The Discovery of the Antiproton

Dirac’ s Equation and Antimatter

- In 1928, Dirac formulated a theory describing the behavior of relativistic electrons in electric and magnetic fields.
  - Dirac’ s equation has negative energy solutions, implying the existence of antimatter.
- The positron was discovered in 1932 from cosmic ray experiments.
  - This method would not work for discovering antiprotons.
  - No accelerator existing at that time was energetic enough to produce antiprotons.

Requirements to Make an Antiproton

- Creating an antiproton would also require the simultaneous production of a proton or neutron.
  - Since the mass of the proton is 938 MeV, the minimum energy required to get an antiproton is two times that, or about 2 GeV (In those days, physicists typically said BeV instead of GeV.)
  - Using the fixed target technology of the time, this would require striking the target with a 6 GeV proton.
- A new accelerator that had an energy of several GeV (or BeV) was required, hence the name Bevatron.

Gli "eventi strani" nei raggi cosmici

E. Hayward, "Ionization of High Energy Cosmic-Ray Electrons", Physical Review 72 (1947)

E. W. Cowan, "A V-Decay Event with a Heavy Negative Secondary, and Identification of the Secondary V-Decay Event in a Cascade", Physical Review 94 (1954)

M. Schein, D.M. Haskin, and R.G. Glasser, "Narrow Shower of Pure Photons at 100000 Feet", Physical Review 95 (1954)

H.S. Bridge, H. Courant, H. DeStaebler, Jr., and B. Rossi, "Possible Example of the Annihilation of a Heavy Particle", Physical Review 95 (1954)

E. Amaldi, C. Castagnoli, G. Cortini, C. Franzinetti and A. Manfredini, "Unusual Event Produced by Cosmic Rays", Il Nuovo Cimento Vol. I N. 3 (1955)

PHYSICAL REVIEW VOLUME 94, NUMBER 1 APRIL 1, 1954

A V-Decay Event with a Heavy Negative Secondary, and Identification of the Secondary V-Decay Event in a Cascade*

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(Received December 31, 1953)

Two cosmic-ray decay events have been photographed in a cloud chamber under conditions that yield mass values from combined magnetic-field momentum measurements and ionization measurements from droplet counting. A method has been developed for assigning meaningful probable errors to the ionization measurements. The first event is interpreted as the decay of a neutral V particle into a positive π meson and a negative particle of mass $1850\pm250m_e$. On the assumption of a two-body decay, the Q value for the decay is 11.7 ± 4 Mev. The second event is a cascade decay that can be summarized by the following reaction:

$$Y^- \to 67\pm12 \text{ Mev} + \pi^- + \Lambda^0$$
$$\searrow 40\pm13 \text{ Mev} + \pi^- + p.$$

The proton of the Λ^0 decay is identified by a measured mass of $2050\pm350m_e$. On the assumption of a two-body decay, the mass of the primary V particle is $2600\pm34m_e$.

"The mass of this particle is near or equal to that of a proton and is not consistent with the mass of any negative particle that has been identified… there is no clear evidence that the particle is actually an antiparticle to the proton. No annihilation phenomenon is observed…" (Cowan 1953)

E. W. Cowan, "A V-Decay Event with a Heavy Negative Secondary, and Identification of the Secondary V-Decay Event in a Cascade", Physical Review 94 (1954)

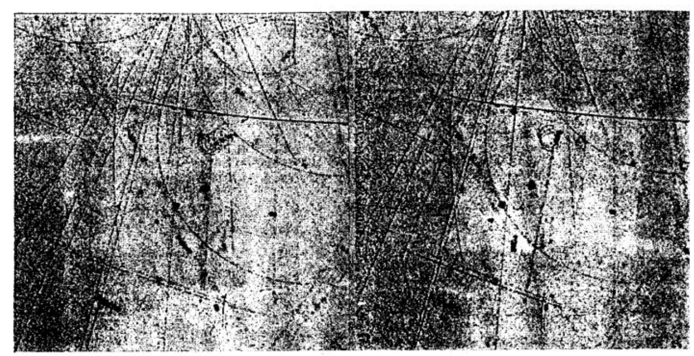

FIG. 1. A V-decay event with a heavy negative secondary.

"... The mass of this particle is near or equal to that of a proton and is not consistent with the mass of any negative particle that has been identified... there is no clear evidence that the particle is actually an antiparticle to the proton. No annihilation phenomenon is observed... "

E. Hayward, "Ionization of High Energy Cosmic-Ray Electrons", Physical Review 72 (1947)

(a) (b) (c)

FIG. 5. Cloud-chamber photographs of unusual events, as described in the text.

"... is a photograph of the track of a particle that ionized above five times as much as an average mesotron and also seems to have produced a huge shower in the lead below.... Other possible explanations are that... it is a negative proton giving up all of its energy in interacting with the lead plate"

M. Schein, D.M. Haskin, and R.G. Glasser, "Narrow Shower of Pure Photons at 100000 Feet", Physical Review 95 (1954)

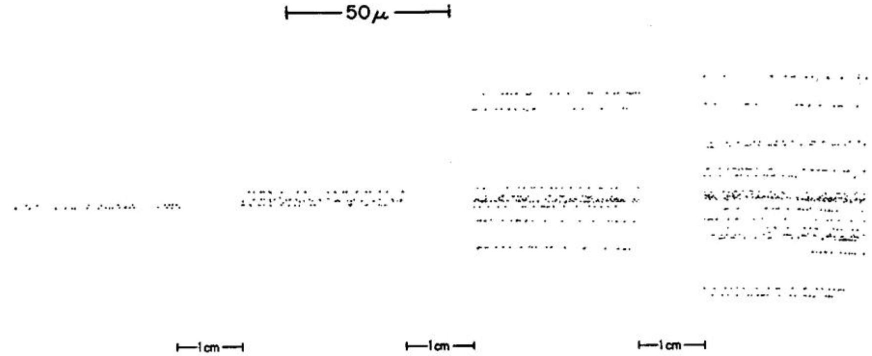

FIG. 1. Narrow shower of pure photons. Sections at arbitrary intervals to show development of shower. Note pair starting in last section.

" Such a phenomenon would appear to be incompatible with the production of these photons by any conventional electromagnetic process... One possibility... is that it may be produced by an annihilation process in flight at very high energy"

“Other possible explanations are that… it is a negative proton” (Hayward 1947)

“One possibility… is that it may be produced by an annihilation process” (Schein et al. 1954)

Possible Example of the Annihilation of a Heavy Particle*

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(Received June 21, 1954)

THE picture in Fig. 1 and the sketch in Fig. 2 show an unusual cosmic-ray event photographed with the M.I.T. multiplate cloud chamber at Echo Lake, Colorado. The chamber contained eleven brass plates, each 0.50 inch thick (11.1 g cm^{-2}) and was triggered by a penetrating-shower detector placed above it. Two additional views, taken at different angles, are available.

Three electron showers, *b*, *c*, *d*, appear to be associated with the stopping of a charged particle, *a*, in one of the plates. Within the experimental errors, the axes of the three showers and the direction of the last visible segment of track (*a*) intersect at one point in the plate.

From the number of small showers with no apparent origin occurring in our cloud chamber, we found an upper limit of 10^{-3} for the probability that either (*c*) or (*d*) may be a case of chance association. It is practically impossible to explain shower (*b*) in a similar way for a survey of about 10 000 pictures has not revealed a single shower of the size of (*b*), with no apparent origin and going upward.

H.S. Bridge, H. Courant, H. DeStaebler, Jr., and B. Rossi, "Possible Example of the Annihilation of a Heavy Particle", Physical Review 95 (1954)

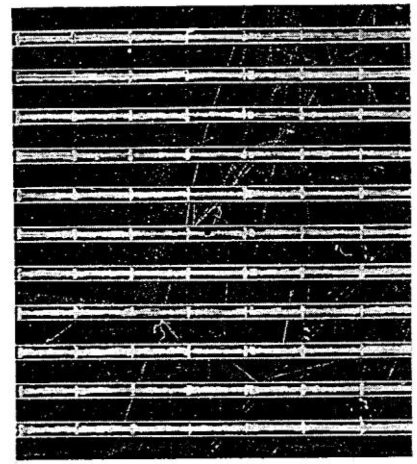


FIG. 1. Cloud-chamber photograph of the cosmic-ray event.

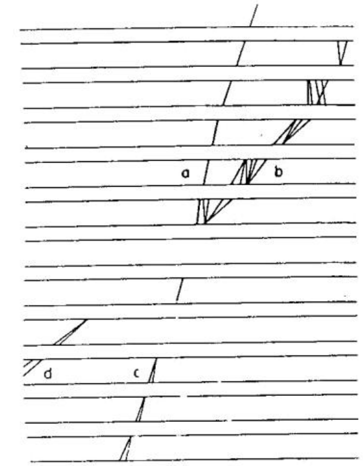


FIG. 2. Sketch of the cosmic-ray event.

"In view of the difficulties of interpreting the event as a decay or an absorption process, one should consider the possibility that the event represents the annihilation process of two heavy fermions. For example, the incident particle might be an antiproton (or an antihyperon) that undergoes annihilation with an ordinary proton. A large fraction of the energy liberated in such a process may well be changed into π^0 mesons and thus ultimately appear in the form of γ rays"

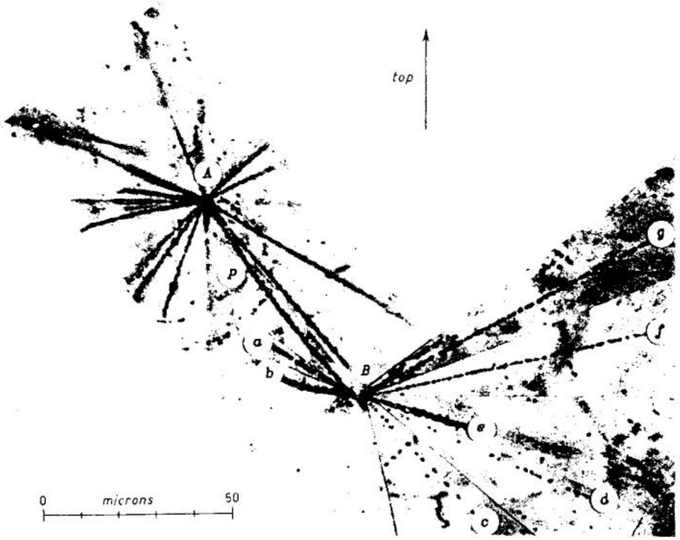
B. Rossi, Rochester Conference, 1956:

"... we used the photometric method to re-analyze the M.I.T. antiproton event, and found a value of 823 ± 155 Mev for the rest energy of this primary particle.... there is thus little doubt that the M.I.T. event was indeed the annihilation of an antiproton"

"… there is thus little doubt that the M.I.T. event was indeed the annihilation of an antiproton" (Rossi 1956)

"Unusual Event Produced by a Heavy Particle at Rest"

"Unusual Event Produced by Cosmic Rays"



"... the interpretation of this track in terms of a high energy fragment... is very improbable. Such a conclusion is definitely confirmed by the fact that the deflection of a fast fragment through an angle of 90° should be associated with a rather long recoil track, even in the case of a target nucleus as heavy as silver. No recoil is observed in the present case.... the track is due to a low energy particle.

... the event could also be due to an accidental coincidence in space. Therefore we have evaluated the probability for such a coincidence... the value is sufficiently small to entitle us to look for an interpretation of the observed event in terms of a physical process... We are left to consider the star B as produced by the track p. Then the corresponding particle either has rest energy of the order of 1.5 $\div$ 2 GeV, or, being an antiproton, it has been annihilated by a nucleon, releasing $2\ m_p c^2 = 1876$ MeV.

One can conclude that the probability of an accidental coincidence can not be disregarded although it is rather small. If one excludes this possibility the more likely interpretation seems to be that of an annihilation process of a heavy particle... the many questions raised by the discussion of this event will obviously find their final answer only if other similar events will be observed."

IL NUOVO CIMENTO VOL. I, N. 3 1° Marzo 1955

Unusual Event Produced by Cosmic Rays.

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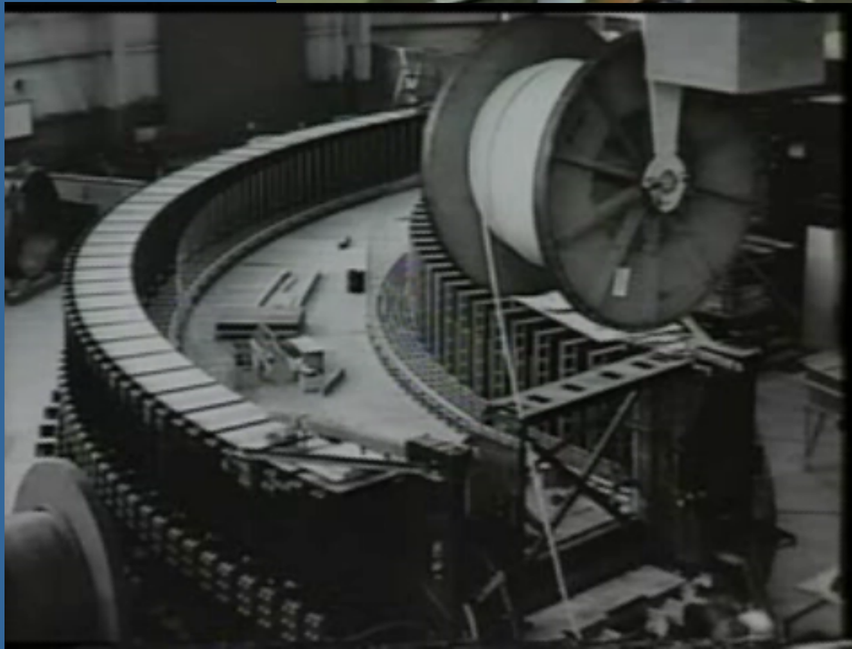
(ricevuto il 18 Febbraio 1955)

Summary. – The authors describe an event consisting of two stars respectively of about 5 and 1-2 GeV energy. The probable value of the number of accidental space coincidences that one expects to observe in the scanned volume, is about $4 \cdot 10^{-4}$. This value, although it does not allow us to exclude an accidental process, justifies the consideration of interpretations in terms of some physical process. Special attention is devoted to the production, capture and annihilation of a negative proton.

"Faustina", l'evento "strano" rintracciato all'inizio del 1955 dal gruppo di Roma nelle lastre esposte alla radiazione cosmica durante la spedizione di Sardegna del 1953

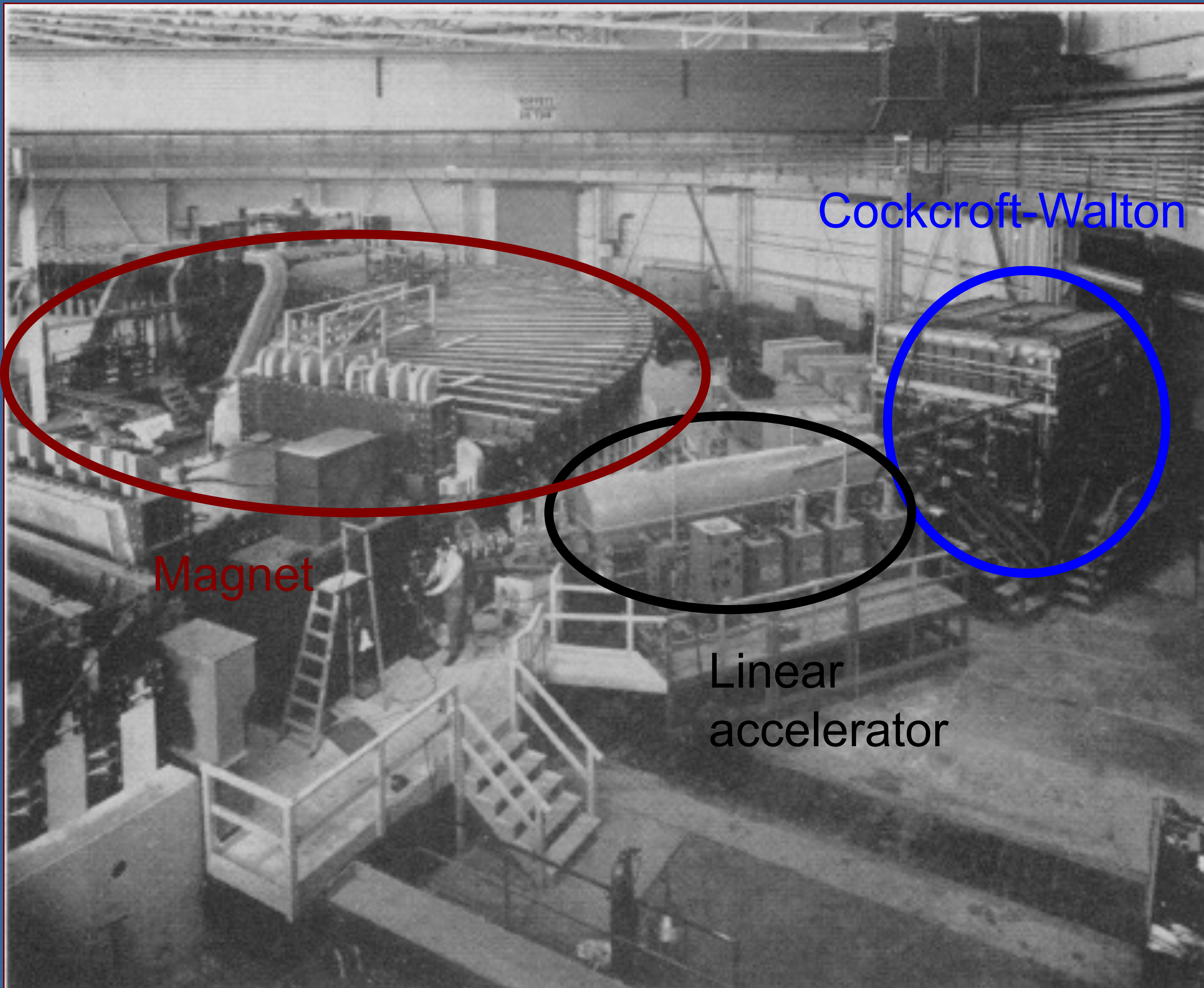
The Beginning

- Design started in 1947 under the direction of Ernest Lawrence. The primary designer was engineer William Brobeck.
- Construction began in 1949 at The University of California Radiation Laboratory at Berkeley. (The lab was later named the Lawrence Berkeley National Laboratory).
- The first beam at the full energy of 6.2 BeV (GeV) was delivered on April 1, 1954.



The Bevatron

- The protons are held in a circular path by a magnetic field.
- An accelerating electrode is used to give repeated increments of energy to the protons.
  - Electrodes are exited with radio frequency in synchronism with the particles.
- Unlike earlier accelerators, the radius of the particle is approximately constant.
  - The magnetic field varies during the accelerating cycle.
  - The frequency of the accelerating voltage increases with particle speed.

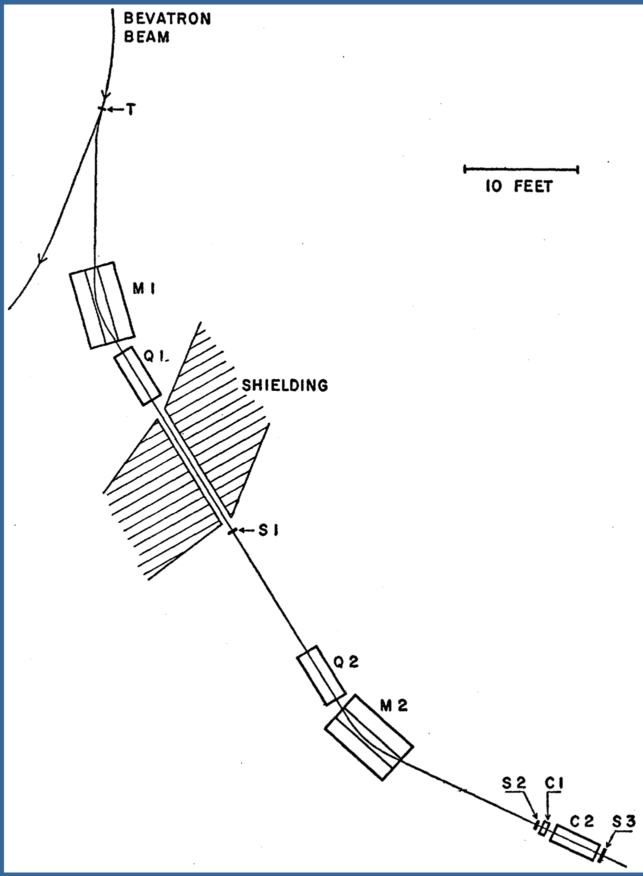

Cockcroft-Walton
Magnet
Linear
accelerator

Acceleration in the Bevatron

- At the time of injection into the Bevatron, the magnetic field is 300 gauss.
- Radio frequency power is applied to the accelerating electrode.
  - Each time the protons pass through the accelerating electrode, they gain 1500 eV.
  - The magnetic field and frequency of the accelerating power are continuously increased.
- After 2 seconds, the magnetic field has increased to 15,500 gauss, and the protons have an energy of 6.2 BeV (GeV).

Antiprotons or Pions?

- The antiprotons had to be found in large background of π^-.
- The negative particles were deflected and focused by magnet M1 and quadrupole focusing magnet Q1.
- The particles passed through scintillation counter S1.
- The particles were again focused and deflected by Q2 and M2 on their way to S2.
- By measuring the time of flight between S1 and S2, antiprotons could be distinguished from π^-.
- *S1* and *S2* are *12 m* apart in the beam. The time of flight for π (with $\beta > 0.96$) for this distance was *40 ns*, while for antiprotons ($\beta \sim 0.76$) it was *51 ns*.

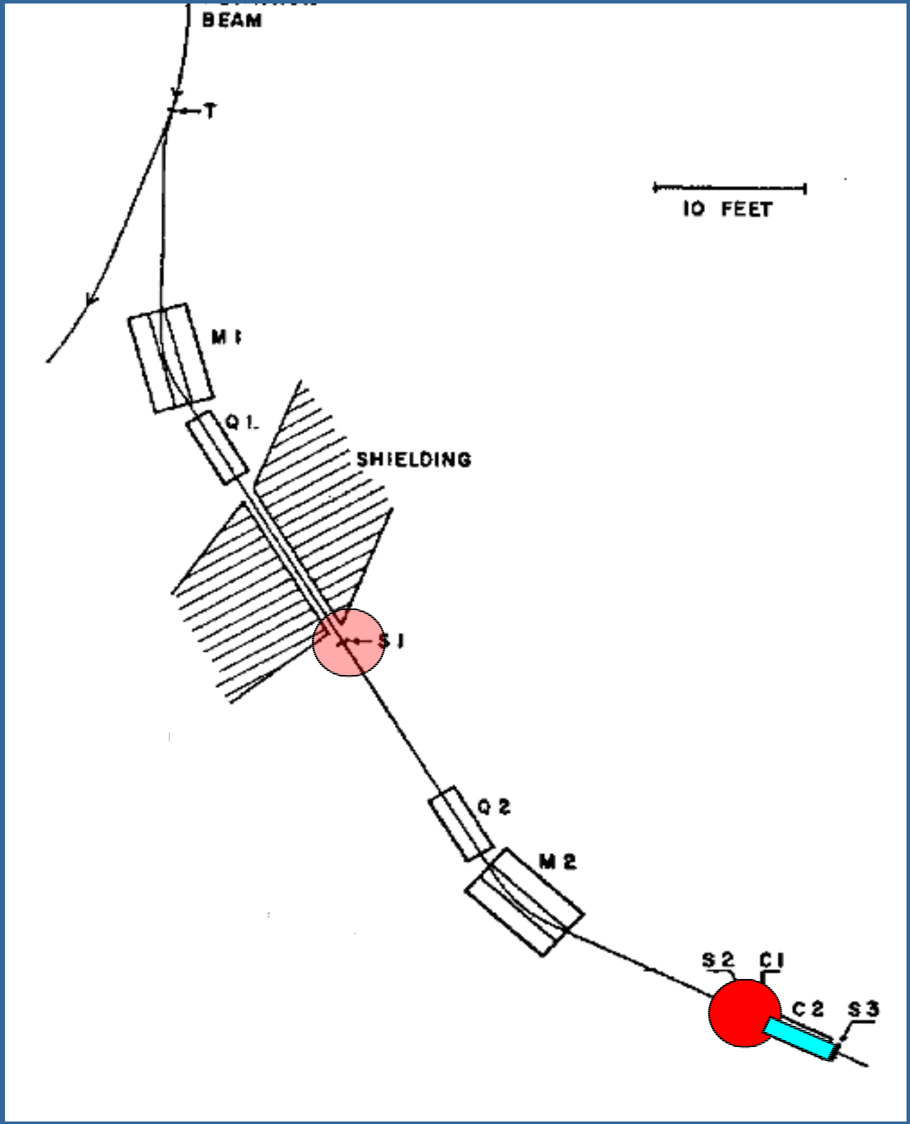


Antiprotons or pions?

Since the antiprotons must be selected from a heavy background of pions it has been necessary to measure the velocity by more than one method.... C2 is a Cerenkov counter that counts particles only within a narrow velocity interval 0.75 < β < 0.78 ... the requirement that the particle be counted in this counter constituted one of the determinations of the velocity of the particle....

the apparatus has some shortcomings ... Accidental coincidences between S1 and S2 cause some mesons to count .... [and] C2 could be actuated by .... [one of these] if the meson suffered a nuclear scattering in the radiator of the counter [C2] . ... Both of these deficiencies have been eliminated by the insertion of the guard counter C1 , which records all particles of β > 0.79. A pulse from C1 indicates a particle (meson) moving too fast to be an antiproton of the selected momentum and indicates that this event should be rejected

Chamberlain et al., 1955 [10]



Observation of Antiprotons*

Owen Chamberlain, Emilio Segrè, Clyde Wiegand, and Thomas Ypsilantis

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

(Received October 24, 1955)

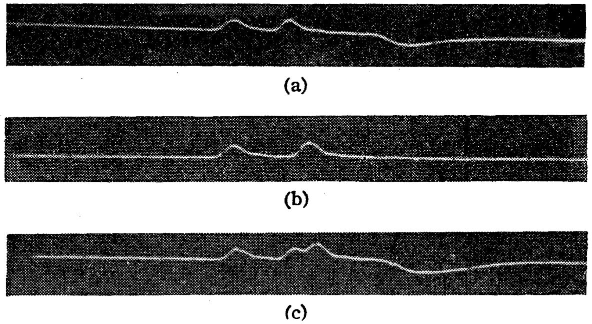


Fig. 2. Oscilloscope traces showing from left to right pulses from $S1$, $S2$, and $C1$. (a) meson, (b) antiproton, (c) accidental event.

- Antiprotons were discovered in 1955.
  - 1959 Nobel Prize in Physics for Chamberlain and Segre.
- Antiprotons have a time of flight over the 40 ft interval of 51 ns.
  - 40 ns for π⁻.

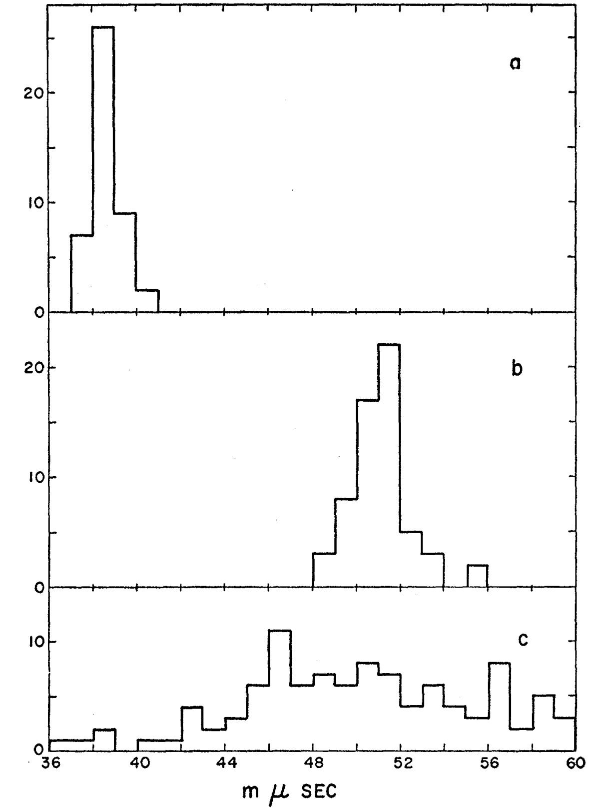


Fig. 3. (a) Histogram of meson flight times used for calibration. (b) Histogram of antiproton flight times. (c) Apparent flight times of a representative group of accidental coincidences. Times of flight are in units of 10^{-9} sec. The ordinates show the number of events in each 10^{-10}-sec intervals.

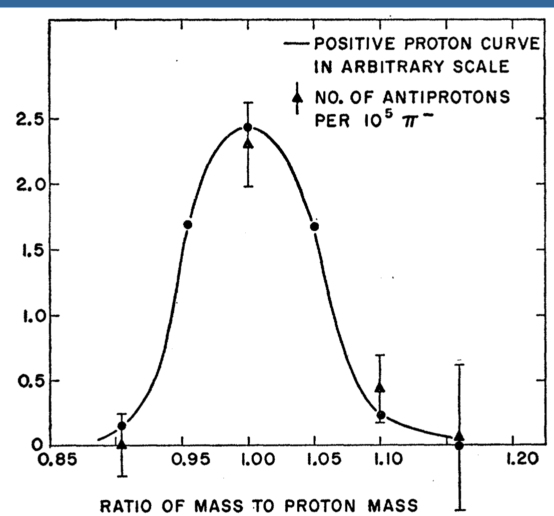


Fig. 4. The solid curve represents the mass resolution of the apparatus as obtained with protons. Also shown are the experimental points obtained with antiprotons.

Visual Confirmation

- The left picture is the annihilation star from an antiproton, viewed in photographic-emulsion stack experiments.
  - Led by Gerson Goldhaber of Segre’s group.
- The right picture is a bubble chamber image.
  - The antiproton enters from the bottom.
    - Upon striking a proton, four positive and four negative pions are created.