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ABSTRACT

A lead glass photon spectrometer has been used to measure the total attenuation cross section of Pb and Al for photons of energy 2.5 ± 0.5 Bev produced in the Berkeley Bevatron. The electron-pair cross sections have been inferred from the measured total cross sections. Preliminary data indicate that the electron-pair cross section is 34.6 ± 6.6 barns in Pb and 1.22 ± 0.17 barns in Al.

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I. Introduction

The dominant interaction of photons with matter is the production of electron pairs. This effect has been studied experimentally at energies up to approximately 500 Mev,[1] and good agreement has been obtained with the total cross-section calculations by Davies, Bethe, and Maximon.[2] An empirical correction has been found[1] to the older Born-approximation total cross-section calculations of Bethe and Heitler which adequately accounts for the failure of the Born approximation in heavy elements. The correction is given by

$$\phi_p\ (k, Z) = \underset{\text{Bethe-Heitler}}{\phi\ (k, Z)}\ (1 - 1.5 \times 10^{-5}\ Z^2). \qquad (1)$$

The theoretical values for $\phi_p\,(k, Z)$ used below are obtained from Eq. (1).

This paper describes preliminary results of a further test of the theory at 2.5 ± 0.5 Bev. We measured the total photon-absorption cross sections for aluminum and lead by utilizing high-energy photons produced in the Bevatron. We then inferred the sum of the electron-pair and the electron-triplet cross sections from the measured absorption cross section for each element, and separated the two electron effects by using a theoretical ratio of their cross sections.

*This work was done under the auspices of the U. S. Atomic Energy Commission.

†Now at The Ramo-Wooldridge Corp., 8820 Bellanca Ave., Los Angeles 45, California.

II. Apparatus and Procedure

When the 6.2 Bev protons of the Bevatron circulating beam collide with an internal beryllium target neutral pions are produced, and those pions which decay in nearly the forward direction yield a usable flux of photons in the energy range of a few Bev. These photons were collimated to form a narrow beam at 6° to the direction of the incident protons, as shown in Fig. 1, and the observed spectrum above 2 Bev in the collimated beam was approximately proportional to $k^{-5.5 \pm 0.8}$, where k is the incident photon energy. Charged particles were cleared from the beam by the sweeping magnet, leaving a mixture of photons and neutrons incident upon the absorber. The absorbers were pure (2S) aluminum or commercial-grade lead of approximately one radiation length thickness. The total photon flux contained in the beam was detected by a high-efficiency spectrometer, shown in Fig. 2, which consisted of a charged-particle anticoincidence counter (A), followed by a lead converter for photons and a coincidence counter (B), situated immediately in front of the lead glass Cerenkov counter (C).[4] If an event was simultaneously detected in counters B and C in the absence of a pulse from counter A, the ten-channel pulse-height analyzer was gated on to record the size of the Cerenkov counter pulse. The efficiency of the spectrometer for 2.5 Bev photons was about 60% and its resolution was k/2 full width at half maximum. The energy calibration and the resolution of the Cerenkov counter were checked nightly by observing cosmic-ray muons during the period between successive days' runs. A detailed description of the detector is contained in Ref. 4.

The spectrometer is sensitive to neutrons as well as to photons. These two components of the incident neutral flux were separated by introducing a 1-inch lead shutter S, shown in Fig. 1, into the beam in order to attenuate the 2.5 Bev photons by a factor of 27 without appreciably altering the incident neutron flux. Appropriate counting differences then yielded the photon flux incident upon the spectrometer. The observed ratio of counting rates due to neutrons and photons was approximately unity for the beam incident upon the absorber.

Conventional absorption technique was employed to find the total photon absorption cross section, $\phi_{abs}(k, Z)$, of a given absorber. The ratio of incident to transmitted photon intensity, I_0/I, was determined for an absorber of thickness t. The value of $\phi_{abs}(k, Z)$ is then given by

$$\phi_{abs}(k, Z) = \frac{1}{Nt} \ln \frac{I_o}{I}$$

where N is the number of atoms per cm^3 in the absorber. The transmitted and incident intensities are proportional to the corrected photon counting rates with and without the absorber in place, respectively, and are normalized to a monitor scintillation counter whose response was proportional to the number of protons that struck the internal Bevatron target.

III. Results and Discussion

The total photon absorption cross section, $\phi_{abs}(k, Z)$, for element Z and photon energy k can be written

$$\phi_{abs}(k, Z) = \phi_p(k, Z) + Z\phi_t(k) + \Sigma\phi_i(k, Z),$$

where $\phi_p(k, Z)$ = total electron-pair production cross section,

$\phi_t(k)$ = total electron-triplet production cross section per electron,

and

$\Sigma\phi_i(k, Z)$ = total cross section for all other photoprocesses.

In both aluminum and lead at these energies we have

$$\frac{\Sigma\phi_i(k, Z)}{\phi_{abs}(k, Z)} < 10^{-2}$$

so that the measured value for $\phi_{abs}(k, Z)$ is essentially the sum of pair and triplet cross sections. Then

$$\phi_{p,\,experimental}(k, Z) = \phi_{abs}(k, Z) / \left[1 + \frac{\phi_t(k, Z)}{\phi_p(k, Z)}\right]$$

where $\phi_p(k, Z)$ is calculated from the work of Bethe and Heitler (corrected for the Born-approximation failure in heavy elements) and $\phi_t(k, Z)$ is calculated from the work of Wheeler and Lamb[5] and Borsellino.[6]

Table I contains the observed total-absorption cross sections and the derived total pair-production cross sections, with corrected Born-approximation theoretical cross sections included for comparison. Figures 3 and 4 show the experimental results compared with the work of other authors and with the corrected calculations by Bethe and Heitler.

Table I

Photon total cross sections at k = 2.5 ± 0.5 Bev (barns)

	Experimental		Theoretical (corrected for Born approximation)	
	Pb	Al	Pb	Al
ϕ_{abs}	35.0 ± 6.7	1.31 ± 0.18		
ϕ_{pair}	34.6 ± 6.6	1.22 ± 0.17	39.4	1.30

The screening of both the nuclear and the electron Coulomb fields by the atomic electrons becomes more effective at higher energies,[3] and places an asymptotic high-energy limit on both the pair and triplet cross sections. At 2.5 Bev, and at 4.0 Bev, for example, the Born-approximation calculations indicate that the nuclear pair-production cross section for lead is 96.6% and 97.4% of the asymptotic cross section, respectively. This effect is seen in Figs. 3 and 4.

The failure of the Born approximation for heavy elements leads to the disagreement of experiment with the older theoretical results of Bethe and Heitler. The theoretical curves in Figs. 3 and 4 and the values in Table I have been corrected to account for this failure of the Born approximation. Within the assigned errors, the results of this experiment are consistent both with the corrected theory and with experimental results extrapolated from lower energies. These errors are statistical uncertainties combined with our best estimates of anticoincidence counter inefficiency, dead time, and other systematic or instrumental errors.

The energy spectrum of the photon beam was broad, and extended above the mean energy of 2.5 Bev at which the absorption cross sections were determined. The measured values were subject to negligibly small positive corrections (less than 1%) to account for those photons which were incident upon the absorber with energy greater than approximately 2.5 Bev, and which underwent shower processes in the absorber in a manner that gave rise to photons of energy of approximately 2.5 Bev in the forward direction and were therefore indistinguishable from photons simply transmitted by the absorber. Whenever such photons are accompanied by an associated shower electron that enters the counter geometry, the anticoincidence counter rejects the event, which is an unlikely one even in the absence of the anticoincidence counter.

The systematic errors in the aluminum measurements were considerably greater than for lead. The aluminum results have been included only as an approximate verification of the Z^2 dependence of the electron-pair cross section in the energy interval studied.

It is expected that additional work will be done within the year at 2.5 Bev in order to reduce the over-all uncertainties both for aluminum and for lead, and at 4.0 Bev in an effort to more accurately correlate the theory with experiment at higher energies. Preliminary results are presented at this time because prior commitments prevent the immediate resumption of the experiment.

IV. Acknowledgments

The advice and encouragement of Professors A. C. Helmholz and Burton J. Moyer are gratefully acknowledged. The authors are indebted to Dr. Edward J. Lofgren and the Bevatron operating staff for their cooperation during the experiment.

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6. A. Borsellino, Nuovo Cimento 4, 112 (1947).

Figures

Fig. 1. Sketch (not to scale) of the experimental layout for the measurement of electron-pair production cross sections.

Fig. 2. Schematic arrangement of the spectrometer showing the glass, phototubes, and magnetic shield, as well as the anti-coincidence and coincidence counters, and the lead converter. These two scintillation counters insure that the electron showers, which are pulse-height analyzed, start in the 1/4-in. lead converter and are thus centered in the glass and start at its front surface.

Fig. 3. Electron pair production cross sections. The solid curves show the Bethe-Heitler theoretical values for lead and aluminum as a function of photon energy, corrected for Born-approximation failure in heavy elements. The experimental points are shown. The dashed line represents the case for no screening.

Fig. 4. Experimental values for the photon total-absorption cross section as a function of energy and of Z. The solid lines are calculated values, with the pair-production contribution given by the Bethe-Heitler theory corrected for Born-approximation failure in heavy elements.

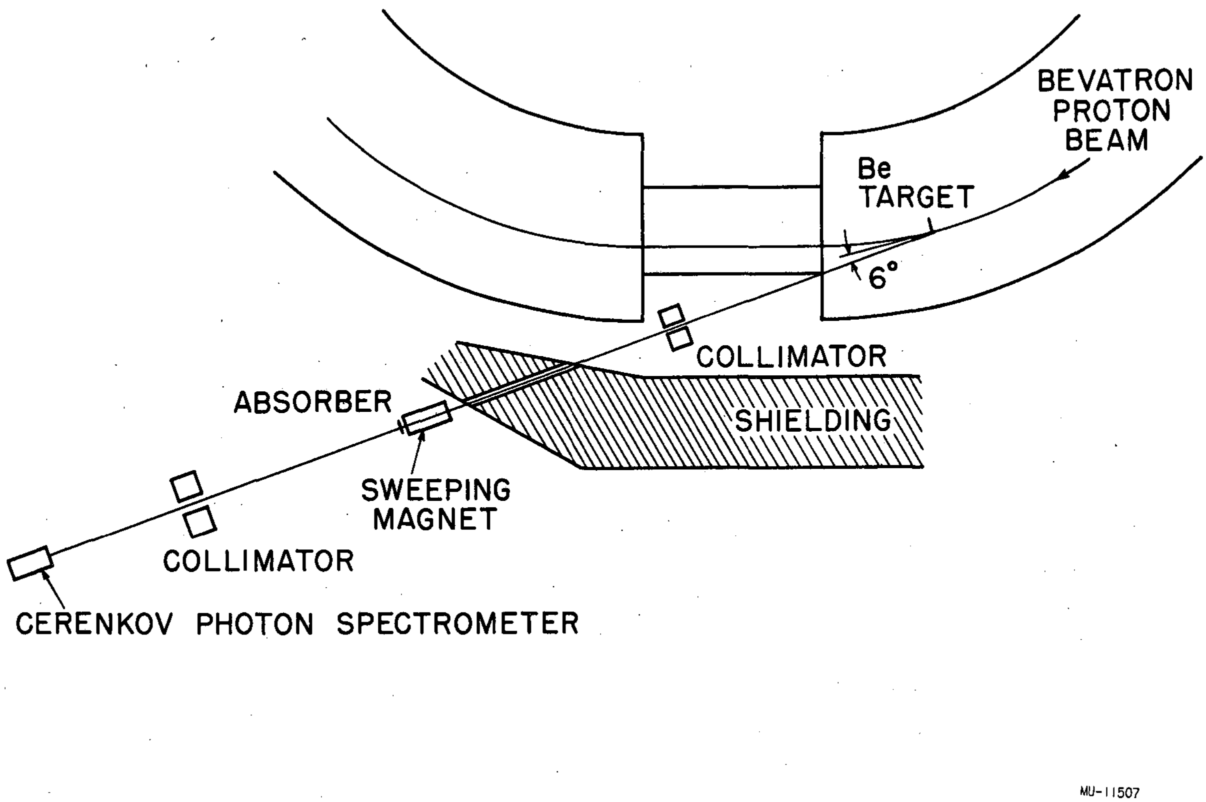
BEVATRON
PROTON
BEAM
Be
TARGET
6°
COLLIMATOR
SHIELDING
ABSORBER
SWEEPING
MAGNET
COLLIMATOR
CERENKOV PHOTON SPECTROMETER
MU-11507

Fig. 1

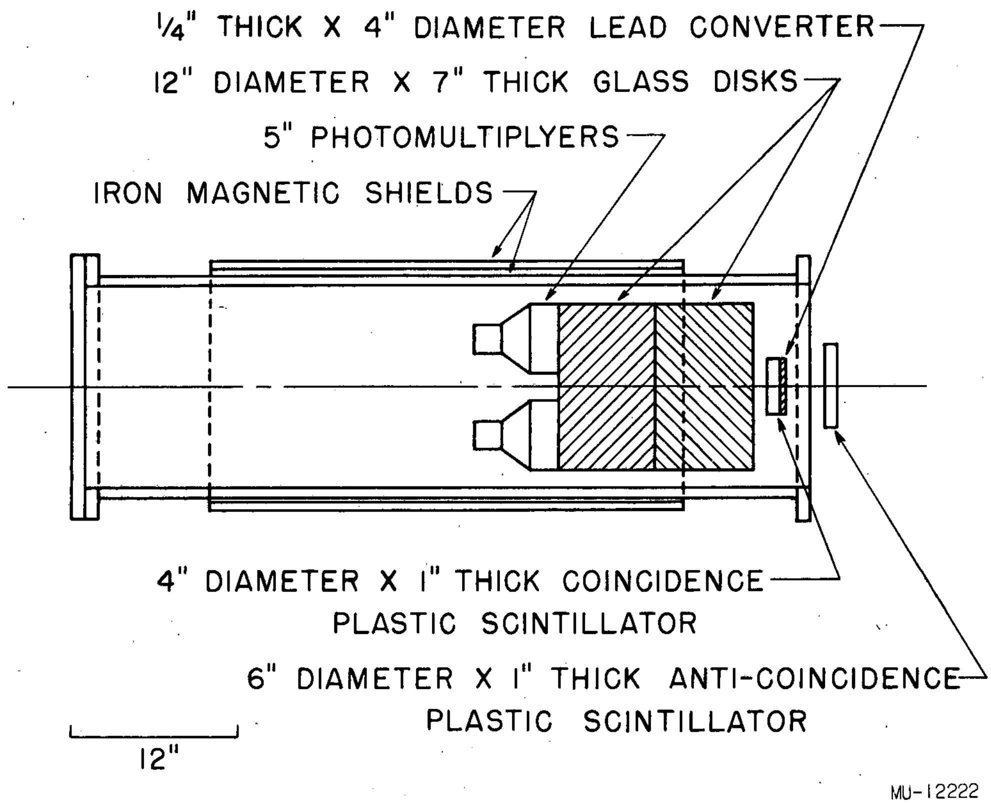
1/4" THICK X 4" DIAMETER LEAD CONVERTER
12" DIAMETER X 7" THICK GLASS DISKS
5" PHOTOMULTIPLYERS
IRON MAGNETIC SHIELDS
4" DIAMETER X 1" THICK COINCIDENCE PLASTIC SCINTILLATOR
6" DIAMETER X 1" THICK ANTI-COINCIDENCE PLASTIC SCINTILLATOR
12"
MU-12222

Fig. 2

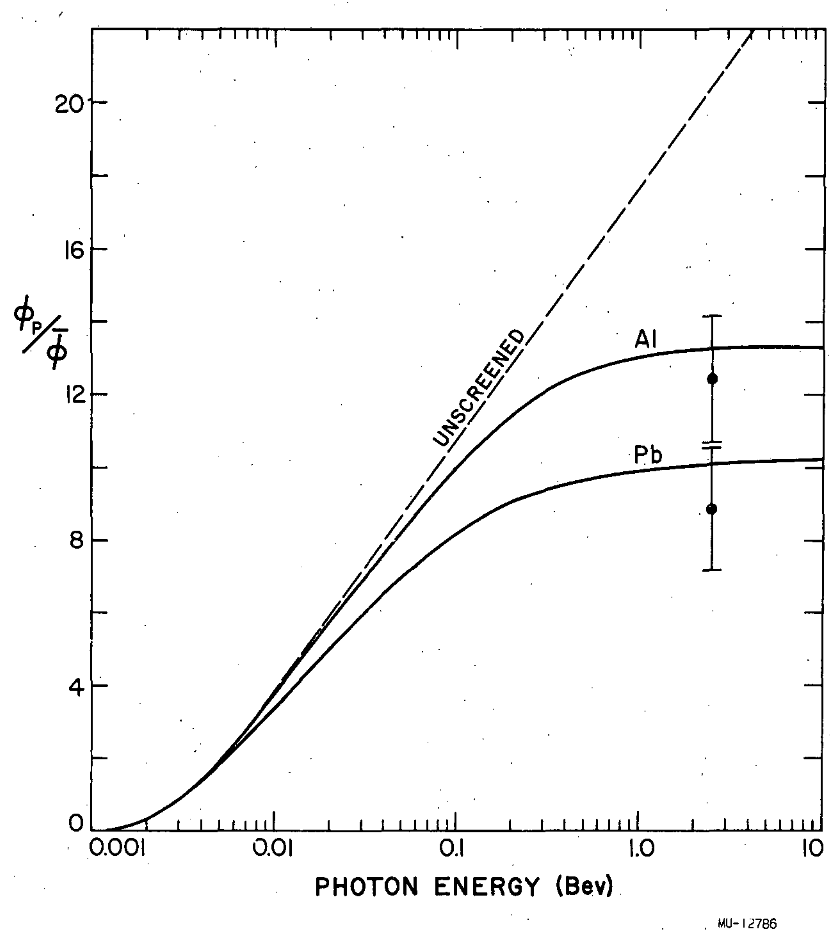
20
16
12
8
4
0
$\phi_P/\bar{\phi}$
UNSCREENED
Al
Pb
0.001
0.01
0.1
1.0
10
PHOTON ENERGY (Bev)
MU-12786

Fig. 3

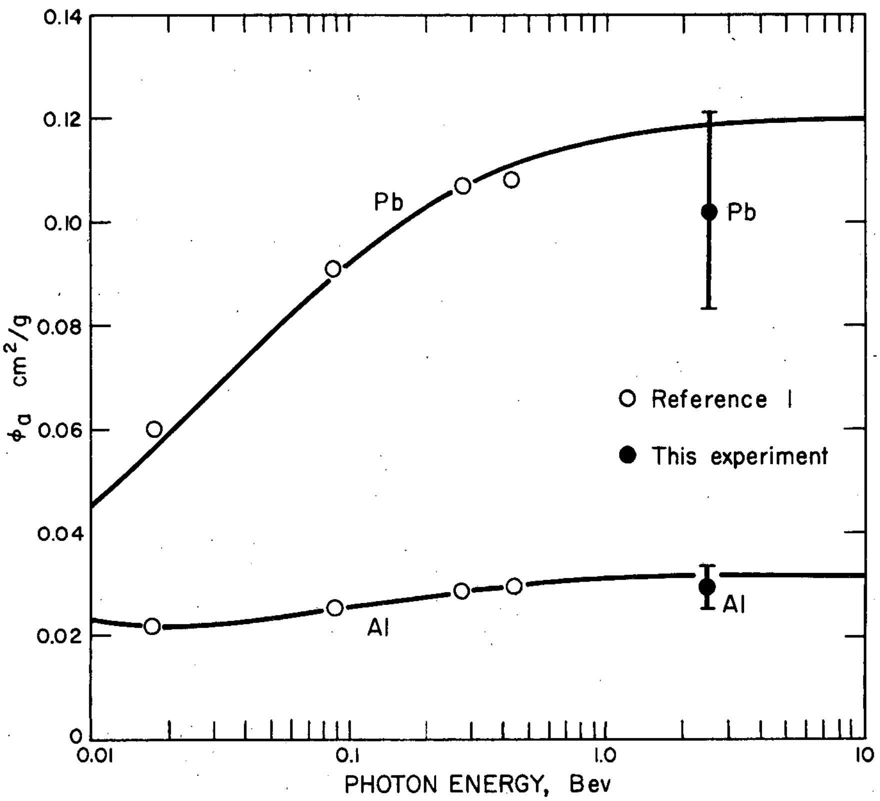

Fig. 4

MU-12950