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Interactions of Antiprotons in Lead Glass*

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An analysis is presented of the pulse distribution produced by antiprotons of 1.2 Bev/*c* momentum entering a lead-glass Čerenkov counter. The calibration of the counter is described. Estimates of the efficiency of containment of the relativistic secondary particles and electronic showers from annihilation events are discussed and shown to be compatible with the observed pulse-height spectrum. Attenuation effects in a copper absorber preceding the counter, and in the first of two sections of the glass counter, demonstrate interaction and absorption cross sections that are nearly twice geometric and which probably increase as the antiproton kinetic energy decreases below 400 Mev.

I. INTRODUCTION

THE work of Chamberlain, Segrè, Wiegand, and Ypsilantis[1] and their co-workers has demonstrated the production of particles in a target in the Bevatron which were identified by a charge- and mass-selector system as negative particles of protonic mass. The momentum interval selected centered at 1.2 Bev/*c*. Coincident with their identification experiments, a study with a lead-glass Čerenkov counter of the interaction of these particles in matter was pursued by the present authors and has been reported in a preliminary letter.[2] It was shown in that letter that the interaction cross section is greater than geometric, and that the energy release observed from the interactions in the glass is on the average considerably greater than that associated with the π^- mesons of the same momentum passing through the glass.

In subsequent work alterations in the Čerenkov counter were made in order to permit a better estimate of energy release and to extend the study of the properties of the negative protons in their interaction with matter.

II. EXPERIMENTAL ARRANGEMENT

In Fig. 1 is displayed the relation of the counters to the beam of particles emerging from the mass-identifying system of reference 1. Three changes have been made from the apparatus employed in reference 2. First: the black, light-absorbing face described in reference 2 on the downstream face of the counter was replaced by reflecting aluminum foil. (The reason for that light "sink" was explained in reference 2.) Second: another Čerenkov counter, identical with the first, was mounted as shown in Fig. 1 to increase the detection volume. Third: the 6-in.-diameter scintillation counter *S* which preceded the Čerenkov counter in reference 2, has been replaced by a 13-in. diameter counter, so as to cover completely the entrance face of the glass and possibly provide a means of identifying antineutrons conceivably formed by charge-exchange scattering in material ahead of *S*.

Each Čerenkov counter consists of a cylinder of glass 12 in. in diameter and 14 in. long, viewed from one end by four 5-in.-diameter photomultiplier tubes with outputs combined. The composition of the glass, by weight, is 52% PbO, 42% SiO_2, 3% Na_2O, and 3% K_2O: its density is 3.89 g/cm^3; and its refractive index for light of the sodium *D*-line is 1.649. The foregoing composition and density account for a radiation length of 2.77 cm (1.09 in.) and a critical energy of 17.5 Mev. Thus, in terms of the radiation length, each counter is 12.85 units long and 5.5 units in radius.

The outputs of each Čerenkov counter and of the preceding scintillation counter were separately displayed on an oscilloscope whose sweep was triggered by a signal from the mass-selector system indicating the passage of a possible antiproton. The oscilloscope traces were photographed, and subsequent indentification of particular traces could be made for those cases which Chamberlain, Segrè, Wiegand, and Ypsilantis finally designated as antiprotons after examination of their oscilloscope records.

III. CALIBRATION

In a manner similar to that previously described,[2] a calibration was established by passing the negative pion beam at minimum ionization through the counters, the passage through being determined by scintillation counters placed before and behind the glass. Rotation

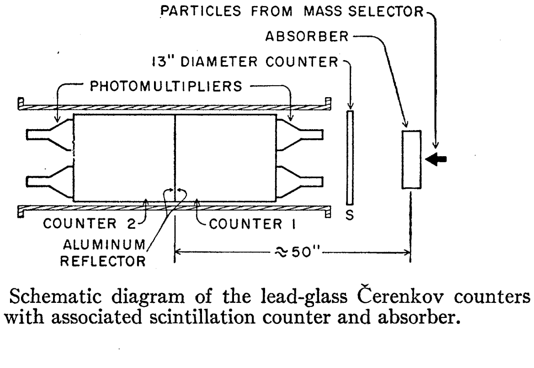

FIG. 1. Schematic diagram of the lead-glass Čerenkov counters with associated scintillation counter and absorber.

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

[1] Chamberlain, Segrè, Wiegand, and Ypsilantis, Phys. Rev. **100**, 947 (1955).

[2] Brabant, Cork, Horwitz, Moyer, Murray, Wallace, and Wenzel, Phys. Rev. **101**, 498 (1956).

of the equipment through 180° permitted calibration of both counters, and measurement of the anisotropy of each, with regard to Čerenkov light collection from particles moving parallel to the axis.

The pions lost about 200 Mev in each counter, essentially all at minimum ionization ($\beta\simeq 1$); the average of the Čerenkov 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.

It was calculated that the average cosmic-ray muon passage through the glass (the counter axis remaining horizontal) delivered about 160 Mev. Its Čerenkov light pulse was compatible with this energy loss on the basis of the pion calibration as described, though there was a minor dependence upon the distance of the muon trajectory from the phototube face in either counter. Time constancy of electronic sensitivity was maintained by daily monitoring with the cosmic-ray muons.

Since the center-of-mass velocity of an annihilation event involving an antiproton and a nucleon in the glass has $\beta \leqslant \sim 0.4$ (the antiprotons enter the glass at 450 Mev, or below, depending upon absorber), the annihilation products do not depart far from spherical symmetry; the fact that most events occur in large nuclei further tends to reduce directional predominance. Consequently the average calibration described above is taken to be appropriate to the annihilation products.

We must recognize that not all the annihilation particles or shower will usually be contained within the glass, and also that a considerable fraction of the energy may be carried away in uncharged or slow particles, which produce no Čerenkov light. Clearly, then, the assignments of energy to events in the glass will represent only *lower limits* to the energies released.

IV. OBSERVED PULSE SPECTRA

Figure 2 displays the spectrum of the total energy release, as summed from both counters, for particles that were identified by the system given in reference 1 as antiprotons and that interacted in the glass. Spectra taken with and without absorber ahead of the counter are closely similar, and the data are combined in Fig. 2. The strong interaction in matter is manifested by the fact that nearly all the energy comes from the first counter, and the interpretation of this is discussed in the following section.

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 owing to 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. A discussion of the pulse-height spectrum to be expected in this system, and its comparison with that which is observed, follows in Sec. VI.

TABLE I. Tabulation of observations on particles identified by the mass selector as antiprotons. 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$\sim$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.

	No absorber		3-in. copper absorber	
	$S>0$	$S=0$	$S>0$	$S=0$
Pulse$\sim$0	15	15	20	53
Pulse$>$0	45	0	25	0
Total particles	75		98	

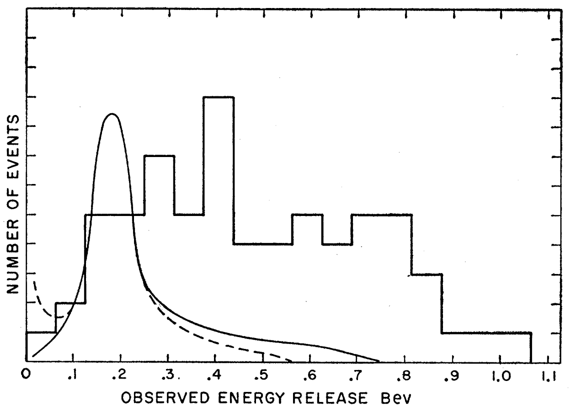

FIG. 2. Histogram spectrum of Čerenkov pulses. Pulse-height spectrum for events produced in the glass by particles mass-selected as antiprotons. Data obtained with and without absorber are combined. Smooth solid curve is spectrum in Counter 1 for particles in total beam without absorber (i.e., 1.2-Bev/c negative pions); dashed curve is same with absorber. Neither of the smooth curves is normalized.

V. COMMENTS ON INTERACTION CROSS SECTIONS

In our earlier communication[2] evidence was presented which demonstrated that the absorption cross section for the selected particles was about 1.5 to 2 times the geometric nuclear cross section. The work reported herein has developed further data in agreement with those results.

A. Attenuation in Copper

Because of 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 Čerenkov counter even when no absorber is in position. Even though some particles miss the counter, the transmission of the 3-in. 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 absorber. The relevant data appear in Table I, and are interpreted as follows: When the

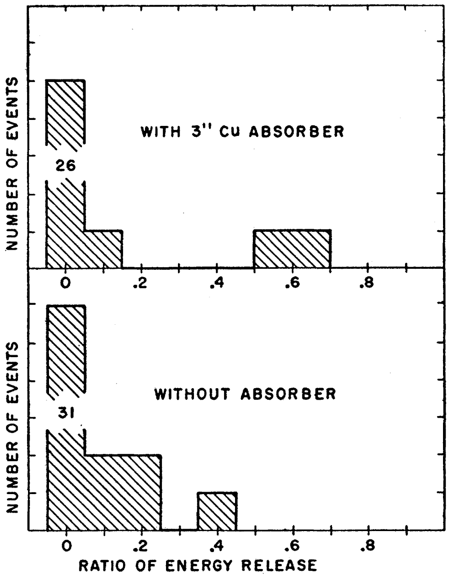

FIG. 3. Energy division between counters. Number of events is plotted *vs* ratio of energy observed in Counter 2 to that in Counter 1.

copper absorber was absent, a total of 75 particles identified as antiprotons passed through the mass selector. Because of the divergence with which they emerged, only the fraction 45/75 was collected and counted by the glass. While the copper was in position, out of 98 passing through the mass selector the glass counter registered the fraction 25/98; but calculation of the multiple Coulomb scattering in the copper leads to a 12% upward correction of this fraction to 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 are occurring in the copper is about 450 Mev. The attenuation cross section is thus 1.2±0.4 barns, where the uncertainty quoted is statistical standard deviation. This is approximately 1.5±0.5 times geometric nuclear cross section when the latter is calculated from a radius of $1.25\times10^{-13}A^{\frac{1}{3}}$ cm. In our earlier communication, based upon independent data but comparable geometry, the copper-attenuation cross section was found to be 1.7±0.7 times geometric.

B. Attenuation in Lead Glass

It was stated above that although Fig. 2 displays the spectrum of the combined pulses registered simultaneously by both Čerenkov counters, nearly all the contribution is from the first counter. When no absorber is employed, protons or antiprotons of initial momentum 1.2 Bev/*c* that survive interaction and scattering penetrate at least one inch 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. 3 we summarize the observed pulses in terms of the energy division between the two counters; and it is seen that only about 10% of the interactions counted at all in Counter 2, whether or not absorber was used. Moreover, in no case is 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, since 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 enough greater than 80 g/cm^2 of lead glass 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 a 10% probability, and an average cross section three times geometric would give a 37% probability for obtaining no such event. The average kinetic energy of the antiprotons in the glass was considerably lower than their energy in the copper for the copper-attenuation experiment; and the low transmission of the lead glass can be understood, in view of the copper-attenuation result, 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 and 400 Mev.[3]

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.

VI. DISCUSSION OF OBSERVED PULSE SPECTRUM

Quantitative inferences of energy release from the interaction events should involve 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 will require recognition of the annihilation modes and the likely nature and multiplicity of secondary products, and of the factors

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[3] The rough value of 1.9±0.6 times geometric cross section obtained in reference 2 for absorption in the lead glass is a lower limit, because those axially collimated antiprotons producing "zero" pulses in the counter were there 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 Čerenkov light therein.

affecting containment of the Čerenkov light-emitting secondary particles within the lead glass.

A. Expected Characteristics of Annihilation Events

It will be assumed that the fundamental annihilation processes for an antiproton in combination with either a proton or a neutron proceed through emission of pions with conservation of isotopic spin.[4] It follows that, on the average, one-third of the pions are neutral, and thus over a large number of events one-third of the energy should be released as photons if the annihilation took place with free nucleons. Also, in view of phase-space weighting,[5] selection rules,[4] and the statistical theory of such high-energy events,[6] the multiplicity of pions produced in the free-nucleon case would be most probably about three, though with decreasing probability it may extend up to several pions.

In the situation discussed here, however, the annihilation processes are occurring with nucleons bound in nuclei, and the pions produced virtually must interact strongly with the adjacent nucleons, causing frequent production of nuclear stars. Also, the proximity of more than one nucleon in the annihilation would be expected to relax the selection rules,[4] which rather strongly suppress two-pion annihilation.

The fact that considerable energy may be released in star fragments is unfavorable toward the present detection system, since neutrons are not seen and protons below 190 Mev produce no Čerenkov light in the glass. Even a 500-Mev proton entering along the beam axis produces a pulse in the "zero" category under the electronic gain settings here employed.

B. Efficiency of the Glass Counters

Since the contribution of the second glass counter to the pulse sizes was small, the following calculations of counter efficiency relate to the first counter alone. They treat separately the detection of neutral pions, charged pions, and nucleon secondary particles.

1. Neutral Pions.—The decay modes that yield neutral pions and thus give rise to electronic showers in the glass can produce the largest Čerenkov-light pulses. The fraction of a shower that will be contained in the glass can be calculated from shower theory and experimental data. The experimental curves given for several elements by Kantz and Hofstadter[7]; and data from Monte Carlo calculations by Yamagata and Yoshimine[8] for a lead-glass medium, and by Wilson[9] for lead, have provided useful information. Containment fractions were averaged over the volume of Counter 1 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%. Since the neutral pions are expected to possess considerable kinetic energy, so that their decay photons will have energies Doppler-shifted into the hundreds-of-Mev region, this fraction is believed to be typical of the efficiency for observing the annihilation energy delivered to the glass in the form of neutral pions.

2. Charged Pions.—The threshold for charged-pion detection is 40 Mev. By averaging over the directions of trajectories initiated within the volume of the glass of one counter, it is found that the average observable energy rises to 100 Mev as the pion kinetic energy increases to 200 Mev, and remains nearly constant at this value for higher kinetic energies. Thus the observed energy will depend upon multiplicity and energy division among the pions; but if, for example, the energy of the annihilation were carried away by three charged pions, the maximum observed energy could hardly exceed 300 Mev.

3. Nucleons.—The efficiency for observing energy released in this form is essentially zero. (See the comments on detection of nucleon secondaries made at the end of Sec. VI.A.)

C. Expected Pulse Spectrum

Under the assumption of annihilation with the typical release of about 2 Bev (since some kinetic energy of the antiproton is typically available), we may estimate the average pulse height to be expected upon the basis of the energy calibration described in Sec. III for selected distributions of secondary products.

In events where no nuclear star is formed, we expect on the average that one-third 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. Actually it might be somewhat lower than this because such a 3-pion event, occurring in flight, would be directed somewhat away from the photomultipliers of Counter 1, and the light collection would be less favorable than normal. (The counter anisotropy, i.e., the pulse-height ratio for pions moving toward and away from the photomultipliers, is 1.5 to 1.)

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

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

The largest pulses must be produced by favorable

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[4] D. Amati and B. Vitale, Nuovo cimento **2**, 719 (1955). Also T. D. Lee, and C. N. Yang (to be published).

[5] D. H. Holland, University of California, Radiation Laboratory (private communication).

[6] J. V. Lepore and M. E. Neumann, Phys. Rev. **98**, 1484 (1955).

[7] A. Kantz and R. Hofstadter, Nucleonics **12**, No. 3, 36 (1936).

[8] T. Yamagata and M. Yoshimine, University of Illinois (private communication).

[9] R. R. Wilson, Phys. Rev. **86**, 261 (1952).

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]

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* 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).

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[4] W. Bothe, Z. Physik **20**, 237 (1923).