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The existence of antiprotons has recently been demonstrated at the Berkeley Bevatron by a counter experiment.[1] The antiprotons were found among the momentum-analyzed (1190 Mev/c) negative particles emitted by a copper target bombarded by 6.2-Bev protons. Concurrently with the counter experiment, stacks of nuclear emulsions were exposed in the beam adjusted to 1090 Mev/c negative particles in an experiment designed to observe the properties of antiprotons when coming to rest. This required a 132 g/cm^2 copper absorber to slow down the antiprotons sufficiently to stop them in the emulsion stack. Only one antiproton was found[2] in stacks in which seven were expected, assuming a geometric interaction cross section for antiprotons in copper. It has now been found[3] that the cross section in copper is about twice geometric, which explains this low yield.

In view of this result a new irradiation was planned in which (1) no absorbing material preceded the stack, (2) the range of the antiprotons ended in the stack, and (3) antiprotons and mesons were easily distinguishable by grain density at the entrance of the stack. In order to achieve these three results it was necessary to select antiprotons of lower momentum, even if these should be admixed with a larger number of π^- mesons than at higher momenta.

In the present experiment we exposed a stack in the same beam used previously, adjusted for 700 Mev/c momentum instead of 1090 Mev/c. Since the previous work[2] had indicated that the most troublesome background was due to ordinary protons, the particles were also passed through a clearing magnetic field just prior to their entrance into the emulsion stacks. The clearing magnet (M_c) had B = 9900 gauss, circular diameter pole faces of 76 cm and a gap of 18 cm, so particles scattered from the pole faces of the clearing magnet could be ignored on the basis of their large dip angles in the emulsions.

With this arrangement we have achieved conditions in which the negative particles enter the emulsions at a well-defined angle, and extremely few positive particles enter the emulsions within the same range of angles. For the first time we have obtained an exposure in which more antiprotons than protons enter the stacks with the proper entrance angles. Under these conditions it is relatively easy to find antiprotons in these stacks even though approximately 5×10^5 negative π mesons at minimum ionization accompany one antiproton. The exposure arrangement is shown in Fig. 1. The beam collimation was such that at any given position at the leading edge of the stacks the angular half width of the pion entrance angles is less than 1° both in dip and in the plane of the emulsions. This very small angular spread allowed us to apply strict angular criteria for picking up antiproton tracks, and thus helped to reduce confusing background tracks to a negligible level. The antiproton tracks were picked up at the leading edge of the emulsions on the basis of a grain count ($\sim$ twice minimum) and angular criteria (angle between track and average direction of pions is less than 5°) and were then followed along the track.

A number of antiproton stars have been observed in these nuclear emulsions.[4] The one we will describe here was found in Berkeley and is of particular interest since it is the first example of a particle of protonic mass $\left(\frac{m}{M_p} = 1.013 \pm 0.034\right)$ which on coming to rest gave rise to a star with a visible energy release greater than $M_p c^2$. This example thus constitutes a proof that the particles here observed undergo an annihilation process with a nucleon, a necessary requirement for Dirac's antiproton.

Description of the Event

The particle marked P^- in Fig. 2 entered the emulsion stack at an angle of less than 1° from the direction defined by the π^- mesons in the beam. It came to rest in the stack and produced an 8-prong star. Its total range was $R = 12.13 \pm 0.14$ cm. Table I gives the results of three independent mass measurements on the incoming particle. The first two methods listed in Table I use measurements made entirely in the emulsion stack. The third combines the range, as measured in the stack, with the momentum as determined by magnetic field measurements. For the position and entrance angle of this particle into the stack the momentum is $P = 696$ Mev/c with an estimated 2% error. All three methods are in good agreement and give a mass of $m = 1.013 \pm 0.034$ in proton mass units.

Of the particles forming the star, five came to rest in the emulsion stack, two left the stack (tracks numbered 4 and 8), and one disappeared in flight (track number 3). The tracks numbered 1, 4, and 6 in Fig. 2 were caused by heavy particles. Particle 4 was near the end of its range ($R_{res.} \approx 2$ mm) when it left the stack. Tracks 1 and 4 are probably due to protons and track 6 to a triton. However, owing to the large dip angles the assignments for tracks 1, 4, and 6 are not certain. Track 2 has the characteristics of a π meson and on coming to rest gives a 2-prong σ star. It is thus a negative π meson. Particle 5 came to rest and gave the typical π-μ-e decay and was thus a positive π meson. From the measured range its energy would have been 18 Mev, however, after 0.22 mm it underwent a 22° scattering that appears to be inelastic. The initial energy as estimated from the grain density change was 30 ± 6 Mev. Track 7 is very steep (dip angle = 83.5°). The particle came to rest as a typical light ρ meson after traversing 30 emulsions. At the end of the track there is a blob and possibly an associated slow electron. The most probable assignment is a negative π meson, although a negative μ meson cannot be ruled out.

In addition to the three stopping π mesons there are two other tracks which we know were caused by light particles, presumably π mesons. Track 8 had $p\beta$ = 190 ± 30 Mev/c and g/g_o = 1.10 ± 0.04, which is consistent with a π meson of 125 ± 25 Mev energy, but is not consistent with a much heavier particle. After 16 mm it shows a 17° scattering with no detectable change in energy. Track 3 is very steep (dip angle = 73.5°) and its ionization is about minimum. The particle traversed 81 plates and disappeared in flight after an observed range of 50 mm. The $p\beta$ has been determined by a new modification of the multiple scattering technique to be 250 ± 45 Mev/c. The new method, which is applicable to steep tracks, is based on measurements of the coordinates of the exit point of the track in each emulsion with reference to a well aligned millimeter grid[5] printed on each pellicle in the stack. A detailed description of this method will be given in a subsequent paper.

The observations do not allow us to rule out the possibility that tracks 3 and 8 are due to electrons. It is, however, very unlikely that a fast electron could travel 50 mm (1.7 radiation lengths) in the emulsion (as does track 3) without a great loss of energy due to bremsstrahlung. The energy (particle 3) deduced from the measured $p\beta$ (E = 250 Mev) must be considered a lower limit.

In Table II the pertinent data on the eight prongs are summarized. The last column gives the total visible energy per particle ($E_{kin.}$ + 8 Mev binding energy per nucleon, or $E_{kin.}$ + 140 Mev rest energy per π meson) for the most probable assignments as discussed above. The total visible energy is 1300 ± 50 Mev, and the momentum unbalance is 750 Mev/c. To balance momentum, an energy of at least 100 Mev is required in neutral particles (i.e., about 5 neutrons with parallel and equal momenta), which brings the lower limit for the observed energy release to 1400 ± 50 Mev.

However, as some of the identity assignments to the star prongs are not certain, we have also computed the energy release for the extreme and very unlikely assignments, given at the foot of Table II, which are chosen to give the minimum energy release. In this case the total visible energy is 1084 ± 55 Mev and the resultant momentum is 380 Mev/c, which to be balanced requires at least 50 Mev in neutral particles (three or four neutrons). In this unrealistic case the lower limit for the observed energy release is 1134 ± 55 Mev, which still exceeds the rest energy of the incoming particle by about three standard deviations.

We conclude that the observations made on this reaction constitute a conclusive proof that we are dealing with the antiparticle of the proton.

A second important observation is the high multiplicity of charged π mesons (1 π^+, 2 π^-, and 2 π mesons with unknown charge). The fact that so many π mesons escaped from the nucleus where the annihilation took place, together with the low number of heavy particles emitted (three), may indicate that the struck nucleus was one of the light nuclei of the emulsion (C, N, O). Two of the outgoing heavy prongs carried rather high energies (70 Mev for the proton, 82 Mev for the triton), and they may have resulted from the reabsorption of another two π mesons.

We are greatly indebted to the Bevatron crew for their assistance in carrying out the exposure. We also wish to thank Mr. J. E. Lannutti for help with measurements and the analysis of the event.

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

Table I

Mass measurements

Method	Residual range cm of emulsion	Mass M/M_p
Ionization - range	2, 5.5, and 12	0.97 ± 0.10
Scattering - range (constant sagitta)	0 - 1	0.93 ± 0.14
Momentum - range	12.13 + 0.12 air and helium equivalent	1.025 ± 0.037
Weighted mean		1.015 ± 0.034

Table II

Measurements and data on the eight prongs of the P^- star shown in Fig. 1

Track number	Range mm	Number of plates traversed	Dip angle	Projected angle	$p\beta$ Mev/c	Ionization g/g_o	Identity	E_{kin} Mev	Total energy Mev
1	0.59	2	-56.5^o	103^o			p (?)	10	18
2	27.9	11	$+6.5^o$	61.5^o			π^-	43	183
3	>50	81	-73.5^o	14.5^o	250±45	1.10±0.04	π (?)	174±40	314±40
4	>14.2	16	$+53^o$	318.5^o			p (?)	70± 5	78± 5
5	6.2	3	$+4^o$	305.5^o			π^+	30± 6	170± 6
6	9.5	15	-63.5^o	281^o			T (?)	82	98
7	18.6	30	-83.5^o	255^o			π^-	34	174
8	>22.3	16	$+33^o$	163^o	190±30	~1	π (?)	125±25	265±25
							Total visible energy[a)]:		1300±50 Mev
							For momentum balance:		≥100 Mev
							Total energy release:		≥1400±50 Mev

a) To obtain the minimum possible value of the visible energy release, still consistent with our observations, one has to make the very unlikely assumptions about the identity of tracks 3, 6, 7, and 8: that tracks 3 and 8 are due to electrons, track 6 to a proton, and track 7 to a μ^- meson. The total visible energy release in this case becomes 1084 ± 55 Mev. To this must be added at least 50 Mev to balance momentum bringing the total energy release to ≥1134 ± 55 Mev.

References

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2. O. Chamberlain, W. W. Chupp, G. Goldhaber, E. Segrè, C. Wiegand, E. Amaldi, G. Baroni, C. Castagnoli, C. Franzinetti, and A. Manfredini, Phys. Rev. 101, 909 (1956), and Nuovo Cimento in press.
3. O. Chamberlain, D. V. Keller, E. Segrè, H. M. Steiner, C. Wiegand, and T. Ypsilantis, Phys. Rev. in press.
4. Several stacks exposed in the 700 Mev/c beam are being studied in Berkeley by A. G. Ekspong and G. Goldhaber; W. W. Chupp and S. Goldhaber; R. Birge, D. H. Perkins, D. Stork, and L. van Rossum; by W. Barkas, H. Heckman, and F. Smith; and in Rome by E. Amaldi, G. Baroni, C. Castagnoli, C. Franzinetti, and A. Manfredini.
5. G. Goldhaber, S. J. Goldsack, and J. E. Lannutti, UCRL-2928 (unpublished).

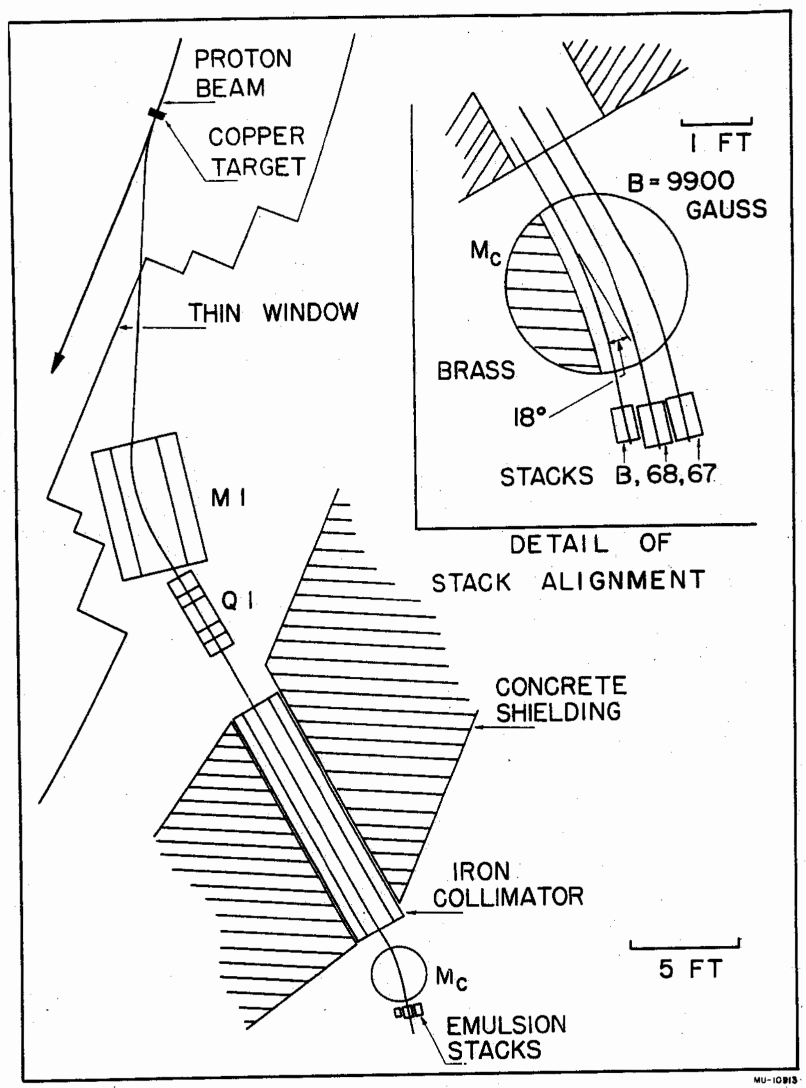
Figure Captions

Fig. 1. Plan of the irradiation.

Fig. 2. Reproduction of the P^- star. The description of the prongs is given in Table II.

Observer: A. G. Ekspong

Photomicrograph by D. H. Kouns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BEAM
COPPER
TARGET
THIN WINDOW
M 1
Q 1
CONCRETE
SHIELDING
IRON
COLLIMATOR
M_C
EMULSION
STACKS
5 FT
1 FT
B = 9900
GAUSS
M_C
BRASS
18°
STACKS B, 68, 67
DETAIL OF
STACK ALIGNMENT
MU-10913

Fig. 1

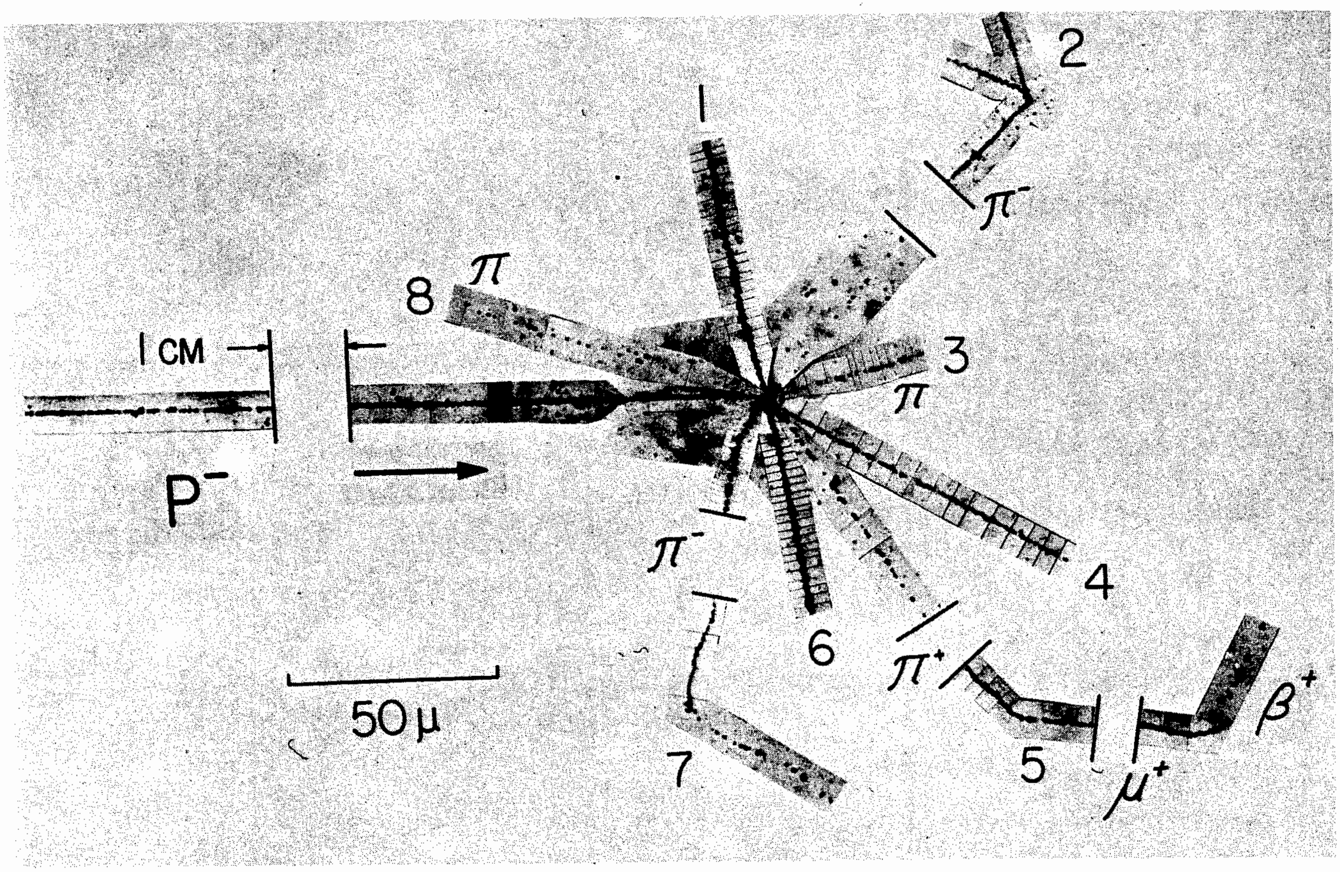

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Fig. 2