Absorption of 280-Mev Photons*†

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Total cross sections for 280-Mev photons have been measured for a number of elements. The source of photons was the bremsstrahlung spectrum of 310-Mev upper limit, which was obtained from the Cornell synchrotron. P hotons above 250 Mev were detected by a pair spectrometer and the transmission through various samples determined. The measured cross sections in units of cm^2/g are 0.01060, 0.0284, 0.0528, 0.0776, 0.1069, and 0.1148 for Be, Al, Cu, Sn, Pb, and U, respectively. The probable statistical errors range from 0.9 to 1.4 percent. These values are lower than the theoretical values by a fraction which is roughly proportional to Z^2 and is about 10 percent for Pb, in agreement with other results obtained at lower energies.

INTRODUCTION

DURING the past several years a number of investigators have determined total cross sections for photons above 10 Mev in various materials, following the initial experiments of Delsasso, Fowler, and Lauritsen.[1] In each case the experiment consisted of measuring the transmission of the photons through known thicknesses of metals. Adams[2] obtained values at 11.0, 13.7, and 19.1 Mev, using the continuous photon spectrum from a 22-Mev betatron and various threshold detectors employing the (γ,n) reaction. Walker[3] determined cross sections for the 17.6-Mev photons from $Li^7(p,\gamma)Be^8$ reaction, using an electron pair spectrometer as a detector. Lawson[4] made similar measurements at 88 Mev, detecting the highest energy photons from a 100-Mev betatron with a pair spectrometer. These experimental results in general show good agreement with the theory for absorbers of low atomic number but significantly low cross sections for the heavy elements. In this paper measurements of cross sections for photons of 280 Mev are described. It will be seen that the results show a similar relation to the theoretical values as those at lower energies.

The method used in this work was to measure the transmission through various metal samples of the photons in the upper energy region of the continuous spectrum from the Cornell synchrotron. The cross sections in the 300-Mev region vary slowly with energy, making it possible to use photons of a rather wide energy spread. However, as Lawson has pointed out,[4] if the energy width is too large, photons which produce effects in the absorber can reappear in the beam either directly or through secondary processes with energies within the sensitive region of the detector. The strength of this effect depends not only on the width of the energy band but also on the geometry. Calculations based on our experimental arrangement indicate that for a bremsstrahlung spectrum with an upper energy limit of 310 Mev, the region above 250 Mev could be used with reductions in the cross section no larger than 0.5 percent.

EXPERIMENTAL EQUIPMENT

A schematic plan of the equipment involved in this experiment is shown in Fig. 1. The slowly diverging beam from the synchrotron passes through the following components:

1. An ionization chamber monitor.
2. A collimating slit in a 6-inch lead wall. Slit dimensions—$\frac{5}{16}$ inch high by 1 inch wide.
3. Another monitor chamber identical to the first.
4. An open region about 30 inches long in which the absorbers are placed.
5. A second lead slit, $\frac{3}{8}$ inch high by 1 inch wide.
6. A region of magnetic field of 10^4 gauss, extending 15 inches along the path.
7. A third lead slit, $\frac{3}{4}$ inch by $1\frac{1}{2}$ inches by 6 inches.
8. A $\frac{1}{2}$-mil gold pair-forming radiator in the magnetic field of the pair spectrometer.

The region from the front of the second slit to the exit from the spectrometer is evacuated to prevent the appearance of electrons in the beam after they have been swept out by the first magnet, which has been aptly called the broom magnet.

The monitor chambers are multiple parallel plate ionization chambers containing air at atmospheric pressure. Each chamber consists of eleven aluminum plates $\frac{1}{32}$ inch thick and 3 inches square, spaced $\frac{1}{2}$ inch apart. Alternate plates are connected to a 270-volt potential and to a condenser which integrates the charge collected during a run. This charge is measured by a balanced electrometer tube circuit.

The broom magnet serves to insure that the spectrometer counts only those pairs which are formed in the gold radiator. Its effectiveness is illustrated by the fact that with the radiator removed the background in the spectrometer under typical operating conditions is decreased by as much as a factor of twenty when the broom is energized.

The heart of the equipment is the pair spectrometer. It is built around a magnetic field in a region shown by the outline in the schematic plan and having a height of 4 inches. Electron pairs formed in the radiator are

* Assisted by the joint program of the ONR and AEC.
† The results given in this paper were contained in Phys. Rev. 82, 447 (1951).
[1] Delsasso, Fowler, and Lauritsen, Phys. Rev. **51**, 391 (1937).
[2] G. D. Adams, Phys. Rev. **74**, 1707 (1948).
[3] R. L. Walker, Phys. Rev. **76**, 527 (1949).
[4] J. L. Lawson, Phys. Rev. **75**, 433 (1949).

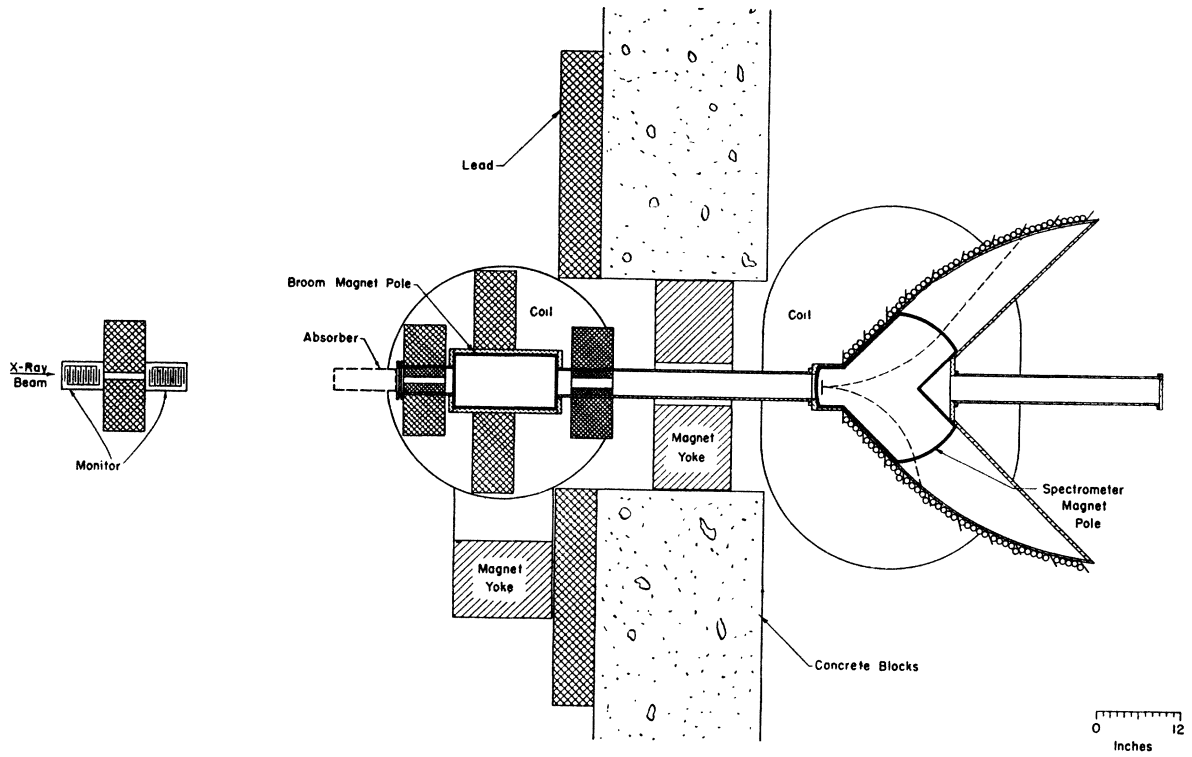

FIG. 1. Schematic plan of the experimental equipment.

separated by the field and pass through the evacuated chamber and a $\frac{1}{16}$-inch aluminum window to the various G-M counters. There are 42 counters on each side of the spectrometer, connected together in 9 groups covering 9 equal momentum intervals. The lowest momentum interval on each side is not covered by counters because of obvious limitations in the design. Since the electrons emerge from the radiator very nearly in the direction of the photon beam, it is desirable to provide a type of focusing wherein particles of a given momentum and direction, but coming from a laterally extended source, are brought to a focus. This was done by cutting off the magnet poles at 45° to the beam direction and placing the counters along the edges. In order to keep the size of the magnet within reason, the poles were cut off as shown causing the higher momentum orbits to leave the region of the field entirely before reaching the counters. The positions of these counters were determined by plotting orbits and finding an empirical curve of focus.

The pairs produced in the radiator are recorded by counting coincidences between pairs of counters on opposite sides of the spectrometer. All the counters of a group are connected in parallel. Each group is connected to a preamplifier which sends pulses to a master coincidence circuit. The purpose of this circuit is to record all coincidences corresponding to the same total momentum of the electron and positron in one output channel. The number of pulses recorded in each output channel is then a measure of the number of photons in the energy increment defined by the momentum width of a counter group. For a given setting of the spectrometer magnet, all the energy response increments are isosceles triangles of equal width and variable heights which can be calculated from the geometry of the spectrometer and the pair production cross section. The resolving time of the coincidence circuit is approximately one microsecond. A desirable feature of the circuit is an anticoincidence action by which the coincidence circuit is rendered insensitive for about 1.5 microseconds whenever two pulses from one side of the spectrometer appear within the resolving time of the circuit. This eliminates recording ambiguous events involving more than one pair of electrons.

CALIBRATION OF THE SPECTROMETER

The energy calibration of the spectrometer involved not only finding an absolute calibration figure to be used in setting the field in future use but also laying out the equal momentum intervals for the counters. This can be done by measuring the magnetic field at many points, then using these data to plot the various orbits. Fortunately, a simpler method was found, based on the fact that a flexible wire held under tension in a magnetic field and carrying an electric current will assume a shape identical to the orbit of a charged particle.[5] If one can neglect the weight of the wire, then the relation

[5] J. Loeb, Compt. rend. **222**, 488 (1946).

between the various parameters is

$$T/i = H\rho,$$

where T is the tension in the wire in dynes, i is the current in absolute emu, and $H\rho$ is the usual representation of the momentum of the represented particle in gauss-cm. Using this technique the absolute calibration can be made in terms of easily measured quantities.

This method was applied to the spectrometer in the manner shown in Fig. 2. The wire[6] was attached at the radiator position to a pivot post which was free to turn about a vertical axis and could be set to the direction of the beam by means of a simple optical lever. By setting the various parameters to predetermined values the momentum intervals were marked off. The internal consistency in the data showed the individual momentum determinations to be accurate to 0.5 percent. After the boundaries of the momentum intervals were marked off, they were adjusted slightly by fitting their positions to a smooth curve. A standard flip coil, mutual inductance, and fluxmeter combination was calibrated against the wire for setting the field of the spectrometer. A field of 14.2 kilogauss is just sufficient to bend a 300-Mev electron into the top counter group.

EXPERIMENTAL PROCEDURE

The program for each cross-section determination consisted of a series of twenty-minute runs, with or without the absorber, in which the high energy photons were counted by the spectrometer. The region of the synchrotron spectrum which was used is shown in Fig. 3, where a plot of the resolution triangles for the three output channels in which data were recorded is shown superimposed on the photon energy spectrum. The energy end point was determined by the spectrometer to be 310±5 Mev. The internal consistency of the data obtained in the separate channels provided a rigid check on the stability of the synchrotron energy and the spectrometer magnetic field. In no case did the results in the individual channels differ from the mean by more than twice the standard deviation.

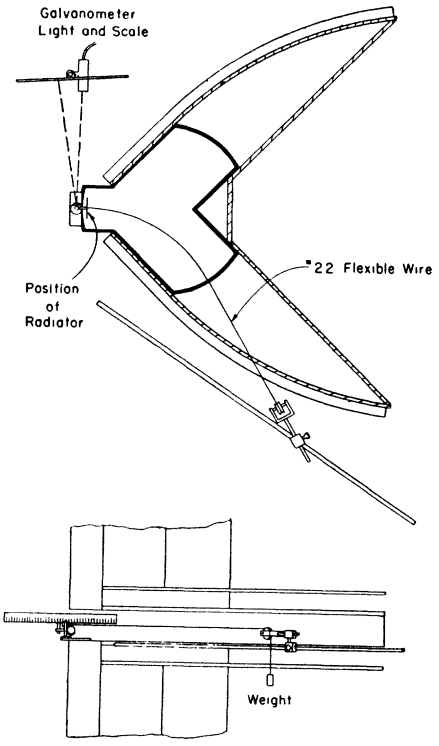

FIG. 2. Experimental arrangement for calibrating the spectrometer.

[6] A very suitable wire is No. 22 "anti-precession" wire made by Sperry Gyroscope Company. It is made of 2-mil strands of cadmium copper.

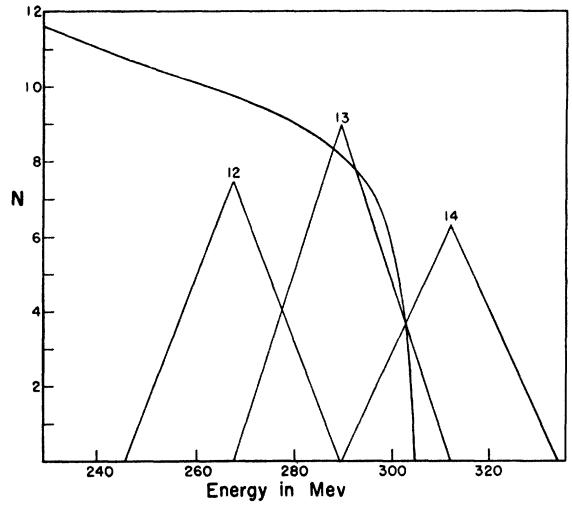

FIG. 3. Spectrometer resolution triangles used in the absorption experiments, superimposed on the photon spectrum from the synchrotron.

The spectrometer records not only true coincidences but also chance coincidences between single particles not related to the same photon. In addition the anti-coincidence feature eliminates some of the true pairs. These effects were separated by using the fact that the true coincidence counting rate is proportional to the beam intensity, while the other effects vary as the square of the intensity. Measurements of the coincidence counting rate for various beam intensities verified this behavior. In the absorption experiments the accidental effects were corrected for by using data obtained at beam intensities three to six times the normal running intensity. The corrections to the cross section were somewhat less than five percent. These accidental effects are magnified by the time dependence of the beam which occurs in pulses about thirty microseconds wide at a rate of thirty per second. It is possible to extend the time width of the beam considerably, but under these conditions the energy stability is probably not very good.

A small background, less than the statistical error, was subtracted from the data. The amount of this background was determined from the residual counts

TABLE I. Experimental total cross sections for 280-Mev photons.

Absorber	Approx. transmission		Cross section (cm^2/g)	Probable statistical error (percent)
Be	0.30		0.01060	1.2
Al	0.22		0.0284	1.2
Cu	0.25		0.0521	1.5
	0.08		0.0530	0.9
		Average	0.0528	0.9
Sn	0.23		0.0776	1.0
Pb	0.20		0.1069	1.2
U	0.24		0.1148	1.4

in the spectrometer channels above the end point of the synchrotron spectrum.

The absorbers were in general chosen to give a transmisson between 0.2 and 0.25. Lower transmissions will yield somewhat better statistical accuracy for a given running time,[7] but small backgrounds of unknown nature become important.

The purity of the samples, with the exception of beryllium and uranium, was determined spectroscopically by the New England Spectrochemical Laboratories, and further chemical analyses in doubtful cases were performed in this laboratory.[8] The only significant impurity was in the aluminum sample, which contained 0.6 percent iron. The correction for this to the cross section amounted to 0.4 percent.

The beryllium absorber was in the form of three blocks of metal which were obtained from the Brush Beryllium Company.[9] Samples of this metal were analyzed by the Brush Company and also by the National Spectrographic Laboratory. The following significant impurities were found:

Beryllium oxide	1.2 percent,
Magnesium	0.4 percent,
Iron	0.08 percent.

The effect of these impurities is to increase the observed cross section by 1.5 percent.

The uranium absorber was borrowed from the AEC.[10] Its stated purity is greater than 99.85 percent.

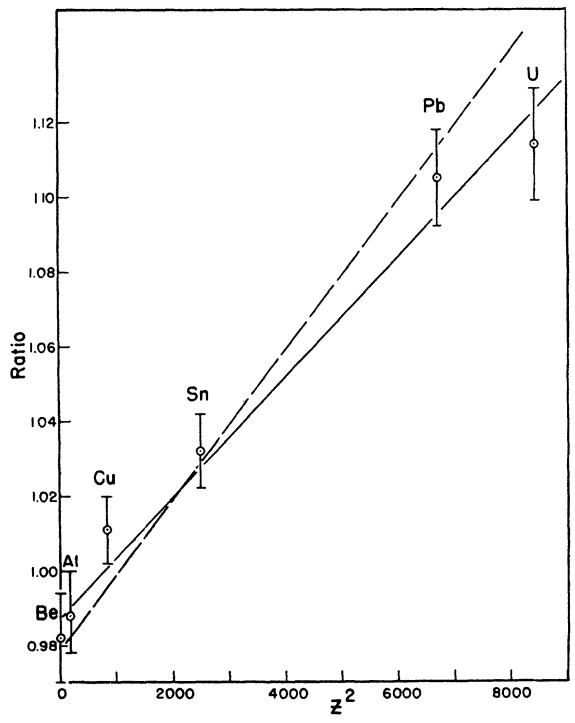

FIG. 4. Ratios of the theoretical to experimental total cross sections plotted as a function of the squares of the atomic numbers of the absorbers. The solid line is fitted to the data; the dashed line is a fit to Lawson's data at 88 Mev.

EXPERIMENTAL RESULTS

The experimental cross sections are given in Table I. The corrections for impurities have been made to the results. The two measurements on copper were made with different absorber thicknesses to check on the exponential absorption. Another check on this aspect of the experiment was made in preliminary measurements at 200 Mev. Results on lead absorbers varying in thickness by a factor of three were in agreement to within the statistical accuracy of several percent.

TABLE II. Theoretical cross sections for 280-Mev photons.

Absorber	Nuclear pairs	Electron pairs	Compton	Total	Total (cm^2/g)
	(barns/atom)				
Be	0.1110	0.0311	0.0138	0.1559	0.01041
Al	1.117	0.096	0.045	1.258	0.02805
Cu	5.33	0.206	0.100	5.64	0.0533
Sn	15.27	0.343	0.172	15.78	0.0800
Pb	39.8	0.55	0.28	40.6	0.1182
U	49.7	0.61	0.32	50.6	0.1280

The statistical errors were computed on the basis of the number of counts. Errors in the background and in the correction for the accidental coincidences are included.

The accumulated monitor readings with and without absorbers represented the relative integrated beam intensities to 0.5 percent or better. This is based on excellent agreement between the two monitors, indicating that the beam did not change its direction during a run and that the amount of radiation scattered backwards from the absorber into the second monitor was negligible.

[7] J. Rainwater and W. W. Havens, Phys. Rev. **70**, 136 (1946); M. E. Rose and M. M. Shapiro, Phys. Rev. **74**, 1853 (1948).

[8] We are indebted to Mrs. Jane Levin for these analyses.

[9] These blocks were obtained on loan by Professor B. D. McDaniel through the courtesy of the Division of Research of the AEC. We wish to thank Professor McDaniel and the AEC for making them available to us.

[10] We are indebted to Dr. D. J. Pflaum and others in the AEC for lending us the uranium.

DISCUSSION

The absorption of photons in this energy region is due essentially entirely to pair production in the Coulomb fields of the atomic nuclei and electrons, and Compton scattering. The Compton cross section is given by the well-known Klein-Nishina formula.[11] The cross section for pair production in the nuclear field has been calculated by Bethe and Heitler,[12] using the Born approximation and screening corrections based on the Fermi-Thomas atomic model. Calculations on pair production in the electronic field have been made by Wheeler and Lamb[13] and others.[14] The results of Wheeler and Lamb are used here, as in Lawson's paper, since they apply particularly to the high energy region.

The calculated cross sections are given in Table II. The nuclear pair cross sections were derived from curves for air and lead plotted by Dr. P. V. C. Hough[15] from the differential cross-section plots of Rossi and Greisen.[16] Bethe[17] has pointed out a convenient method for finding the cross section for any element at any energy from a curve for one element over all energies. The cross section according to the Bethe-Heitler theory can be expressed as

$$\phi/\bar{\phi}=F(\gamma)-(28/27)\log Z,$$

where $\bar{\phi}=Z^2r_0^2/137$ and $\gamma=WZ^{\frac{1}{3}}$, W being the energy of the photon. This relation provided a simple method of computing the cross sections from the data for air and lead. It was found that the air and lead curves gave values of the function F which differed by about 1.5 percent; an average value was used in computing the cross sections.

The electronic pair cross sections were found by multiplying the nuclear cross sections by the quantity $1.12/Z$, which is predicted by the Wheeler and Lamb calculations.

In Fig. 4 the ratios of the calculated to measured cross sections are plotted against Z^2. The solid line is fitted to the data. The dashed line is a fit to the ratios obtained by Lawson at 88 Mev.[18] The difference in the slopes of the two lines shows a trend toward a smaller correction to the Born approximation at high energies, in agreement with the prediction of Bess[19] on the related bremsstrahlung process. However, this difference can hardly be considered significant in view of the statistical uncertainty. Measurements at still higher energies are needed to check this effect.

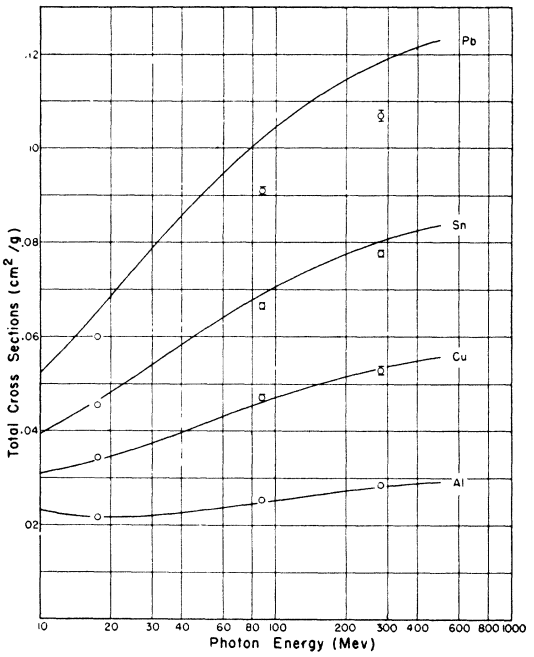

FIG. 5. Total cross sections for photons in the elements for which the most data exist. The curves are the theoretical cross sections. The points at 17.6 Mev are due to Walker; those at 88 Mev to Lawson; those at 280 Mev to the work described in this paper.

The cross section for beryllium is in agreement with the theory, in contrast to Lawson's measurement at 88 Mev which gave a cross section about five percent higher than theory. At present this discrepancy is not understood.

The high energy photon cross sections are summarized in the graph of Fig. 5, where the theoretical curves and experimental points are plotted for the elements for which the most data exist. The results of Adams[2] have not been included, since some corrections for geometry were not applied directly to his experimental values. They are in agreement with Walker's data at 17 Mev.[3] The plots clearly show the good agreement between experiment and theory for the light elements and the well-established difference for the heavy elements, which has been attributed to the inadequacy of the Born approximation.

We are indebted to Professor R. R. Wilson for his generous contributions, particularly to the design of the spectrometer. Much of the development of electronic circuits was done by Mr. L. F. Walker. We are also indebted to Dr. J. S. Levinger and Mr. M. Camac for some calculations on the properties of the spectrometer and collimating system.

[11] W. Heitler, *The Quantum Theory of Radiation* (Oxford University Press, London, 1944), p. 157.
[12] H. Bethe and W. Heitler, Proc. Roy. Soc. (London) **146**, 83 (1934).
[13] J. A. Wheeler and W. E. Lamb, Phys. Rev. **55**, 858 (1939).
[14] F. Perrin, Compt. rend. **197**, 1100 (1933); K. M. Watson, Phys. Rev. **72**, 1060 (1947); P. Nemirovsky, J. Phys. U.S.S.R. **11**, 94 (1947); A. Borsellino, Helv. Phys. Acta **20**, 136 (1947); V. Vortruba, Phys. Rev. **73**, 1468 (1948).
[15] We are indebted to Dr. Hough for computing these data.
[16] B. Rossi and K. Greisen, Revs. Modern Phys. **13**, 240 (1941).
[17] H. A. Bethe, private communication.
[18] See reference 4. The dashed line is not identical to the one drawn by Lawson. It is based on theoretical data computed as described in this paper and is shifted upward by less than one percent.
[19] L. Bess, Phys. Rev. **77**, 550 (1950).