The Antiproton and how it was Discovered

J. Eades,
RIKEN Workshop on Physics with Ultra-Slow Antiproton Beams

December 2005 - 50th anniversary of letter to the Physical Review, announcing discovery of the antiproton at the Berkeley Bevatron

I think that this discovery of antimatter was perhaps the biggest jump of all the big jumps in physics in the 20th century.

Werner Heisenberg (in "The Physicist's Conception of Nature", 1972)

I believe that the antiproton story starts with P.A.M. Dirac, who in 1930 published his paper 'A Theory of Electrons and Protons'

E. Segrè : Talk at the 1985 Symposium 'Pions to Quarks – Particle Physics in the 1950s'

Dirac 1930

Einstein: $E^2 = p^2 c^2 + m^2c^4$

mc^2

Ground.

$- mc^2$

PROBLEMS

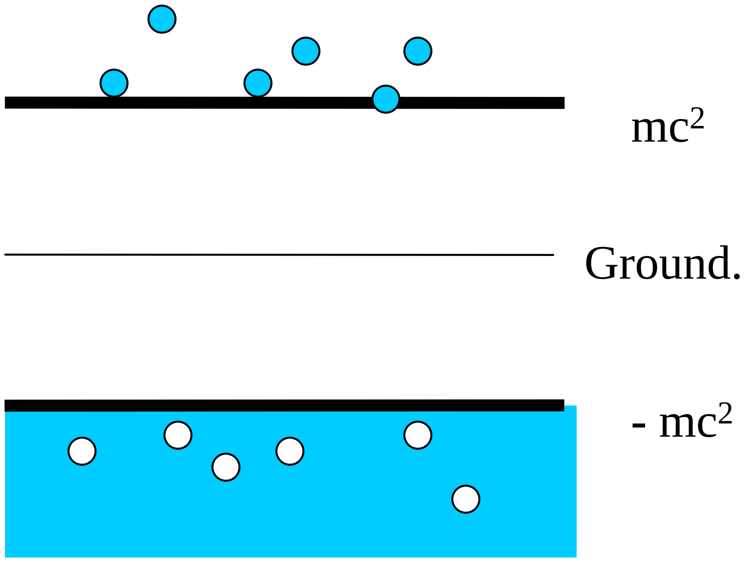
Instability : Transitions to negative energy states can't be avoided in quantum mechanics (although in classical physics they can)

Why then don't all the electrons in the universe just deexcite to infinitely negative energies ?

Way out: exclusion principle

Let us assume that there are so many electrons in the world that all the states of negative energy are occupied except perhaps a few of small velocity. …… We shall have an infinite number of electrons in negative energy states and indeed an infinite number all over the world …..

Dirac, Proc Roy Soc A126 p360, 1 Jan 1930.



But then Maxwell's equations give : div E = - 4 π ρ

so we must find an ∞ div E everywhere

…….but if their distribution is exactly uniform we should expect them to be unobservable….. Only the small departures from uniformity brought about by some of the negative energy states being unoccupied can we hope to observe…

We are led to the assumption that the holes in the distribution of negative energy electrons are the protons.

Dirac, Proc Roy Soc A126 p360, 1 Jan 1930.

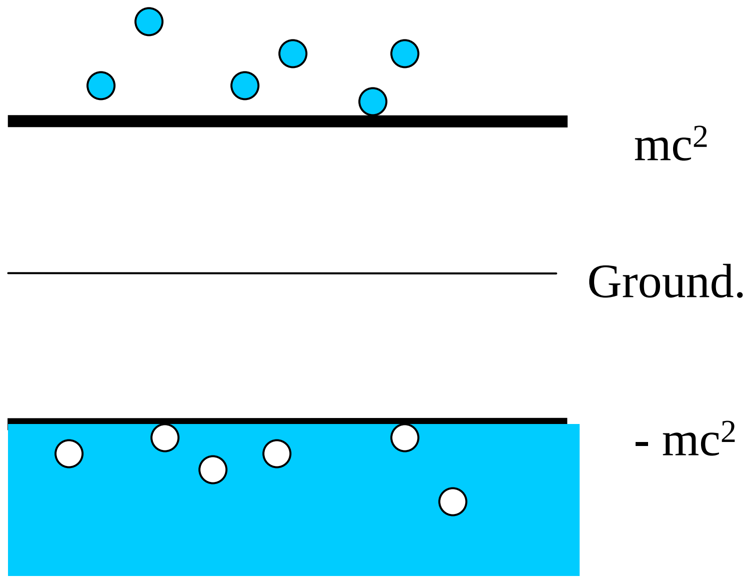
Particle/Cosmological ‘engineering’

a) If, at some time in the past, universe of electrons relaxed into a ‘ground-state’ where nearly all negative energy states are filled, the photons radiated must still be around and can excite transitions negative ↔ positive energies ….

b) Redefinition of the vacuum - forerunner of vacuum renormalisation

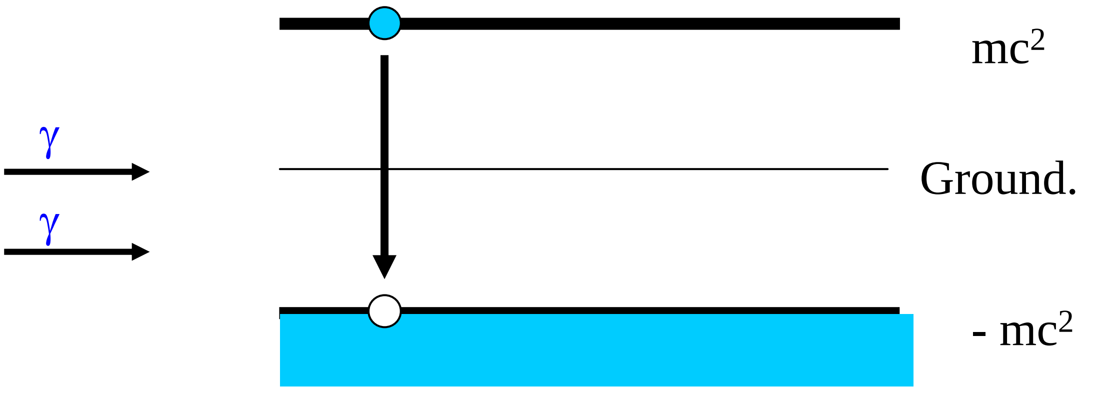
c) If *Unitary Theory* (holes left behind among negative states are protons) is correct - why do the masses of protons and electrons differ so much ?

d) Implicit resurrection of the aether idea….



How long will universe last against annihilation into photons ?

$p^+ + e^- \rightarrow 2\gamma$



Oppenheimer calculated: $T = (m + M)^2 c^3 / 64 \pi^5 e^4 n_p$

n_p local proton density $\approx 10^{25}$ cm^{-3}, m and M are e and p masses

$T = 10^{-10}$ sec *[NB: he made a mistake of a factor $(2\pi)^4$]*

Dirac calculated: $T = m^2 c^3 / \pi e^4 n_e = 1 / n_e \pi r_e^2 c$

n_e = the *hole (unfilled states)* density = proton density n_p

With $m = m_e$ $T = 10^{-9}$ sec With $m = M_p$, $T = 10^{-3}$ sec

[NB: $r_e = \alpha^2 a_0 = 2.8 \times 10^{-15}$ m appears in both formulae $\Rightarrow T \approx 1/ n_e \sigma_e c$ *]*

Oppenheimer and Weyl: first hint of the antiproton

If we RETURN TO THE ASSUMPTION OF TWO INDEPENDENT PARTICLES, WE CAN RESOLVE ALL THE DIFFICULTIES RAISED IN THIS NOTE, and retain the hypothesis that the reason why no transitions to states of negative energy occur, either for electrons or protons is that all such states are filled.

Oppenheimer, Phys. Rev. vol 35 p 562 March 1930

Oppenheimer gets over these difficulties…but only at the expense of of the unitary theory of the nature of electrons and protons. …..There being now no holes which we can call protons, we must assume that the protons are really independent particles. THE PROTON WILL NOW ITSELF HAVE NEGATIVE ENERGY STATES WHICH WE MUST AGAIN ASSUME TO BE ALL OCCUPIED.

Dirac, Nature vol 126, October 18 1930

Subsequent investigation [WEYL] has shown that this particle necessarily has the mass of an electron and if it collides with an electron, the two will have a chance of annihilating one another much too great to be consistent with the known stability of matter… We must abandon the identification of holes with protons… A hole, if there were one, would be a new kind of particle, unknown to experimental physics, having the same mass and opposite charge to the electron. WE MAY CALL SUCH A PARTICLE THE ANTI-ELECTRON. WE SHOULD NOT EXPECT TO FIND ANY OF THEM IN NATURE

Dirac, Proc. Roy. Soc., A133 61 (1931)

Almost immediately, the e^+ *did* appear in nature

On Aug 2 1932, during the course of photographing cosmic-ray tracks produced in a vertical Wilson chamber …tracks were obtained which seemed to be interpretable only on the basis of the existence of … a particle carrying a positive charge but having a mass of the same order of magnitude as that normally possessed by a free negative electron …. In the course of the next few weeks other photographs were obtained which could be interpreted logically only on the positive-electron basis….

Anderson, Physical Review Vol 43 (1933) p 491

We have recently developed a method by which the high speed particles associated with penetrating radiation can be made to take their own photographs… It will be shown that it is necessary to come to the same conclusion that has already been drawn by Anderson from similar photographs. This is that some of the tracks must be due to to particles with a positive charge but whose mass is much less than that of a proton…

Blackett and Occhialini, Proc. Roy Soc. A139 (1933) p 699

The idea of the antiproton becomes explicit

The greater symmetry, however, between the positive and negative charges revealed by the discovery of the positron should prove a stimulus to search for the evidence of negative protons…

Anderson, Physical Review Vol 43 (1933) p 491

One would like to have an equally satisfactory theory for the proton. One might perhaps think that the same theory (as the electron one) could be applied to protons. This would require the possibility of the existence of negatively charged protons *forming a mirror image of the usually positively charged ones…. We must regard it as an accident that the earth (and presumably the whole solar system) contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about…. There would be no way of distinguishing them by present astronomical methods.*

Dirac, Nobel Prize lecture (1933)

The situation in 1955

Speculations about the existence or non-existence of antiproton were rife during the planning stages of the experiment, and even included a 25 cent bet between Physics Division Head EdMcMillan and Segrè. (By the way 25 cents was a heretofore unimaginably high amount when it came to bets by Segrè). Most of the members of our group were on the pro-antiproton side. The detailed technical planning for the experiment was done primarily by Chamberlain and Wiegand. Tom soon joined the effort and played an active role in all aspects of this work. I was a graduate student who was fortunate enough to be sucked in as well.

Herbert Steiner, private communication

…Until experimental proof of the existence of the antiproton was obtained, it might be questioned whether a proton is a Dirac particle in the same sense as the electron. For instance the anomalous magnetic moment of the proton indicates that the simple Dirac equation does not give a complete description of the proton.

Chamberlain et al., Physical Review 100 (1955) p 947

As to bets my brother Maurice did indeed bet [Hartland Snyder] $500 against the existence of the antiproton. As I understand his motivation 1) No antiproton galaxies, 2) The proton had an anomalous magnetic moment i.e. not obviously a Dirac particle like the positron. This was long before CP violation and Sakharov's argument.

Gerson Goldhaber, private communication

The antiproton experiment

There have been several experimental events recorded in cosmic ray investigations which might be due to antiprotons although no sure conclusion can be drawn from them at present.

Chamberlain et al., Physical Review 100 (1955) p 947

When we started thinking about an experiment to find the antiproton (1953-1954) we decided to build a spectrometer which could measure both mass and charge rather than trying to observer the annihilation process. This decision… turned out to be crucial.

T. Ypsilantis, in The Discovery of Nuclear Antimatter (L. Maiani and R.A. Ricci eds., Italian Physical Society, Bologna 1996

This spectrometer consisted of bending magnets to measure momentum, plus time of flight measurement

The Berkeley ‘spectrometer’

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 < < 0.78…

The velocity of the particles counted has also been determined by observing the the time of flight from counter S1 toS2, separated by 40 feet….

As outlined so far, the apparatus has some shortcomings …

** Accidental coincidences between S1 and S2 …*

** C2 could be actuated by …. meson suffered a nuclear scattering in the radiator…. …*

Both of these deficiencies have been eliminated by the insertion of the guard counter C1 , which records all particles of $\beta > 0.79$. A pulse from C1 indicates … that this event should be rejected

Chamberlain et al., Phys. Rev. 100 (Oct 1955) p 947

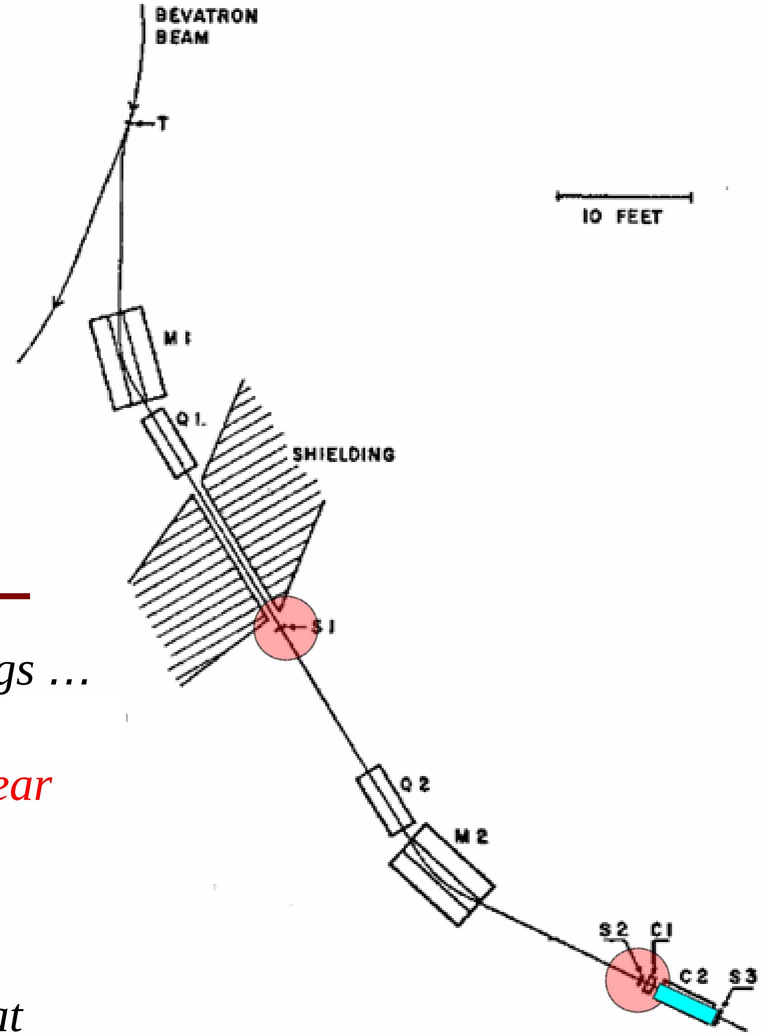


FIG. 1. Diagram of experimental arrangement. For details see Table I.

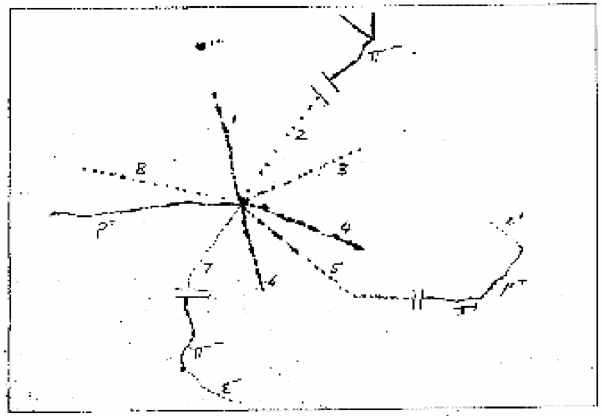
Confirmation from emulsion

SCIENCE

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-protons can exist permanently, but on earth they are short-lived. As soon as one of them touches the nucleus of an ordinary atom, it is annihilated. Both its own matter and the matter of a proton or neutron in the nucleus turn into a flash of energy.

Anti-protons were created last fall by the world's most powerful particle accelerator, the Bevatron, at Berkeley, Calif.,



DRAWING OF ANTI-PROTON TRACKS
P^- equals -2 particles.

but they could be detected only indirectly by a complicated electronic method ... Scientists wanted ... by one of the more direct methods that they use to make subatomic particles visible. So the Berkeley scientists shot anti-protons from their great machine into a stack of photographic films. Their hope was that they would find microscopic tracks in the films that could be identified as the work of an anti-proton.

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 to anti-protons (see cut).

The wheel like star tells what happens when one of the alien particles is annihilated. The anti-proton (P^-) enters from the left. It is moving fast at first, but gradually slows down and merges with the nucleus of some unfortunate atom. There it combines with a proton or neutron, and both particles vanish, turning 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 of the lines (1, 4 and 6) were traced by protons. The rest were made by pi mesons: short-lived particles that emerge when a nucleus is disrupted. There must have been neutrons too, but since they have no electric charges, they do not leave tracks in photographic film.

The 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 1,300 million electron volts. Since only 938 million electron volts can be released by turning a single particle into energy, more than one particle must have been annihilated. Physicists consider this an elegant proof that anti-protons really perform as theorists many years ago predicted that they would.

Balloons for the Jet Stream

A wily Japanese tactic in World War II was to launch balloons carrying small explosive or incendiary bombs in the hope that they would drift across the Pacific and land in the U.S. Some of them actually did land in the Pacific Northwest, and although they caused almost no damage, they proved that the westerly winds at high altitude are fine balloon carriers. Last week the U.S. Navy was following the Japanese lead by launching balloons of plastic film from Oppama, Japan. Instead of bombs the balloons carried instruments to report weather conditions encountered on their long voyages.

The Navy's balloons are helium-filled and 39 ft. in diameter. Besides their in-

I arrived as a postdoc to Berkeley in September 1955 and could follow the progress of the counter experiment. I got deeply involved in the parallel emulsion search and discovery of the annihilations.
Gösta Ekspong, private communication

However, the major crime was forgetting Fermi motion, protons were below threshold… For protons on a copper target at the Bevatron, the true antiproton threshold was only 3.5 GeV/c. At 6.2 GeV/c, the lab antiproton momentum distribution peaked at 0.6 – 0.7 GeV/c, not 1 GeV/c. So no degrader was necessary, just retune of the beam! Of course that was done later
D. Perkins, private communication

Aftermath: P, C, T, CP- violation and CPT invariance

Originally, [the equality of the] p- $\bar{p}$ charge, mass, spin, magnetic moment) were derived from C-invariance – a possible .physical situation is transformed into another possible physical situation. by changing the sign of all electric charges. Since this principle is violated in weak interactions, it is important to point out that it is not necessary to establish the properties listed above, but that the weaker requirement expressed by the invariance under CPT is sufficient ….

Segrè Ann Rev vol 8 (1958) p 127

It is not widely known that Dirac had never believed in either parity or time reversal invariance anyway.

A transformation of this (Lorenz) type may involve a reflection of the coordinate system in three spatial dimensions and it may involve a time reflection… I do not believe there is any need for physical laws to be invariant under these reflections, although the exact laws of nature so far known do have this invariance.

Dirac, Rev. Mod. Phys. , vol 21 (1949) p 392

Footnote: Antideuteron experiments a) at CERN….

In spite of not believing in P- and T- invariance, it is said that Dirac was convinced that C-invariance had to be valid right up until 1956, and did not accept the validity of the CPT theorem until the antideuteron was discovered in 1965…..

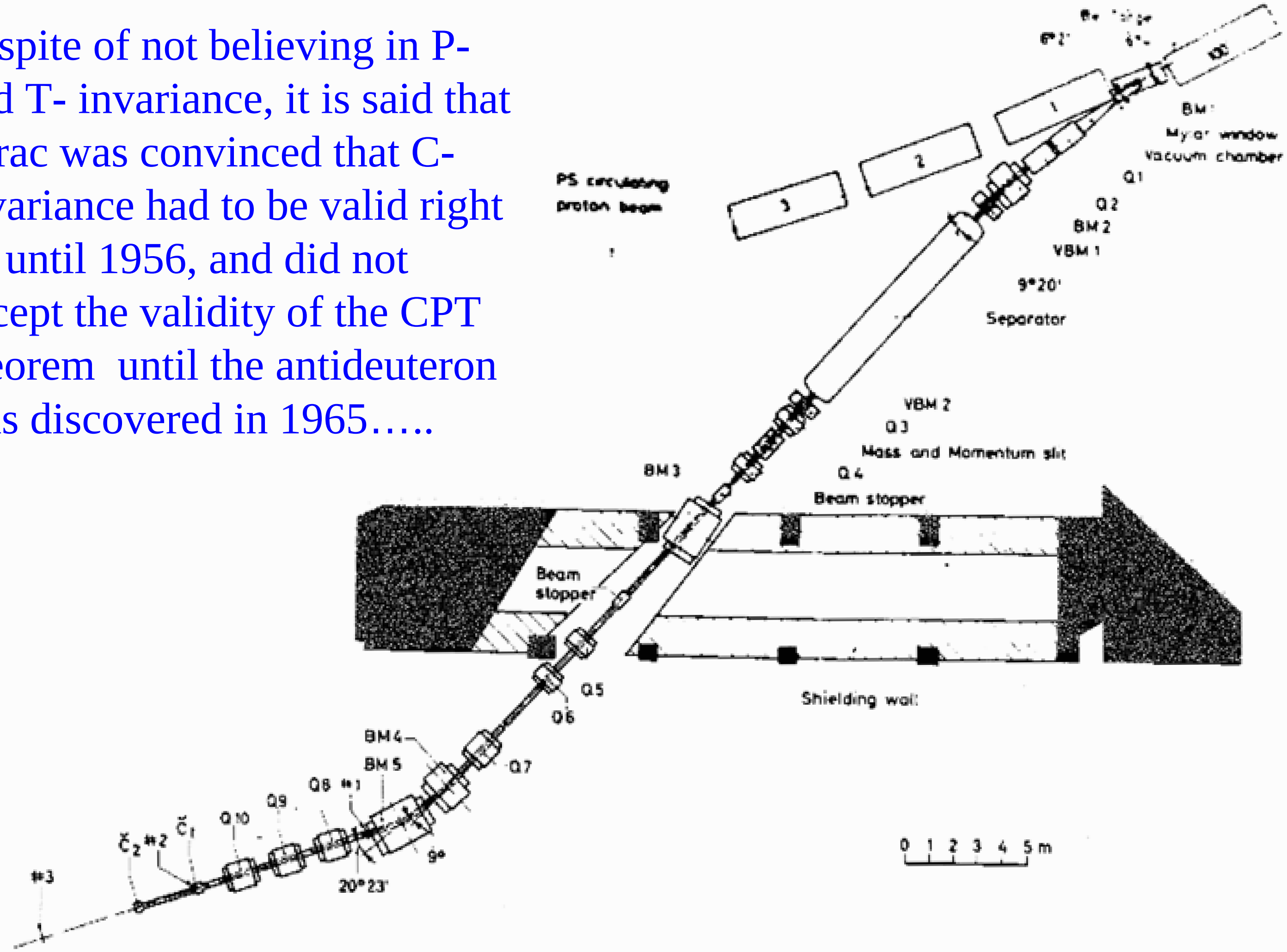
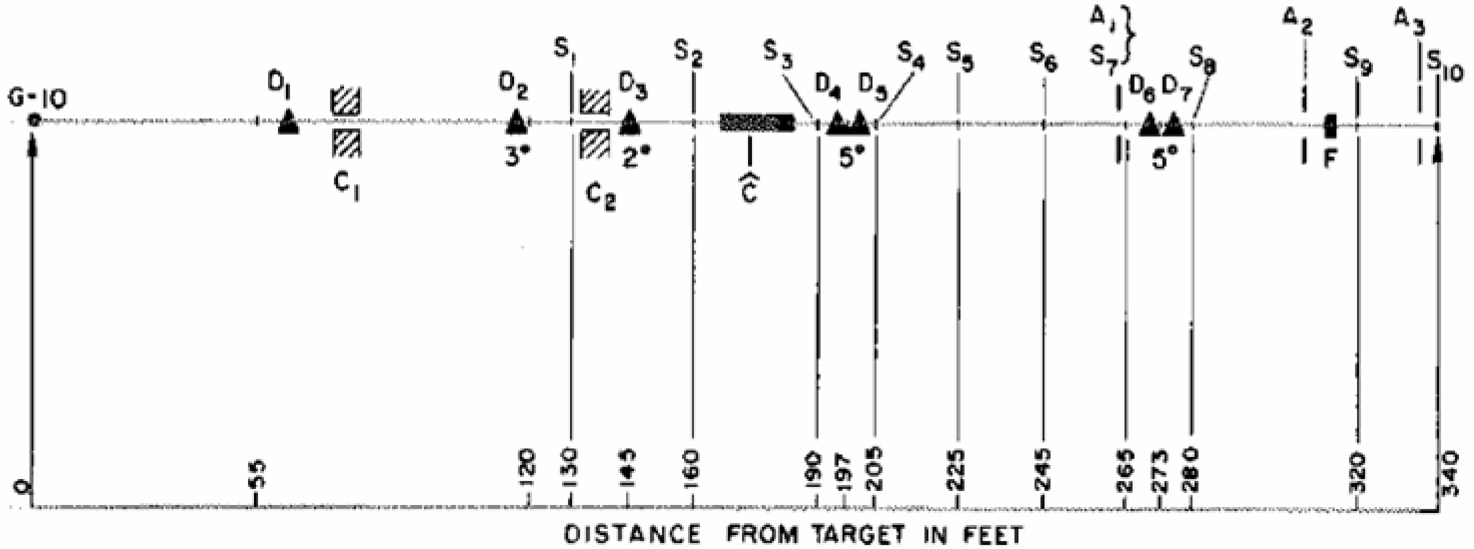


Fig. 1. – Beam layout and set-up. BM are bending magnets; VBM are two vertical bending magnets which compensate the deflection produced in the electrostatic separator; Q are quadrupoles; 1, 2, 3 are scintillation counters of $(12.5 \times 16.5 \times 0.8)$ cm^3 used for the time-of-flight measurements; $\check{C}_1$ and $\check{C}_2$ are gas Čerenkov counters filled with 5 kg/cm^2 of ethylene; they are 7.40 m and 2.50 m long respectively.

… and b) at BNL



SYMBOLS

▲	18 D72 DIPOLE MAGNET, DEFLECTIONS SHOWN FOR 10 BeV/c
C	COLLIMATORS
S	SCINTILLATION COUNTERS (APPROX. 4" X 5" X ⅛")
$\hat{C}$	30' H_2 CERENKOV COUNTER (7" DIA.)
F	5 cm (FITCH) CERENKOV COUNTER
A	GUARD COUNTERS

FIG. 1. Schematic beam layout.

In retrospect

If this story is concerning the antideuteron is true it could only be because the CPT theorem is a theorem about RQFTs , and no RQFT for hadrons existed in 1955 (or for decades afterwards). Only with a CPT-invariant QCD would the p-n binding be guaranteed to be the same as the $\bar{p}$- $\bar{n}$ binding.

In retrospect we can now see that the reason field theory failed back in the 1950s and 1960s to give an adequate account of the strong interactions was not that it was wrong but that it was misapplied. The fundamental fields of the strong interactions correspond not to the hadronic quanta but rather to the quarks, and the gluons that bind them together. In the mid 1970s theoretical physicists finally invented a successful field theory of the strong interaction – quantum chromodynamics – based on interacting quarks and gluons.

Heinz Pagels, The Cosmic Code p 295.

Conclusions

Science history is more difficult than science itself

Confusing mass of ideas papers and books, without the connections and sequenced presented in textbook accounts

All surrounded by complete mystery as to how much person A knew about what B was doing, and when did he know it

Symbols, terminology, modes of expression of the time are unfamiliar to us

BE SKEPTICAL OF ALL HISTORICAL ACCOUNTS

(INCLUDING THIS ONE !)

Thanks to Gösta Ekspong (Stockholm)
Gerson Goldhaber and Herbert Steiner (Berkeley)
Don Perkins (Oxford)
….and to Tom Ypsilantis………