The Bevatron: Discovery of the Antiproton

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Dirac's Equation and Antimatter

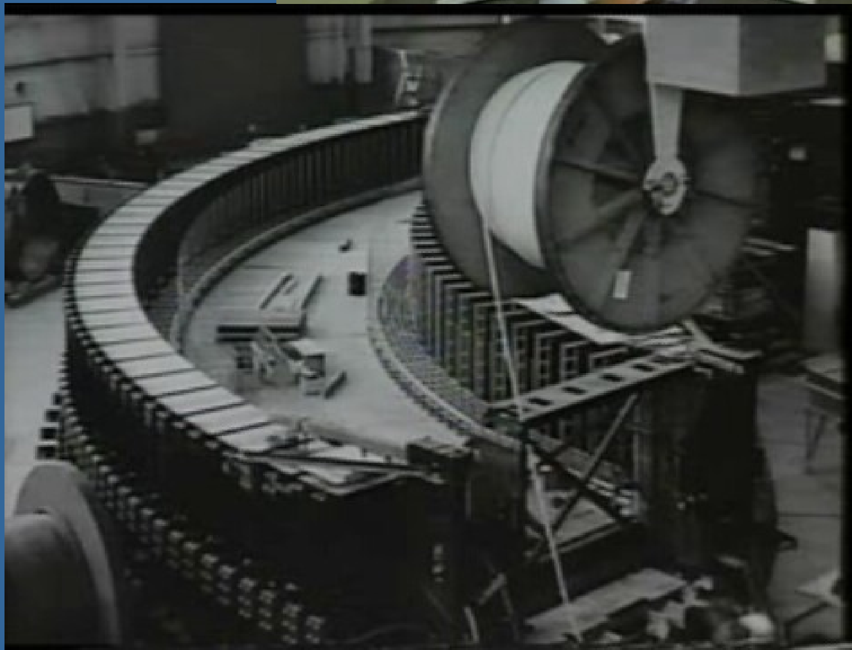
- In 1928, Dirac formulated a theory describing the behavior of relativistic electrons in electric and magnetic fields.
  - Dirac's equation has negative energy solutions, implying the existence of antimatter.
- The positron was discovered in 1932 from cosmic ray experiments.
  - This method would not 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.

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.

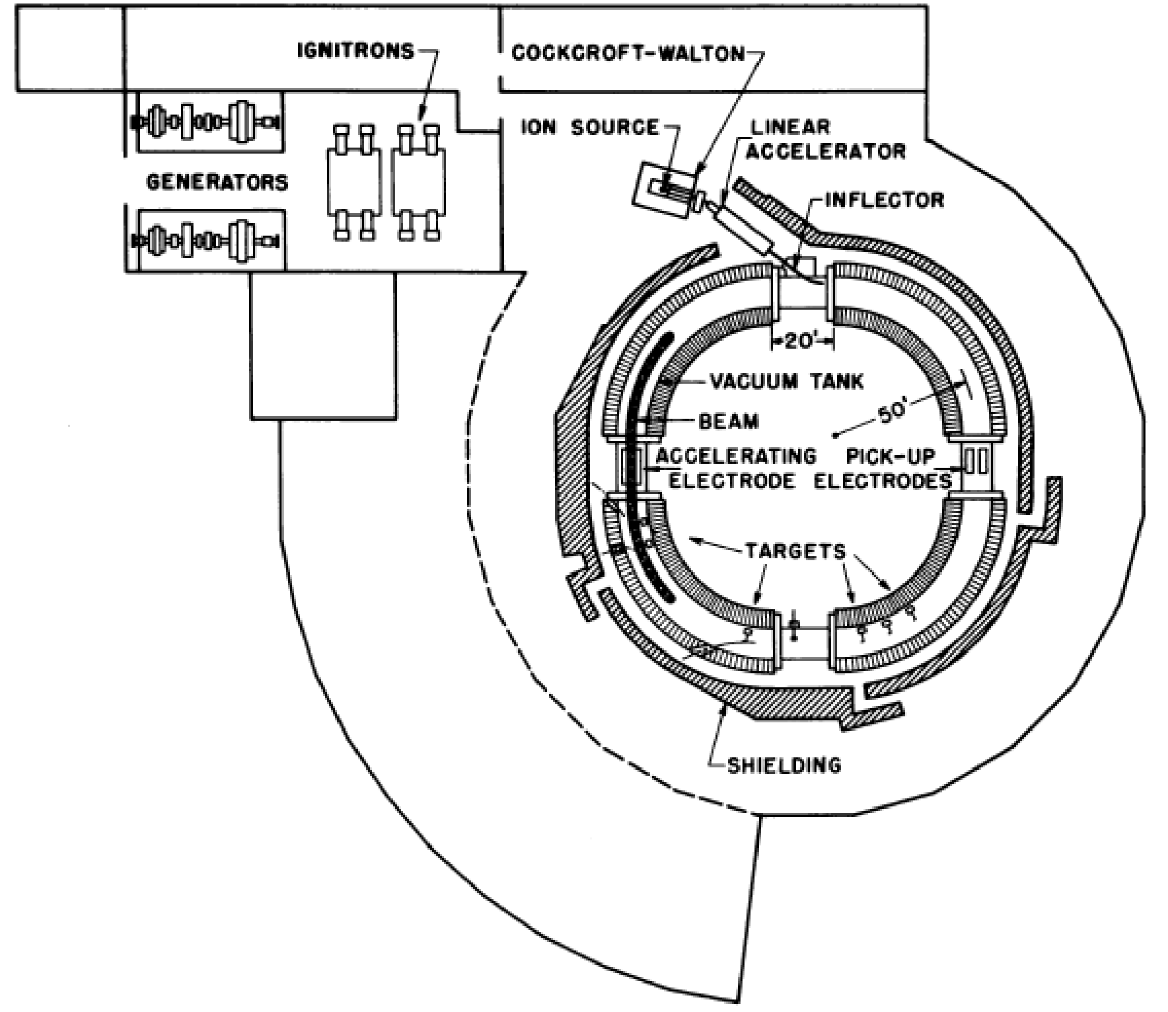


The Bevatron

- 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.

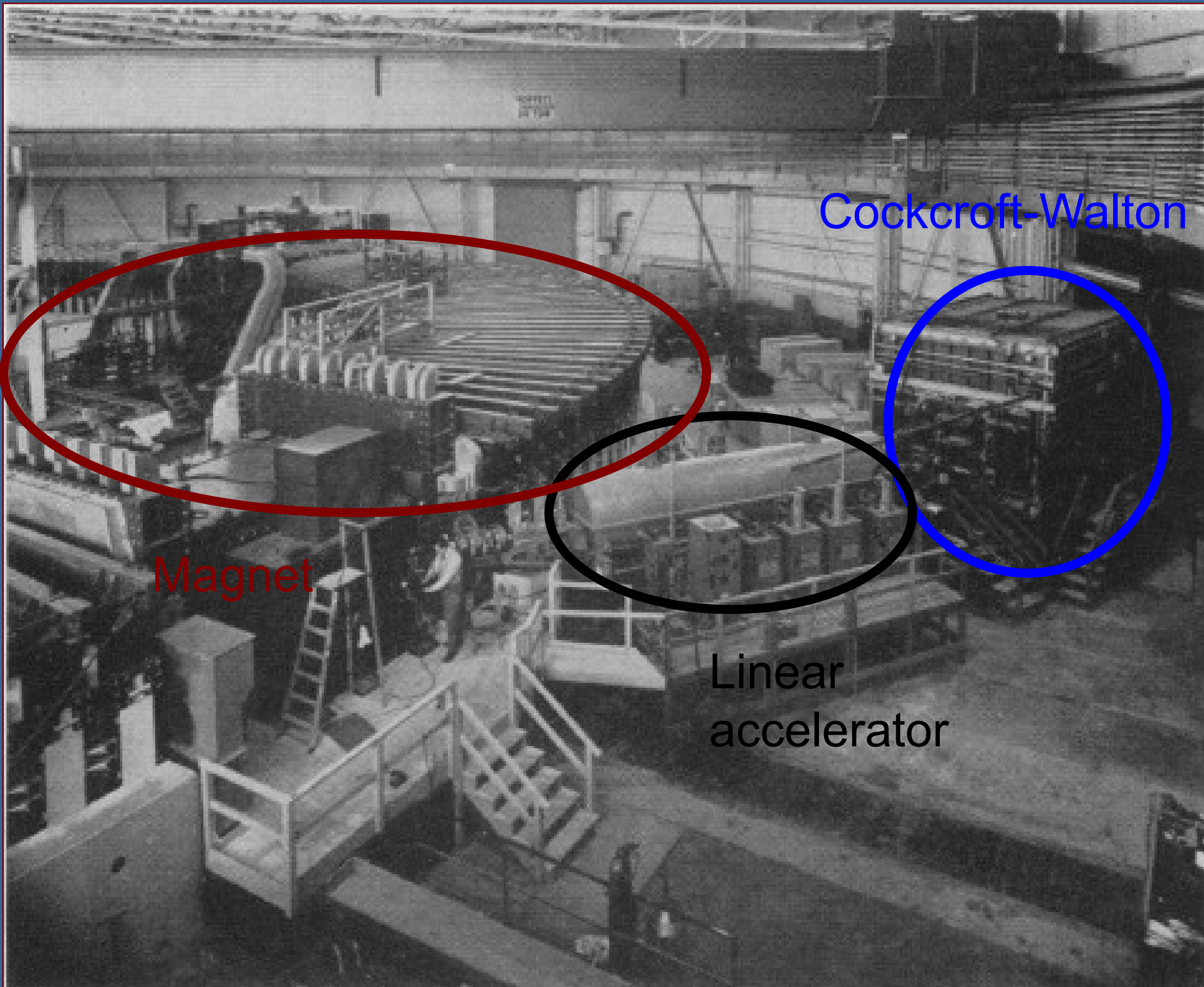
The Components

- The magnet
  - Four pieces, 50 ft. radius, separated by 20 ft.
- The vacuum tank
  - Extends through magnet quadrants and space between them.
  - Provides a proton path of about 400 ft in circumference.



Injection System

- The first part of the injection system is a 0.5 MeV Cockcroft-Walton accelerator.
  - A DC potential from a voltage-multiplying rectifier is applied to protons from a hydrogen discharge.
- These protons are injected into a linear accelerator.
  - It is a copper vacuum tank with an alternating axial electric field.
  - Hollow tubes are placed at appropriate spacings.
    - The protons are inside the field free tubes when the field would be decelerating them.
    - The protons are between the tubes when the field would accelerate them.
  - The protons are accelerated to 10 MeV and injected into the Bevatron.

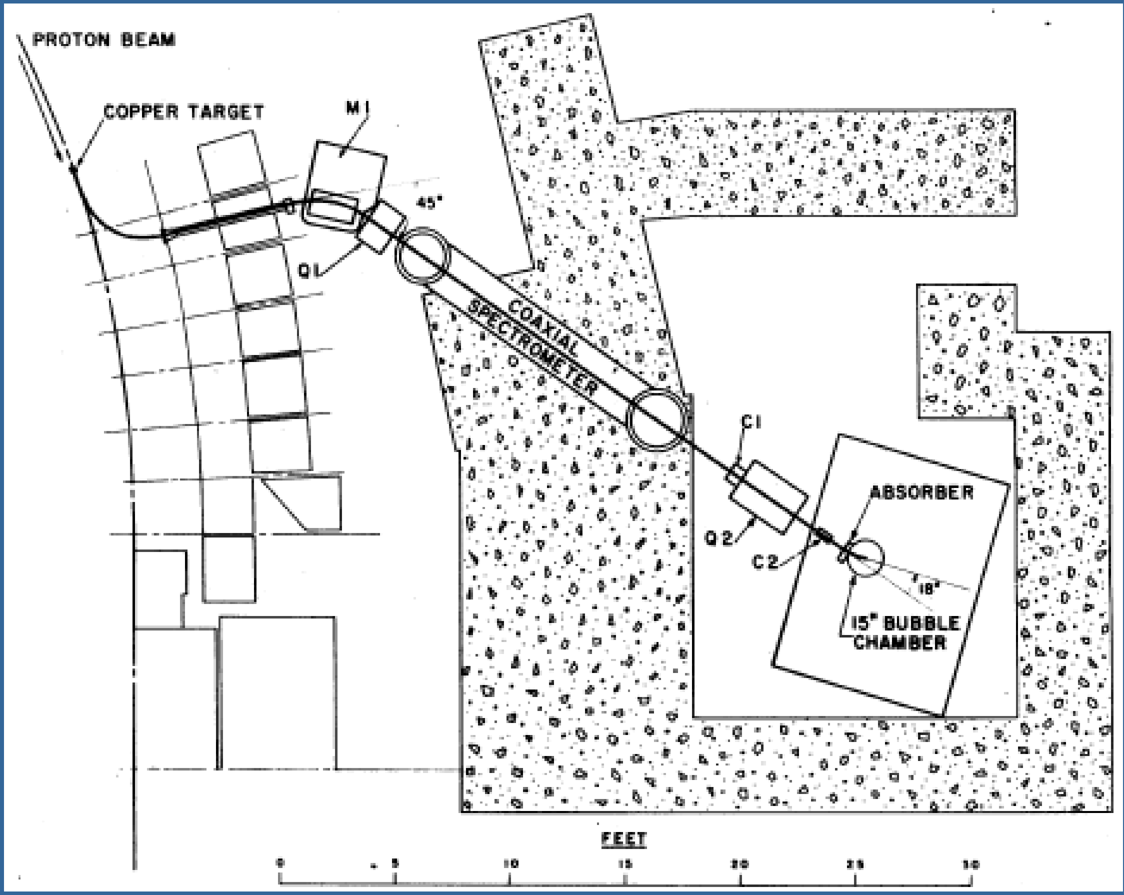

Cockcroft-Walton
Magnet
Linear
accelerator

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).

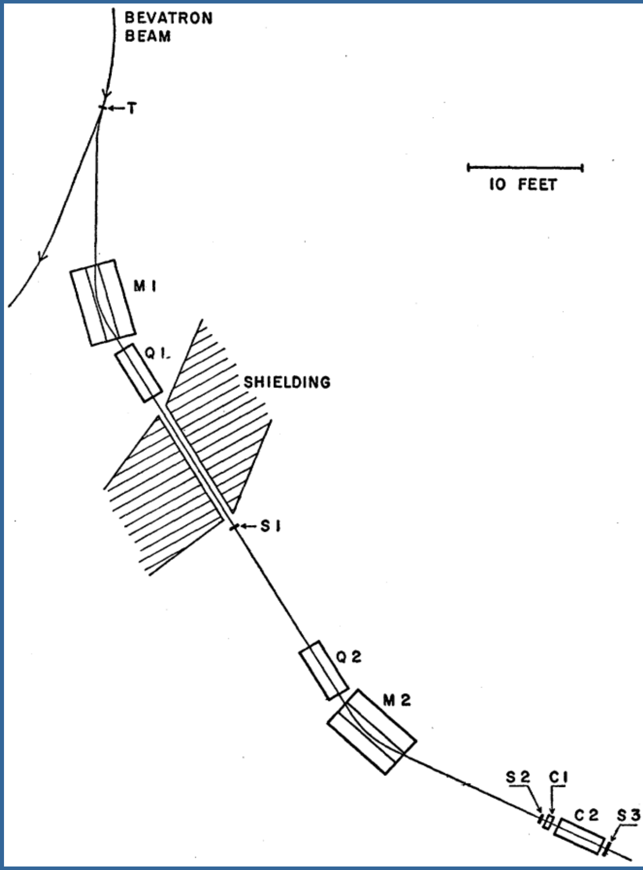
Striking the Target

- When fully accelerated, the beam has a cross section of a few square inches.
- The target is moved into place.
- The beam path is changed by altering the radio frequency or by using an auxiliary magnet.
- The beam strikes the target.
  - 10^{11} protons are accelerated per pulse.



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^-.



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)

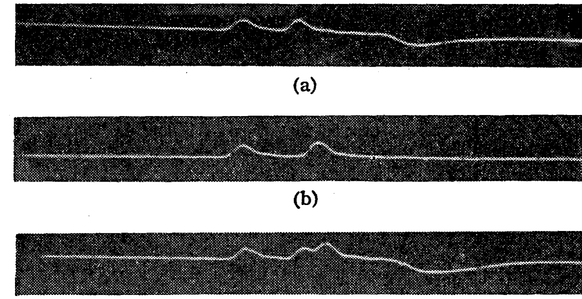


Fig. 2. Oscilloscope traces showing from left to right pulses from *S*1, *S*2, and *C*1. (a) meson, (b) antiproton, (c) accidental event.

- 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^-.

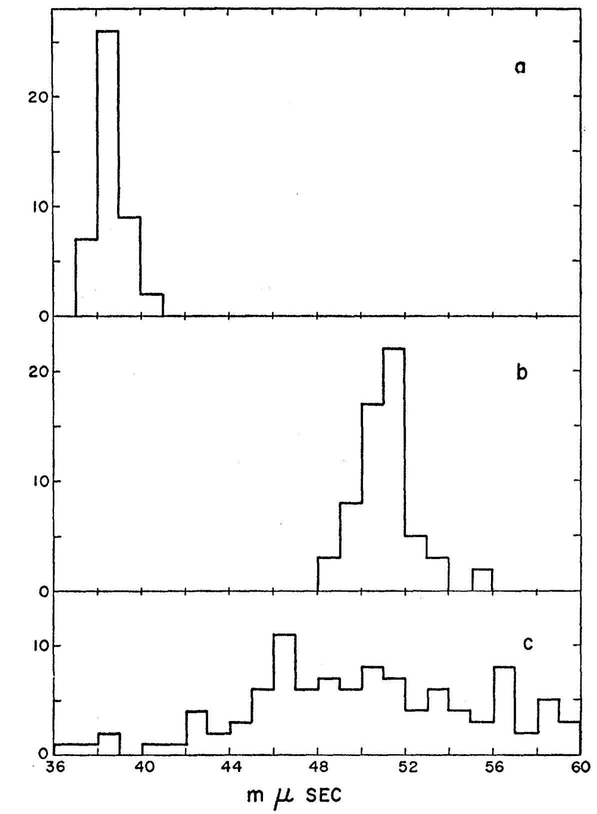


Fig. 3. (a) Histogram of meson flight times used for calibration. (b) Histogram of antiproton flight times. (c) Apparent flight times of a representative group of accidental coincidences. Times of flight are in units of 10^{-9} sec. The ordinates show the number of events in each 10^{-10}-sec intervals.

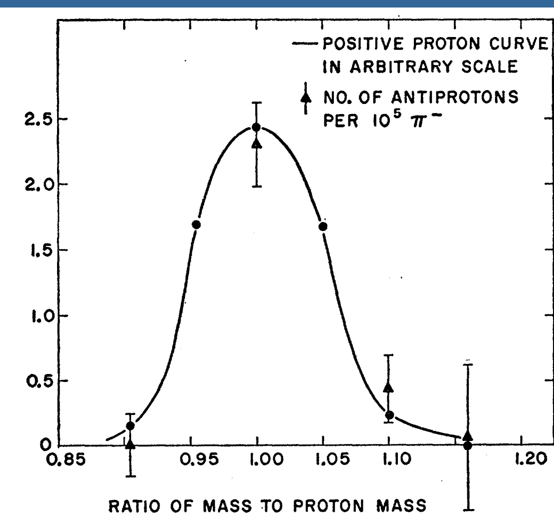
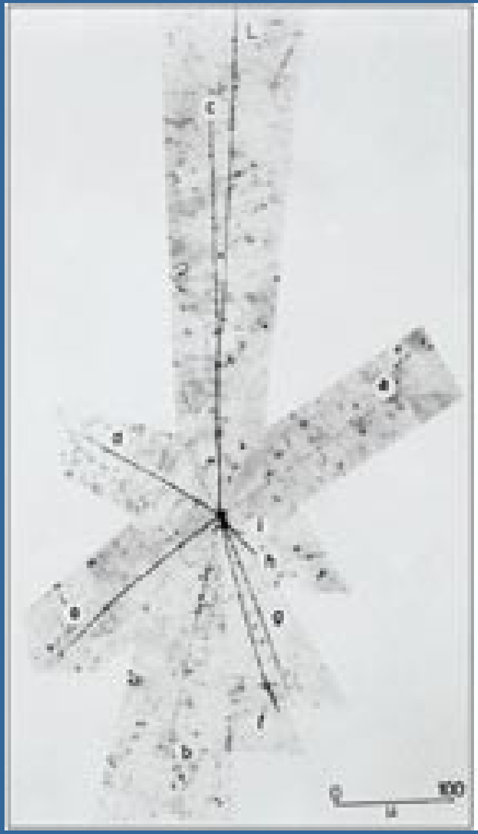


Fig. 4. The solid curve represents the mass resolution of the apparatus as obtained with protons. Also shown are the experimental points obtained with antiprotons.

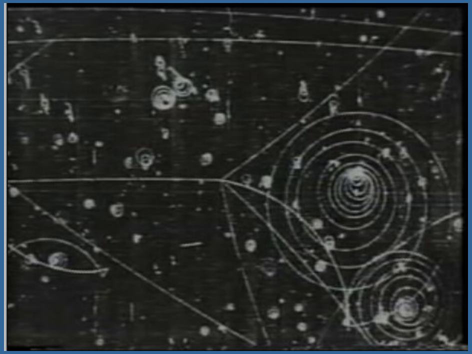
Visual Confirmation

- 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.



A Selection of Other Significant Advances

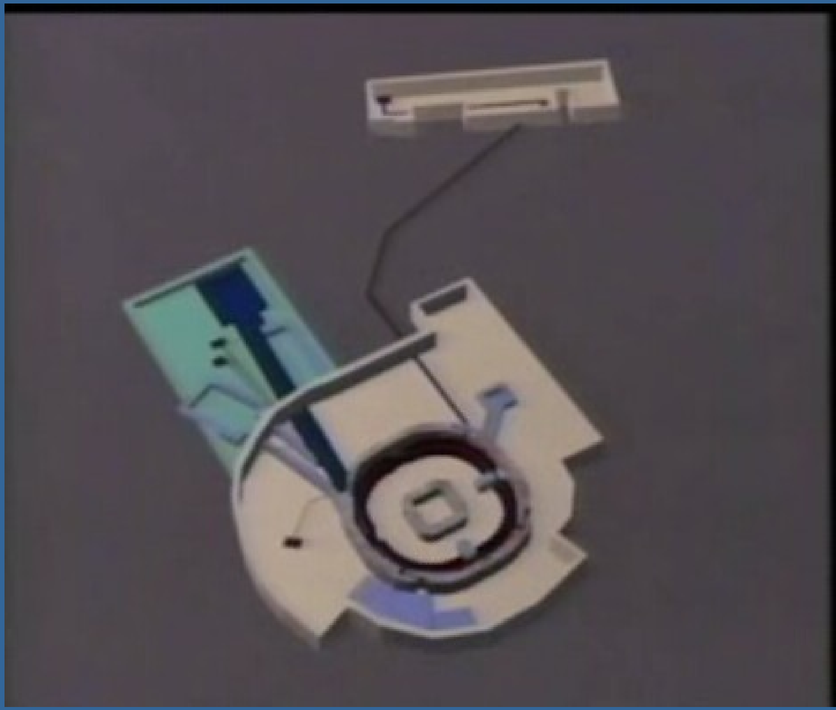
- Mass measurements of different K particles, as well as other particles, such as: τ, $K_{\mu 2}$, $K_{\pi 2}$, $K_{\mu 3}$, and K_e



- Development of the liquid hydrogen bubble chamber.
  - 1968 Nobel Prize in Physics for Luis Alvarez.
- Used the bubble chamber to observe parity violation in the decay of A hyperons in 1956.
- Discovered resonances such as Y*(1385), K*(890), and Y*(1405).

The Bevalac

- As a proton accelerator, the Bevatron became obsolete.
- In the 1970s, it was connected to the SuperHILAC linear accelerator.
  - Heavy ions from the linear accelerator were directed into the old Bevatron for continued acceleration.
  - This combination, the Bevalac, could now be used for heavy ion physics.
  - The Bevalac could accelerate all elements up to Uranium.

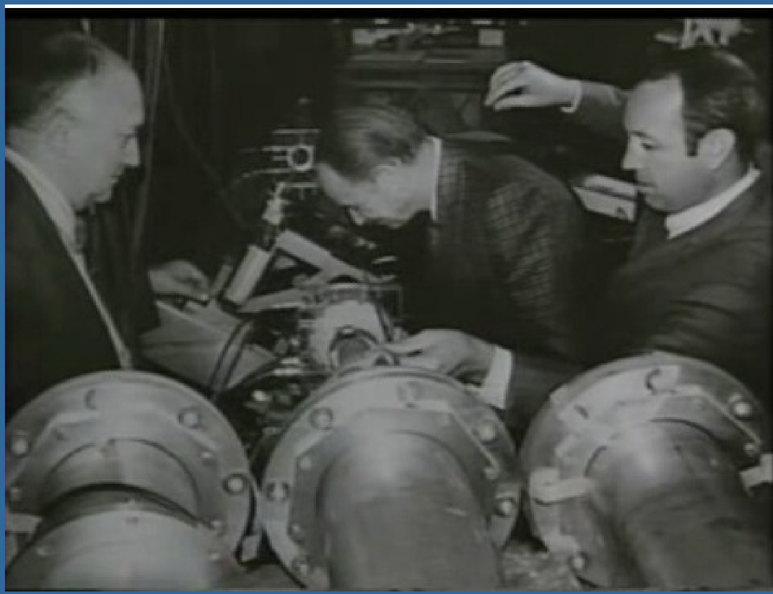


Cancer Treatment

- From the 1970s through the 1980s, over 1330 patients were treated with charged particle beams (often helium or neon ions).
  - The charged particles can be directed more precisely.
  - More effective at killing tumor cells, and at avoiding healthy tissue.

Space Studies

- Could test the effect of cosmic rays on astronauts.
- The goal of one particular experiment was to understand what was keeping astronauts awake.
  - Astronauts claimed to see flashes of light when their eyes were closed.
  - Bevalac scientists actually looked directly into the heavy ion beam, and saw similar flashes.
    - Astronauts were seeing heavy ions in cosmic rays.



Shutdown and Demolition

- The Bevatron was closed in 1993.
  - The beam was turned off permanently on February 20, 1993.
- Demolition started in 2009 and is scheduled for completion in 2011.

References

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