multiplicities of neutral pions. However, even if all the annihilation energy should be carried by a few neutral pions which developed showers with random direction of particles, the 50% containment factor would limit the expected pulse size to about 1 Bev.

The observed pulse spectra are consistent with this picture with respect to the value of the average pulse height; and the fact that the largest pulse observed is about 1100 Mev is understandable. That the particles producing these pulse spectra are indeed antiprotons—rather than another proton-mass particle of negative charge—is indicated, since a particle other than an antiproton could surrender a self-energy of only about 1 Bev, and if its decay patterns were to yield both charged and neutral pions it would be essentially impossible for it to yield an average pulse size of about 450 Mev as observed here. Only if practically all the energy of such an hypothesized particle were delivered always into photons or neutral pions could this result be obtained.

VII. ATTEMPT TO OBSERVE ANTINEUTRONS

In spite of the small solid angle (1/20 steradian) subtended by the lead-glass counter at the absorber, it was hoped that antineutrons from the charge-exchange scattering of antiprotons in the copper absorber might be detected. Antineutrons would not count in the 13-in. diameter scintillation counter ahead of the glass, and yet would give a sizable pulse in the lead-glass counter. The effect could be separated from that due to occasional energetic γ rays from annihilation in the absorber by interposing a converter of high-Z material just ahead of the scintillation counter.

Table I shows that of the 25 particles detected when the copper absorber was in place, each was accompanied by a pulse in the scintillation counter. These results yield an upper limit of about 60 mb for the production in copper of antineutrons from 450-Mev antiprotons into a solid angle of 1/20 steradian. This part of the experiment should of course be repeated with a larger solid angle and better statistics.

VIII. ACKNOWLEDGMENTS

We are gratefully indebted to Professor David Frisch of the Massachusetts Institute of Technology for his loan to us of the additional lead glass with which the second counter was constructed. For our supply of antiprotons we acknowledge again the cooperation of Professor Owen Chamberlain, Professor Emilio Segrè, Dr. Clyde Wiegand, and Dr. Tom Ypsilantis, together with the Bevatron staff under Dr. Edward J. Lofgren.

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Total Electron Compton Cross Section at 319 Mev*

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The total cross section for Compton scattering of 319-Mev photons by electrons was measured in an indirect manner to be 2.8±0.4 mb per electron. This result is 8% smaller than the theoretical cross section given by the Klein-Nishina formula, but agrees within the experimental error.

The data also yield the triplet-production cross section for beryllium, which was found to be 36.0±3.5 mb per beryllium atom. The theoretical value is 30.2 mb per beryllium atom.

The total-absorption cross sections for 319-Mev photons in beryllium and lead were found to be 161.3±1.0 mb per beryllium atom and $(37.620\pm0.225)\times10^{-24}$ cm^2 per lead atom. The ratio of the pair-forming cross sections in beryllium to those in lead, for 319-Mev photons, was found to be $(3.986\pm0.020)\times10^{-3}$.

The deviation from experiment of the Bethe-Heitler theory for pair production can be expressed by $\phi_p{}^z=\phi_p{}^z(\text{B.H.})[1-aZ^2]$, and a value $a=(1.50\pm0.08)\times10^{-5}$ is derived from the measured absorption cross section for lead.

Tables of the principal photon interaction cross sections in beryllium at 319 Mev are included.

I. INTRODUCTION

EARLY investigations of soft x-ray scattering essentially confirmed Thomson's theory[1] of elastic photon scattering by free electrons. In 1922, Compton[2] discovered that hard monochromatic x-rays undergo inelastic scattering from light elements, and he also observed this scattering to be preferentially forward. These deviations from Thomson scattering led Compton to formulate his well-known photon scattering theory. The ejection of an electron in the scattering event was predicted by Compton and was first seen by Wilson[3] and Bothe in 1923.[4]

* This work was done under the auspices of the U. S. Atomic Energy Commission.
[1] E. O. Wollan, Phys. Rev. **37**, 862 (1931).
[2] A. H. Compton, Bull. Natl. Research Council, Washington, October, 1922; Phys. Rev. **21**, 483 (1923); Phys. Rev. **22**, 409 (1923); Phys. Rev. **21**, 207 (1923); Phys. Rev. **21**, 715 (1923).
[3] C. T. R. Wilson, Proc. Roy. Soc. (London) **104**, 1 (1923).
[4] W. Bothe, Z. Physik **20**, 237 (1923).

In 1929, Klein and Nishina[5] gave a theoretical treatment of the Compton effect, and after a small radiation correction[6] their expression predicts quite accurately the results of photon scattering experiments within the entire energy range below 300 Mev. Figure 1 shows the energy dependence of the Klein-Nishina formula after integration over all photon scattering angles. Previous to Lawson's experiment[7] in 1949, the Klein-Nishina formula had been quite generally used to account for Compton scattering at high energy without adequate experimental verification, even though the theory might be expected to break down at very high energy.[8]

Experimental checks by Lawson[7] have shown that the Klein-Nishina formula deviates from the measured Compton cross section by less than 15% at 88 Mev. Observations of the Compton effect over wide energy intervals up to 200 Mev by Emigh[9] have shown that the average difference between theory and experiment over the 50- to 200-Mev interval is negligible, within the experimental error of 3.4% in aluminum. The latter result weights the cross-section observations essentially as $1/E$ in the interval, thereby emphasizing the lower energy interactions. Coensgen,[10] at this laboratory, has observed the Compton scattering of 250-Mev photons directly by counting the scattered photon in coincidence with the recoil electron. His measurements of the differential cross section, in the angular interval from 4° to 25° for the scattered photon, verify the relative angular dependence of the Klein-Nishina formula to within 10% experimental error. The theoretical total cross section is 17% smaller than the value obtained from integrating Coensgen's data over all angles. The two total cross sections are equal within the experimental error, however.

The total-interaction cross section for photons of energy $\gg m_0c^2$ in matter has been subjected to extensive experimental investigation over the last 7 or 8 years. In the work reported to date,[11] interest has centered principally about the electron pair-production process, which dominates all other high-energy photon interactions. It has been found that the early calculations of Bethe and Heitler,[12] together with those of Wheeler and Lamb[13] and Klein and Nishina,[5] quantitatively predict the observed total absorption cross sections at all energies up to 300 Mev in certain light elements.

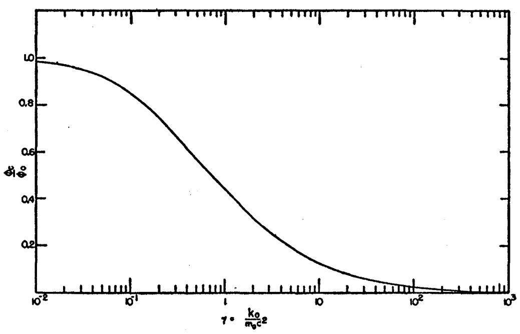

FIG. 1. Total Compton cross section per electron in units of $(8/3)\pi r_0^2$ *versus* incident photon energy.

Adams[14] first pointed out the discrepancy between theory and the measurements at 20 Mev in lead, and suggested that the first Born approximation, employed in the pair-production calculations, is not valid for lead. Since then, several investigators[11] have compared the theoretical pair-production cross sections given by Bethe and Heitler,[12] ϕ_p^z(B.H.), with measured values, ϕ_p^z, in the energy range between 19.5 Mev and 300 Mev by writing

$$\phi_p^z=\phi_p^z(\text{B.H.})[1-aZ^2], \qquad (1)$$

where $1.4\times10^{-5}<a<1.55\times10^{-5}$. More recent theoretical investigations by Bethe, Maximon, and Davies[15] have successfully accounted for the observed pair production and bremsstrahlung cross sections.

The subject of this paper is the measurement of the total cross section for the Compton effect at 319±4 Mev without recourse to absolute monitoring of the photon beam intensity. This method, employed by Lawson,[7] is less difficult and more indirect than the definitive procedure of observing the Compton recoil fragments themselves. The method of this paper yields additional information, however. The absolute photon-attenuation cross sections for beryllium and for lead (see Table I), which were measured during the investigation, and the derived value for a in Eq. (1) (see Table III) agree with previously published work in this energy range.[11] The ratio of pair-forming cross sections in beryllium to those in lead was also measured (see Table I), and a value was derived for the triplet cross section which agrees with the results of a somewhat more accurate and independent determination (see Table III) reported by Anderson *et al.*[16]

II. METHOD

The total photon-attenuation cross section ϕ_a^z for element Z can be written as the sum of the following

[5] O. Klein and Y. Nishina, Z. Physik **52**, 853 (1929).
[6] L. M. Brown and R. P. Feynman, Phys. Rev. **85**, 231 (1952).
[7] J. L. Lawson, Phys. Rev. **75**, 433 (1949).
[8] R. Serber, University of California Radiation Laboratory Report BP-96, 1947 (unpublished), p. 27.
[9] C. R. Emigh, Phys. Rev. **86**, 1028 (1952).
[10] F. H. Coensgen, University of California Radiation Laboratory Report UCRL-2413, November, 1953 (unpublished).
[11] J. L. Lawson, Phys. Rev. **75**, 433 (1949); Dewire, Ashkin, and Beach, Phys. Rev. **83**, 505 (1951); R. L. Walker, Phys. Rev. **76**, 527, 1440 (1949); G. D. Adams, Phys. Rev. **74**, 1707 (1948); C. R. Emigh, Phys. Rev. **86**, 1028 (1952); A. I. Berman, Phys. Rev. **90**, 210 (1953).
[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] G. D. Adams, Phys. Rev. **74**, 1707 (1948).
[15] H. A. Bethe and L. C. Maximon, Phys. Rev. **93**, 768 (1954); Davies, Bethe, and Maximon, Phys. Rev. **93**, 788 (1954).
[16] Anderson, Kenney, McDonald, and Post, following paper [Phys. Rev. **102**, 1632 (1956)], henceforth referred to as AKMP.

total cross sections for photon interactions:

ϕ_p^z, total nuclear pair cross section,
ϕ_t^z, total atomic triplet cross section,
ϕ_c^z, total atomic Compton cross section,
$\sum \phi_i^z$, total atomic cross section for all other photon-scattering and photon-absorption processes;

thus

$$\phi_a^z = \phi_p^z + \phi_t^z + \phi_c^z + \sum \phi_i^z. \tag{2}$$

For 319-Mev photons, the binding energy of electrons in the atom is negligible, so that the free electron total Compton scattering cross section ϕ is then given by $\phi = \phi_c^z / Z$. The cross section ϕ_c^z is related to measurable quantities by Eq. (2). It is required that element Z be a light element in order to minimize the pair-production background.

The indirect approach, taken in the work reported here, was to determine for beryllium both ϕ_a^{Be} and the sum $\phi_p^{\mathrm{Be}} + \phi_t^{\mathrm{Be}}$ and to estimate $\sum \phi_i^{\mathrm{Be}}$ from existing data on the processes involved (see Table II).

Rewriting Eq. (2) in a form to show the terms that were determined experimentally, and putting in a factor containing the lead cross sections, we have

$$4\phi = \phi_c^{\mathrm{Be}} = \phi_a^{\mathrm{Be}} - \left[\frac{\phi_p^{\mathrm{Be}} + \phi_t^{\mathrm{Be}}}{\phi_p^{\mathrm{Pb}} + \phi_t^{\mathrm{Pb}}}\right] \phi_a^{\mathrm{Pb}} (1-f) - \sum \phi_i^{\mathrm{Be}}, \tag{3}$$

where the calculated fraction f is $f = (\phi_c^{\mathrm{Pb}} + \sum \phi_i^{\mathrm{Pb}}) / \phi_a^{\mathrm{Pb}} = 0.0691$.

The ratio $(\phi_p^{\mathrm{Be}} + \phi_t^{\mathrm{Be}}) / (\phi_p^{\mathrm{Pb}} + \phi_t^{\mathrm{Pb}})$ is determined by finding the relative electron pair yields from thin converters of beryllium and of lead. Detailed consideration of the spectrometer scattering losses is avoided by determining the yields from several converter thicknesses of each element and using the extrapolated zero-thickness values in calculating the ratio. The vertical "scattering" losses due to wide-angle pair production are sufficiently independent of Z to be included in the Z-independent spectrometer efficiency.

At photon energies much greater than the electron rest energy, nearly the whole momentum of the photon appears as negatron and positron momenta in pair production. The same relationship holds in triplet production,[17] since the energy of one of the negatron fragments is nearly m_0c^2 for photon energies much greater than m_0c^2. In practice, a high-energy triplet and a high-energy pair are then indistinguishable to the spectrometer, and therefore one measures the sum of the pair and triplet cross sections by counting the yield of high-energy electron pairs from the converter.

The spectrometer geometry yields the pair cross section ratio for nearly equal pair-fragment energies. This equipartition ratio is not equal to the ratio of total cross sections because of slightly different relative shapes of the lead and beryllium differential cross sections, $\phi_p^z(E+)$ and $\phi_t^z(E+)$. These cross sections were calculated by the method given in AKMP[16] and were used in correcting the equipartition ratio for the shape effect.

The two total-absorption cross sections in Eq. (3) are determined by the usual good-geometry attenuation technique.

The total cross section for triplet production in beryllium can be inferred from the data. An experimental value for ϕ_t^{Be} compared with the theoretical value for ϕ_t^{H} given in AKMP[16] would be a valuable check on the screened theory. Our experimental value for ϕ_t^{Be} is obtained from (4).

$$\phi_t^{\mathrm{Be}} = \frac{\phi_p^{\mathrm{Be}} + \phi_t^{\mathrm{Be}}}{\phi_p^{\mathrm{Pb}} + \phi_t^{\mathrm{Pb}}} \phi_a^{\mathrm{Pb}} (1-f) - [\phi_p^{\mathrm{Be}} \text{ (calculated)}] \tag{4}$$

$$= 36.0 \pm 3.5 \text{ mb.}^{18}$$

In AKMP,[16] the theoretical value given for ϕ_t^{H} is 7.68 mb. Apart from screening differences in hydrogen and beryllium, one can write

$$\phi_t^{\mathrm{Be}} = 4\phi_t^{\mathrm{H}}. \tag{5}$$

The numerical values given in Table III are seen to satisfy Eq. (5) within experimental error. Experimental uncertainties preclude the derivation of an accurate value for ϕ_t^{Be} from our data, and the errors would have to be smaller by approximately a factor of 6 in order to detect any departure from Eq. (5) due to screening effects.

III. APPARATUS

The synchrotron beam was collimated to $\frac{1}{8}$-inch diameter at a distance of 56 inches from the internal synchrotron target. The collimated portion of the beam then passed through the experimental apparatus, which was arranged as shown in Fig. 2. The secondary collimator served to define the scattering geometry. At the secondary collimator the beam diameter was somewhat smaller than the 0.5-inch collimator aperture, so that in the region between the primary collimator and pair spectrometer converter the beam was intercepted by

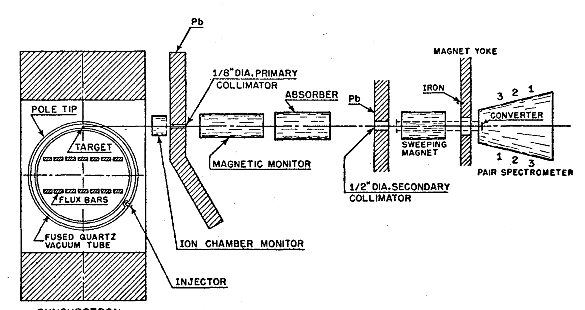

FIG. 2. Schematic arrangement of apparatus. The approximate locations of counters in the spectrometer for each of the double-coincidence channels are marked with the channel numbers.

[17] K. M. Watson, Phys. Rev. 72, 1060 (1947).

[18] 1 mb = 10^{-27} cm^2.

nothing but the absorber and the air column. The absorption and scattering effects due to both the air column and the thin entrance window of the vacuum system can be lumped with the spectrometer efficiency, which cancels in determining counting-rate ratios. The observed value for ϕ_a^{Be} was corrected for absorption by the air column displaced by the absorber. Charged-particle contamination in the beam was reduced to negligible proportions by the monitor magnetic field. Charged particles from the absorber were removed by the sweeping field so that the spectrometer counting rate fell to zero when the converter was removed.

The pair spectrometer magnet was provided with six scintillation counters connected to three independent energy channels, each sensitive to the same photon energy interval. (See Fig. 2.) Electron-positron coincidences were observed independently and simultaneously in each channel by Neher diode bridge coincidence circuits[19] with resolving time of 1.2×10^{-9} second.

The spectrometer channel width was determined by folding the electron radiation straggling in the converter, multiple scattering of electrons in the converter, and geometric channel width. The full width at half-maximum was 8 Mev for the converter used during the measurement of ϕ_a^{Be} and ϕ_a^{Pb}.

The correction for cascade shower effects in the absorber was negligible.

The beryllium absorber and beryllium converters were analyzed for impurities by Mr. Conway and Mr. Tuttle of the spectrochemical group of this laboratory. Corrections of less than 1% for impurities were made to the observed beryllium cross sections. The corrections to the lead data were negligible.

The monitor was located in the photon beam between the main collimator and the absorber, and it was required to be relatively transparent to high-energy photons. It was sensitive only to photon energies in the region of 300 Mev, and consisted of a magnet which deflected approximately 300-Mev positrons from a converter into a channel observed by a sodium iodide crystal and a 5819 photomultiplier. The 5819 output was integrated by an electrometer circuit. The positron flux into the monitor detector was greater than the pair spectrometer counting rate by a factor of at least 20, making it unnecessary to consider statistical variations in monitor readings in the reduction of the data. The ratio of pair-spectrometer counting rate to monitor integration rate was independent of changes in the shape and quantum limit energy of the spectrum to two parts in 10^3 over a range of spectrum variations which was wider, by a factor of 3, than was observed during normal operation. The monitor-spectrometer counting-rate ratio was essentially independent of variations in beam intensity over a factor of 20. This satisfactory operating condition was achieved by adjusting the monitor's mean channel energy while its behavior was observed as a function of synchrotron operating parameters. A detailed account of this monitor will be submitted to *The Review of Scientific Instruments.*

IV. EXPERIMENTAL PROCEDURE

All quantities determined experimentally were counting-rate ratios. The two experimental conditions, representing numerator and denominator counting rates respectively, were accurately reproducible. A typical day's running schedule consisted of alternating the two conditions approximately 20 times, including a periodic determination of the accidental counting rates. In this way, all data were collected in a uniform manner over the running period, and long-term drift effects tended to be minimized.

The total-absorption cross section was determined for two beryllium absorbers which differed in thickness by a factor of 2. The observed values were equal within statistical error of 0.3%. This time-consuming measurement was not repeated with the lead absorber.

V. ESTIMATE OF $\Sigma\Phi_i^{Be}$

In order to estimate $\sum \phi_i^{Be}$ in Eq. (3), all photon interaction processes having cross sections greater than approximately $\frac{1}{10}\phi_c^{Be}$, i.e., greater than 1 mb, must be considered. It will be seen that photoproduction of pions and stars are the principal contributing effects. Crude estimates of other photo processes having smaller cross sections are also contained in Table II.

Estimates of the charged-pion production in beryllium are based upon the total cross section for photoproduction of pions from hydrogen measured by Walker *et al.*[20] and Tollestrup *et al.*[21] to be 0.21 mb per 319-Mev photon. Littauer and Walker[22] give the photoyields of positive and negative pions from beryllium relative to the photopion yield from hydrogen as 2.39 and 5.39, respectively. These data are for 65-Mev pions observed at 135° from 310-Mev bremsstrahlung. Medicus[23] has found the ratio of negative to positive photopion yields from 322-Mev bremsstrahlung incident on beryllium to be 2.0 at 90°. Motz, Crowe, and Friedman[24] observe no strong angular or energy dependence of the π^-/π^+ ratio in carbon. Assuming a mean ratio of 2.1 for beryllium, the total production of charged pions then becomes 1.6 mb per 319-Mev photon, accurate to approximately 20%.

The total neutral-pion production in beryllium is given by Panofsky, Steinberger, and Steller[25] as 0.555 mb per 260 Mev photon, accurate to a factor of 2. Correcting this value to 319 Mev, using the observed

[19] L. Neher, University of California Radiation Laboratory Report UCRL-2191, April, 1953 (unpublished).

[20] R. L. Walker *et al.*, Phys. Rev. **99**, 210 (1955).
[21] A. V. Tollestrup *et al.*, Phys. Rev. **99**, 220 (1955).
[22] R. M. Littauer and D. Walker, Phys. Rev. **82**, 746 (1951).
[23] H. A. Medicus, Phys. Rev. **83**, 662 (1951).
[24] Motz, Crowe, and Friedman, Phys. Rev. **98**, 268(A) (1955).
[25] Panofsky, Steinberger, and Steller, Phys. Rev. **86**, 180 (1952).

TABLE I. Experimental values measured in this work, with values from DeWire *et al.*[a] for comparison.

Quantity	Experimental cross section per photon	Photon energy (Mev)	Source
ϕ_a^{Be}	161.3 ± 1.0 mb	319	This work
ϕ_a^{Be}	$(0.01060\pm1.2\%)$ cm²/g	280	DeWire *et al.*
ϕ_a^{Be}	163.0 ± 2.0 mb	319	DeWire *et al.*, corrected to 319 Mev by Bethe-Heitler excitation function
ϕ_a^{Pb}	$(37.620\pm0.225)\times10^{-24}$ cm²	319	This work
ϕ_a^{Pb}	$(0.1069\pm1.2\%)$ cm²/g	280	DeWire *et al.*
ϕ_a^{Pb}	$(37.220\pm0.447)\times10^{-24}$ cm²	319	DeWire *et al.*, corrected to 319 Mev by Bethe-Heitler excitation function
$\dfrac{\phi_p^{Be}+\phi_t^{Be}}{\phi_p^{Pb}+\phi_t^{Pb}}$	$(3.986\pm0.020)\times10^{-3}$	319	This work

[a] See reference 11.

excitation function of Goldschmidt-Clermont *et al.*[26] for neutral pions from hydrogen, we find the neutral pion production to be 0.78 mb per 319-Mev photon in beryllium, accurate to a factor of 2.

The sum of cross sections for production of charged and neutral photopions is then 2.4 mb per 319-Mev photon, accurate to approximately 30%.

The production of photostars in emulsion has been investigated by Miller[27] and Peterson.[28] Miller derives an excitation function for stars of three or more prongs in carbon and in silver, and the integral of this excitation function over the bremsstrahlung spectrum gives a total cross section in agreement with Peterson's data. Experimental conditions prevented the determination of cross sections for stars of one and two prongs so that Miller's star cross section should be increased to account for one- and two-prong star production. This is done by including the cross section for high-energy photoprotons, which is estimated below.

The beryllium photostar cross section was derived from Miller's carbon data by assuming that the cross section is proportional to A. The value is 0.75 mb per 319-Mev photon, accurate to approximately 50%.

The photoproton yield from beryllium is obtained from data on carbon by assuming that the cross section varies as $Z/k_0^{\frac{3}{2}}$. Normalizing the carbon angular distribution found by Feld *et al.*[29] to the absolute value of $d\sigma/d\Omega|_{60°,\,190\text{ Mev}}$ for carbon obtained by Weil and McDaniel,[30] and integrating over solid angle, one obtains a value of 0.36 mb per 319-Mev photon for the beryllium cross section, accurate to approximately 100%.

[26] Goldschmidt-Clermont, Osborne, and Scott, Phys. Rev. **97**, 188 (1955).
[27] R. D. Miller, Phys. Rev. **82**, 260 (1951).
[28] V. Z. Peterson, Phys. Rev. **96**, 850 (1954).
[29] B. T. Feld *et al.*, Phys. Rev. **85**, 680 (1952).
[30] J. W. Weil and B. D. McDaniel, Phys. Rev. **92**, 391 (1953).

No other processes contribute significantly to the interaction of 319-Mev photons in beryllium. The various low-energy photoeffects and Compton scattering from the nucleus as a whole contribute less than 10^{-3} mb per 319-Mev photon to the 319-Mev photointeraction cross section in beryllium and are therefore neglected. It is assumed that the neutrons that are observed at high energy arise from events discussed above. It seems reasonable that the principal mechanisms for photon interactions with nuclei and with nucleons involve photon coupling to nucleons through their Coulomb and meson fields. At photon energies near 300 Mev the ejection of a neutron unaccompanied by a charged particle or a neutral meson seems relatively improbable.

VI. RESULTS

The total interaction cross sections for 319-Mev photons incident on beryllium and on lead were determined in good-geometry attenuation experiment. The values are given in Table I. The ratio $(\phi_p^{Be}+\phi_t^{Be})/(\phi_p^{Pb}+\phi_t^{Pb})$ was inferred from relative electron-pair yields from thin converters of beryllium and of lead placed in the pair spectrometer. This ratio appears in Table I. The estimated value of $\sum\phi_i^{Be}$ is given in Table II.

TABLE II. Contributions to the term $\Sigma\phi_i^{Be}=3.5\pm1.0$ mb in Eqs. (2) and (3).

Process	Cross section in millibarns per 319-Mev photon per beryllium atom	Estimated error
Charged photopion production (π^+ and π^-)	1.6	20%
Neutral photopion production (π^0)	0.78	100%
Photostars of 3 or more prongs	0.75	50%
Photoproton production	0.36	100%
High-energy tails of low-energy photoeffects, and Compton scattering from the nucleus as a whole	$<10^{-3}$	factor 5

From these data Eq. (3) yields a value for ϕ_c^{Be}, the 319-Mev total cross section for electron Compton scattering in beryllium. The experimental value for $\phi=\phi_c^{Be}/4$ is given in Table III. The Klein-Nishina cross section per electron per 319-Mev incident photon is given for comparison in Table III.

VII. DISCUSSION

Real deviations of the measured total Compton cross section from the Klein-Nishina formula would be of interest. Figure 1 shows the energy dependence of the Klein-Nishina formula integrated over solid angle. Brown and Feynman[6] have calculated radiative corrections to the Klein-Nishina formula by considering Compton scattering when the electron emits and reabsorbs a virtual photon in the scattering event. The leading radiative correction term is of order e^6 and therefore is small. Integrating it over all photon scattering angles gives a correction to the Klein-Nishina total cross section of approximately $+1.4\%$ at 319 Mev. This small deviation is difficult to detect by the method employed in this investigation.

The damping correction, corresponding to the classical force proportional to $d^2\mathbf{v}/dt^2$, is shown by Heitler[31] to be negligible at all energies.

One expects details of the electronic structure to enter the theory when incident photon energies k are given by

$$k > (\hbar c/e^2)m_0c^2 = 70 \text{ Mev}, \qquad (6)$$

in the frame in which the electron remains at rest. In the Compton effect there is no such frame, since the electron at rest in the laboratory is usually relativistic after the scattering event. A covariant generalization[8] of Eq. (6) for Compton scattering shows that the incident photon energy must be greater than approximately 5 Bev for electronic structure effects to become important.

The experimental uncertainty in ϕ_c^{Be} does not allow a detailed comparison of results with the integrated Klein-Nishina formula and its radiative correction. The reduction of our experimental error for ϕ_c^{Be} by as much as a factor of 2 is a difficult undertaking because the uncertainty in the term $\sum \phi_i^{\text{Be}}$ in Eq. (3) contributes approximately 40% of the final error. However, the principal conclusion of this paper is that the Klein-Nishina theory appears to be correct to at least 15% for photon energies in the 300-Mev region.

The value given for ϕ_t^{Be} should be regarded only as a general check on the triplet cross section in beryllium, and the reader is referred to AKMP[16] for a more accurate value of the fundamental triplet-production cross section in hydrogen.

A second-order Born approximation calculation of ϕ_p^z shows that the observed deviations of Bethe and Heitler's original calculations from ϕ_p^z should be proportional to Z^2, which justifies the form of Eq. (1). The measured value for ϕ_p^{Pb} obtained in this experiment gives $a = (1.50 \pm 0.08) \times 10^{-5}$ in Eq. (1), which is in good agreement with the values for a obtained by other investigators from observations of several elements.

[31] W. Heitler, *The Quantum Theory of Radiation* (Oxford University Press, New York, 1954), p. 335.

TABLE III. Comparison values derived from data in Table I together with theoretical values.[a]

Quantity	Cross section in millibarns per 319-Mev photon	Source
$\phi = \frac{1}{4}\phi_c^{\text{Be}}$	2.8±0.4	Equation (3) of this work (experimental)
ϕ	3.043	Klein-Nishina Formula (theoretical)
ϕ_t^{Be}	36.0±3.5	Equation (4) of this work (experimental)
$4\phi_t^{\text{H}}$	30.72	Table I of AKMP[b] (theoretical)
$\phi_p^z = \phi_p^z(\text{B.H.})[1-(1.50\pm0.08)\times10^{-5}Z^2]$		

[a] The quoted values for experimental uncertainties include the root-mean-square statistical counting errors as well as our best estimates of the systematic effects involved. Errors in the corrections for accidental coincidences and monitor background have also been considered.
[b] See reference 16.

VIII. ACKNOWLEDGMENTS

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