mev, two thicknesses each of Pb and U were measured to check the internal consistency of the measurement. Our values for Cu and Pb at 17.6 Mev agree with those of Walker[2] well within the experimental error. For Sn, however, at this same

TABLE III. Screening corrections.

Energy (Mev)	5.3	10.3	17.6
Cu	-0.011	-0.018	-0.029
Sn	-0.014	-0.026	-0.039
Pb	-0.019	-0.032	-0.050
U	-0.020	-0.036	-0.053

[20] See reference 19, p. 157.
[21] P. V. C. Hough, Phys. Rev. **73**, 266 (1948).
[22] A. Borsellino, Helv. Phys. Acta **20**, 136 (1947).
[23] Walker, McDaniel, and Stearns, Phys. Rev. **80**, 807 (1950).
[24] J. Heidman and H. A. Bethe, Phys. Rev. **84**, 274 (1951).
[25] We must make the further reasonable assumption that $(\gamma, 2n)$ processes are negligible at this energy for Cu.
[26] H. Wäffler and O. Hirzel, Helv. Phys. Acta **21**, 200 (1948).
[27] Johns, Katz, Douglas, and Haslam, Phys. Rev. **80**, 1062 (1950).
[28] V. E. Krohn and E. F. Shrader, Phys. Rev. **87**, 685 (1952).
[29] W. Ogle and J. McElhinney, Phys. Rev. **81**, 344 (1951).

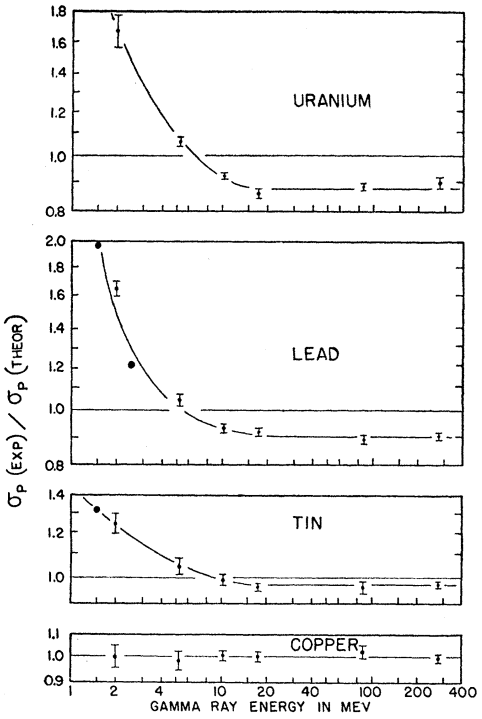

FIG. 3. The ratio of the experimental nuclear pair production cross section to the theoretical (Bethe-Heitler) cross section plotted as a function of energy for Cu, Sn, Pb, and U. The values at 1.5 and 2.5 Mev are from Hulme and Jaeger (reference 8), at 2 Mev from Hahn *et al.* (reference 9), at 88 Mev from Lawson (reference 3), and at 280 Mev from DeWire *et al.* (reference 4).

energy there is disagreement of the order of two standard deviations.

At high gamma-ray energies, where pair production is the only major contributor to the total cross section, the discrepancy between the Bethe-Heitler theory and experiment has been blamed on the failure of the Born approximation. In the limiting case of extremely high energies, the Born approximation requires that $Z/137 \ll 1$, which certainly is not the case for elements in the upper part of the periodic table. The failure is presumably worse as the gamma-ray energy is decreased. However, at low gamma-ray energies, there is fair agreement between the experimental and theoretical values of the total cross section since the pair cross section becomes a successively smaller fraction of the total cross section. In order, therefore, to investigate the behavior of the pair cross section, we have obtained an "experimental" pair cross section by the expedient of subtracting from the experimental value of the total cross section the contributions due to the photoelectric and Compton effects, electronic pair production, and our best estimate of photonuclear processes. The ratio of this "experimental" value to the theoretical cross section for pair production is plotted as a function of energy in Fig. 3. The values of Lawson[3] at 88 Mev and of De Wire *et al.*[4] at 280 Mev have been included to show the limiting values of this ratio. It has been assumed that at 88 Mev and 280 Mev all other processes are small compared to pair production.

At low energies Hulme and Jaeger[8] have calculated the pair production cross section using the proper wave function. The ratio of their value to the corresponding Bethe-Heitler value are plotted in Fig. 3 for Pb at 1.5 and 2.5 Mev and Sn at 1.5 Mev. Hahn *et al.*[9] have measured the relative pair production cross section as a function of Z at a mean energy of 2 Mev. They give the value of $\sigma_p(Z)/Z^2$, where $\sigma_p(Z)$ is the cross section as a function of Z with $\sigma_p(1)$ set equal to the theoretical Bethe-Heitler value for $Z=1$. Their values of σ_p/Z^2 are also plotted in Fig. 3 at an energy of 2 Mev.

For Cu there is good agreement between the Bethe-Heitler theory and experiment at all energies. However, a discrepancy appears for Sn and is larger the higher the Z value. The present data show the expected smooth transition from the previously obtained results at high energies to those at low energies.

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