CHARACTERISTICS OF A LEAD-GLASS PHOTON SPECTROMETER AND ITS USE IN STUDYING THE ABSORPTION OF PHOTONS AND ANTINUCLEONS

Author
Brabant, John M.

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John M. Brabant
(Thesis)

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CHARACTERISTICS OF A LEAD-GLASS PHOTON SPECTROMETER AND ITS USE IN STUDYING THE ABSORPTION OF PHOTONS AND ANTINUCLEONS

John M. Brabant
Radiation Laboratory
University of California
Berkeley, California

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ABSTRACT

A spectrometer for analyzing photons of energies extending up to several Bev has been constructed. This instrument contains in a lead-glass medium a large fraction of the cascade shower that is initiated by the incoming photon and observes by means of phototubes the Cerenkov radiation that is emitted by the electrons in the shower. It has been calibrated up to 1.5 Bev photon energy, and its response is very nearly linear.

Using this device, a good-geometry experiment has been performed to measure the electron-pair production cross sections at $2.5 \pm 0.5$ Bev in lead and aluminum. Photons from an internal target of the Bevatron were used. The measured cross sections were $34.6 \pm 6.6$ barns in lead and $1.22 \pm 0.17$ barns in aluminum.

In a modified form, this instrument has been used to study the interaction of antiprotons in matter. Estimates of the efficiency for containing the annihilation products and of the type and multiplicity of these products indicate that the pulse spectra that are expected to be observed are compatible with those measured. Attenuation effects in a copper absorber and the lead glass indicate that the absorption cross sections are about twice geometric at about 450 Mev and increase as the antiproton energy decreases below 450 Mev.
I. INTRODUCTION

To begin some experiments on photons produced by the UCRL Bevatron, it was decided that a moderately low-resolution, but high-efficiency, gamma-ray spectrometer would be desirable for surveying the gamma rays from the targets in the machine. It was thought that the light from the Cerenkov radiation produced in a piece of high-lead-content glass of sufficient size to absorb a large fraction of the energy of a photon-induced electron-photon shower would be nearly proportional to the energy of the incident gamma ray. Such an instrument would provide a rough evaluation of gamma spectra extending to very high energies, and would indicate whether it would be desirable to later undertake the construction of an electron-pair spectrometer of higher resolution but much lower detection efficiency and far greater expense. Accordingly, the device described in this paper has been constructed, calibrated, and used successfully.

Because any charged particle moving through the glass medium with sufficient velocity will emit Cerenkov radiation which can be detected by sensitive phototubes, this spectrometer may be used for a variety of purposes. First, it can be used as a photon spectrometer to measure the energy of high-energy photons incident upon it. This method of operation is discussed in Section IV. An experiment that utilizes this mode of operation, the measurement of the electron-pair production cross sections in lead and aluminum at a photon energy of 2.5 Bev is discussed in Section V. A second application depends upon the phenomenon that incident charged mesons of sufficient energy can produce a Cerenkov light pulse in the glass. This has been seen and used as discussed in Section IV. Third, charged pions of sufficient velocity and the showers from the decay photons of neutral pions produced by the nuclear interaction of high-energy particles that penetrate the volume of glass also create observable Cerenkov light pulses. An application of the device in this manner is described in Sections VI and VII where the use of the instrument in a modified form to measure the spectra of pulse heights arising from the annihilation of antiprotons produced by the UCRL Bevatron is discussed. Other uses are obvious and the two experiments discussed here merely illustrate the range of this spectrometer.
II. THEORY OF THE SPECTROMETER

For gamma rays of energies greater than a few Mev, the largest interaction with matter is through the process of electron-pair production. This production occurs when a photon within this energy range is incident upon a body of material. If the medium is of sufficient depth, these electrons will in turn radiate, thus producing more photons. This multiplicative process continues, and produces what is known as a cascade shower. If the medium is sufficiently large so as to completely contain this shower, the energy of the photon may be determined by measuring the total energy absorbed by the medium.

One of the ways in which this may be done is to observe the light pulse produced by a medium that scintillates when traversed by charged particles. The low stopping power of such a medium for a shower makes it necessary to have an extremely large volume of medium to contain a large fraction of the shower. This leads to quite bulky and cumbersome equipment when photons of several Bev energy are to be studied. As a less unwieldy instrument was desired, another method, discussed below, was used in this spectrometer.

The lead glass medium used in this spectrometer has a rather high absorbing power for these showers and so tends to contain a shower in a relatively small volume. The high average atomic number $Z$ and high density $\rho_0$ of the glass are responsible for the favorable absorbing power.

As the glass does not scintillate when traversed by charged particles, the sampling of the energy contained is accomplished by observing the pulse of Cerenkov radiation produced by the electrons in the cascade shower. This Cerenkov effect, first observed by Cerenkov\(^2\) in 1934 and theoretically explained by Frank and Tamm\(^3\), occurs whenever a charged particle travels through a medium with a velocity greater than that of light in the medium. This radiation is emitted in the visible region of frequencies with a photon distribution that is independent of photon frequency. The number of quanta emitted per unit frequency interval is proportional to \((1 - n^{-2} \beta^{-2})\) where $n$ is the index of refraction of the medium, and $\beta$ is the particle velocity divided by the
velocity of light in free space (see Appendix). This expression also shows how the large index of refraction of the glass reinforces this effect in this spectrometer. As the glass is transparent in this frequency range, the light pulse resulting from such an event is observed by photomultiplier tubes which are also sensitive in this region.

The total Cerenkov radiation produced by the electrons in such a shower is essentially proportional to the energy of the initial photon contained in the medium, as all electrons having energies greater than about 0.5 Mev emit nearly the same amount of Cerenkov radiation per increment of path. As the energy of the initial photon increases, a decreasing fraction of the total shower is actually contained in the glass medium, thus making its pulse-height response with respect to incident photon energy not quite linear.
III. DESCRIPTION OF THE SPECTROMETER AND ASSOCIATED EQUIPMENT

A. The Spectrometer Assembly

The spectrometer shown in Fig. 1 and diagrammed in Fig. 2 consists of a 400-lb. soft-iron magnetic shield, which also serves as a case for the glass and photomultipliers used to detect the Cerenkov radiation in the glass. The spectrometer was designed to operate in a field of 100 gauss, the level that prevails in some of the experimental areas of the Bevatron building.

The glass used in the spectrometer, in which the showers develop and the Cerenkov light is produced, is in the form of a cylinder 12.25 in. in diameter and 14 in. long. The cylinder is made of two pieces of glass, each 7 in. thick. The flat faces of these cylinders have been ground and polished to optical quality. The two pieces of glass and the photomultipliers are optically coupled by a thin layer of Dow-Corning 200 silicone compound having a viscosity of 2,500,000 centistokes and an index of refraction of 1.4. When held under pressure the DC 200 gives an excellent optical bond.

Before assembly, the glass was wrapped in aluminum foil, except for the end facing the photomultipliers, and it was also wrapped circumferentially in sheet rubber and μ metal, a material of high magnetic permeability. The photomultiplier assembly is in contact with one flat face of the glass cylinder, and an assembly consisting of a setscrew-retaining ring and a rubber washer is placed against the other face. Snap rings, which fit into internal grooves cut into the main iron shield, hold the entire assembly rigidly in place by the compression of the setscrews. The setscrews apply sufficient axial load to the glass so that the spectrometer may be placed in any operating position with negligible movement of the 180 lb. of glass.

The circuit boxes containing the bases of the phototubes are held to the assembly by springs that press the faces of the tubes against the glass. Each end of the magnetic shield case has a gasket groove for a rubber gasket. This permits a light-tight seal between the case and the end covers, which are held in place by bolts. Each circuit box contains a high-voltage input, two signal outputs, and a filament- and plate-voltage
supply input. These are attached by cables to cable lead-throughs in one end cover. Cables lead from the outer side of this end cover to the amplifiers and recording equipment. The tubes are operated with their anodes at positive high voltage with respect to their photocathodes and ground. This is done so that there will not be a large voltage gradient across the glass envelope of the tube between the photocathodes and the lead glass against which the tubes are pressed. The circuit schematic is shown in Fig. 3.

Figure 2 also shows the position of the 6-inch-diameter antico- incidence plastic scintillation counter, the 4-inch-diameter lead converter, and the 4-in.-diam. plastic scintillation coincidence counter. The lead converter is 0.25-in. thick, and each scintillator is 1-in. thick. Four DuMont 6364 tubes are used to take the Cerenkov light pulse from the glass, and each scintillator is viewed by four RCA 1P21 photomultipliers. The entire assembly weighs about 800 lb.

B. The Glass

The glass itself is a special casting by the Corning Glass Company of a dense flint glass code no. 8392. This glass has a density of 3.89 g per cc and consists of 52% PbO, 42% SiO₂, 3% K₂O, and 3% Na₂O by weight. The index of refraction for the sodium "D" line is 1.649, and the dispersion is 33.8. The light transmission, not corrected for two surface reflections, from 6700 Å to 4300 Å is 80% for one 7-in. thickness, with a sharp cutoff at 4000 Å. The index 1.649 gives a threshold for Cerenkov radiation of 0.13 Mev for electrons, 28 Mev for muons, 36 Mev for pions, and 240 Mev for protons. One radiation length is 2.77 cm, so that there are 12.85 radiation lengths in the 14-in. length of glass. The critical energy in the glass is 17.5 Mev.

Although ionization-energy loss plays no part in the production of light in the spectrometer, charged particles traveling axially at minimum ionization (velocity = 0.955 c) through the glass encounter 138 g/cm² and lose 1.47 Mev/ g/cm². This corresponds to an energy loss of 203 Mev for passage through the counter parallel to its symmetry axis.
A singly charged particle (with velocity approximately \( c \)) radiates 338 quanta of Cerenkov radiation in the visible range of 4,000 to 7,500 Angstroms per cm of path in the glass. The Cerenkov energy lost in the same region is 806 ev/cm. The calculated values in this section were obtained by the use of the equations in the Appendix and assume that the index of refraction is constant over the frequency range considered.

C. Magnetic Shielding

The 6364 photomultipliers are extremely sensitive to magnetic fields. The counting rate varies over a wide range with the orientation of the tube in the earth's fraction-of-a-gauss field. Operation in the pulsing stray field of the Bevatron, where the field frequently reaches 100 gauss, presented a serious problem. A second cylinder of soft iron 0.5-in. thick and separated from the main outer shield by 0.25 inch of dielectric, a cylinder of \( \mu \) metal 20-mil thick inside the main shield, and cylindrical \( \mu \) metal shields around each individual phototube were found to be necessary to reduce the effect of the external magnetic fields to a negligible value. To test the magnetic shielding the spectrometer was gated to count for 0.1-sec. intervals during various phases of the 2-sec. Bevatron magnetic pulse. It was found that at the locations where the spectrometer was to be used, the foregoing precautions were sufficient to give the same cosmic-ray counting rate and pulse-height distribution for all phases of the stray magnetic field of the Bevatron.

D. Associated Equipment

The output pulse from each 6364 photomultiplier anode is fed into a cathode follower at the base of the tube. This lengthens the duration of the pulse and matches the output-cable impedance. The outputs from all four cathode followers are then added and fed into a UCRL linear amplifier. The output pulses from the last dynode of each 6364 photomultiplier are added together. These additions are made by passive
adding networks each consisting of a junction box and short connecting cables. The 1P21 photomultipliers on the scintillators have their outputs added in pairs, so that each counter has two independent outputs. The two from the anticounter go to a fast double-coincidence circuit, while the two from the coincidence counter and the added dynode pulses from the Cerenkov counter go to a fast threefold-coincidence circuit. All signals are properly amplified by 200-Mc wide-band distributed amplifiers. The fast output of each coincidence circuit then goes to an anticoincidence circuit, which will deliver an output only when the anticoincidence counter has not fired and the coincidence arrangement has. The combined resolving time of the entire system is $6 \times 10^{-8}$ sec.

The properly delayed output of the anticoincidence circuit furnishes a signal for a triple-coincidence unit which gates a UCRL ten-channel pulse-height analyzer. The second signal to the triple coincidence circuit comes from the Bevatron gating circuit, which allows the analyzer to count only while the beam is actually bombarding a target. This reduces the effect of machine and cosmic-ray background. The third signal into the triple-coincidence unit is the output of the linear amplifier. This is the signal that is pulse-height analyzed. The differential pulse-height analyzer has a double-pulse resolving time of approximately 7 μsec.
IV. SPECTROMETER CALIBRATION

A. Experimental Procedure

Because of the requirement that the photon telescope must be triggered when analyzing photons, the showers originated by both photons and electrons incident from the same direction begin in the lead converter if they are to be recorded. The fact that the showers originated by both photons and electrons that are studied begin in the lead converter allows the response of the spectrometer to photons to be measured by studying its response to electrons. Photons produced in the primary target of the Bevatron interact in a small lead disc. The resulting electrons are magnetically analyzed, then enter the spectrometer parallel to its axis and trigger the 4-inch-diameter coincidence counter. The 6-inch-diameter anticounter is not used in this calibration. For obtaining electrons of energy less than 400 Mev, photons from the bremsstrahlung beam of the synchrotron are used in place of the Bevatron photons.

B. Response of the Counter

The requirement that the 4-in. scintillator be triggered in response to either electrons or photons insures that the shower to be analyzed begins essentially at the same place. Decreasing the diameters of the coincidence scintillator and lead converter did not noticeably increase the resolution of the spectrometer but merely decreased the sensitive area of the telescope. By using a standard light source we equalized the gains of all four spectrometer photomultipliers by varying the voltage on each one individually, thus markedly enhancing the resolution of the counter.

Electrons of a known energy produce a distribution of pulse heights in the spectrometer when they enter parallel to its axis and trigger the 4-inch-diameter coincidence counter. A calibration spectrum for 1-Bev electrons is shown in Fig. 4. Spectra with other energies are similar. A Gaussian curve was fitted to the experimental points, and the pulse height corresponding to the peak of the distribution was taken to be the
characteristic response for this energy. The width of the Gaussian distribution at half maximum is approximately 50% of the pulse height at the peak. This value is essentially constant above 200 Mev but increases below that. If we adopt the criterion that two such distributions of equal intensity can just be resolved if their peak positions differ by 60% of the full width at half maximum, the resolution of the spectrometer is seen to be 30%. This has been verified experimentally.

The calibration curve in Fig. 5 shows peak pulse-heights obtained in this manner plotted vs the corresponding electron energy. The energy spread of the calibration electrons was 10% in the energy range below 400 Mev and 20% above 400 Mev. Estimates of the uncertainties of the positions of the peaks of the pulse-height distributions are shown. In this fashion the spectrometer has been calibrated up to 1.5 Bev. This calibration has been compared with the pulse distribution produced by cosmic-ray \( \mu \) mesons passing through the spectrometer both axially and normal to the axis. The peak of the distribution for muons normal to the axis has the same value as the peak of the distribution for \( 180 \pm 20 \) Mev calibration electrons. Because this muon distribution may be used for standardization of the spectrometer at any time, stability can be monitored during extended experiments.

The width of the calibration peaks is attributed to the statistical nature of the cascade shower, the fluctuation in the fraction of the shower that escapes from the glass, and the statistical fluctuations in the number of photoelectrons liberated from the photocathodes of the tubes by the Cerenkov photons. The fact that the calibration electrons were not actually monoenergetic but had an energy spread of about 10% or 20% also contributes to this width. Estimates for the effect of this energy spread indicate that the resolution of the counter as defined above is about 20% for truly monoenergetic electrons or photons. This, however, has not been verified experimentally.

When operated without the counter telescope in front, the Cerenkov counter has an efficiency of almost 100% for \( \gamma \)-ray detection; when it is used as a spectrometer the efficiency is limited only by that of the photon telescope which consists of a lead converter and two scintillation counters.
C. Evaluation of Experimental Calibration

The energy response of the counter can be somewhat anticipated by the use of curves such as are contained in Kantz and Hofstadter and Wilson. Applying their curves to this counter, one obtains containment factors for several energies. These are shown in Fig. 6.

The results from Wilson (curve A), who uses the correct cross sections but assumes an infinitely wide medium in a Monte Carlo calculation, are higher than those from Hofstadter (curve B). To obtain the latter curve it is necessary to assume that Approximation B of shower theory holds. In this approximation, all elements are the same if lengths are expressed in radiation lengths and energies in multiples of the critical energies. From the experimental curves obtained by Hofstadter, one can determine energy-containment factors for counters of particular geometries. Applying these to the geometry of this spectrometer, we obtain containment factors for several elements at one energy. Using Approximation B to convert these factors for the several elements at one energy to several energies in the glass, we obtain curve B in Fig. 6. Curve A predicts too large a containment factor because of the assumption of infinite absorber width. Curve B predicts too rapid a decrease with energy due to the reduction in validity of Approximation B, particularly in heavy elements at lower energies, where the measurements were made from which curve B was obtained.

The near linearity of the energy-containment-factor curves suggests that for a limited range above 100 Mev the containment factor $C(E) \approx Ec/E = a(1 - bE)$ where $Ec$ is the energy contained in the spectrometer, $E$ is the energy of the original photon, and $a$ and $b$ are constants. The constant $a$ determines the zero-energy value; the shape of the curve is given by the parameter $b$. Evaluating this constant, $b$, from the curves, we obtain for curves A and B respectively $0.8 \times 10^{-4}$ Mev$^{-1}$, and $3.7 \times 10^{-4}$ Mev$^{-1}$. The value of $b$ obtained from the solid curve of the above form fitted to the spectrometer calibration (Fig. 5) is $1.6 \times 10^{-4}$ Mev$^{-1}$. This experimental value is intermediate between the two predicted values obtained from curves A and B.
V. DETERMINATION OF ELECTRON-PAIR CROSS SECTIONS

A. Discussion of the Problem

For gamma rays of energy greater than a few Mev the largest contribution to the total cross section in all elements except hydrogen is that due to pair production in the nuclear Coulomb field. The theory for this process, including the screening of the nuclear charge by the orbital electrons, was given by Bethe and Heitler in 1934 using Dirac's concept of negative-energy states and the first Born approximation. For high-Z elements the Born-approximation condition \((Z/137 < 1)\) is not satisfied. This was first seen experimentally by Adams at 20 Mev in lead. The discrepancy with theory has been confirmed by several authors, among them Lawson at 88 Mev; DeWire, Ashkin and Beach at 280 Mev; Emigh at 300 Mev; and Anderson, Kenney and McDonald at 319 Mev. These investigators have compared the theoretical pair-production cross sections given by Bethe and Heitler \(\phi_p^Z (B.H.)\) with measured values \(\phi_p^Z\) in the energy range between 19.5 Mev and 300 Mev by writing

\[
\phi_p^Z = \phi_p^Z (B.H.) \left[ 1 - a Z^2 \right]
\]

where \(1.4 \times 10^{-5} < a < 1.55 \times 10^{-5}\).

The differential cross section in the limit of high energies, neglecting screening, has been calculated without recourse to the Born approximation by Maximon and Bethe and has recently been integrated over positron energy. It is shown in the last reference that the correction is equally applicable to cases with complete, incomplete, or no screening. The correction term has a \(Z^2\) dependence just as the experiments above indicate.

Using cosmic-ray photons, Pinkou has determined with relatively large statistical uncertainties this cross section for photons of energy greater than 10 Bev in Ilford G.5 stripped emulsion. His results also tend to confirm the disagreement with the Bethe-Heitler theory.

The paucity of experimental data for energies above a few hundred Mev makes it desirable to measure this effect at higher energies. The
availability of photons of several Bev energy produced in the Bevatron and the characteristics of the photon counter discussed in Section IV suggested the use of this spectrometer for these measurements. The measurements were made for both lead and aluminum in order to determine the dependence of the cross section on the atomic number \( Z \) over a wide range of \( Z \) values. The energy interval chosen for study was \( 2.5 \pm 0.5 \) Bev, which is approximately one order of magnitude higher than the previous experiments done with small uncertainties.

B. Physical Layout

The sketch in Fig. 7 shows the experimental arrangement used for this experiment. The spectrometer is operated in the manner discussed in Section IV. The collimators are arranged so as to allow the photons from the Be target to illuminate an area only 3 in. in diameter at the center of the front face of the photon telescope and spectrometer assembly. Extensive shielding (not shown in detail) was placed outside the cone defined by the photon beam to reduce the effects of the quite intense high-energy neutron flux that is also emitted from the target toward the counter. This shielding amounted to about 10 geometric mean-free-paths of lead and uranium. The sweeping magnet, having a field of about 16 Kgauss for a distance of 5 ft. along the photon beam, effectively clears all charged particles from the photon beam incident upon the absorber.

The photons of several Bev energy incident upon the spectrometer in this experiment are emitted from an internal Bevatron target at an angle of \( 6^\circ \) with respect to the direction of the bombarding proton beam of about 6 Bev, and emerge through a thin aluminum window in the side of the machine. They are most probably Doppler-shifted secondary photons resulting from the decay of energetic neutral pions produced in the target by the incident protons.

A device constructed so that a lead shutter one inch in thickness may be inserted in the photon beam at any time is located just before the first collimator. The absorbers for which the attenuation measurements are made are located after the sweeping magnet as shown in Fig. 7.
C. Experimental Method

At the energies under consideration here (several Bev) the only interactions contributing an appreciable amount to the total interaction cross section of photons are the processes of electron-pair and electron-triplet production. All other processes such as the electron Compton effect and photo-meson production are sufficiently small so as to be negligible. In this experiment the cross section for electron-pair production was determined by measuring the total attenuation and then correcting for the triplet production which is discussed theoretically by Borsellino. This correction consists of multiplying the experimentally measured total cross section by the ratio $Z/(Z+1)$.

Theoretically, the pair-production cross section is expected to be very nearly constant in this energy region and a wide energy channel was therefore used. Although the spectrometer has not been well calibrated above 1.5 Bev, the near linearity of its energy response (see Fig. 5) and this near constancy of the cross section allow a 1-Bev interval to be used with very small error. Also, because of this near constancy, the measurements in this experiment were not highly sensitive to the efficiency of the photon telescope of the spectrometer. It was not necessary to know this efficiency with extreme accuracy; it was only necessary that the efficiency remain fixed throughout the experiment.

The data taken consisted essentially of four counting rates normalized to the same Bevatron proton-beam level by a beam-monitoring counting system. These rates were the four permutations of absorber and lead shutter in and out of the beam of photons and neutrons incident upon the spectrometer. The lead shutter removes essentially all of the photons from the beam without appreciably attenuating the neutron flux, and allows a subtraction procedure to be followed which corrects for the background produced by these neutrons. The four normalized counting rates observed are: (0,0) no shutter or absorber, (S,0) shutter and no absorber, (0,A) no shutter but with absorber and (S,A) both shutter and absorber. The apparent photon counting rate without absorber (condition $\alpha$) and the apparent photon counting rate with absorber (condition $\beta$) are given in terms of the number of photons $N$ incident upon the
counting system in the defined solid angle per unit of time, the number of counts per unit time produced by neutrons $N_n^p$, the fraction $T$ of the photons transmitted through the absorber, the efficiency of the photon telescope $\epsilon$, and the inefficiency $I$ of the anticoincidence counter by the two expressions

$$a = (0,0) - (S,0) = (N_n + \epsilon N_\gamma) - N_n = \epsilon N_\gamma$$

$$\beta = (0,A) - (S,A) = \left[ N_n + \epsilon TN_\gamma + I(1 - T)N_\gamma \right] - N_n$$

$$= \left[ \epsilon T + I(1 - T) \right] N_\gamma$$

The quantity $I(1 - T)N_\gamma$ is the counting rate from electrons that result from photons interacting in the absorber and that pass through the anticoincidence counter without registering; such events are indistinguishable from events produced by photons that are merely transmitted by the absorber. The probability is less than 1% that both of the secondary electrons produced by the interaction of a photon in the absorber do not enter the anticoincidence scintillator because of multiple scattering in the absorber.

The apparent transmission is then given by $\beta/a$. From this we obtain for the true transmission

$$T = \frac{\beta}{\epsilon a} - \frac{I}{\epsilon}$$

$$1 - \frac{I}{\epsilon}$$

The instrumental correction factor $I/\epsilon$ is given by the fraction $(0.03 \pm 0.03)/0.566$. This is equal to $0.053 \pm 0.053$ where $\epsilon$ is the calculated conversion efficiency for 0.25 in. of lead for photons of 2.5 Bev energy, and $I$ is estimated from considerations of instrumental dead times and instantaneous counting rates.
D. Experimental Results

The cross-section values in this experiment are the means of several determinations. The 1-Bev energy width was divided into three channels and the apparent transmissions ($\beta/\alpha$) were measured for each one separately. These agreed within the statistical uncertainties and so were then combined. The values of $\beta/\alpha$ were thus measured for 0.349 in. of commercial grade Pb, 4.0 in. of pure (2S) Al, and 7.5 in. of Al to be $0.394 \pm 0.035$, $0.382 \pm 0.031$, and $0.391 \pm 0.030$, respectively. The errors are statistical and all counting rates have been corrected for dead-time losses.

These measured values are subject to a small positive correction to account for those photons incident upon the absorber with energies greater than the upper limit (3 Bev) of the energy width used in this experiment. These could undergo cascade-shower processes in the absorber or lead shutter, and thus degrade their energies down into the channel of interest. These cascade photons were indistinguishable from photons that were simply transmitted by the absorbers in the energy channel studied. This calculated correction was less than one percent and was thus neglected in view of the other uncertainties indicated above.

The cross sections calculated from the values of $\beta/\alpha$ above indicate that the electron-pair cross section for photons of energy $2.5 \pm 0.5$ Bev is $34.6 \pm 6.6$ barns in lead and $1.22 \pm 0.17$ barns in aluminum. (One barn = $10^{-24}$ cm$^2$.) The expressed experimental uncertainties include both statistical errors and estimated operational and instrumental systematic uncertainties. The value stated for aluminum is the average of the two values calculated for the two thicknesses of Al absorber.

The theoretical values at 2.5 Bev obtained from the Bethe-Heitler theory (including screening)$^1$ corrected by the $Z^2$ correction factor discussed above are 39.4 barns in lead and 1.30 barns in aluminum. The values experimentally determined here agree with the theoretical ones within the expressed experimental uncertainties. The solid curves in Fig. 8 show the corrected theoretical cross sections for the production of electron pairs in lead and aluminum in units $\bar{\sigma} = r_0^2 Z^2/137$ as a
function of photon energy ($r_0$ is the classical electron radius); the broken curve shows the theoretical value in the absence of screening. The experimental points at 2.5 Bev are indicated in the same units. These points clearly show the effect that the screening of the nuclear charge by the orbital electrons has on the cross section. They also definitely show the $Z$ dependence of the cross section as discussed above in agreement with the experiments at lower energies.

Figure 9 shows the calculated total-attenuation cross section in units $\text{cm}^2/\text{g}$ in four elements as a function of photon energy. These curves have not been corrected for the departure from the Born approximation expected in high-$Z$ elements. The experimental points from this and other $^9, 10, 11, 19$ experiments show this departure, however.
VI. TECHNIQUE FOR STUDYING ANTIPROTON ABSORPTION IN MATTER

A. General Discussion

One of the striking features of Dirac's theory of the electron was the appearance of solutions to his equations that implied the existence of an antiparticle which was later identified as the positron. The extension of the Dirac theory to the proton requires the existence of an antiproton, a particle that has the same relationship to the proton as the positron has to the electron. It may be questioned, however, whether a proton is a Dirac particle in the same sense as the electron. For example, the anomalous magnetic moment of the proton indicates that the proton is not completely described by the simple Dirac equation.

The experimental demonstration of the existence of antiprotons and a study of their properties was thus one of the objectives considered in the planning of the Bevatron. The minimum laboratory kinetic energy sufficient for the formation of an antiproton in a nucleon-nucleon collision is $6m_p c^2$ (5.6 Bev). If the target nucleon is in a nucleus, the threshold for production is lowered because of the momentum distribution of the nucleons in the nucleus. Assuming a maximum Fermi energy of 25 Mev, one may calculate that the threshold for formation of a proton-antiproton pair is approximately 4.3 Bev. Another process that has been considered by Feldman has an even lower threshold.

Chamberlain, Segré, Wiegand, and Ypsilantis have recently observed negatively charged particles of mass $1840 \pm 90 m_e$ emerging from a target of the Bevatron. These particles were identified as antiprotons. In their experiment, protons of 6.2-Bev energy bombarded a Cu target, and secondary particles of unit negative charge emitted near $0^\circ$ with respect to the bombarding protons were selected in a momentum orbit of $1.19 \pm 0.02$ Bev/c by a system of deflecting and focusing magnets. Measurements of flight time over a 40-ft portion of the path in conjunction with certain response requirements in special Cerenkov counters allowed the identification of mass within the above limits.

A simultaneous experiment, discussed here, was performed to study the interaction of these particles in matter. This experiment
had three objectives. The first purpose was to show that the behavior of these particles in matter was different from the behavior of pions. The fact that each of these unique particles was accompanied by about $4.4 \times 10^4$ negative pions within the defined momentum channel emphasizes the importance of background rejection. Because it is required of an antiproton that it be capable of annihilation in combination with a nucleon, the second goal was to obtain a measure of the total energy release in such an annihilation. The third aim of this experiment was to determine cross sections for interaction of these particles with matter.

For these purposes it was necessary to use a device that would have sufficient stopping power to stop a large fraction of these particles, have sufficient size so as to contain in its volume the products of such an annihilation, and yet allow one to analyze the event. The Cerenkov spectrometer in a modified form satisfied all of these requirements and was used in this experiment in two different physical arrangements.

B. Counter Modifications and Physical Arrangements

The counter was used in the two physical arrangements labeled A and B shown in Fig. 10 and Fig. 11 respectively.

1. Arrangement A

In this arrangement the arrow represents the momentum-selected beam of negative particles that emerges from the apparatus of Reference 21 and is directed through an absorber, a 6-in. by 6-in. scintillation counter S, and into the glass C. The glass cylinder was so oriented that the beam in the glass moved away from the photomultiplier face and toward a black end face which formed a light sink.

The purpose of the black end, and of this orientation, was to minimize the Cerenkov light signal from the 1.2-Bev/c negative pions that traverse the well-defined momentum orbit in great abundance relative to the particles of protonic mass. These latter particles arrive with about 500 Mev of kinetic energy and should project their secondary (or annihilation) products with rather uniform probability
in any direction, whereas the pions of the beam yield their Cerenkov light primarily into the light sink.

2. Arrangement B

In this arrangement the relationship of the counters to the beam of particles emerging from the mass identifying system is the same as for Arrangement A. Three changes have been made from the apparatus employed in Arrangement A. First, the black, light-absorbing face on the downstream face of the counter was replaced by reflecting aluminum foil. Second, another Cerenkov counter, identical with the first, was mounted as shown in Fig. 11 to increase the detection volume. Third, the 6-in.-diameter scintillation counter which preceded the Cerenkov counter in A has been replaced by a 13-in.-diameter counter so as to completely cover the entrance face of the glass.

C. Experimental Procedure

For both Arrangements A and B the pulses from the Cerenkov counters and from the scintillation counter were presented upon a photographically recorded oscilloscope trace. The sweep of the oscilloscope was triggered by a signal from the system of Ref. 21 so that a trace was generated whenever their system was triggered, and a system of accounting was established that allowed the subsequent unique identification of our particular traces with those considered by Chamberlain et al. 21 to belong to particles of protonic mass.

The observations performed involved counting with absorber and without absorber before the glass. In A the absorber consisted of a 2.5 in. thickness of copper sufficient to cause the range end of these proton-mass particles of 1.2-Bev/c momentum to fall somewhat short of the exit (black) face of the glass. When the absorber was removed, these particles, if they did not react in the glass, could emerge from the exit face with about 250 Mev of kinetic energy remaining. In B the absorber was 3 in. of copper. The purpose of comparing these absorber conditions was to ascertain the fraction of the proton-mass particles that interacted in the copper absorbers.
D. Calibration of the System

Nucleon annihilation within the glass can give rise to electronic showers generated from $\pi^0$-decay photons or from direct photon products of the annihilation, and the Cerenkov radiation from the showers is measured in terms of the pulse height of the photomultiplier response. Consequently, the observed pulses are not expected to be representative of the total energy release, but rather of that portion of the energy converted into electronic showers, plus a contribution from relativistic charged pions that may be among the products.

The energy calibration was made in terms of the light pulse produced by cosmic-ray muons passing through the counter. As discussed in Section IV:B, cosmic-ray $\mu$ mesons passing through the counter normal to the axis produce a pulse-height spectrum which corresponds to that produced by the absorption of a photon of about $180 \pm 20$ Mev incident along the axis. The collision-energy loss of a muon at minimum ionization in passing through 12 in. of glass is calculated to be 174 Mev (see Section III). The close agreement of these two values is not surprising as the energy absorption of a shower actually proceeds through the collision-energy loss of the minimum-ionizing electrons that compose the charged component of such a shower.

As the collision loss for a singly charged minimum-ionizing particle passing through 14 in. of the glass is 203 Mev, the pulse size resulting from a 1.2-Bev/c pion passing axially through the System A toward the photomultipliers is associated with 200-Mev energy that is lost in the counter. The trajectories of the pions were defined by a scintillation-counter telescope. When the counter direction is reversed so that the pions approach the black face, the pulse is one-fourth as large and corresponds to about 50 Mev. The spatial distribution of Cerenkov light emitted by a shower is thought to be more similar to that produced by a meson traversing the counter normal to its axis than one moving axially. The assignment of a 200-Mev energy loss by a shower to a pulse of the same size as that produced by a pion moving axially toward the phototubes makes the visible-energy values that are assigned to the pulses in Arrangement A the lower limits of total energy contained. This is because the
light from the axially moving pion is collected with a greater efficiency than that from a shower. The major importance of the spectra in A was to show that these special events were not produced by pions; the spectrum in B is considered to be more indicative of the actual visible energy released in an annihilation.

In B, where the condition of the counter is more like that in Section IV, a calibration was also established by passing the negative-pion beam through the counters. Rotation of the equipment through 180° permitted calibration of both counters and measurement of the anisotropy of each with regard to Cerenkov light collection from particles moving parallel to the axis. The average of the Cerenkov light pulses obtained from the two directions of passage was associated with 200 Mev of energy delivered by a shower or by relativistic particles into the glass, as this simulated the spatial diffusion of the light from a shower. Each of the two counters in B was adjusted to have the same energy response.

The behavior in the glass of ordinary protons of the same kinetic energies as the selected particles was experimentally determined by reversing the magnetic fields of the particle-selecting system. The pulses resulting from ordinary protons of about 500-Mev kinetic energy thus passed through the glass were not detectable under the electronic-gain settings employed.

The energy values assigned to the observed pulse heights mean that the amount of Cerenkov light collected was appropriate to the absorption either of an electronic shower containing the energy stated or to an energy loss at minimum ionization of the value stated for a Cerenkov-light emitting particle. As will be discussed in detail later, an appreciable amount of the energy released in an annihilation will escape from the glass. In addition, a considerable fraction of the energy released may be carried away by uncharged or slowly moving particles that produce no Cerenkov light. Because of these two factors, the assignments of energy to events in the glass indicate only energy actually seen as discussed above and represent only lower limits of the energies actually released in the annihilation.
### Table I

Classification of 92 selected particles in Arrangement A.

<table>
<thead>
<tr>
<th>Scintil. pulse</th>
<th>Absorber in Glass pulse</th>
<th>Number</th>
<th>Scintil. pulse</th>
<th>Absorber out Glass pulse</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>YES</td>
<td>= 0</td>
<td>11</td>
<td>YES</td>
<td>= 0</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>&gt; 0</td>
<td>16</td>
<td>&gt; 0</td>
<td></td>
<td>23</td>
</tr>
<tr>
<td>NO</td>
<td>= 0</td>
<td>21</td>
<td>NO</td>
<td>= 0</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>&gt; 0</td>
<td>5</td>
<td>&gt; 0</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>53</td>
<td></td>
<td></td>
<td>39</td>
</tr>
</tbody>
</table>

### Table II

Tabulation of observations on particles identified by the mass selector as antiprotons in Arrangement B. S refers to the scintillation counter preceding the glass, and S > 0 means that the particle (or a charged secondary) registered itself in the scintillation counter. "Pulse ~ 0" means that the particle did not register in the glass, implying that it produced less than about 30 Mev equivalent of electronic shower or of path length at minimum ionization.

<table>
<thead>
<tr>
<th>No. absorber</th>
<th>3-in. copper absorber</th>
</tr>
</thead>
<tbody>
<tr>
<td>S &gt; 0</td>
<td>S = 0</td>
</tr>
<tr>
<td>Pulse ~ 0</td>
<td>15 15</td>
</tr>
<tr>
<td>Pulse &gt; 0</td>
<td>45 0</td>
</tr>
<tr>
<td>Total particles</td>
<td>75 98</td>
</tr>
</tbody>
</table>
VII. EXPERIMENTAL RESULTS OF ANTIPROTON STUDY

A. Interpretation of Types of Pulses

In both Arrangements A and B there are several possible classifications of the pulses in the two counters. In the following discussion, events associated with a scintillation (S) pulse are termed YES pulses while those for which the scintillation pulse is absent are termed NO events. These pulses are further defined into those which produced Cerenkov (C) pulses in the glass distinctly above the background amplifier noise level and those which did not produce an observable pulse in the glass. Tables I and II summarize the pulse data of Arrangements A and B. The interpretation of NO pulses with glass pulse $= 0$ is that scattering, either in preceding counters of the mass-analysis system or in the absorber, prevented the particles from registering in either S or C; and if the selected particle interacted while passing through the absorber, none of the secondary particles registered. NO pulses with glass pulse $> 0$ in Arrangement A imply that a selected particle, or a relativistic secondary capable of yielding observable Cerenkov light in the glass, missed S but entered C peripherally or by in-scattering from tube-base structures between S and C. It is also conceivable that neutral secondary particles could emerge from the absorber and interact in the glass without registering in S. In Arrangement B, NO pulses with glass pulse $> 0$ did not occur.

YES pulses with glass pulse $= 0$ can arise from scattered or secondary particles that missed the glass after registering in S, or that are not capable of generating sufficient Cerenkov light in the glass to be observed. It is important to note that the proton-mass particles are in this last category if they do not interact in the glass. Finally, the YES pulses with glass pulse $> 0$ imply selected particles that registered in S and interacted in the glass with considerable yield of Cerenkov light. Ionizing secondary particles from the absorber can also fall in this category if they have sufficient energy; but the number of these is small because the cross section of the glass at its center subtends at the absorber only about $1/20$ steradian in both arrangements. A water Cerenkov counter (not shown in Fig. 11) placed after the absorber in Arrangement B shields both S and C. This counter has its detection threshold at $\beta = 0.75$, which is higher than the $\beta$ of any antiproton traversing it whenever the absorber
is in place. For charged pions this is a kinetic energy threshold of 71 Mev as compared to 36 Mev in the lead-glass counter. The water counter was equivalent to about 22 gm/cm² of Cu. The energy lost by collision by pions of kinetic energy less than about 100 Mev in passing through the water counter is greater than the difference in thresholds of the two counters. Consequently, any pion sufficiently energetic to produce an observable pulse in the lead-glass counter also produces an observable pulse in the guard counter. This arrangement thus eliminates the incorrect recording of these spurious secondary products.

B. Pulse-Height Spectra Observed

The pulse-height spectrum for Arrangement A of selected-particle events of the YES (> 0) type when the absorber is present is plotted in Fig. 12. The number of cases of glass pulse = 0 is also indicated but is not plotted as part of the histogram spectrum. The smooth curve represents the spectrum of pulses obtained from the total beam, preponderantly negative pions at about 1 Bev, normalized to the histogram area. This curve was obtained from a few thousand beam particles selected by the scintillation-counter telescope mentioned in Section VI: D, and the arrow indicates the largest pulse seen in this manner. The dots along the base line indicate the pulse-height values of the 27 YES events, of which 16 are > 0. The X's also plotted show eight events recorded before the S counter had been installed, and these have been included in the histogram.

Figure 13 presents the same kind of display for the data of Arrangement A secured with absorber removed. Here, of the 26 YES events, 23 are > 0 in pulse height.

Figure 14 displays the spectrum of the total observed-energy release, as summed from both counters in Arrangement B, for these unique particles that interacted in the glass. Spectra taken with and without the absorber ahead of the counter are closely similar and the data are combined in Fig. 14. The largest energy release observed here is about 1100 Mev and to such a lower limit on the total energy release we attach a 30% uncertainty, because of calibration problems relating to unknown locations
of interaction events and unknown directions of the trajectories of the secondary particles. The most probable pulse height is about 450 Mev. The smooth solid curve is the spectrum in Counter 1 for the particles in the total beam without the absorber; the dashed curve is the same for the absorber in place. Neither of the smooth curves is normalized. The smooth curve spectra are plotted for pulses from Counter 1 only as Counter 1 contained practically all the energy from antiproton events that was absorbed; Counter 2 contributed only an occasional, smaller, simultaneous pulse.
C. Discussion of Observed Spectra

1. Arrangement A

The effect of the blackened end is to reduce the energy-detection efficiency of the counter so that the energy spectrum for Arrangement B discussed in the next sub-section has a more meaningful interpretation. In the discussion of the data for Arrangement A shown in Fig. 12 and Fig. 13, the following observations can, however, be made:

a. The negative pions incident at about 1 Bev, which constitute essentially all of the beam, in passing through the glass toward the black face produce a most probable Cerenkov pulse height corresponding to about 50 Mev (smooth-curve peak position) on our shower-energy calibration scale as discussed in Section VI: D. The low tail extending to higher energies is considered to be due to interaction of these beam pions in the glass, resulting in the release of large visible energies probably through the production of neutral pions by charge-exchange interaction. The "ledge" on the high-energy side of the total beam-pulse spectrum in Fig. 13 (without absorber) is not clearly explained; it may involve the simultaneous observation of more than one beam particle, since the S pulses associated with this "ledge" appeared also to be larger than average. It is conceivable, however, that it is due to some other component of the beam that is strongly attenuated when the absorber is in place.

b. In Fig. 12 and Fig. 13 the histogram spectra of the selected, proton-mass particles are distinctly richer in large pulses than are the pion-beam spectra. This provides the answer to the first problem with which this experiment was concerned, which was to show that these selected particles behaved differently from the pion background in their interactions. In Fig. 12, it is apparent that the lower-limit assignments on the selected pulses extend higher than the largest pulses observed from several thousand pions of 1.2 Bev/c entering the glass.

c. It is apparent from Table I that a large fraction of the proton-mass particles interact in flight in the glass. With no absorber in the beam, these particles in the absence of interaction would have passed through the glass without registering a Cerenkov pulse and emerged
with about 250-Mev kinetic energy remaining. Only 3 out of 26 associated with a YES pulse apparently did thus pass through.

d. The presence of the absorber gives rise to many secondary particles that register in S but not in C. This is evident from the large number of YES events with zero glass pulse in Table I. These particles can be explained as being the reaction products of a nuclear star resulting from antiproton annihilation in the absorber.

2. Arrangement B

This arrangement was primarily concerned with the second objective of the experiment, which was to measure the energy release in an antiproton annihilation. Quantitatively, this inference of energy release from the interaction events involves attention both to the upper limit on observed pulse size and to the average size. On either basis, estimates of expectations from antiproton-annihilation events can be compared with observations. These estimates require recognition of the annihilation modes, the likely nature and multiplicity of secondary products, and the factors affecting the containment of the Cerenkov light-emitting secondary particles within the lead glass.

It is assumed that the fundamental annihilation process for an antiproton in combination with either a proton or a neutron proceeds through the production of pions with conservation of isotopic spin. It follows that, on the average, about 1/3 of the pions are neutral and thus over a large number of events 1/3 of the energy should be released as photons if the annihilations took place with free nucleons. Also, in view of phase-space weighting, selection rules, and the statistical theory of such high-energy events, the multiplicity of pions produced in the free-nucleon case would most probably be about three, although with decreasing probability it may extend to more. In the situation discussed here, however, the annihilation processes are occurring with nucleons bound in nuclei, and the pions produced virtually may interact strongly with the adjacent nucleons, causing frequent production of nuclear stars. This is expected to relax the selection rules for annihilation.
3. Efficiency of the Glass Counters

Because the contribution of the secondary glass counter was small, the following calculations of counter efficiency relate only to the first counter in Arrangement B. The detection of neutral pions, charged pions, and nucleon secondary particles is treated separately.

a. Neutral pions

The decay modes that yield neutral pions and thus give rise to electronic showers in the glass can produce the largest Cerenkov light pulses. The fraction of a shower that will be contained can be estimated from shower theory and experimental data. The experimental curves given for several elements by Kantz and Hofstadter, and data from Monte Carlo calculations by Wilson and Yamagata and Yoshimine, for a lead-glass medium, have provided useful information. Containment factors were averaged over the volume of the first counter for all directions of emission of shower particles initiated by photons of a few hundred Mev energy. The average containment factor obtained in this way was 50% to 60%. Because the neutral pions are expected to possess considerable kinetic energy, the decay photons will have energies Doppler-shifted into the hundreds-of-Mev region. This containment factor is believed to be typical of the efficiency for observing annihilation energy delivered to the glass in the form of neutral pions.

b. Charged pions

The threshold for charged-pion detection is 36 Mev. By averaging over the directions of trajectories initiating within the volume of the glass of the one counter, it is found that the average observable energy rises to 100 Mev as the pion kinetic energy increases to about 250 Mev, and remains nearly constant at this value for higher kinetic energies. The observed energies will thus depend upon the multiplicity and energy division among the pions. The average observed energy response for both charged and neutral pions is shown in Fig. 15 as a function of pion energy.
c. Nucleons

The efficiency for observing energy released in this form is essentially zero. The fact that considerable energy may be released in star fragments is, therefore, unfavorable toward the present detection system.

4. Expected Pulse Spectrum

Under the assumption of annihilation with the typical release of about 2 Bev (because some kinetic energy of the antiproton is typically available), we may estimate the average pulse height to be expected on the basis of this energy calibration.

In events where no nuclear star is formed, we expect that, on the average, 1/3 of the energy will be carried by neutral pions which will induce showers 50% to 60% contained in the glass. The charged pions are expected to contribute an average of 100 Mev each in pulse size; thus, for a 3-pion event in which one pion is neutral, an average pulse size would be about 550 Mev.

If all the pions were charged, an average pulse of 300 Mev would be expected for a 3-pion event and about 400 Mev for a 5-pion event.

The more realistic assumption that star formation is likely will of course lower both of these averages. Consequently, it is to be expected that the most probable pulse size observed will be in the vicinity of 400 to 500 Mev. This is in conformity with the data we obtained on the basis of our calibration.

The largest pulses must be produced by favorable multiplicities of neutral pions. However, even if all the annihilation energy should be carried away by a few neutral pions that develop showers with random direction, 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 other proton-mass particles of negative charge—is indicated, as a particle other than an antiproton can 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 of the energy of such a hypothesized particle were always delivered into photons or neutral pions could this result be obtained. This then affords the answer to the second question with which this experiment is concerned.
D. Antiproton-Interaction Cross Sections

1. Attenuation in Copper

From comparisons of the data with and without the absorber, it is possible to compute the attenuation in copper for the proton-mass particles for a geometry in which the detector subtends a solid angle of 0.05 steradian. Because of the divergence of the beam emerging from the mass-selecting system and because of scattering and absorption in counters and accessory equipment ahead of the glass, not all the particles identified by mass selection as antiprotons enter the Cerenkov counter even when no absorber is in position. Although some particles miss the counter, the transmission of the copper absorber may be calculated from the fraction of the selected antiprotons counted in the glass when the absorber is present compared to the count without the absorber.

In each case in Arrangement A, the number of incident selected particles is the sum of the YES and NO events. When the absorber is in place, we consider the YES \((>0)\) events to represent the number of these particles surviving passage through the 2.5 in. of copper. Only YES \((>0)\) pulses are accepted because the residual range due to collision-energy loss lies in the counter when the absorber is in place, and, by our definition, an antiproton interacting in the counter must produce an observable pulse. When the absorber is removed, all the YES events are accepted because a zero glass pulse is now admissible as a pass-through event. We obtain the transmission through the copper by evaluating the ratio:

\[
\frac{[\text{YES} (>0)]/([\text{YES} + \text{NO}])\{\text{with absorber}\}}{[\text{YES}/([\text{YES} + \text{NO}])\{\text{without absorber}\}}.
\]

From the data of Table I, this ratio is \(16/53 \div 26/39\) = 0.45. This ratio leads to an attenuation cross section 1.9 ± 0.9 times the geometric value for copper, where the latter is computed from a radius formula \(R = 1.25 A^{1/3} \times 10^{-13}\) cm. The expressed uncertainty is statistical only. Because of the large uncertainty, no correction is made here for the multiple-Coulomb scattering in the copper absorber.
The relevant data in Arrangement B appear in Table II and are interpreted as follows: When the copper absorber was absent, a total of 75 particles identified as antiprotons passed through the mass selector. Because of the divergence with which these antiprotons emerged, only the fraction 45/75 was collected and counted by the glass. While the copper was in position, the glass counter registered 25 out of 98 particles passing through the mass selector, but calculation of the multiple-Coulomb scattering in the copper leads to a 12% upward correction of this count to 28 so that the fraction of these antiprotons detected was 28/98. The transmission of the copper is then obtained from the ratio of the last fraction to the first, namely, 0.48 ± 0.12. This attenuation of the beam is due to absorption and to nuclear scattering through angles greater than 7°, and the mean kinetic energy at which these events occur in the copper is about 450 Mev. The attenuation cross section is thus 1.2 ± 0.4 barns, where the uncertainty quoted is one statistical standard deviation. This is approximately 1.5 ± 0.5 times the geometric nuclear cross section.

2. Attenuation in Lead Glass

If, in Arrangement A, for the case of no absorber, we assume that the proper interpretation of the YES events with glass pulse equal to zero (Table I) is passage through the glass without interaction, we may calculate a cross section for interactions in flight producing large energy loss. The transmission through the 14 in. of glass is 3/26 = 0.12. If we consider the composition and density of the glass, a cross section value that is 1.9 ± 0.6 times the geometric cross section is obtained. This value is a lower limit because those axially collimated antiprotons producing "zero" pulses in the counter are assumed to have passed through without interaction, whereas they could have failed to survive passage through accessory material ahead of the glass, or they might have interacted in the glass but failed to deliver products yielding enough Cerenkov light therein.

It was stated above that although Fig. 14 displays the spectrum of the combined pulses registered by both Cerenkov counters in Arrangement B, nearly all the contribution is from the first counter.
no absorber is employed, protons or antiprotons of initial momentum 1.2 Bev/c that survive interaction and scattering penetrate at least 1 in. into the glass of Counter 2; and when the 3-in. copper absorber is in place, surviving protons penetrate about two-thirds the thickness of Counter 1. In Fig. 16 we summarize the observed pulses in terms of the energy division between the two counters. It is seen that only about 10% of the interactions were counted at all in Counter 2, whether or not absorber was used. Moreover, in no case was the pulse from Counter 2 greater than that from Counter 1.

These results imply that all interactions observed occurred in the first piece of glass, even with absorber absent, and moreover that the locations of the interactions were well before the boundary between counters, as events near the boundary would in some cases give the larger energy release in Counter 2. The fact that only about 10% of the observed interactions registered at all in the second counter is consistent, for example, with the 10% solid angle subtended by Counter 2 at the center of Counter 1, all interactions being assumed to occur near the central region of the first counter and to produce, on the average, one secondary particle with range sufficient to give an observable pulse in the second counter.

If we attempt to estimate the probability of finding no event for which the second counter pulse is larger than the first (with the copper absorber removed), we find that an average absorption cross section of twice geometric would give only about a 10% probability, and an average cross section three times geometric would give about a 40% probability for obtaining no such event. The average kinetic energy of the anti-protons in the glass here was considerably lower than their energy in the absorbers for the attenuation experiments above. This low transmission of the lead glass can be understood, in view of the above results, by assuming the average cross section to be about twice geometric for energies in the 400 to 500 Mev region and to average possibly three or four times geometric for energies between 150 to 400 Mev.

It is to be noted that the attenuation observed within the glass is seen with "poor" geometry, and thus includes very little contribution from scattering.
E. Comparison with Other Experiments

The results of this experiment are consistent with the results of other experiments. The energy release data thus obtained complements the more recent data derived from analysis of antiproton annihilation stars in emulsion.\textsuperscript{29} It should be noted that the type of particle whose energy is seen most efficiently by this device is seen with very low efficiency by the emulsions. The converse is also true.

The summary of available emulsion data in Reference 29 shows that the antiproton-nucleon annihilation proceeds primarily through the production of pions with the occasional production of K particles. The average pion multiplicities observed in Reference 29 for all antiproton stars seen in emulsions are $5.3 \pm 0.4$ pions produced in the primary process. Of these, 1 pion is absorbed in the nucleus and 0.3 is inelastically scattered. A total of 4 K mesons was found in a total of 35 antiproton stars analyzed. The energy distribution inferred among the secondary particles for stars produced by antiprotons both in flight and at rest is indicated in Table III. If the neutral component is assumed to consist of neutral pions, this total energy balance of all particles emitted in the annihilation implies a ratio of charged to neutral pions consistent with charge independence. This reference also concludes, conversely, that if the annihilation events proceed in accordance with charge independence that the energy emitted directly into electromagnetic radiation or neutrinos is small.

Using the above pion multiplicities, the energy balance in Table III, and the counter efficiencies discussed in Section VII C, we may calculate the size of the average pulse expected to be observed in our experiment. We assume that the neutral component consists solely of neutral pions and that the K mesons, because of their small average energy and heavy mass, behave in the Cerenkov counter similarly to the charged nucleon component and thus produce no observable Cerenkov light pulse. We further assume that the 0.3 pion per interaction scattered inelastically loses sufficient energy in the encounter so as to contribute little to the energy attributed to pions. If we then assume charge independence holds
Table III

Energy distribution in average antiproton annihilation star

<table>
<thead>
<tr>
<th>Type of particle</th>
<th>Energy (Mev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged pions</td>
<td>913 ± 120</td>
</tr>
<tr>
<td>Neutral particles</td>
<td>485 ± 170</td>
</tr>
<tr>
<td>K particles</td>
<td>150 ± 120</td>
</tr>
<tr>
<td>Nucleon component</td>
<td>400 ± 30</td>
</tr>
<tr>
<td>Total (average)</td>
<td>1948</td>
</tr>
</tbody>
</table>

for the 4.0 ± 0.4 pions remaining, we have 2.67 charged pions and 1.33 neutral pions per interaction on the average (±10%) to carry off 913 ± 120 Mev and 485 ± 170 Mev, respectively; this leads to an average total energy per pion of about 340 Mev and 360 Mev, respectively. The charged pions then deliver 100 Mev of visible energy each to the Čerenkov counter for a total of 267 ± 27 Mev, and the 50% containment factor for neutral pions indicates that they deliver 242 ± 85 Mev. The protons and inferred neutrons of the nucleon component and the K mesons do not contribute to the pulse. Thus a total pulse of 509 ± 112 Mev on the average is expected to be seen in the Čerenkov counter for this average star. As the average antiproton kinetic energy in our experiment was about 200 Mev higher than for these stars, we raise the energies of all the particles by 10% to correct for this. This raises the visible energy delivered to the glass by neutral pions to 266 ± 94 Mev; increasing the energy of the other particles does not increase the observed pulse height. This then gives an average pulse height to be expected in our experiment (Arrangement B) of 533 ± 121 Mev; the average pulse observed (Fig. 14) was about 450 Mev.

It is of interest to note that the division of the energy of an antiproton-nucleon annihilation that is inferred from these figures to be dissipated in the modes of charged pions, neutral pions, and nucleons (K mesons are classed with nucleons here), respectively, is very similar to the division of energy of a primary cosmic-ray particle that is dissipated in the form
of charged pions, neutral pions, and the nucleonic component. In the
annihilations discussed in Reference 29 the fractions of the total energy
that go to these modes are $0.47 \pm 0.06$, $0.25 \pm 0.09$, and $0.28 \pm 0.08$,
respectively. At a latitude of 50 degrees North, these fractions for the
vertical beam of cosmic rays have the values: $0.42$, $0.27$, and $0.31$,
respectively. No errors are indicated by Puppi for these cosmic ray values. It is interesting to speculate that this similarity of energy
division may imply that these two processes both proceed as if a large
quantity of energy is dumped into a small volume of space and that the
secondary products then emerge in a fashion that is independent of the
manner in which this concentration of energy was created.

The first measurements of the reaction cross sections of antiprotons
in matter (Arrangement A) and the later measurements of Arrangement B
and other experiments$^{29,31,32}$ are also in agreement. With Arran-
gement A, we obtained values (Sec. VII:D) for the annihilation cross
sections of antiprotons of energies in the 400 to 500 Mev range in both
copper and the lead glass of the counter which are about twice the
geometric cross section ($\sigma_0 = 1.25 \times 10^{-13}$ cm). The cross sections ob-
tained in Reference 31 at about the same energies in copper and beryllium
are respectively $1.58 \pm 0.22$ barns and $0.365 \pm 0.059$ barns. These give
values of $2.02 \pm 0.33$ and $2.05 \pm 0.36$ respectively for the measured ratios
of the inelastic interaction cross sections of antiprotons to those of
protons. These values are also about twice the geometric cross section
and are in agreement with our results. Data from Reference 32 have not
been fully evaluated; however, preliminary results are consistent with
those given here.

In Reference 29 the cross section in nuclear emulsion at an average
kinetic energy of 140 Mev was found to be $2.9 \pm 0.9$ times the geometric
cross section ($\sigma_0 = 1.2 \times 10^{-13}$ cm). This value is consistent with our
lead-glass cross-section results where the data were interpreted as
implying that the cross section averaged possibly three or four times
geometric for energies between 150 and 400 Mev.
Sequences of the attributes of the spectrometer discussed above were calculated from theoretical formulae. The formulae are given here for completeness.

The characteristic length used in discussing shower phenomena is known as the radiation length $L_r$. For a single element this is given by

$$L_r^{-1} = \frac{4a r_0^2 N Z(Z+1)}{1 + 0.12 \left(\frac{Z^2}{82}\right)^{1/3}} \ln \left(\frac{183}{Z^{1/3}}\right)$$

where $a = 1/137$, $r_0$ is the classical radius of the electron, and $N$ is the number of atoms of atomic number $Z$ per cm$^3$.

For a medium consisting of several elements the radiation length $L_r$ is given by

$$L_r^{-1} = \sum_i \frac{\rho_i}{\rho_0 L_i}$$

where $\rho_i$ is no. gm. per cm$^3$ of substance $i$, $L_i$ is radiation length (cm) in substance $i$, and $\rho_0$ is density of the medium.

Nearly all of the energy of the electrons is absorbed by collision loss while the electrons are at the minimum of the ionization loss curve. This ionization loss for a compound $dT/dx$ (Mev cm$^2$/gm) is given by

$$\frac{dT}{dx} = \frac{4\pi r_0^2 \mu}{\rho_0 \beta^2} \sum_i N_i Z_i \left[ \ln \left( \frac{2 \mu \beta^2 \gamma^2}{I_i} \right) - \beta^2 \right]$$

where $\mu$ is 0.511 Mev, $\beta$ is velocity of the particle over $c$, $N_i$ is the number of atoms of atomic number $Z_i$ per cm$^3$, $I_i$ is the mean ionization potential of element $Z_i$, and $\gamma^2$ is $(1 - \beta^2)^{-1}$.

The critical energy $\epsilon_0$ is defined as that energy of an electron at which the energy loss by radiation and collision are the same if the asymptotic value for the radiation loss is used. For a compound this leads to the implicit equation

$$\sum_i N_i Z_i \left[ \ln \left( \frac{2 \mu \beta^2 \gamma^2}{I_i} \right) - \beta^2 \right] = \frac{4\pi r_0^2 \mu}{\rho_0 \beta^2}$$
\[ \epsilon_c = 0.153 L_r \sum_i \frac{Z_i \rho_i}{A_i} \left[ 23 + 2 \ln \left( \frac{\epsilon_c}{\mu Z_i} \right) \right] \]

where \( A_i \) is the atomic weight of substance \( i \) and the other symbols are defined above.

From the discussion of Cerenkov radiation in Schiff\textsuperscript{36} the number of quanta \( N(\omega) d\omega \) with angular frequency between \( \omega \) and \( \omega + d\omega \) emitted per cm by a particle of charge \( e \) moving with velocity \( \beta c \) through a dielectric of refractive index \( n \) is

\[ N(\omega) d\omega = \frac{a}{c} \left( 1 - \frac{1}{n^2 \beta^2} \right) d\omega \]

The total energy radiated by the particle per unit angular frequency range per cm \( E(\omega) \) is

\[ E(\omega) = \frac{e^2}{c^2} \left( 1 - \frac{1}{n^2 \beta^2} \right) \omega. \]
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35. R. Sternheimer, AECU Report No. 2982.
Fig. 1. View of the Cerenkov spectrometer tilted up for cosmic ray muon calibration. Note that there are coincidence counters placed above and below the spectrometer which limit its acceptance to relativistic muons.

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Fig. 1. View of the Čerenkov spectrometer tilted up for cosmic ray muon calibration. Note that there are coincidence counters placed above and below the spectrometer which limit its acceptance to relativistic muons.
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. Circuit diagram of the phototube and cathode follower.
Fig. 4. A calibration spectrum of electrons of 1-Bev energy showing the number of counts per channel plotted against the mean channel pulse-height. The experimental histogram has been fitted by a Gaussian normalized to the same area. The Gaussian has a full width at half maximum of 10.4 volts which gives an energy resolution of 25%.
Fig. 5. The calibration curve of the spectrometer showing the characteristic pulse height in volts as a function of the calibrating-electron energies in Bev. The energy spread of the electrons below 0.4 Bev was 10% and above 0.4 Bev 20%. The statistical uncertainties of the peak positions of the pulse-height distribution are indicated. The solid curve is of the form discussed in the text and has a value of $b$ equal to $1.6 \times 10^{-4}$ Mev$^{-1}$. 
Fig. 6. Energy dependence of the containment factor of the spectrometer as calculated by use of the curves in References 7 and 8.
Fig. 7. Sketch (not to scale) of the experimental layout for the measurement of electron-pair production cross sections.
Fig. 8. Electron-pair production cross sections. The solid curves show the corrected theoretical values of this cross section in lead and aluminum as a function of photon energy. The experimental points are shown. \((\phi = a r_0^2 Z^2\text{.})\) The dashed line represents the case for no screening.
Fig. 9. Calculated total attenuation cross sections, $\phi_a$, in four elements as a function of photon energy. Experimental points of this and other experiments are shown.
Fig. 10. Schematic diagram of the glass Cerenkov counter with associated scintillation counter and absorber in Arrangement A.
Fig. 11. Schematic diagram of the lead-glass Cerenkov counters with associated scintillation counter and absorber in Arrangement B.
Fig. 12. Pulse-height distribution for YES (≥ 0) events when absorber is in place in Arrangement A. (The smooth curve is the pulse spectrum for pions.)
Fig. 13. Pulse-height distribution for YES (> 0) events when absorber is removed in Arrangement A.
Fig. 14. Histogram spectrum of Cerenkov pulses in Arrangement B. Pulse-height spectrum for events produced in the glass by particles mass-selected as antiprotons. Data obtained with and without absorber are combined. Smooth solid curve is spectrum in Counter 1 for particles in total beam without absorber (i.e., 1.2-Bev/c negative pions); dashed curve is same with absorber. Neither of the smooth curves is normalized.
Fig. 15. Estimated average efficiencies of one counter in Arrangement B for observing the energies of photons, neutral pions, and charged pions resulting from antiproton annihilations in the counter. The dashed line denotes an efficiency of unity.
Fig. 16. Energy division between counters in Arrangement B. Number of events is plotted vs ratio of energy observed in Counter 2 to that in Counter 1.
Fig. 16. Energy division between counters in Arrangement B. Number of events is plotted vs ratio of energy observed in Counter 2 to that in Counter 1.