The Observation of Antiproton Annihilation

Gerson Goldhaber

University of California
and LBNL

Talk at the "50 Years of Antiprotons Anniversary Symposium"
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I am going to discuss 4 experiments at the bevatron related to the annihilation process. The first question is has the antiproton been discovered or is it a negative proton, in the sense of a baryon triplet, P+, P0 =n, P-. Alternatively could it be a heavy meson with a mass close to the proton mass? The experiment we just heard had no doubts, however, some other people did.. The previous talk showed that a negative particle of near protonic mass has been discovered, but was it the antiproton?
In the Segre group we decided to approach the antiproton search by two methods.

1. Chamberlain and Wiegand would construct a beam in which momentum and velocity of the negative particles was to be measured.
2. Gerson Goldhaber was to search for antiproton annihilations in photographic emulsions in collaboration with Edoardo Amaldi's group in Rome.

Thus while the double arm spectrometer, we heard about from Steiner, was under construction I exposed emulsion stacks in August 1955, as soon as the first focus was reached. The idea was to expose emulsion stacks large enough so that the expected antiprotons could come to rest and then to check whether they annihilated. We were however too clever for our own good. We decided that an optimal momentum for the production of antiprotons was 1090 Mev/c however the maximum range in our emulsions was about 15 cm. This meant that the antiprotons had to be slowed down to about 700 MeV/c. This needed a 5 inch cooper absorber! Here was our mistake. This absorber had two bad effects. As we learned later the antiproton cross section is twice geometric.
One day Gosta Ekspong tells me Edward Teller come to my laboratory and exclaimed excitedly (Edward always spoke that way) that he understood why we were not finding any antiproton candidates. It was that he had realizes that antiprotons had a twice geometric cross section. A normal cross section like all strongly interacting particles but then an extra add on because of the annihilation. (We learned from Harari's talk that this is not the right explanation). Secondly we were done in by the absorber because of all the protons produced in it which entered our emulsions. Thus the-along-the-track following which proved so successful later on, was not possible here because of all the proton background.
While we had exposed the emulsions well before the total beam was completed, the emulsion scanning was endless. After exposure I developed the emulsions and divided the stack into 2 halves. One which we scanned and remained in Berkeley, the other half was sent to Rome for scanning. Finally by Dec 1955 one antiproton event was found in Rome.
Our collaboration had a method which was perhaps unique in particle physics. I had worked out a technique by which it was easy to follow a track from one emulsion sheet to the next. This

consisted of printing a number grid with x and y co-ordinates on each sheet. So while we divide the stack between Berkeley and Rome some tracks that appeared of interest to us would traverse this particular gap. Thus we have an extensive set of letters between Amaldi and myself as well as Segre in which one of us asked the other to follow a track by supplying the corresponding grid co-ordinates. One such request from Amaldi to me is illustrated herewith. I apologize for the quality of the image, but a 50 year old carbon copy just does not look that good.

The first experiment was the emulsion exposure behind the 5 inch copper absorber.
After very extensive and laborious scanning one single event was found, in Amaldi's half of the stack, with a visible energy release of 826 MeV. Consistent with antiprotons but not yet a proof.

The second is an attempt to observe antiproton annihilation in a lead glass cerenkov counter. This experiment was carried out by members of the Moyer and Lofgren groups. They set up their counter behind the second focus of Chamberlain et al. They triggered their instrument with one of the pulses from Chamberlain et al. for particles of negative charge and near protonic mass. With this trigger they studied the pulse height in their lead glass counter. Their conclusion was that since the highest signal they observe was 0.9 GeV they gave corroborative but not conclusive evidence for antiprotons.

The third experiment was one in which we did away with the absorber and looked at antiprotons of 700 MeV. We were encouraged by Ed Lofgren, the head of the Bevatron , by making time available for this experiment. At this time I was joined by Gosta Ekspong, a very fruitful collaboration. This time I also introduced a final magnet to make sure that we looked at only negative particles and swept out any possible proton contamination. At this momentum the pions, the most copius of particles were still at minimum ionization, while antiprotons were at twice minimum. This meant that at the leading edge of the emulsions one could readily distinguish between pions and protonic mass particles. As soon as the emulsions were dry, about 10 days after the exposure Gosta Ekspong started to scan for twice minimum tracks and began following them. Essentially the first track he followed came to rest after 12 cm and produced a large star.
He and I spent the next few weeks following and measuring all the tacks that came out of this star, 5 pions , 2 protons and one possible triton. Fortunately none of these tracks went into that half of the stack which I had sent to Rome. This was the star that proved the annihilation process since 1300 MeV of visible energy, considerably more then Mpc2 was observed. In this exposure we also exposed emulsion stacks for all the emulsion groups at the Rad. Lab. The yield was so great that the same morning that Gosta Ekspong had observed the first star a scanner for Sula Goldhaber in the Lofgren group observed a second antiproton star.

The fourth experiment gives the results from the Antiproton Collaboration Experiment. Between all 5 groups, the Barkas group, Lofgren group, Richman group ,Amaldi group and my work in the Segre group, we observed 35 antiprotons from the 700 MeV/c exposure. Of these more then half gave a visible energy greater than Mpc2. We also were able to measure the cross section and found indeed that the antiproton cross section was about 2 times geometric.

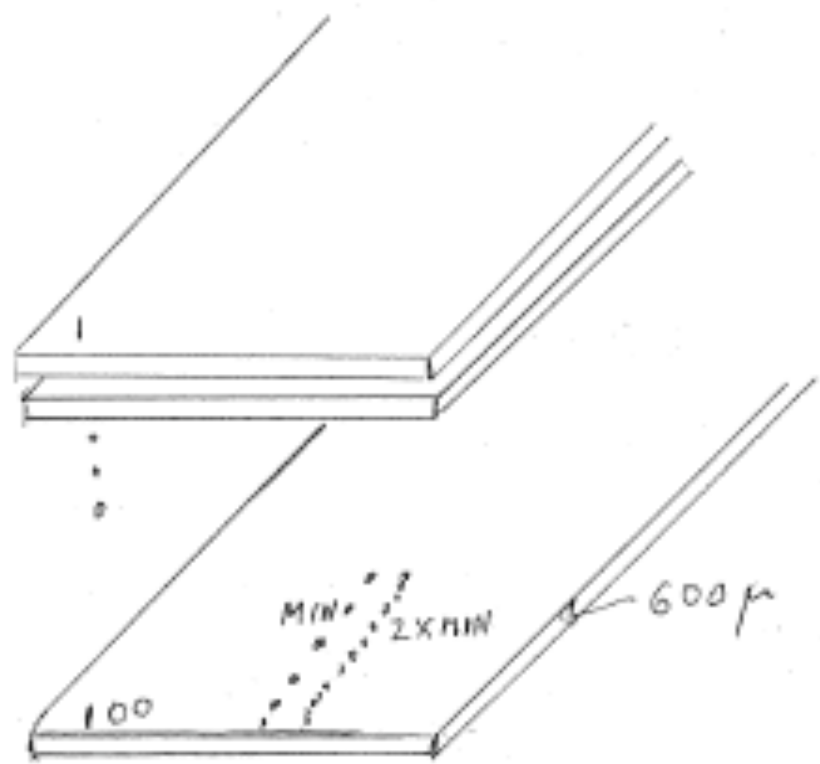
In the Segrè group we decided on two separate tracks to try and discover the antiproton

1. The double arm spectrometer which measured momentum and velocity of the negative particles. This was designed and built by Owen Chamberlain and Clyde Wiegand.
2. An emulsion stack large enough to allow potential antiprotons to come to rest and annihilate. This was exposed, as soon as the above beam had reached the first focus, and developed by Gerson Goldhaber and scanned in collaboration with Edoardo Amaldi

Emulsion Stack

200, 600 micron Sheets.

Minimum Ionizing and 2 times minimum ionizing Tracks indicated



Excerpts from a Letter from Amaldi to Segrè and Goldhaber with a report on candidate protonic Tracks found in Berkeley and followed in Rome

UNIVERSITÀ DEGLI STUDI - ROMA
ISTITUTO DI FISICA "GUGLIELMO MARCONI"

December 10, 1955

Proff. E. Segrè and G. Goldhaber
Physics Department
University of California
BERKELEY 4, CAL.

Dear Segrè and Goldhaber,

we have followed all tracks send to us by Goldhaber and our results are summarized in the table. We suggest for future cases that you send to us also the following data at least approximately: they can be useful to speed up our work:

1) angle of dip of the track at the point in which it leaves your last emulsion.
2) its direction with respect to the grid.
3) an approximate value of g/g_0.

:

We are very anxious to get the 4th part of the manuscript of the paper for Nuovo Cimento.

With best wishes

Edoardo

(E. Amaldi)

Series of tracks from Berkeley followed in Rome

BERKELEY-ROME TRACKS

stack	track	Number of crossed emulsion	Range followed	
65	091-079	1	560 μ	proton stopping in emulsion (?)
65	080-081	11	6.9 cm	proton stopping in emulsion
65	136-101	1	570 μ	" " " " (?)
62	026-089	1	2.87 mm	disappear in flight: $g/g_0 = 1.86 \pm 0.12$
62	038-132	5	2.05 cm	proton stopping in emulsion

First Antiproton Event Observed in Emulsions

Antiproton Star Observed in Emulsion*

O. CHAMBERLAIN, W. W. CHUPP, G. GOLDHABER, E. SEGRÈ, AND C. WIEGAND, *Radiation Laboratory, Department of Physics, University of California, Berkeley, California*

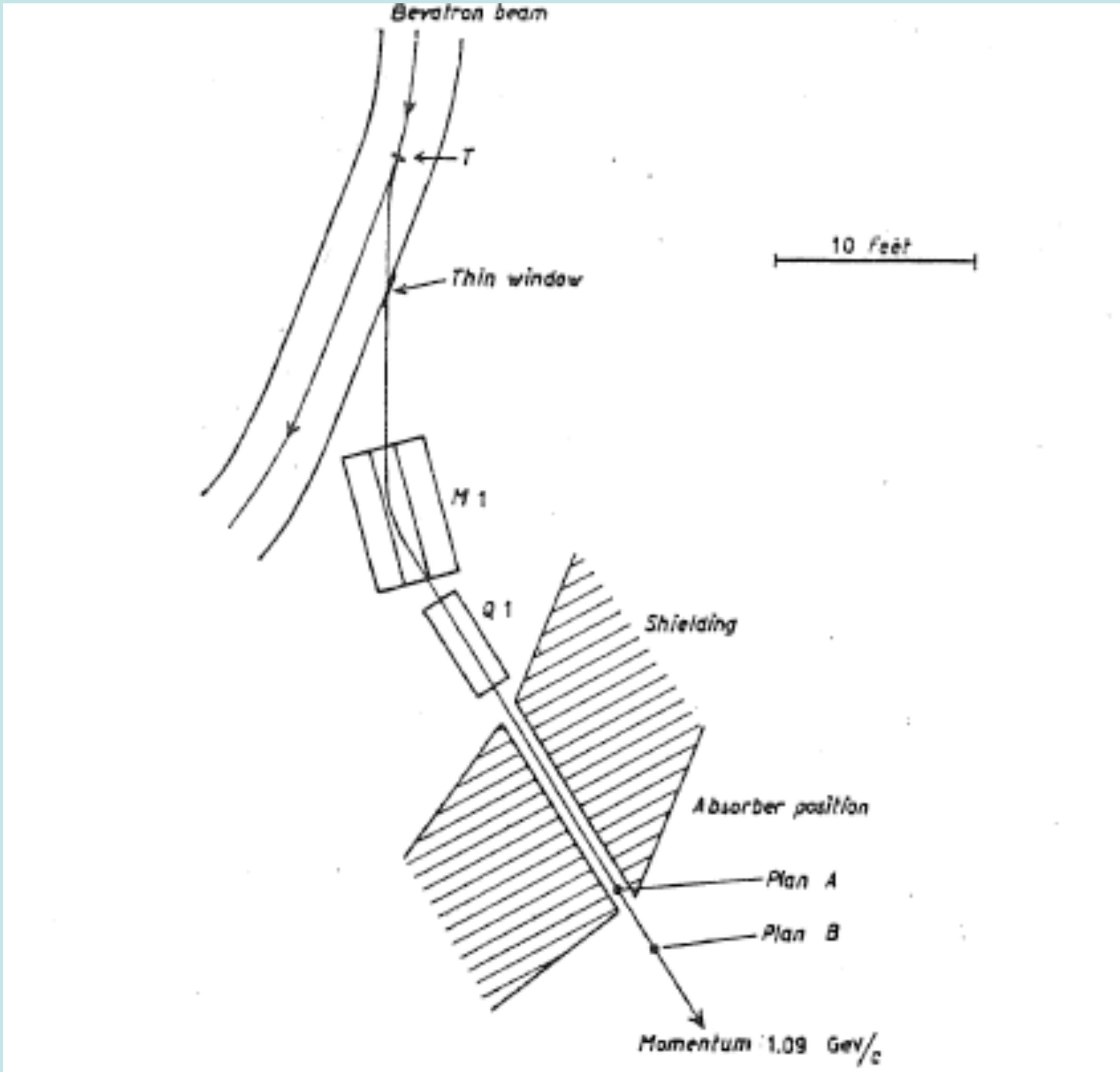
AND

E. AMALDI, G. BARONI, C. CASTAGNOLI, C. FRANZINETTI, AND A. MANFREDINI, *Istituto di Fisica della Università, Roma Istituto Nazionale di Fisica Nucleare, Sezione di Roma, Italy*

(Received December 16, 1955)

Emulsion exposure at the Bevatron

in the 1090 MeV/c Antiproton Beam Line at the first focus of the Chamberlain-Wiegand beam



Emulsion Exposure

with 5 inch Copper Absorber

in 1090 MeV/c Beam Plan A

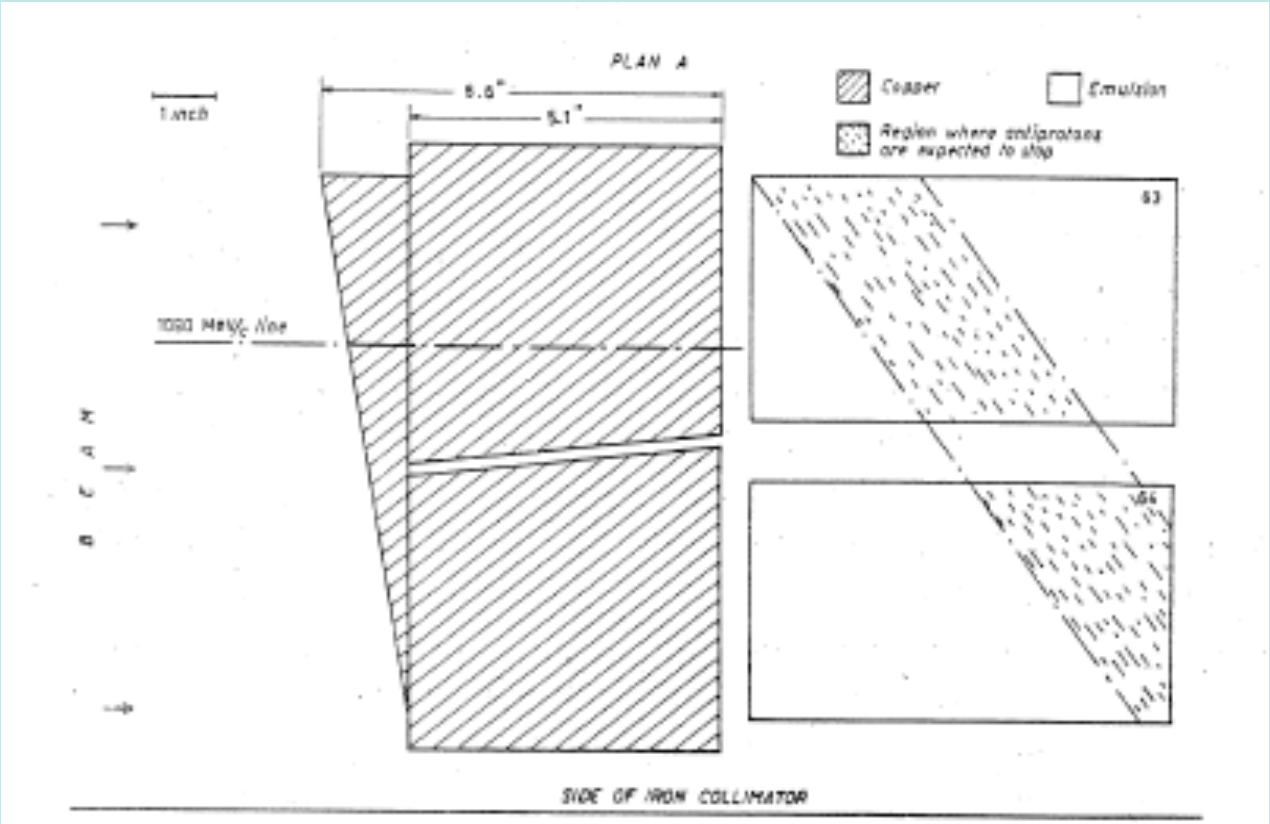


Fig. 2. – Arrangement of absorbers and emulsions in plan A.

Emulsion Exposure

with 5 inch Copper Absorber in

1090 MeV/c Beam Plan B

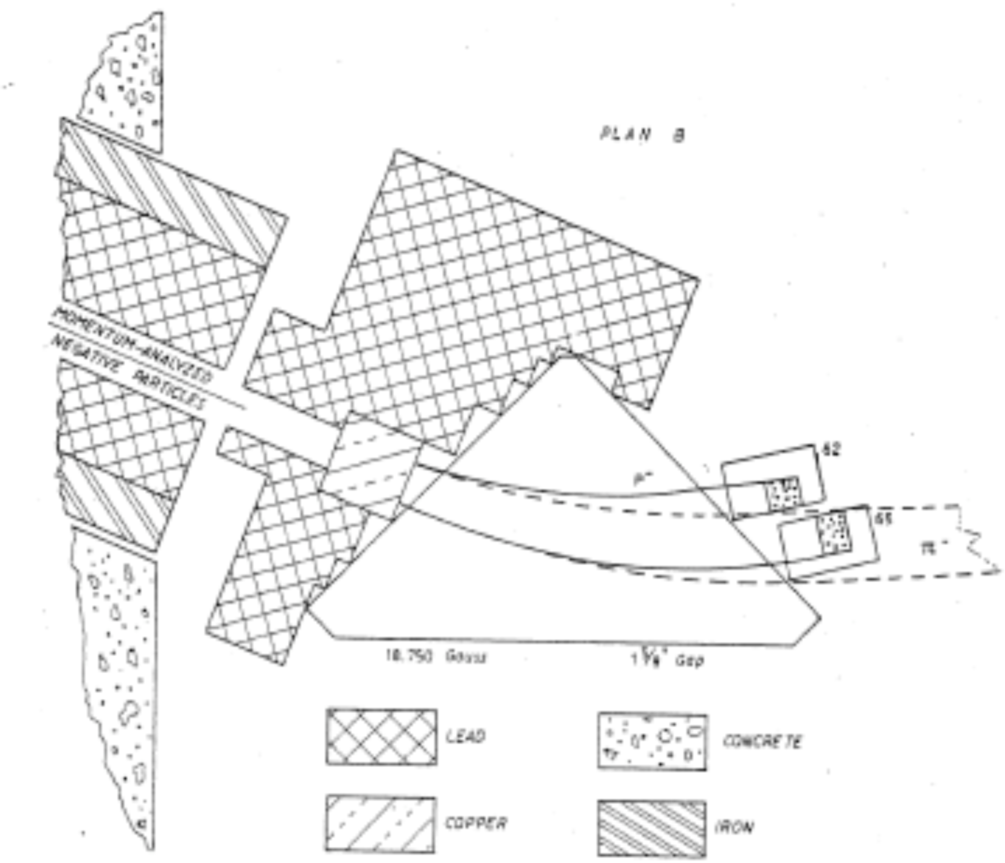
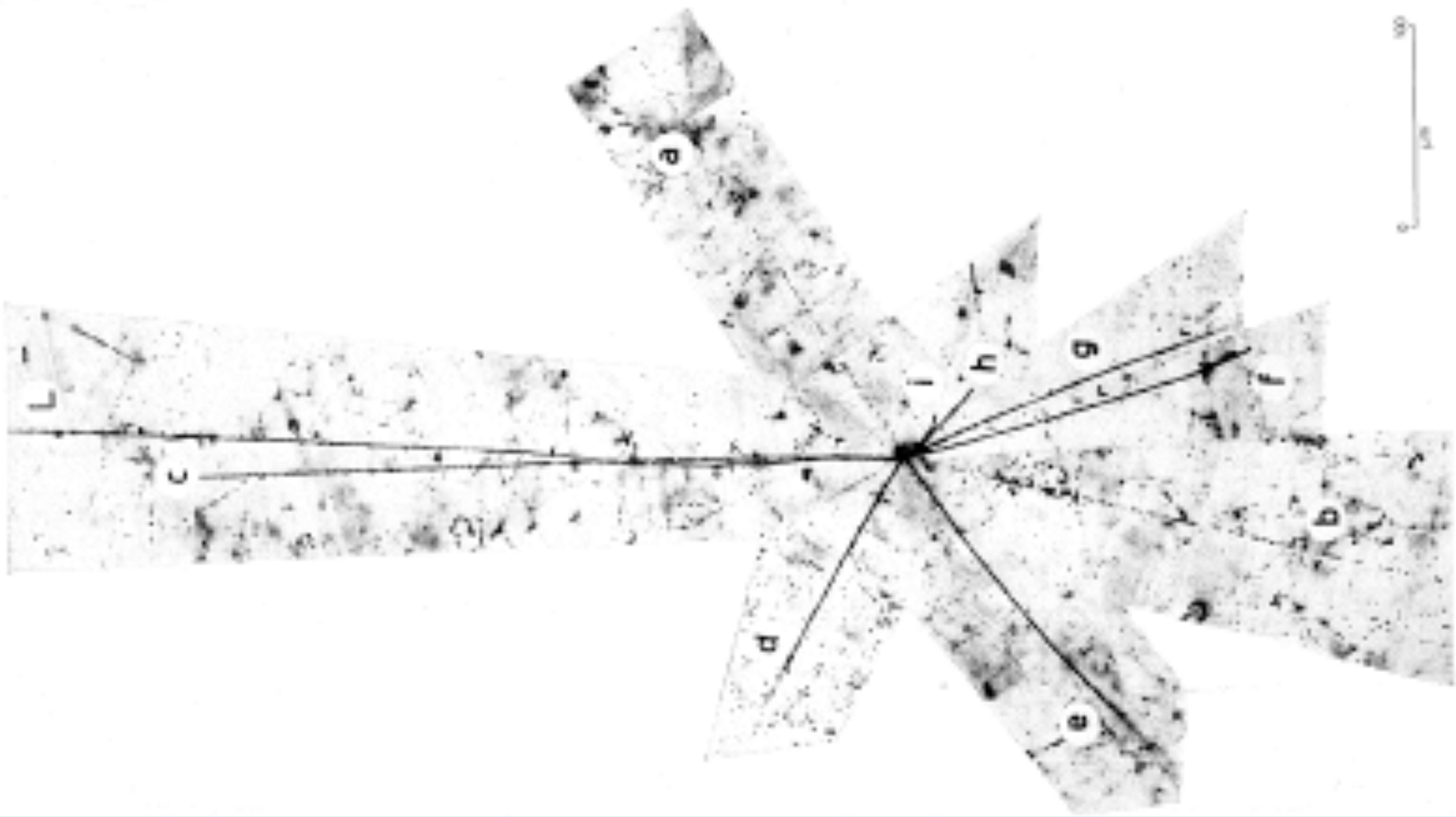


Fig. 3. – Arrangement of plan B.

First Antiproton Event in Emulsions

Visible Energy = 826 MeV



Corroborative evidence from first emulsion event

This event is corroborating evidence, but not final proof, for the interpretation given in reference 1 that the new particles observed at the Bevatron are antiprotons. It also gives support to the hypothesis that the star described in reference 5 was indeed due to an antiproton.

Lead Glass Čerenkov Counter

Terminal Observations on "Antiprotons"*

John M. Brabant, Bruce Cork, Nahmin Horowitz, Burton J. Moyer, Joseph J. Murray, Roger Wallace, and William A. Wenzel

Radiation Laboratory, Department of Physics, University of California, Berkeley, California

(Received November 21, 1955)

Lead Glass Čerenkov Counter

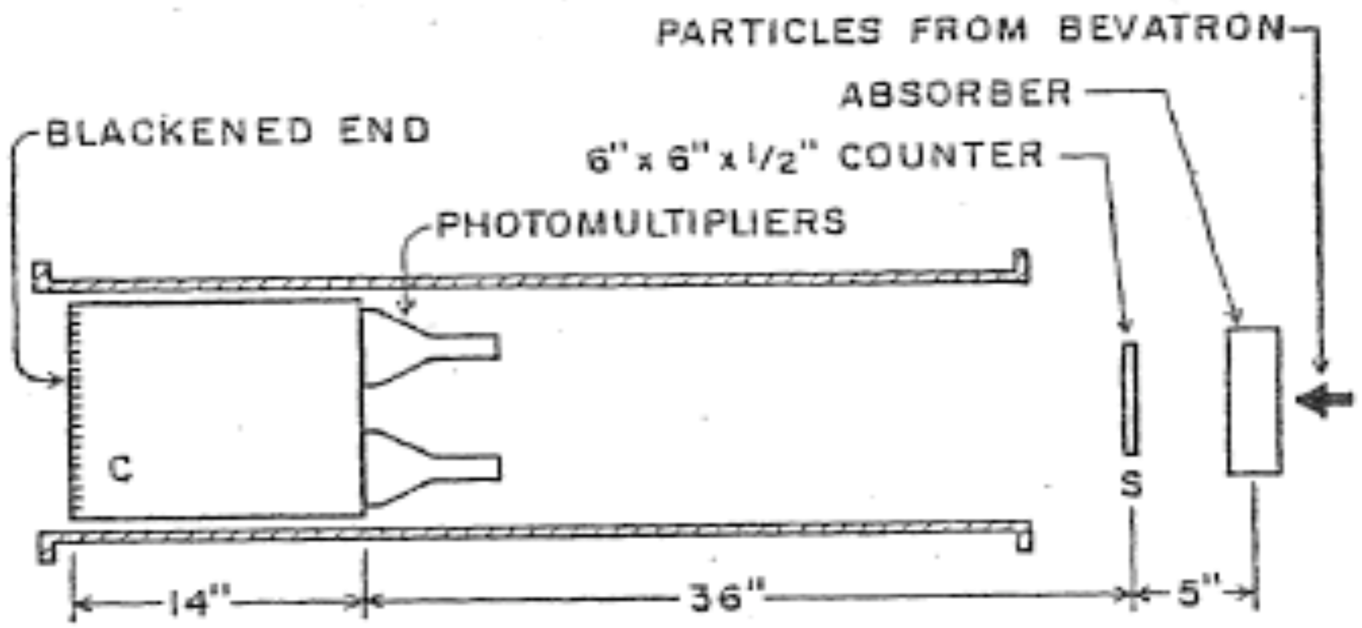
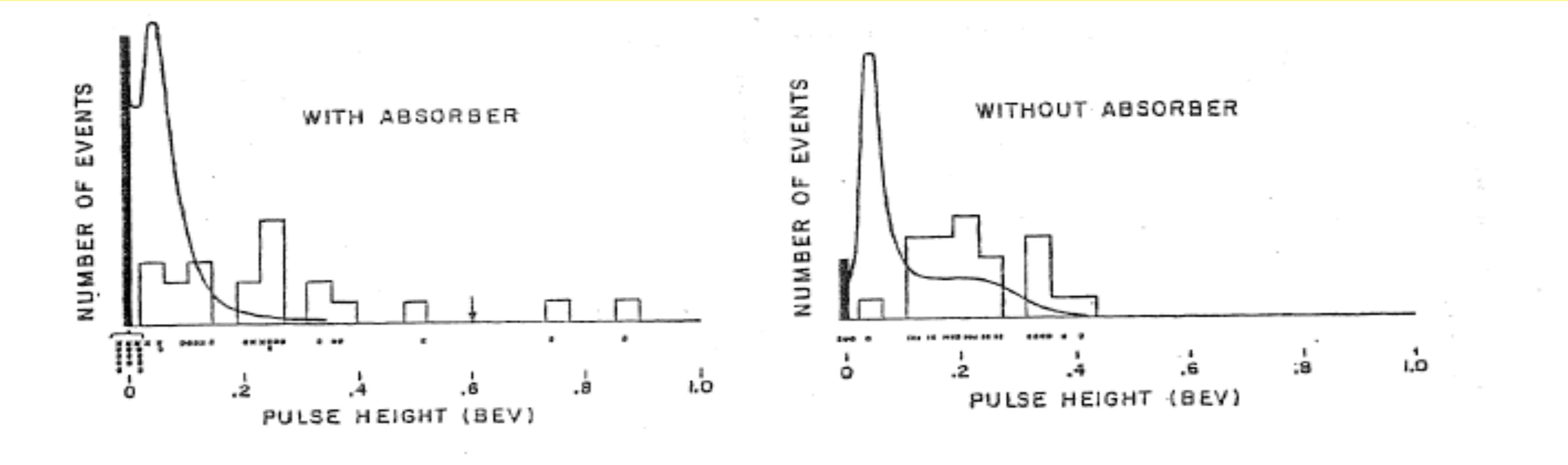


FIG. 1. Schematic diagram of the glass Čerenkov counter with associated scintillation counter and absorber.

Observed Signals



Observations with Antiproton Trigger from Chamberlain et al.

Conclusions.—The results here reported are not inconsistent with expected behavior of antiprotons. The lower limits observed for the energy release in events associated with the passage of these negative, protonic-mass particles through matter could be appropriate to antiprotons, but the energy values are not so high as to demand this conclusion, since the largest lower limit here recorded is about 0.9 Bev in the form of particles producing Čerenkov light.

Proof of Annihilation

Example of an Antiproton-Nucleon Annihilation

O. Chamberlain, W. W. Chupp, A. G. Ekspong, G. Goldhaber, S. Goldhaber, E. J. Lofgren, E. Segrè, and C. Wiegand,
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AND

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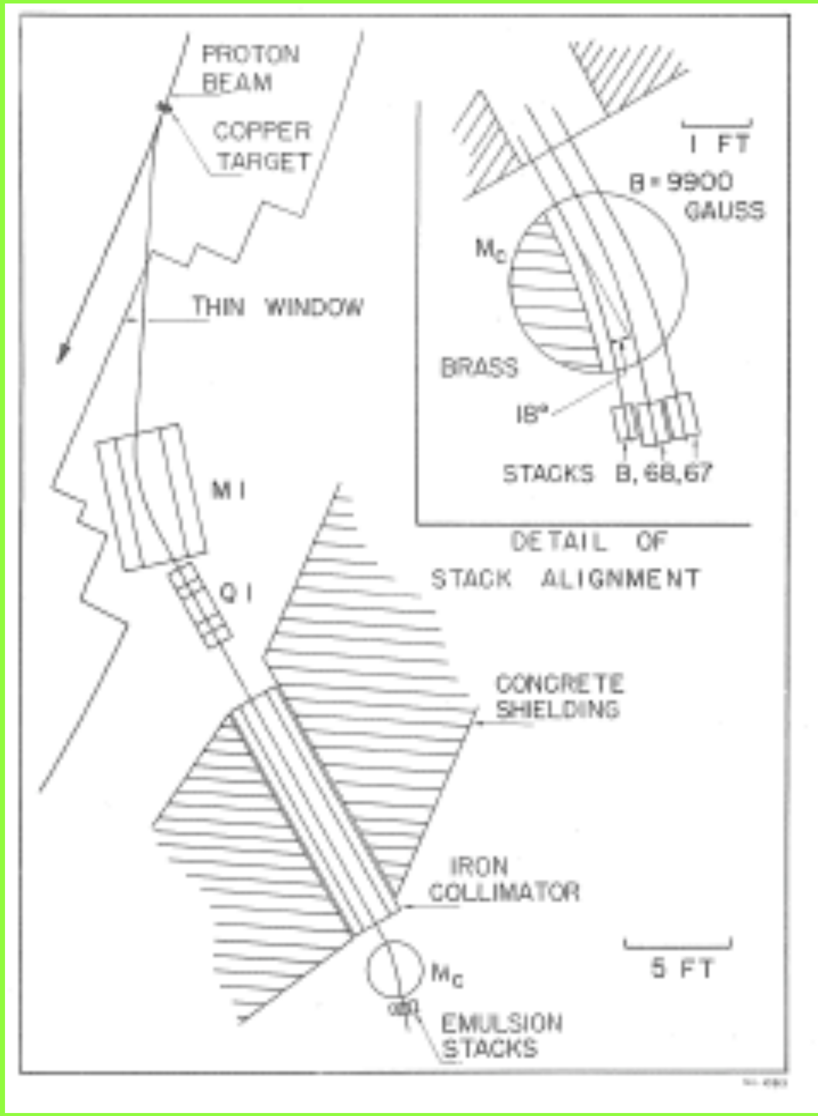
(Received March 8, 1956)

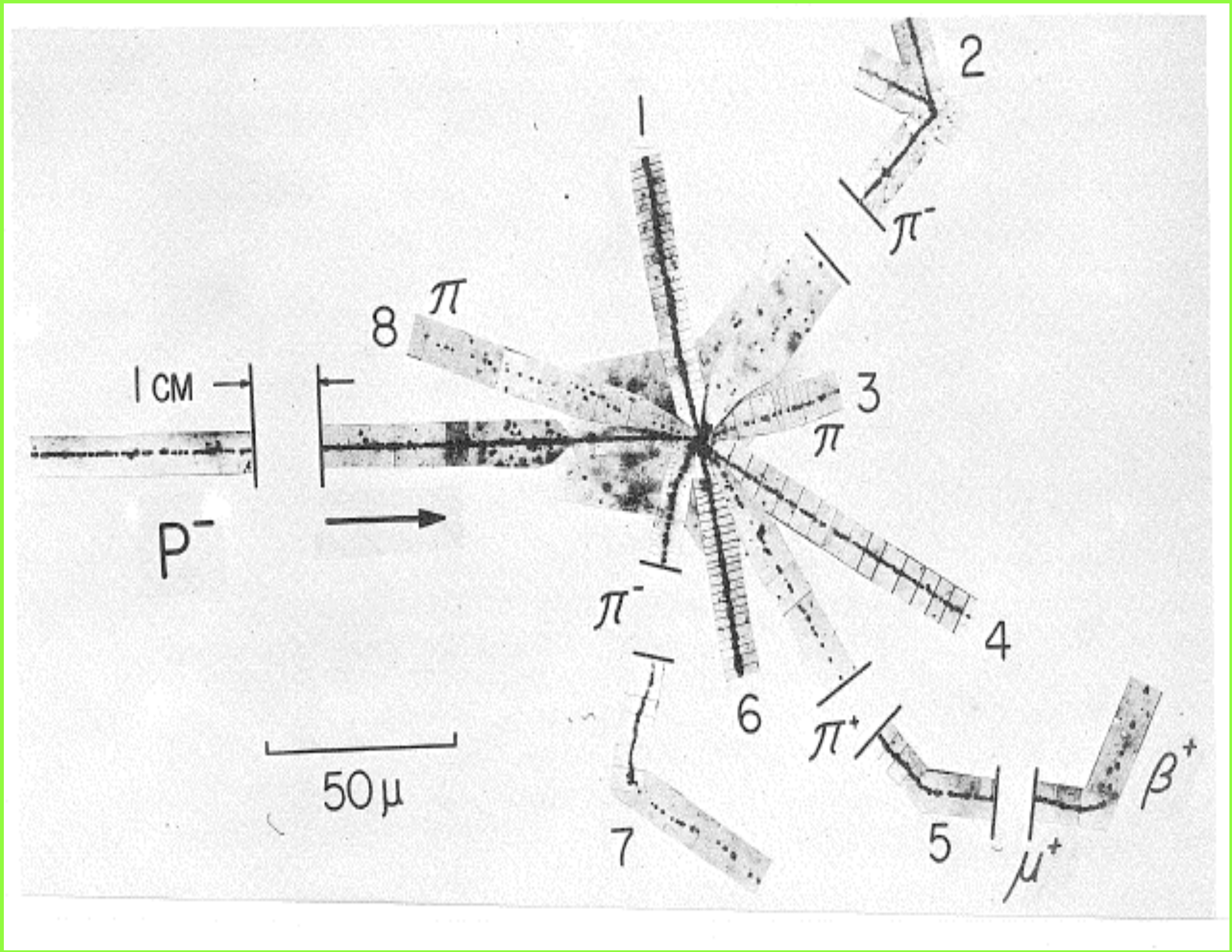
700 Mev/c Antiproton Beam for

Emulsions with no Absorber and with Sweeping Magnet



Antiproton Annihilation Event

Visible Energy = 1300 +/- 50 MeV



Antiproton Annihilation Event Vis. Energy = 1300 +/- 50 MeV

Fig. 4. An annihilation star showing the particles as numbered.

No.	1	2	3	4	5	6	7	8
Identity	p?	π^-	π?	p	π^+	H^3(?)	π^-	π
T (MeV)	10	43	175	70	30	82	34	125

Total visible energy 1,300 MeV. Total energy release > 1,400 MeV.

Mass Measurements

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		1.013 ± 0.034

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

Proof that Antiprotons have been Observed

- The experiment of Chamberlain, Segrè, Wiegand and Ypsilantis observed 3 NECESSARY conditions for antiprotons :
- 1. Negative charge
- 2. Mass within 5% of proton mass
- 3. Pair production from excitation function

Proof that Antiprotons have been Observed

- The Lead Glass Counter experiment (Brabant et al.) demonstrated energy release from the interaction of these particles. Again a NECESSARY condition.
- The SUFFICIENT condition of annihilation was observed in our emulsion experiment.

Owen Chamberlain, Nobel Prize talk 1959

… The work with photographic emulsions involved many people, among whom I would like to mention especially Professor Gerson Goldhaber and Professor Edoardo Amaldi from Rome. I would like to mention that it was a young Swedish physicist, Dr. A. G. Ekspong, now at the University of Uppsala but then working with us in Berkeley, who observed under the microscope the first of the annihilation events with very large visible release of energy.

That star gave the final visual proof through the phenomenon of annihilation that we were dealing with antiprotons, rather than with any other similar particle.

The large release of energy showed not only that the incoming particle (antiproton) died in the production of the star, but that additional energy must have been supplied by the death of an ordinary nucleon (neutron or proton). …

Emilio Segrè, Nobel Prize talk 1959

… Initially the effort was mainly directed toward establishing the fact that the energy released was $2mc^2$ (m is the mass of the proton), thus furnishing a final proof of the annihilation.

In the early investigations with photographic emulsions carried out in my group especially by Gerson Goldhaber and by a group in Rome led by Amaldi,

we soon found stars showing a visible energy larger than mc^2, giving conclusive evidence of the annihilation in pairs of proton and antiproton

With great pleasure I recognized in. the Nobel diploma the image of the first star of this type, found in Berkeley by Prof. Gösta Ekspong,now of Stockholm.

My Sketch in Time Magazine

SCIENCE

P 34

Star of Annihilation

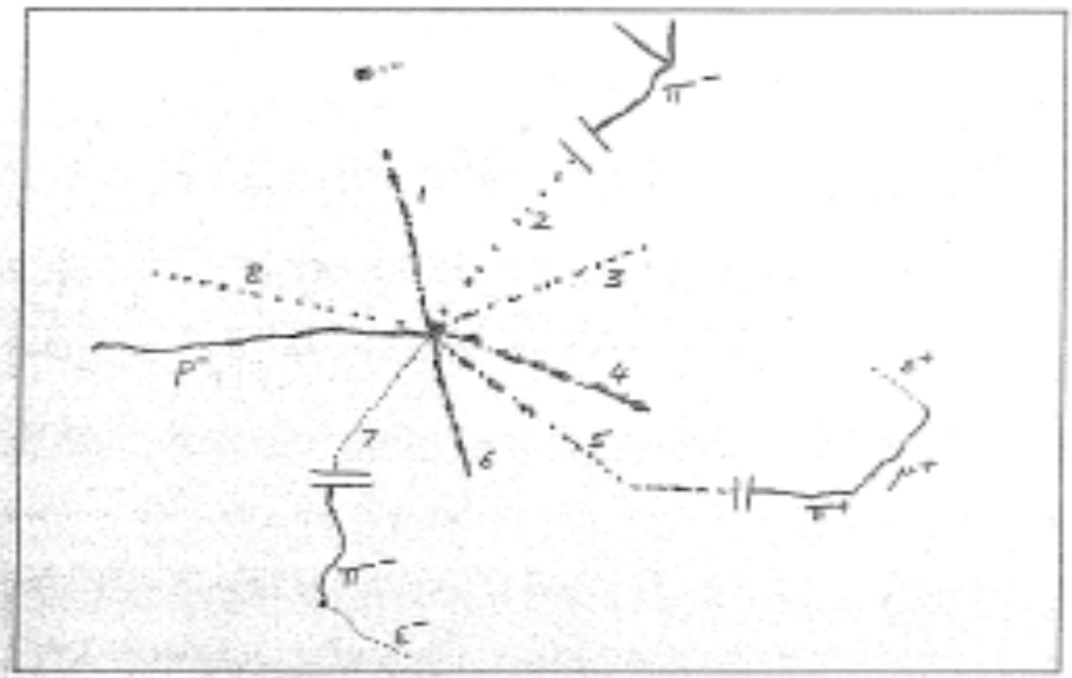
One of physics' most exciting recent discoveries is the anti-proton. It resembles an ordinary proton (present in the nuclei of all atoms), except that its electric charge is negative instead of positive. There may be (but probably are not) places in the universe where anti-proto… can exist permanently, but on earth… are short-lived. As soon as … touches the nucleus of an … it is annihilated. Both … and the matter of a proto… the nucleus turn into a flash…

Anti-protons were created … by the world's most powerful particle accelerator, the Bevatron, at Berkeley, Calif., into 1,876 million electron volts of energy. The resulting explosion—extremely violent on the atomic scale—drives off fast-moving fragments that trace the lines of the star.

Some … (1, 4 and 6) were tra… rest were made by … particles that … disrupted. There … neutrons too, but since … electric charges, they do not … in photographic film.

… energy carried away by each particle can be measured by examining closely the track that it made. In this star, the total energy of the visible particles alone adds up to 1,230 million electron volts. Since only 938 million electron volts can

At last week's New York meeting of the American Physical Society, Dr. Owen Chamberlain of the University of California showed a drawing of films exposed anti-protons (see 414).



Drawing of Anti-Proton Tracks

P^- equals -2 particles.

25th Anniversary of the Annihilation Discovery
1980 Midsummer Night Sweden.

Antiproton Collaboration

This experiment observed 35 annihilation events

21 annihilate in flight, 14 at rest.

This gives a cross section of (2.9+/-0.7) x geometric

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Antiproton-Nucleon Annihilation Process* (Antiproton Collaboration Experiment)

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(Received October 26, 1956)

Visible Energy Distribution

More than 1/2 the
events have a visible energy greater than M_pc^2

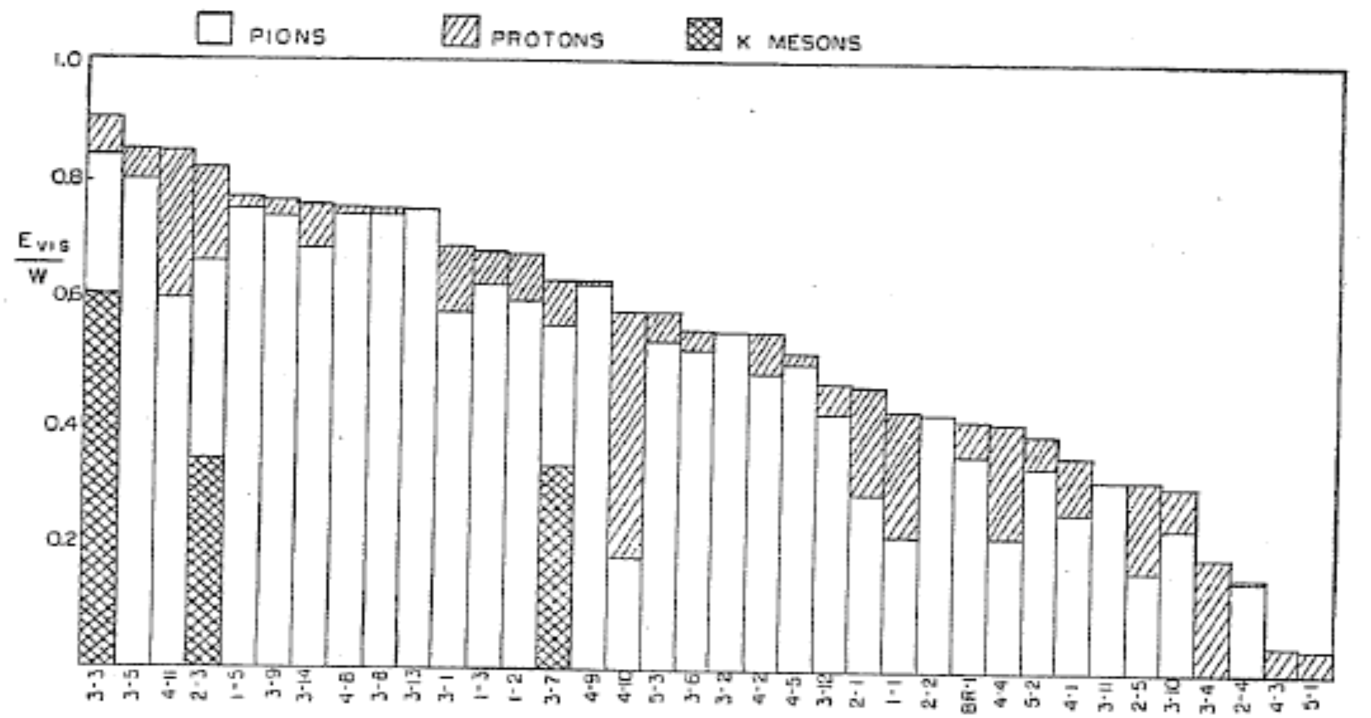

FIG. 6. Visible energy release in antiproton annihilation stars, expressed as a fraction of the available energy. The star reference number is given for each entry.

The Fermi Statistical Model Puzzle

- The observed pion multiplicity in antiproton annihilation is 5.3 +/- 0.4.
- This required a very large (10-15 times geometric) interaction volume.
- However we later (1959-60) discovered the Goldhaber Goldhaber Lee Pais (GGLP) effect - namely that pions obey Bose-Einstein statistics.
- This gave a geomeric interaction volume.

The answer to the Puzzle

- This can be understood if in the annihilation process not just pions but pion resonances are also produced.
- Thus the discrepancy of our two results, as now interpreted, was an indirect indication for the existence of pion resonances. These were later discovered by Alvarez et al. 1961-62.

The first anti-Ω^- event

The 82 inch Deuterium bubble Chamber exposed to a 12 GeV/c K+ beam at SLAC. Firestone, Goldhaber, Lissauer, Sheldon and Trilling 1970