ANTIMATTER

Academic Training Lectures
24 - 26 April 2006

Rolf Landua
CERN

Lecture Plan

I. History of Antimatter

II. Antimatter and the Universe

III. Production and trapping of antiparticles

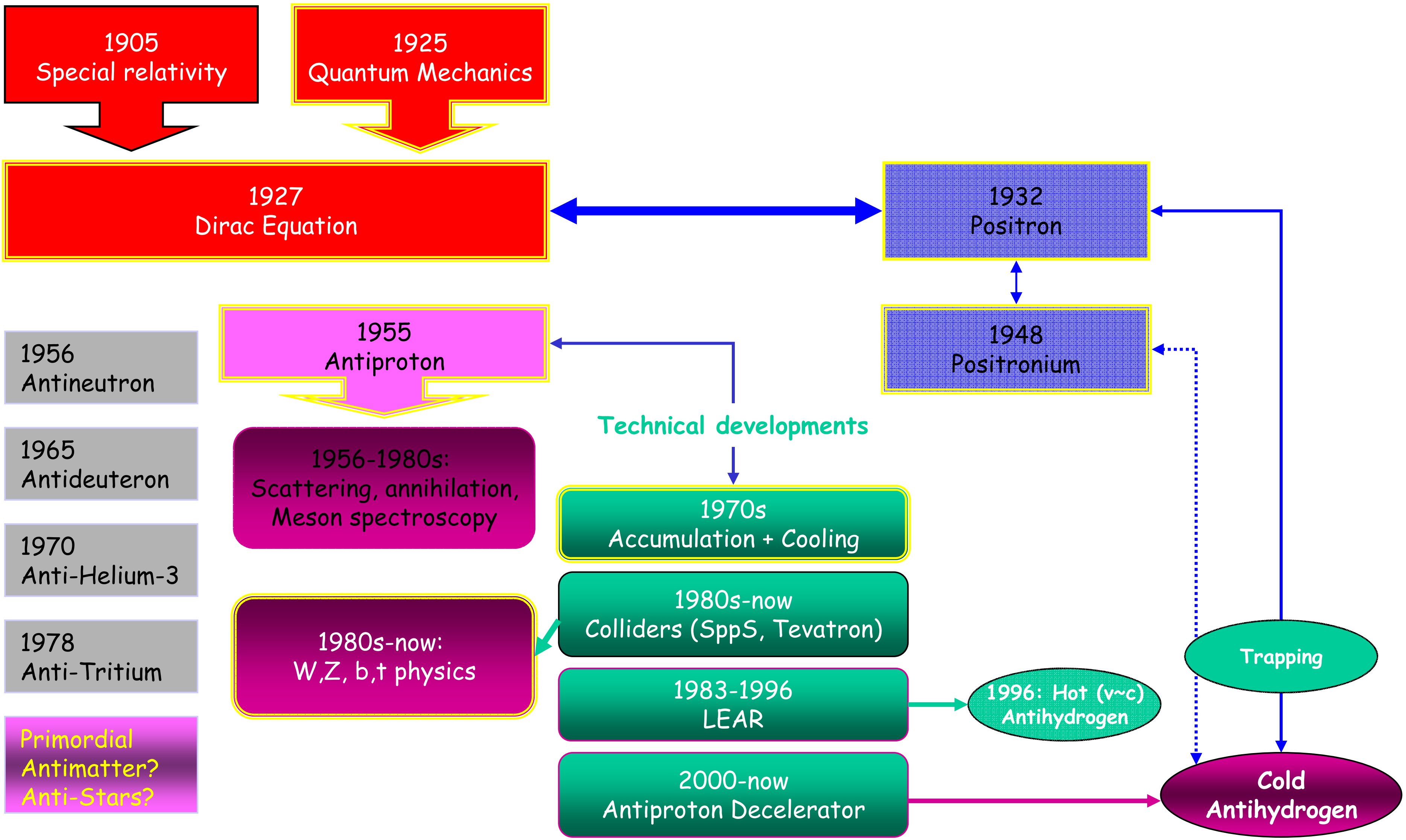
IV. Precision tests of particle-antiparticle symmetry

V. AD Physics and Antihydrogen

VI. Antimatter technologies

Goal: Overview about theoretical concepts, experiments and technologies

I. History - Overview



Early ideas of antimatter

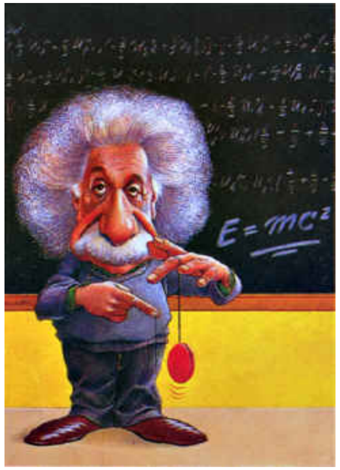
1897: J.J. Thompson discovers the electron

1898: The physicist Arthur Schuster writes to 'Nature' :

If there is negative electricity, why not negative gold, as yellow as our own ?

1905: Relativity

All attempts to find a motion of e.g. the Earth with respect to the "ether" had failed. The speed of light had the same value independent of the relative velocity between source and observer.



Einstein:

1) No preferred inertial system
2) Speed of light always constant

Consequences:

- Lorentz transformations of space-time coordinates

  (time dilation, space contraction)

$$t' = \frac{t - \frac{v}{c^2}x}{\sqrt{1-\frac{v^2}{c^2}}}$$

$$x' = \frac{x - vt}{\sqrt{1-\frac{v^2}{c^2}}}$$

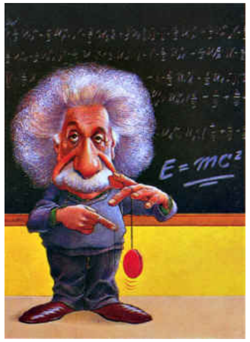
$$y' = y$$

$$z' = z$$

Physical laws must 'look the same' in different inertial reference frame (Lorentz invariance):

space and time coordinates are to be treated equally

1905: Relativity



Lorentz invariance is **guaranteed** if laws of physics are written in terms of 'invariant products of four-vectors'

- **Maxwell equations** of electromagnetism are o.k.
  (space and time coordinates are treated equally)

$$\vec{\nabla} \cdot \vec{D} = \rho$$
$$\vec{\nabla} \cdot \vec{B} = 0$$
$$\vec{\nabla} \times \vec{E} + \frac{\partial \vec{B}}{\partial t} = 0$$
$$\vec{\nabla} \times \vec{H} - \frac{\partial \vec{D}}{\partial t} = \vec{J}$$

o.k.

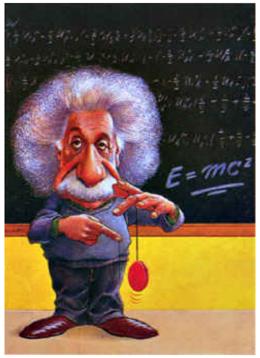
- **Newton's law**: not o.k.
  need to modify definition of momentum
  (define energy-momentum 4-vector (E,p))
  Energy and momentum are related by:

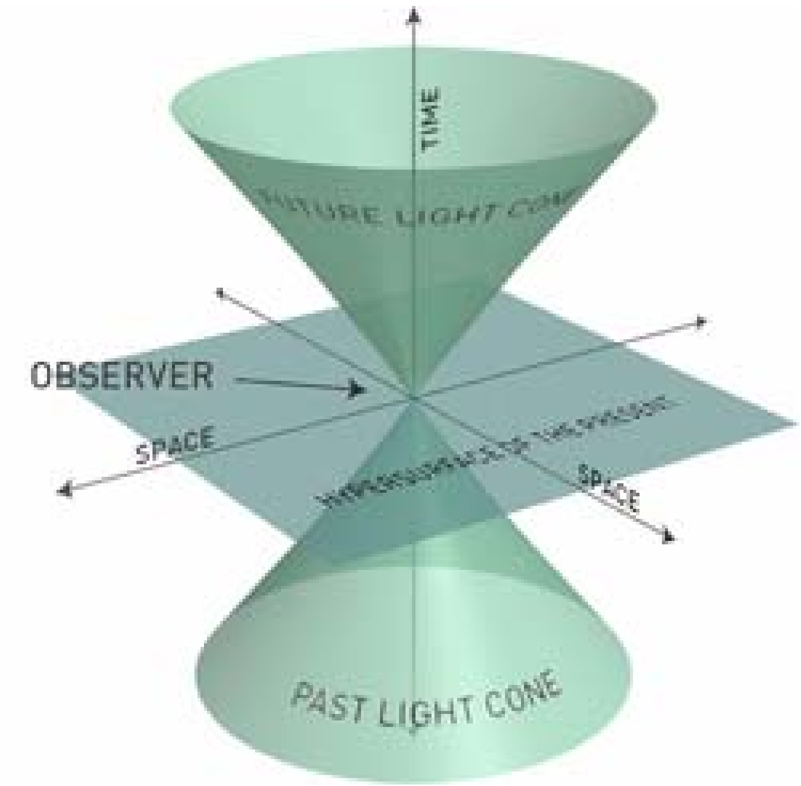
$$E^2 = m^2c^4 + p^2c^4$$

$$m\frac{\partial^2}{\partial t^2}r = -G\frac{mM}{r^2}$$

not o.k.

Speed of light limits the causal connection of events





Causal connection between two 'events' only within "light cone"

Clear distinction between the 'PAST' and the 'FUTURE' (for any given observer)

Quantum Physics (1923-1925)

1913 (Bohr) Angular momentum quantized in atom $r \cdot p = n \cdot \hbar$

1923 (de Broglie) Particles have wave properties $\lambda = \frac{\hbar}{p}$

1925 (Heisenberg) Uncertainty relation $\Delta p \cdot \Delta x \geq \hbar$

1926 (Schrödinger*) Non-relativistic wave equation

$$E = \frac{p^2}{2m} \rightarrow i\hbar \frac{\partial}{\partial t}\psi = -\frac{\hbar^2}{2m}\nabla^2\psi$$

Particle described by **probability amplitude** ψ**(x)**

Observables are described by **operators** acting on ψ**(x)**

$$E \rightarrow i\hbar\frac{\partial}{\partial t} \qquad \mathbf{p} \rightarrow \frac{\mathrm{h}}{i}\nabla$$

*Schrödinger also tried …

$$E^2 = p^2 + m^2 \rightarrow -\hbar^2\frac{\partial^2}{\partial t^2}\psi = -\hbar^2\nabla^2\psi + m^2\psi$$

… but could not solve 'negative energy' problem

Dirac equation (1) - Relativistic electrons?

Which equation describes a relativistic electron (c=1)?

Dirac: Take the 'square root' - and deal with negative solution

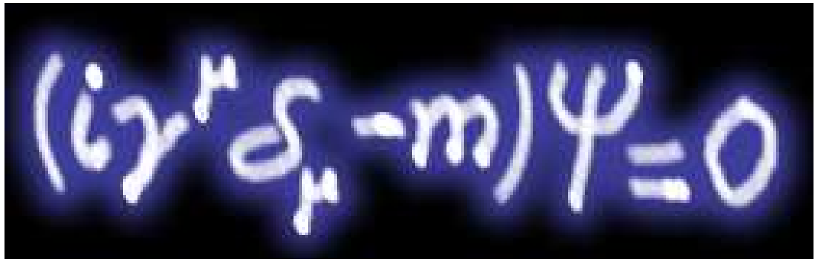
$$E^2 = p^2 + m^2 \rightarrow$$
$$E = \pm(\alpha \cdot p) + \beta m$$

Linear equation, based on relativistic energy-momentum conservation

$$i\frac{\partial}{\partial t}\psi = -i\,(\alpha_x \frac{\partial}{\partial x}\psi + \ldots) + \beta m\ \psi$$

Solution: α, β are 4x4 matrices (called "γ^μ")

ψ has 4 components ("spinor")



What does ψ stand for??

P.A.M. Dirac, *Proc. Roy. Soc.* **A118**, 351 (1928)

Dirac equation (2) - Four components?

Electron had spin 1/2 (two ways of alignment in a magnetic field).
Description by a two-component Pauli 'spinor' (spin-up and spin-down).

But: ▪ ψ had two spin 1/2 particles !

$$\psi_+ = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} \text{ or } \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix} e^{-imt} \qquad \psi_- = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix} \text{ or } \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} e^{+imt}$$

These are the two spin states of an electron with positive energy

These are the two spin states of something (similar) with 'negative' energy ????

For moving electrons, the upper and lower components mix.

The 'one-particle' wave function describes now a multi-particle wave function

Dirac 1929: 'negative' energy states with positive charge = **proton** ??

Dirac's Interpretation: Holes in the vacuum

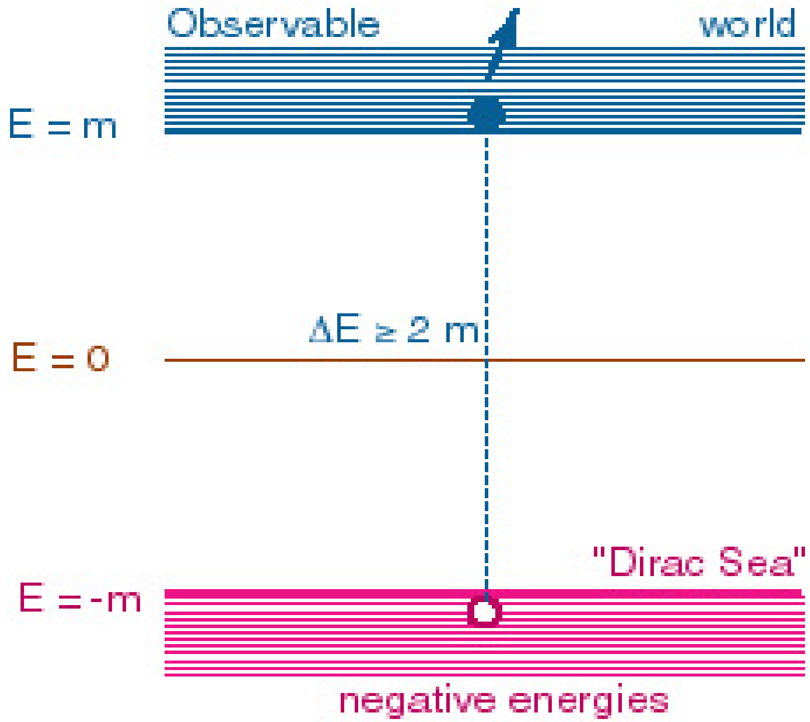
Dirac 1931: "Subsequent investigations, however, have shown that this particle necessarily has the same mass an an electron and also that, if it collides with an electron, the two will have a chance of annihilating one another … "

All negative energy states occupied by electrons. 'Pauli exclusion principle' prevents electrons to fall into the "Dirac sea" (otherwise $t_{trans} \sim 10^{-8}$ sec).

Pair creation: By absorbing radiation ($E \geq 2m$), an electron can be lifted from negative to positive energy state. The remaining hole (absence of negative charge) behaves like a positive electron - the positron.

Vacuum had become very complicated

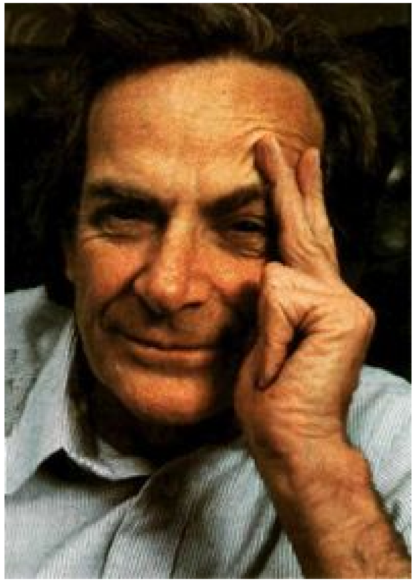
(**infinite zero-point energy**, infinite charge)



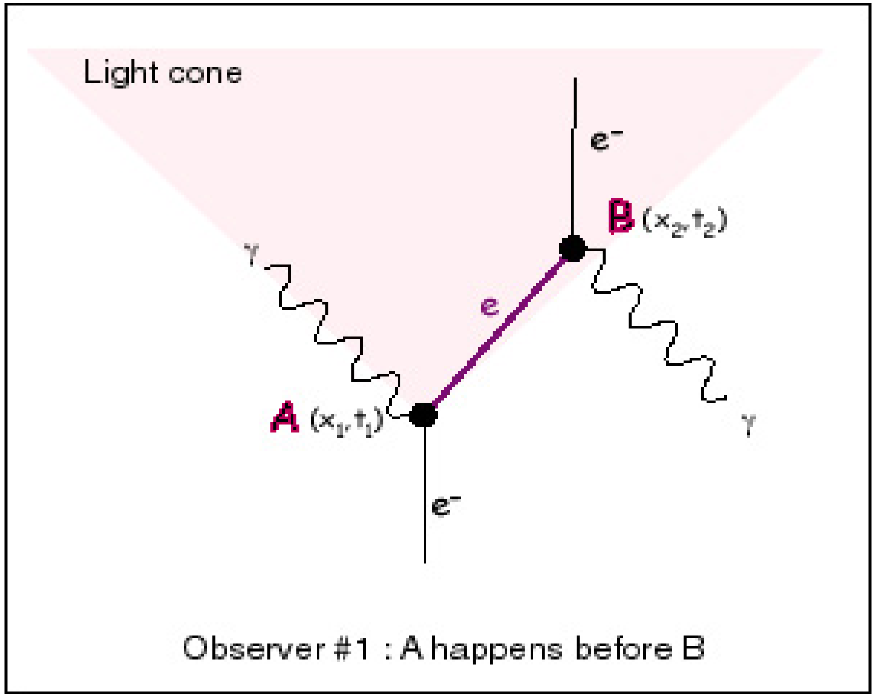
Proc. Roy. Soc. A133, 60 (1931)

Relativity + Quantum Mechanics = Antimatter

"Second quantization" - the electron (field) is no longer described by a wave function but an operator that creates and destroys particles. All energies are positive.



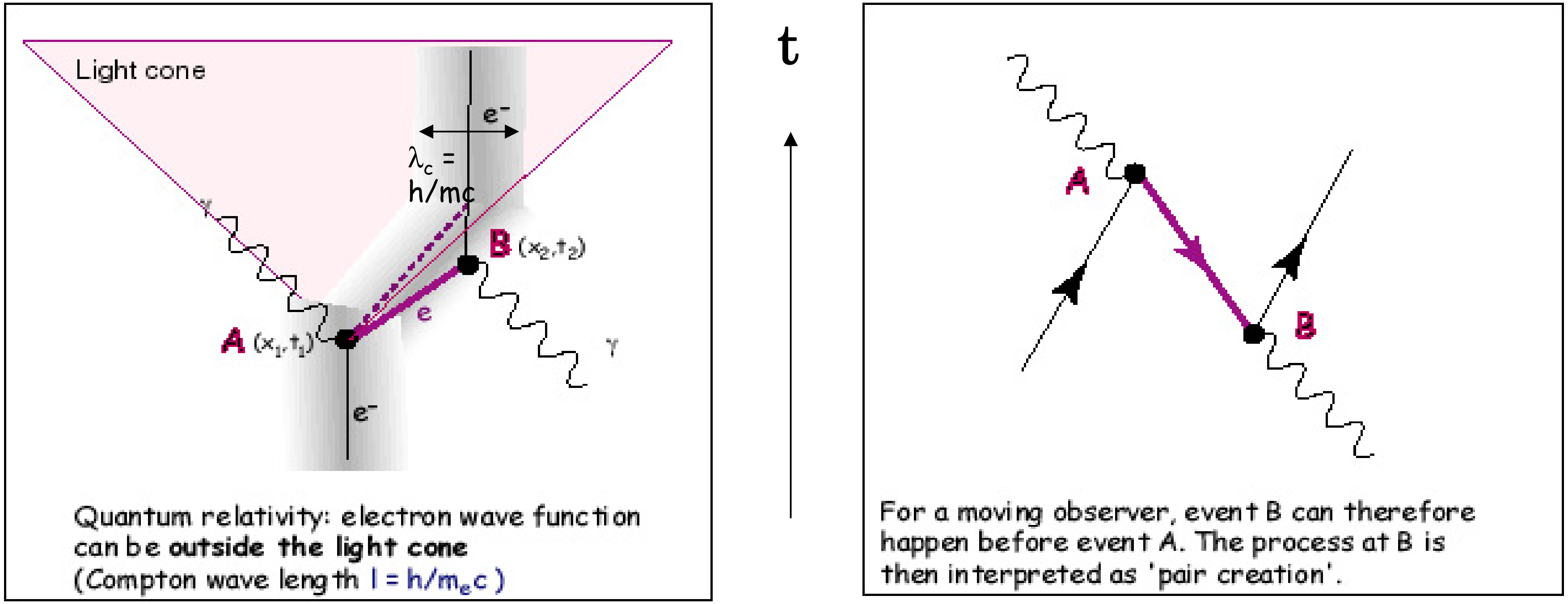
Richard Feynman



An electron can emit a photon at A, propagate a certain distance, and then absorb another photon at B.

Antiparticles restore (micro-) causality

Quantum physics: the wave function is spread out over the Compton wave length ($\lambda_c = h/mc$).



"One observer's electron is the other observer's positron".

The presence of antiparticles is necessary to restore the **causal structure** to the process seen in another inertial system.

Positron discovery (1932)

Anderson used cloud chamber in a 15 kG magnetic field

CC had two parts, separated by a 6-mm lead plate.

Greater curvature of upper track indicates that particle entered the chamber from below. This determines the positive charge of the particle.

From the track curvature and track length (= energy loss per cm) Anderson concluded that the positive charge of the particles is less than twice that of proton and the mass is less than twenty times the proton mass.

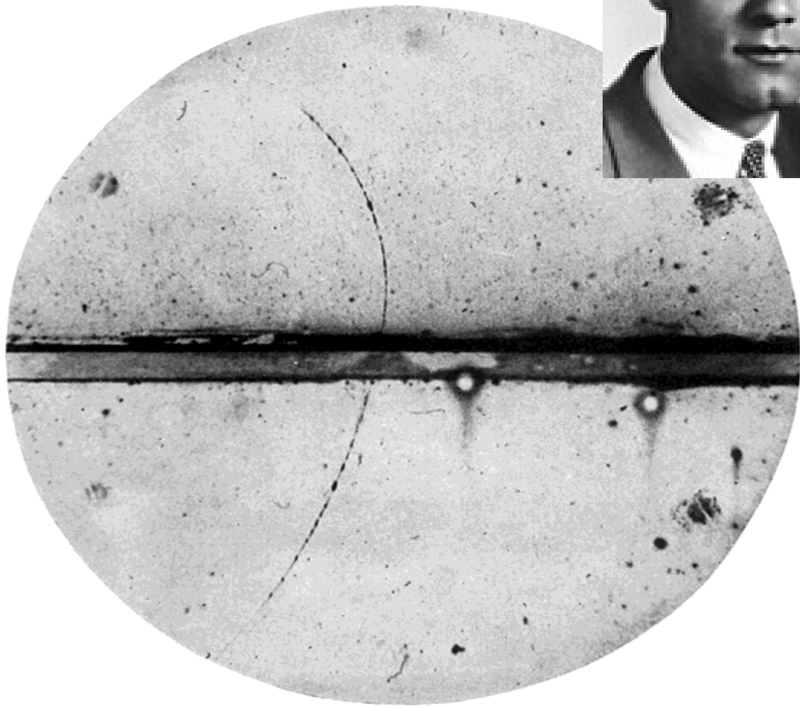


FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

C. D. Anderson. "The positive electron", *Phys. Rev.*, **43**, 491 (1933).

Positron discovery- why so late ?

A comment by Dirac on why the positron was not discovered until 1932

"Why did the experimentalists not see them? Because they were prejudiced against them.

The experimentalists had been doing lots of experiments where particles were moving along curved tracks in a magnetic field. ....

[They] sometimes saw the opposite curvature, and interpreted the tracks as electrons which happened to be moving into the source, instead of the positively charged particles coming out. That was the general feeling.

People were so prejudiced against new particles that they never examined the statistics of these particles entering the source to see that there were really too many of them." --

Dirac, in J. Mehra, ed. **The Physicist's Conception of Nature**, pg. 12.

Discovery of the antiproton (1955)

But even in 1955, many prominent physicists remained doubtful if baryons would have antiparticles. After all, the magnetic moment of the proton (g = 5.58 ≠ 2) seemed to indicate that the proton was **not** a Dirac particle. As an example, Maurice Goldhaber bet against* the existence of the antiproton …

… and lost

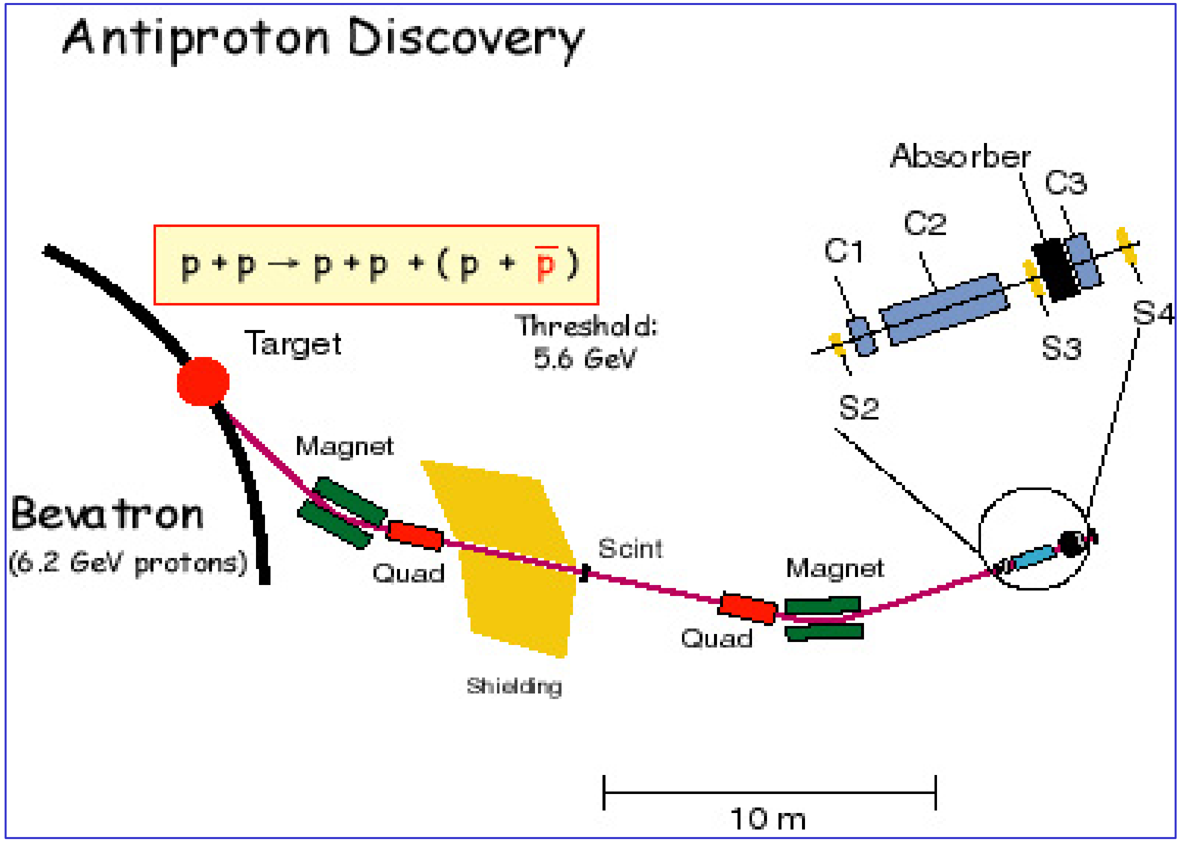
(he gave Snyder 500 $

in November 1955).

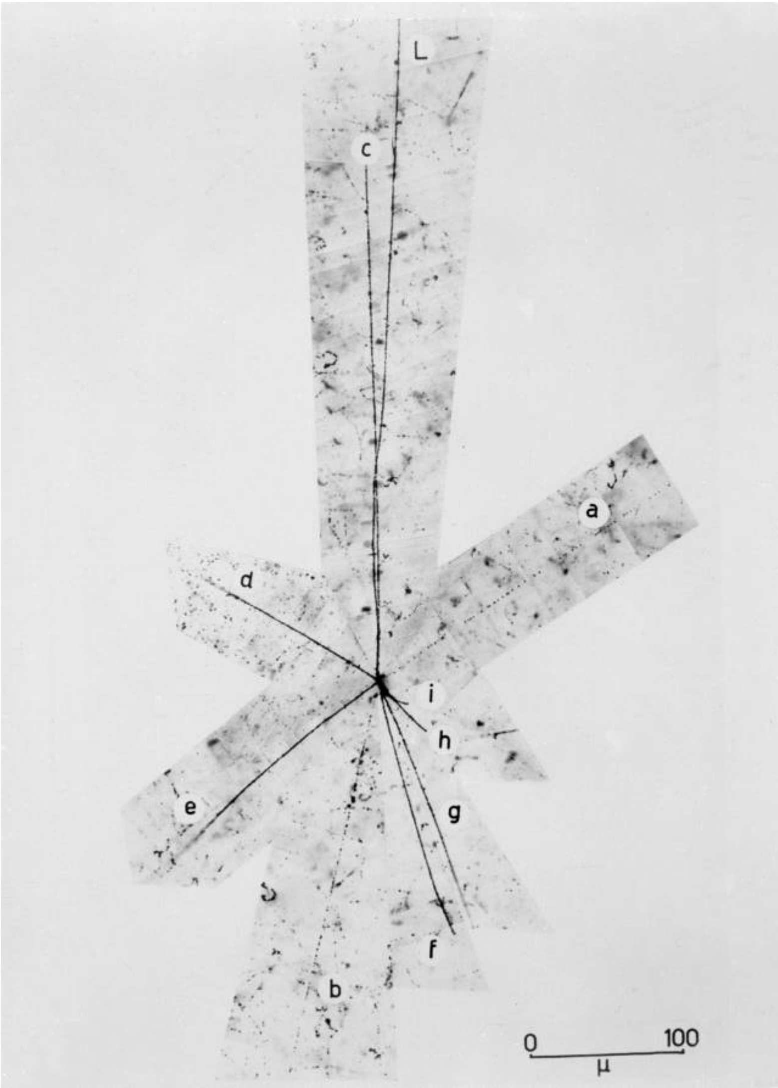
***Hartland Snyder**

(co-discoverer of the strong focussing method)

The energy of the Bevatron at Berkeley had been designed for the production of the antiproton and as built by Ernest Lawrence and his team.



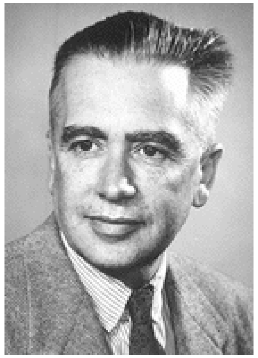
The final proof



Antiproton annihilation

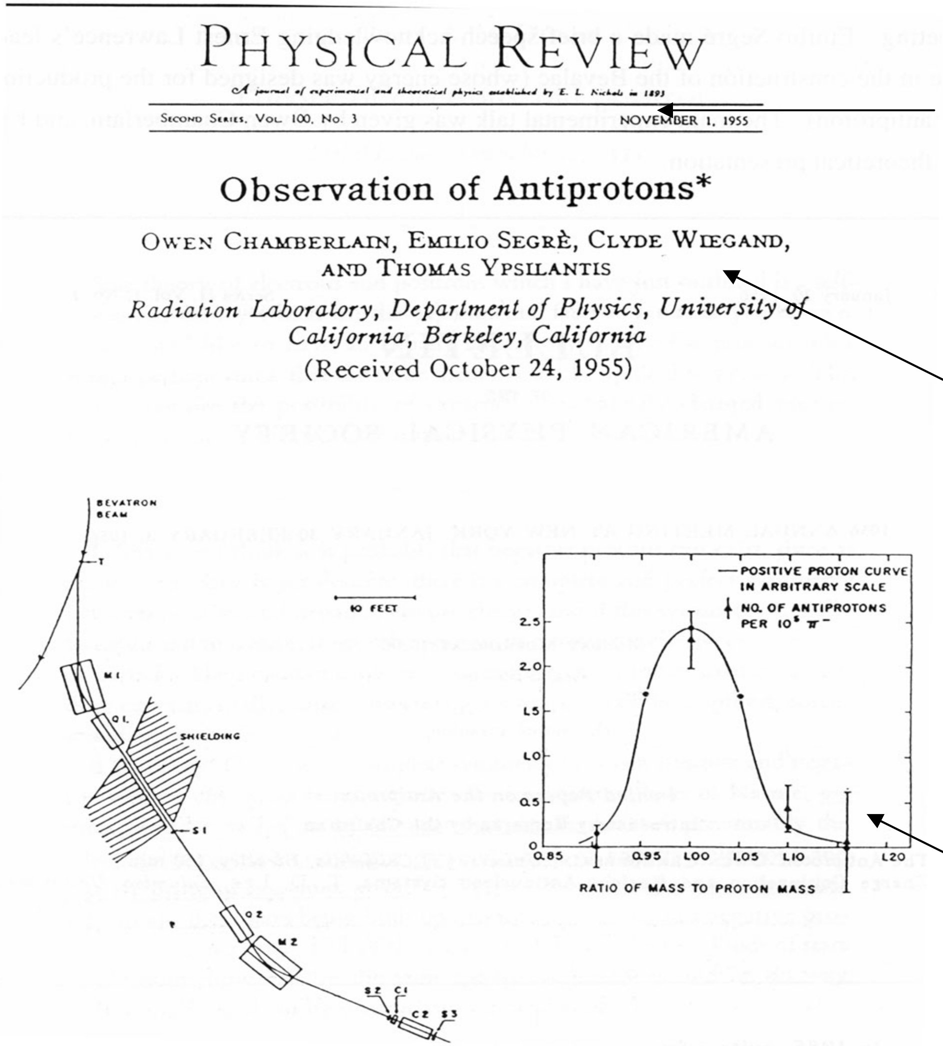
First symmetry tests - mass, charge agreed to ~10%

Discovery of the antiproton (2)



Segrè

Chamberlain



PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 100, No. 3 — NOVEMBER 1, 1955

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)

Paper published in Nov 1955

Nobel prize (1959)
for 50% of the collaboration

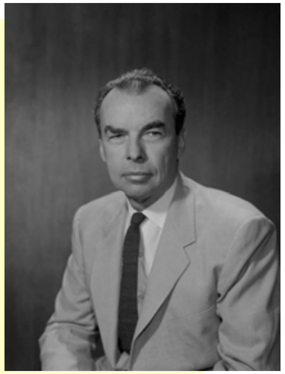
Tedious analysis ….

Antineutron, Antinuclei

Berkeley, 1956: Discovery of **antineutron**
(**Cork**, Lambertson, Piccioni, Wenzel)

using the 'antiproton beam' and **charge-exchange reaction**

antiproton + proton → antineutron + neutron



The produced antineutron was recognizable by its annihilation properties, forming a star in the cloud chamber that is very similar to an antiproton star.

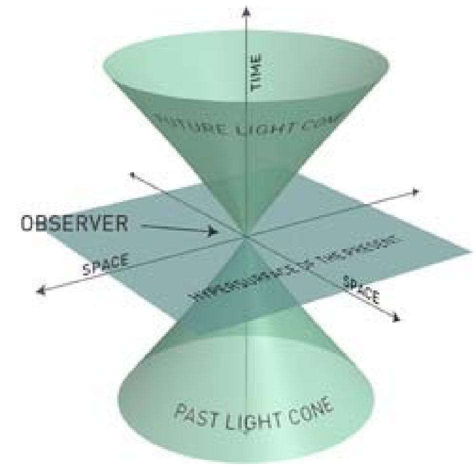
CERN, 1965: Discovery of the **anti-deuteron**
(Massam, Muller, Righini, Schneegans, Zichichi)

The results reported imply the conclusion that a negative particle exists with mass equal to 1867 ± **80 MeV**. The most simple interpretation of these data is to identify this particle with the anti-deuteron.

CPT theorem

All Quantum Field Theories (including the Standard Model) are built upon:

1) Locality (no action at a distance)
2) Lorentz invariance (all inertial frames are equivalent)
3) Causality (no interaction between two space-time points outside light cone)
4) Vacuum is the lowest energy state ($\rightarrow$ spin-statistics connection)



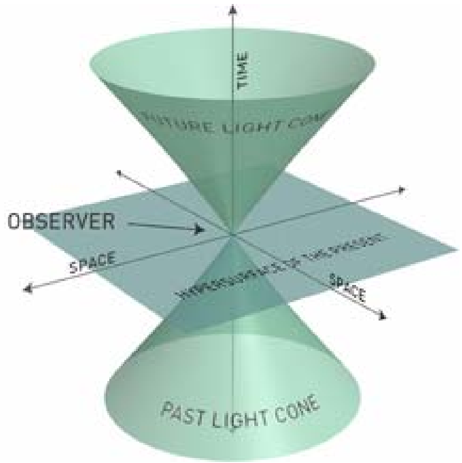
The 'CPT theorem' - based on these assumptions - states:

In a mirror world, where particles are replaced by their antiparticles, and where time runs backwards - all physical processes would be identical.

Particles and antiparticles have **exactly** equal masses, lifetimes, magnetic moments, etc.

CPT theorem (cont'd)

However, the proof of the CPT theorem is based on further assumptions:



1) Point-like particles

2) Flat 4-D space time

[e.g. G. Barenboim et al., PLB 534 (2002) 106; O.W. Greenberg, PRL 89 (2002) 231602]

These assumptions are not necessarily valid at the Planck (or another fundamental) scale.

Several models **speculate with CPT violation**, induced by e.g.

Quantum Gravity (loss of unitarity through space-time foam/black holes)

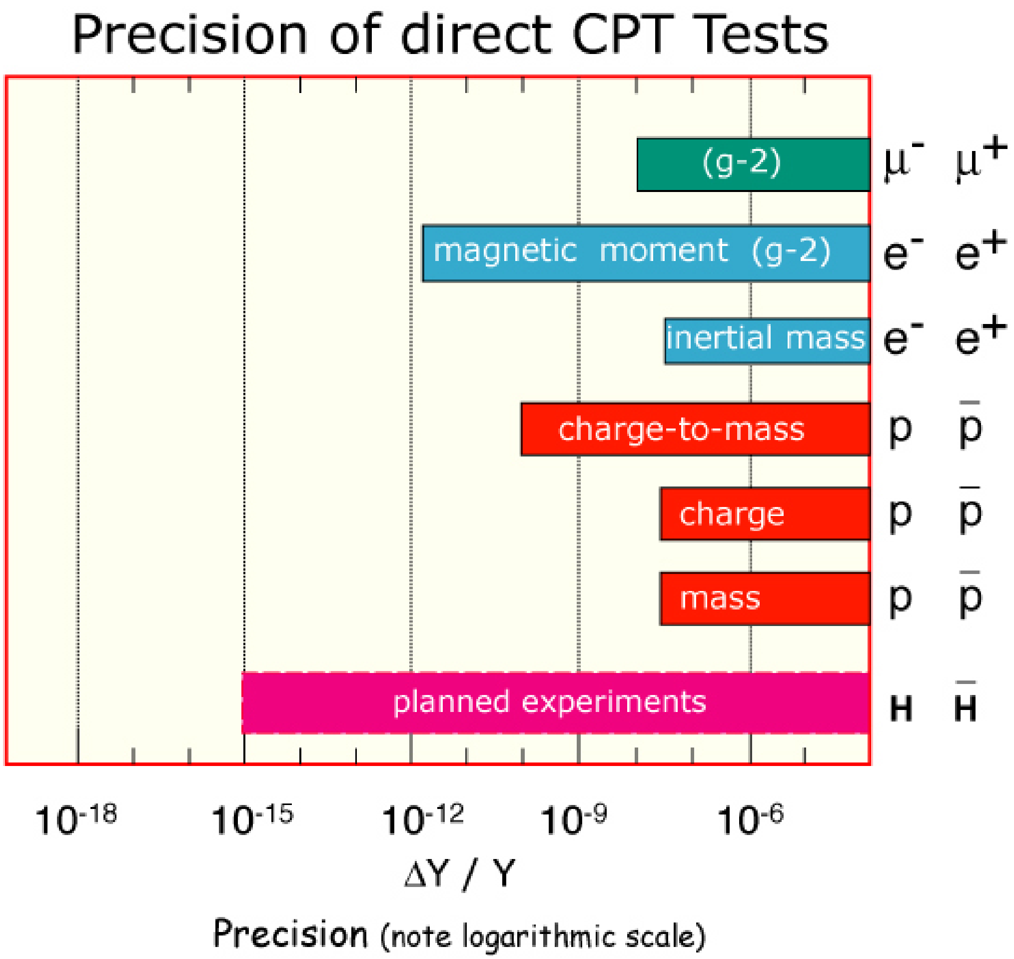
String theory (spontaneous breaking of Lorentz symmetry)

Overview : CPT Violation - Theory and Phenomenology

(Nick Mavromatos, arXiv:hep-ph/0504143, 2005)

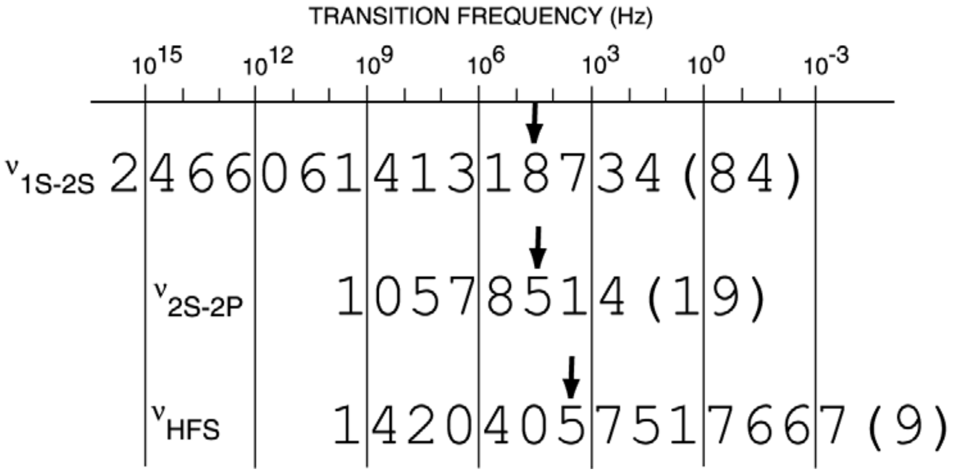
Direct comparison of stable particles and antiparticles

1) **Compare relative precisions (divide error by value)**



CPT symmetry (2)

2) Compare absolute values/errors in terms of energy/frequency



Hydrogen atom

1S-2S transition

Lamb shift (2s-2p)

Ground state HFS

- THERE IS NO "THEORY" OF CPT VIOLATION
- DIRECT TESTS CONFIRM CPT ~ 10^{-12} LEVEL
- HYDROGEN - ANTIHYDROGEN COMPARISON PROMISING (< 10^{-15})

Gravitation and Antimatter

WEAK EQUIVALENCE PRINCIPLE

The world line of a freely falling test body is independent of its composition or structure.

Equivalence principle

No way to distinguish locally between gravitational potential and constant acceleration.

Experimental tests:

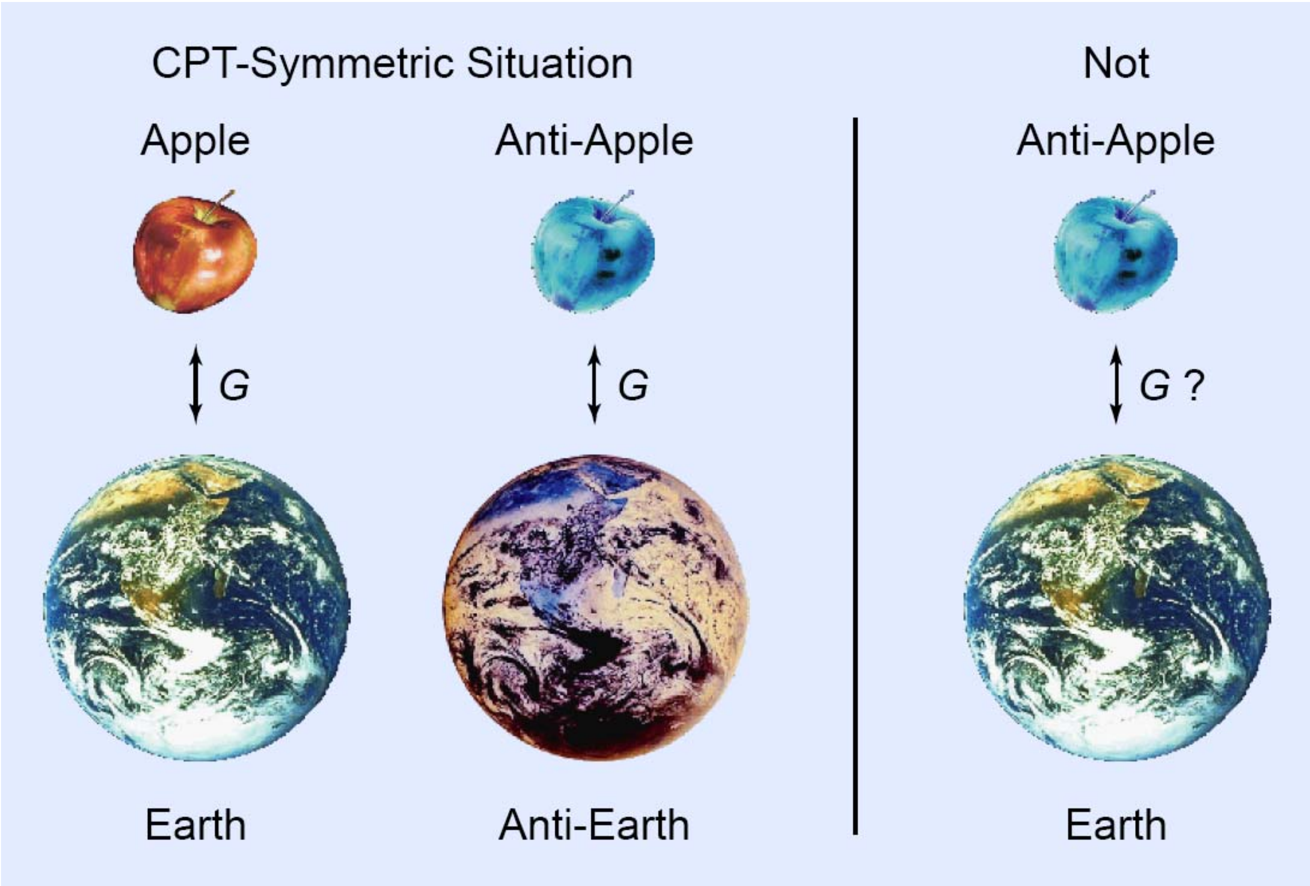
Galileo, Huygens, Newton, Bessel, Eotvos, Dicke; Eot-Wash (Seattle)

$m_i = m_g$ with $\Delta m/m < 10^{-12}$

Argument in favour :

The masses of particles and antiparticles obey $E = mc^2$. Since it is this energy that curves space, antimatter must have the same gravitational interaction as matter

Gravitation is not constrained by CPT



Non-Newtonian Gravitation?

BUT - THERE MAY BE DEVIATIONS FROM THE (WEAK) EQUIVALENCE PRINCIPLE

Newton gravity: Tensor force (graviton - spin 2) = attractive.

Non-Newtonian: Scalar force (spin 0) = attractive

Vector force (spin 1) = attractive or repulsive (changes sign for antimatter);

may be of finite range

The additional components of the gravitational field would show up as a '5th force' (searched for in the early 1990's). The present limit on these components to ~ 10^{-4} of the gravitational interaction for typical terrestrial distances.

Extended discussion for and against 'antigravity' in the literature, eg.

M. M. Nieto, T. Goldmann "Arguments against antigravity ...", Phys. Rep. 205 (1991) 221

P. Morrison, Approximate nature of physical symmetries, Am.J.Phys. 26 (1958) 358 (energy conservation)

L.I. Schiff, Sign of the gravitational mass of a positron, Phys. Rev. Lett. 1 (1958) 254 (vacuum polarization)

M.L. Good, K_2^o and the equivalence principle, Phys. Rev. 121 (1961) 311 (Ks regeneration)

Antiparticle gravitation experiments have been attempted, but …

No measurement of gravitational effects on antiparticles has yet succeeded ..

(one controversial result by Witteborn + Fairbanks for positrons, and a failed attempt with antiprotons at LEAR).

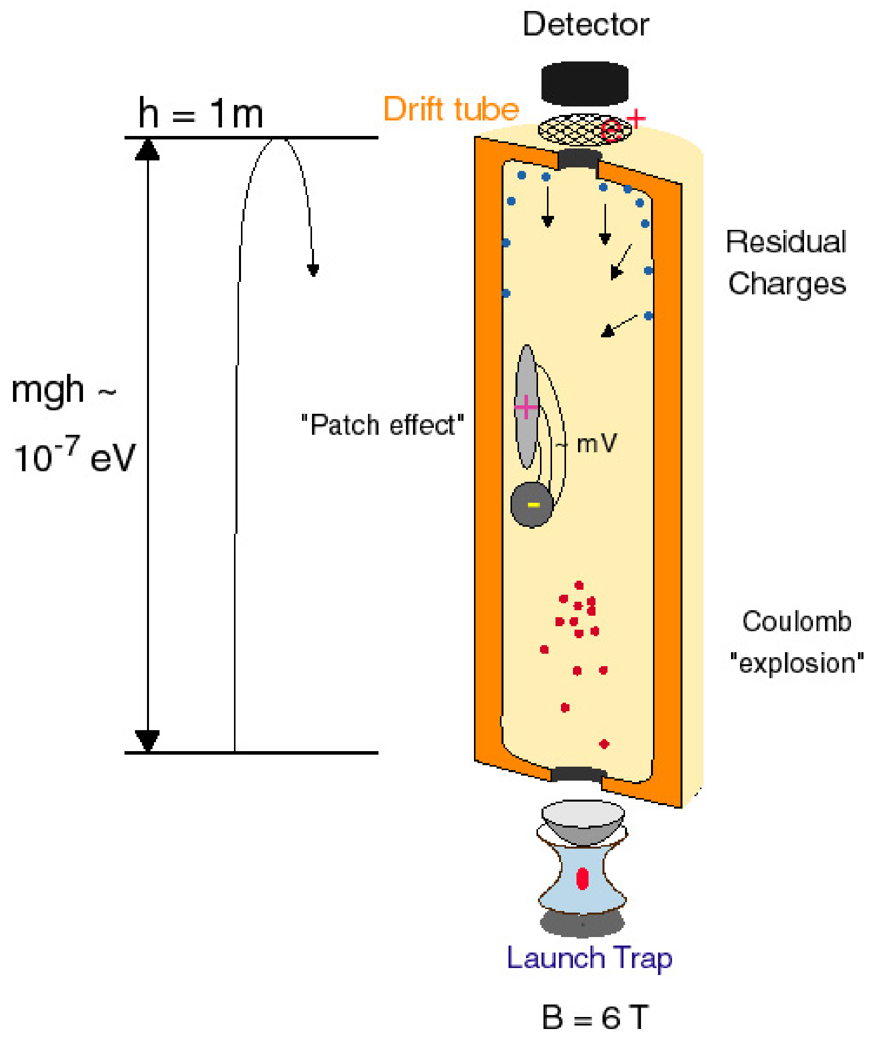
Problems:

- Coulomb explosion
- Patch effect (mV/cm)
- Residual charges

  (10^{-7} eV ~ 1 electron at 1 m distance)

Solution:

Use neutral, stable system = antihydrogen



Conclusion: Antimatter Gravity

Weak equivalence principle is well tested with ordinary matter*, but not at all with antimatter

*** Overview: B.R. Heckel et al., Adv. Space Res. 25 (2000) 1125**