Precision tests of the Standard Model with trapped atoms 1st lecture

Luis A. Orozco
SUNYSB

The Standard Model
(brief review)

Symmetries ⇔ Conserved quantities

Gauge Symmetries (local and continuous) ⇔ Particles that carry the interaction

Discrete Symmetries:

Parity , Time	Space-time
Charge	Internal

The Standard Model unifies
Electromagnetism and Weak interactions

Then comes the Strong interaction

Finally Gravity (not in the standard model)

There are many parameters, the left handedness is put into the model; it needs the Higgs.

Limit our discussion to the Electro-Weak sector

4 Bosons:

	Charge	Mass
γ (photon)	0	0
Z^0	0	91.18 GeV
W^+	+e	80.41 GeV
W^-	-e	80.41 GeV

What can Atomic Physics do at low energy to test the standard model?

Test discrete symmetries:

a) CPT
b) CP ; T
c) Parity and its relationship with the electro-weak sector

Types of measurements:

1) measure precisely an effect.
2) look for other effects.

Measure zero is very different from zero measurement!

CPT mass measurements of particle and antiparticle; Antihydrogen spectroscopy.

T Electric dipole moment (EDM) in electron, neutron (atoms).

P Parity non conservation in atoms and nucleus.

Tests of CPT

Particle and antiparticle have equal mass; equal lifetime; equal absolute value of their magnetic moments.

For mesons:

$|(m_{K^0bar} - m_{K^0})/ m_{average}| \leq 10^{-18}$

For leptons (measured in Penning Trap:

$|(m_{e+} - m_{e-})/m_{average}| < 4 \times 10^{-8}$, CL = 90%

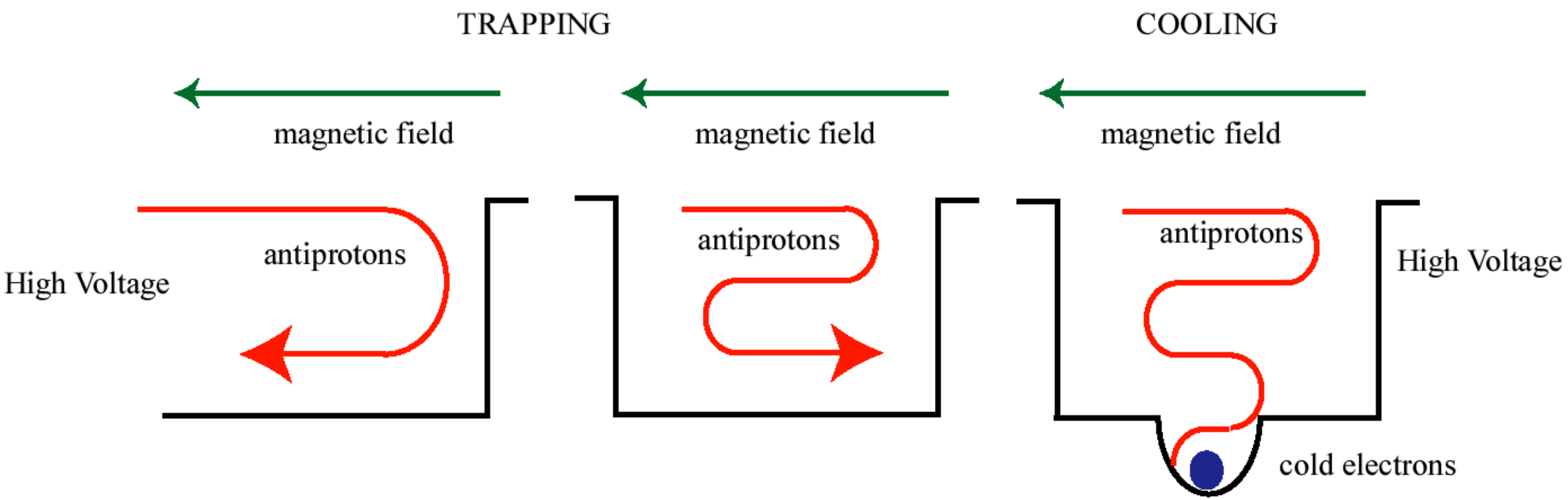
$|(g_{e+} - g_{e-})/g_{average}| = (-0.5 \pm 2.1) \times 10^{-12}$

For baryons:

$(|q_{pbar}/m_{pbar}| - q_p/m_p)/ |q/m|_{average}$ $(9 \pm 9) \times 10^{-11}$

All these tests are model independent.

G. Gabrielse has led the trap collaboration to measure and compare the charge to mass ratio of the antiproton with that of the proton in a Penning Trap.



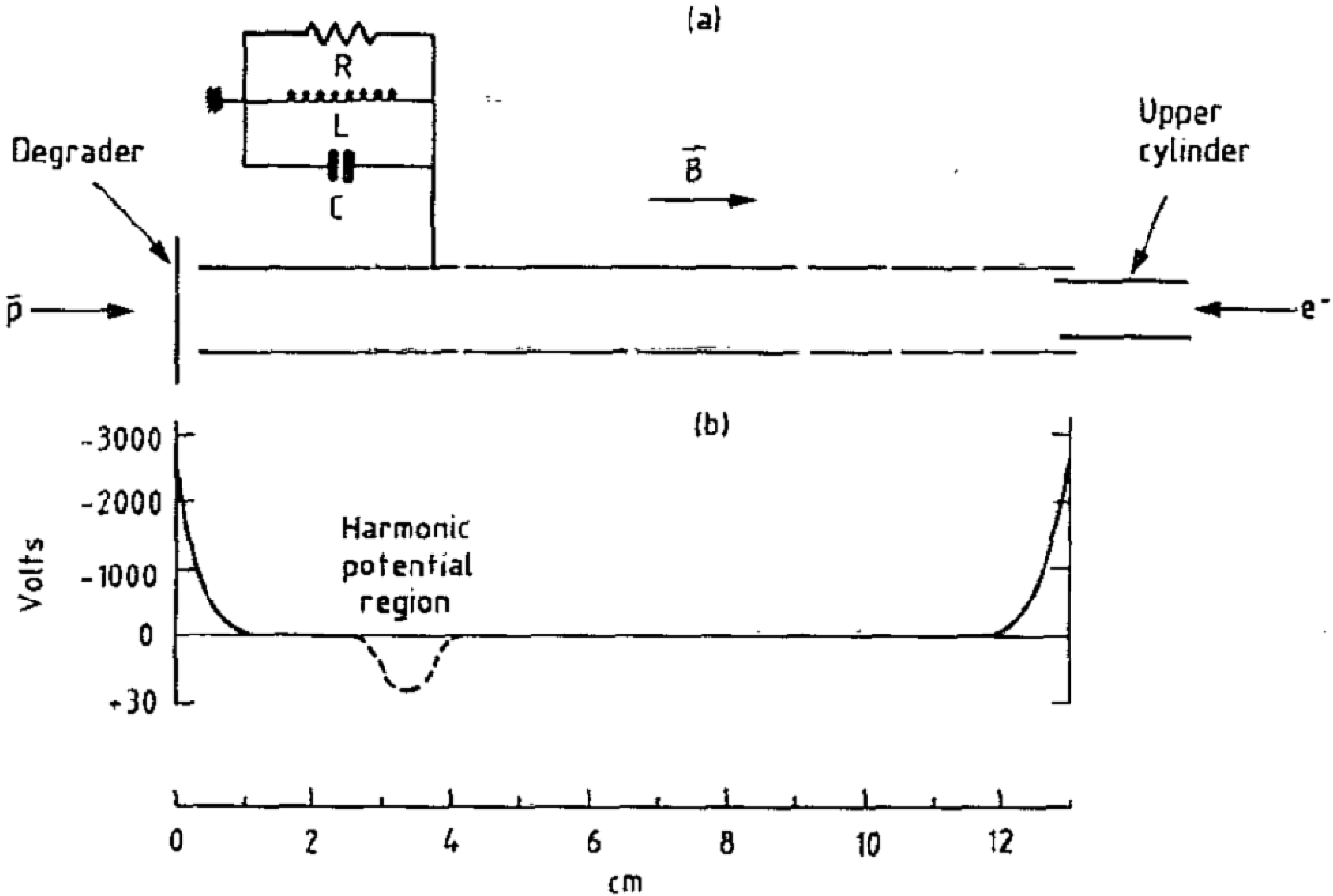


FIG. 1. (a) Trap apparatus and (b) the potential along the axis of the trap.

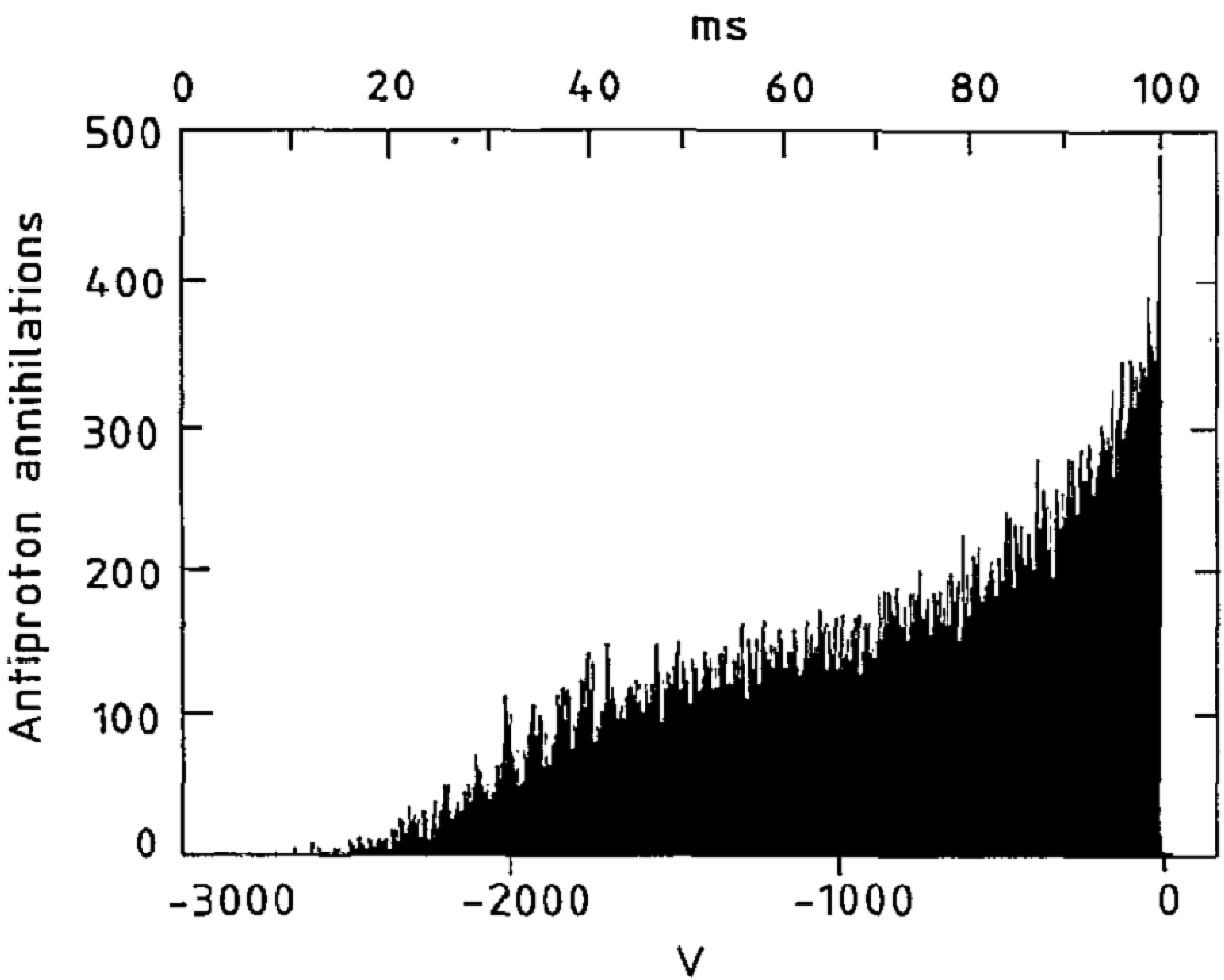
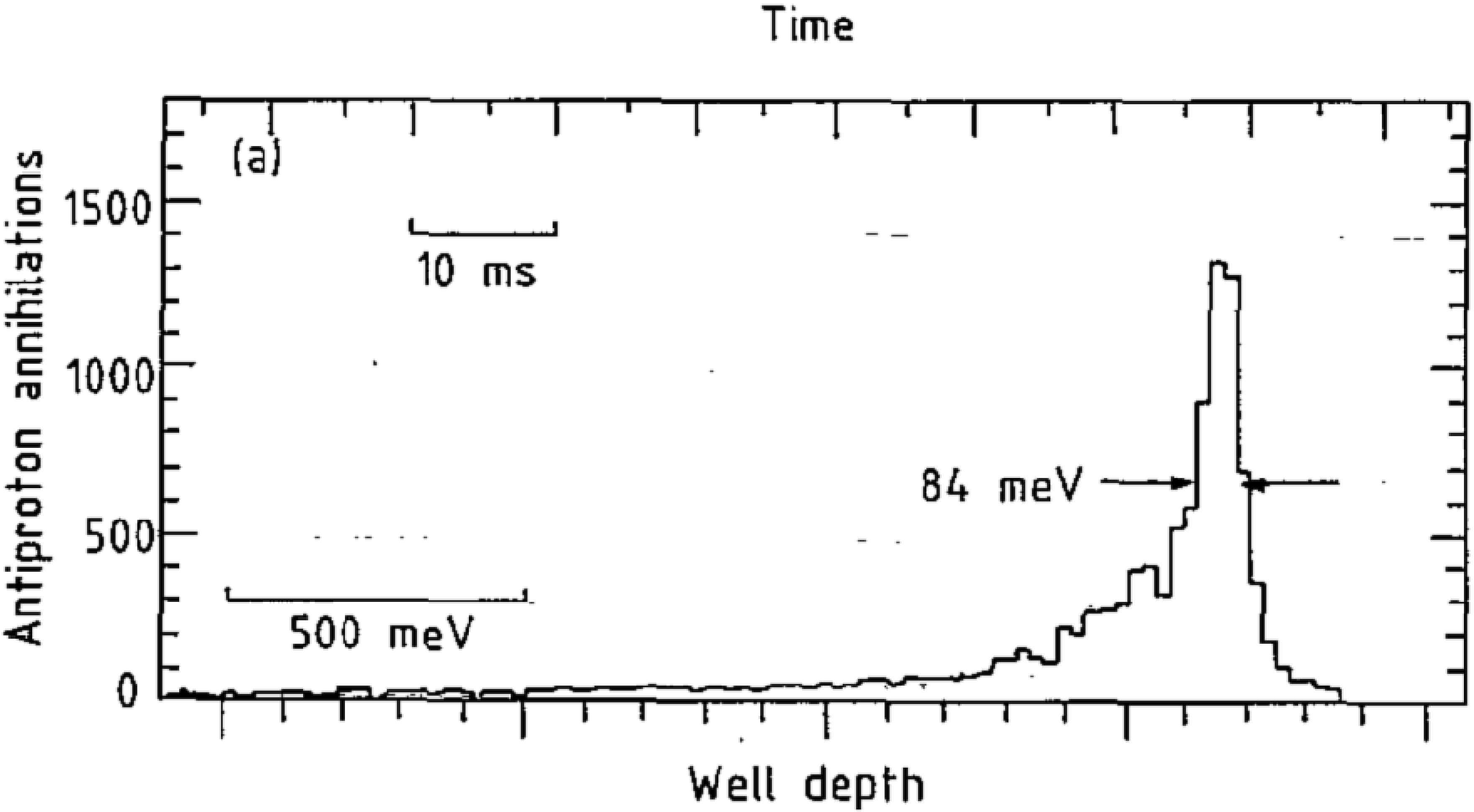


FIG. 2. Spectrum for antiprotons held 100 s.


Time
(a)
10 ms
500 meV
84 meV
1500
1000
500
0
Antiproton annihilations
Well depth

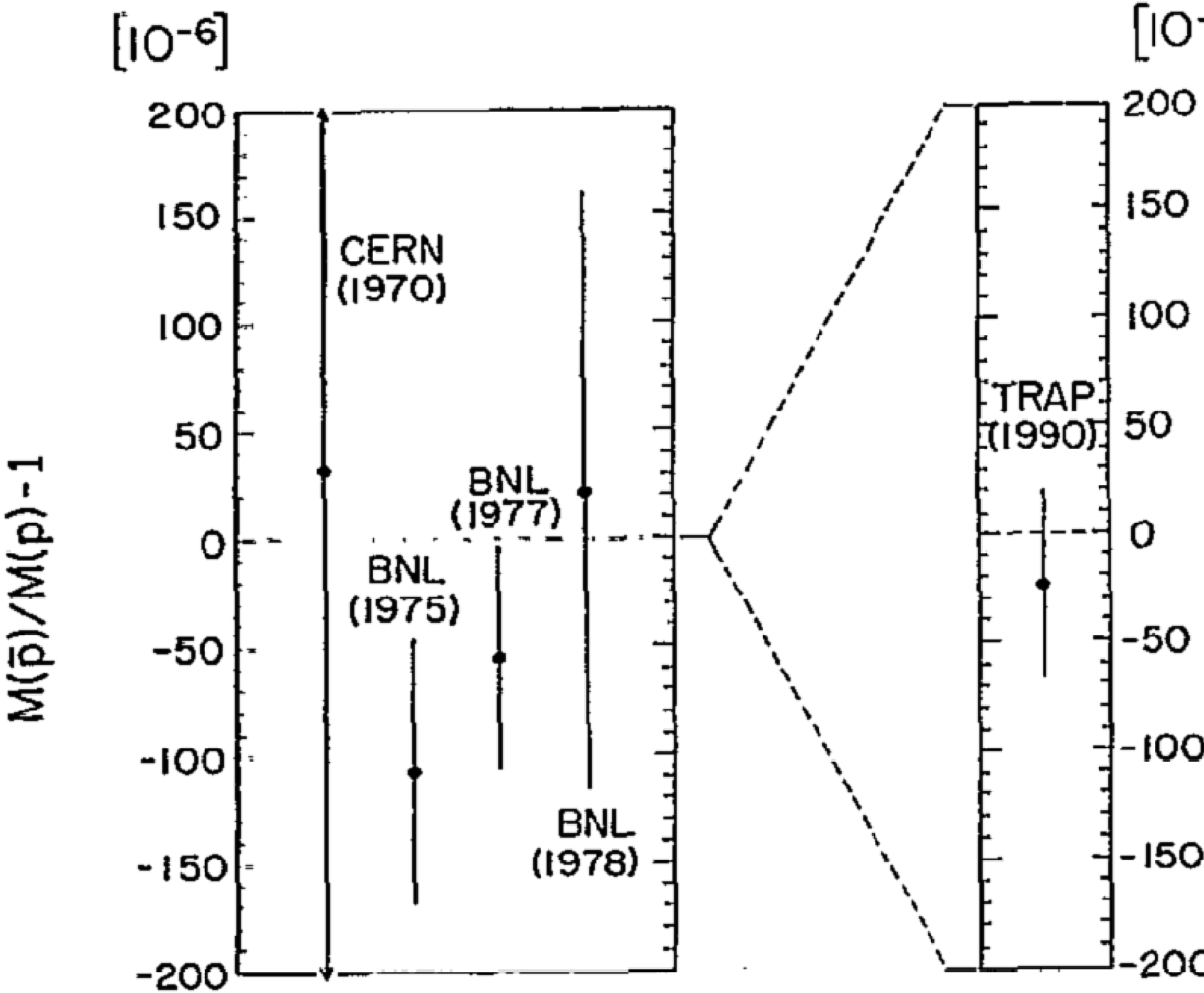


FIG. 1. Measurements of the ratio of antiproton to proton masses (Refs. 1–4). The new measurement on the right-hand side is on a scale expanded by 1000.

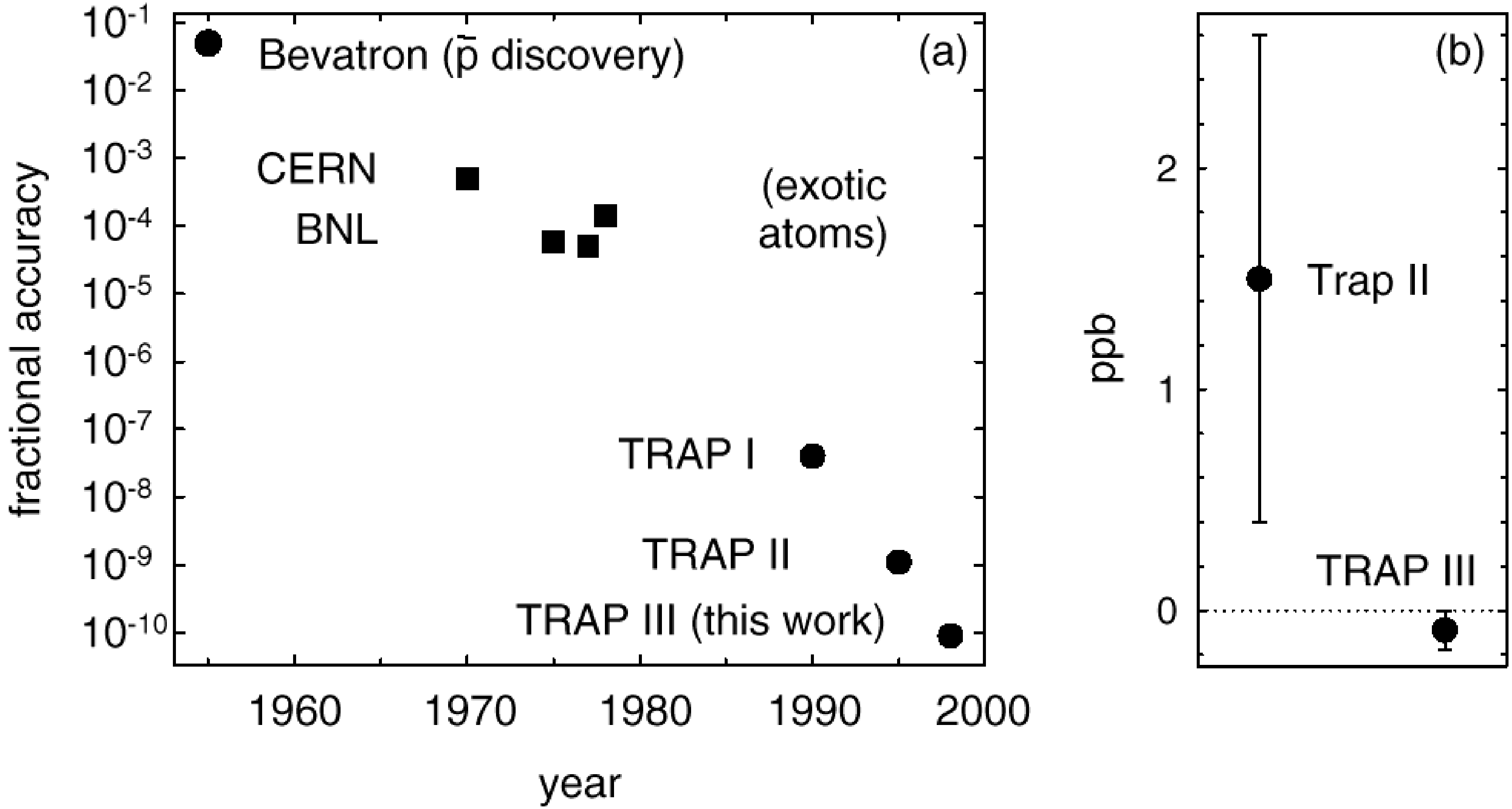


FIG. 1. (a) Accuracy in comparisons of $\bar{p}$ and p. (b) The measured difference between $|q/m|$ for $\bar{p}$ and p (TRAP III) is improved more than tenfold.

There are two projects at CERN to create, trap and perform spectroscopy on Antihydrogen.

The difficulties are very large.

Merging clouds of antiprotons and positrons can create through three body collisions some antihydrogen atoms in a high Rydberg state, that have to decay back to the ground state to be trappable in a magnetic trap as those used by the Hydrogen BEC experiment at MIT. The cascading down process could be stimulated with lasers.

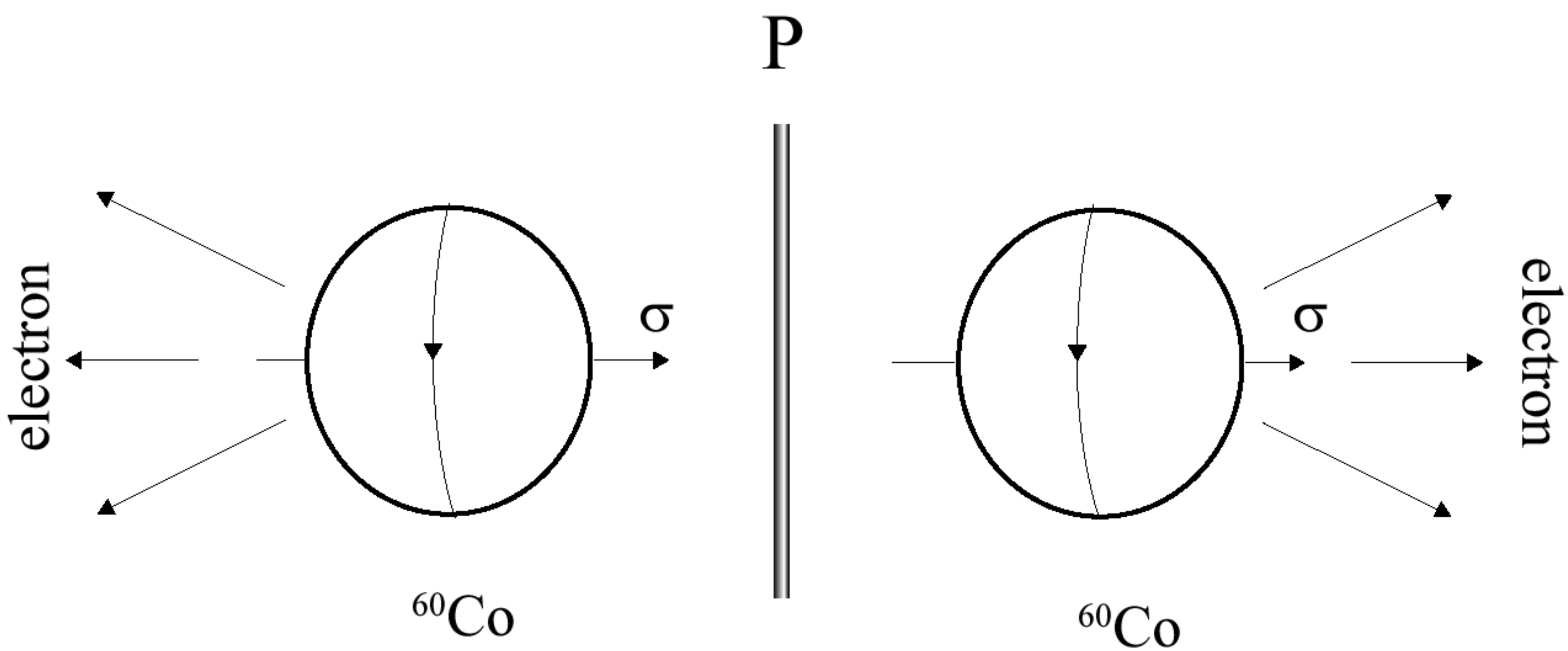
CP and T

1950 Purcell and Ramsey say that P and T invariance should be tested.
1957 Zero (within the experimental uncertainty) electric dipole moment of the neutron Smith, Purcell and Ramsey.
1964 CP is violated in K_L; K_S (with strangeness). It is violated a little bit, only about α/π.
The Standard Model accommodates it with the CKM matrix.

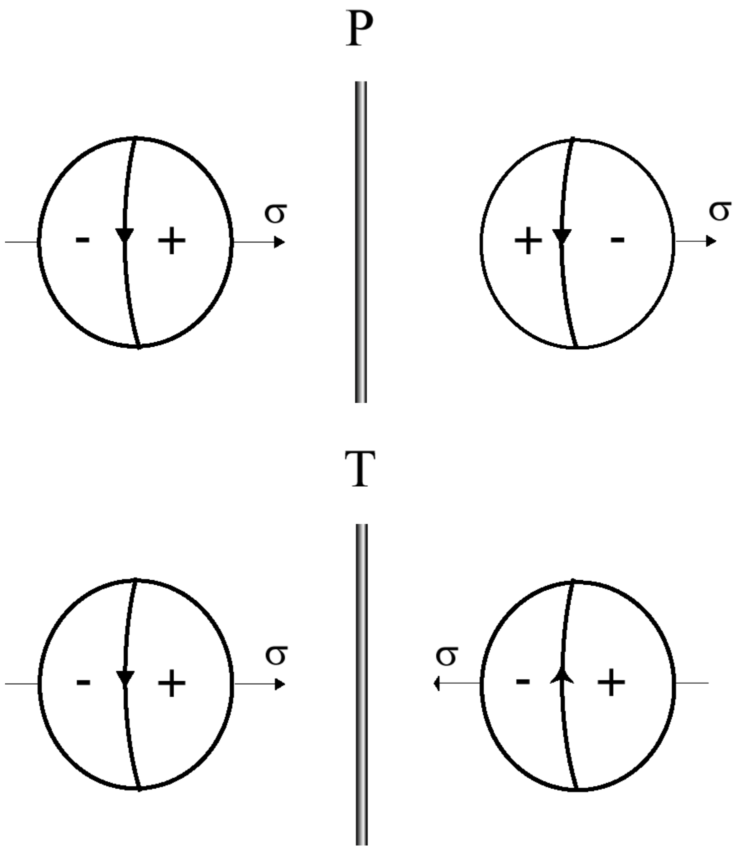
CP Lear at CERN has recently measured both CP and T violations with kaons. No measurements exists yet with a system of particles with only u and d quarks.

There are many interesting proposals, we already heard one from Rudy Grimm using atoms in a far detuned trap.

Nature lacks P symmetry.
1950 Purcell and Ramsey say it should be tested.
1956 T. D. Lee and C. N Yang point to the weak interaction.
1957 Three experiments show that the weak interaction violates P: Wu, Lederman and Telegdi lead the three efforts.
The Columbia-NBS experiment by Wu, Amber, Hayward, Hoppes and Hudson studied β decay of Cobalt.



P and T reflections of an Electric Dipole Moment.



An elementary system with angular momentum σ, and a permanent dipole moment violets both P and T symmetry.

The three experiments of 1957 found that parity is maximally violated.

The Columbia-NBS experiment on β decay in ^{60}Co can give information on how maximally is violates, by looking at the distribution of electrons.

This is the motivation to perform accurate measurements of the distribution to put limits on the existence of certain currents not allowed by the standard model.

To perform these experiments it is necessary to have:

- Radioactive neutral atoms
- High phase space (cooled)
- Polarized nucleus

^{60}Co β decay

Wu, Ambler, Hayward, Hoppes, and Hudson; Columbia, National Bureau of Standards (now NIST).

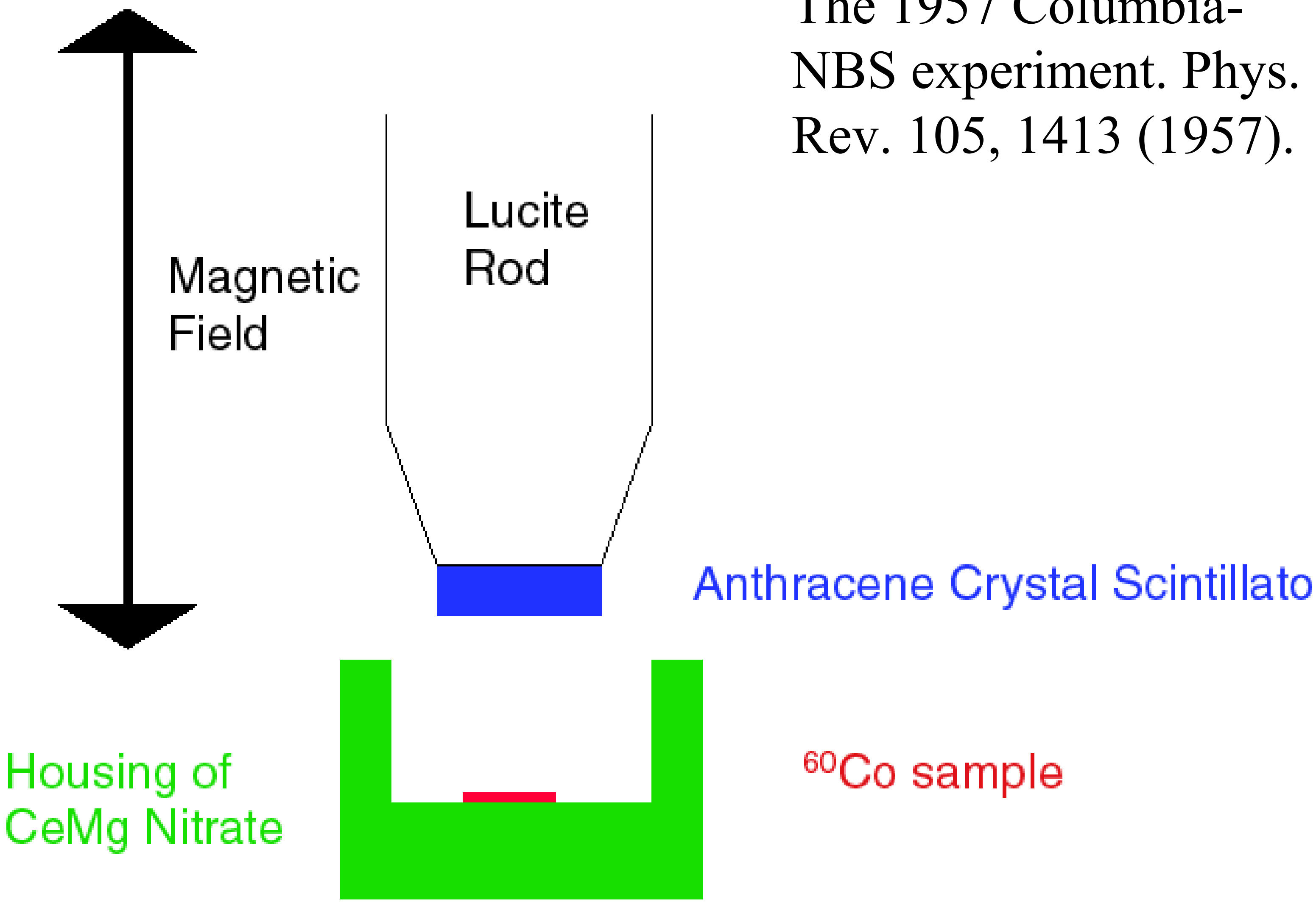
Look for a correlation between:

Nuclear spin σ and the momentum of the electron **p**

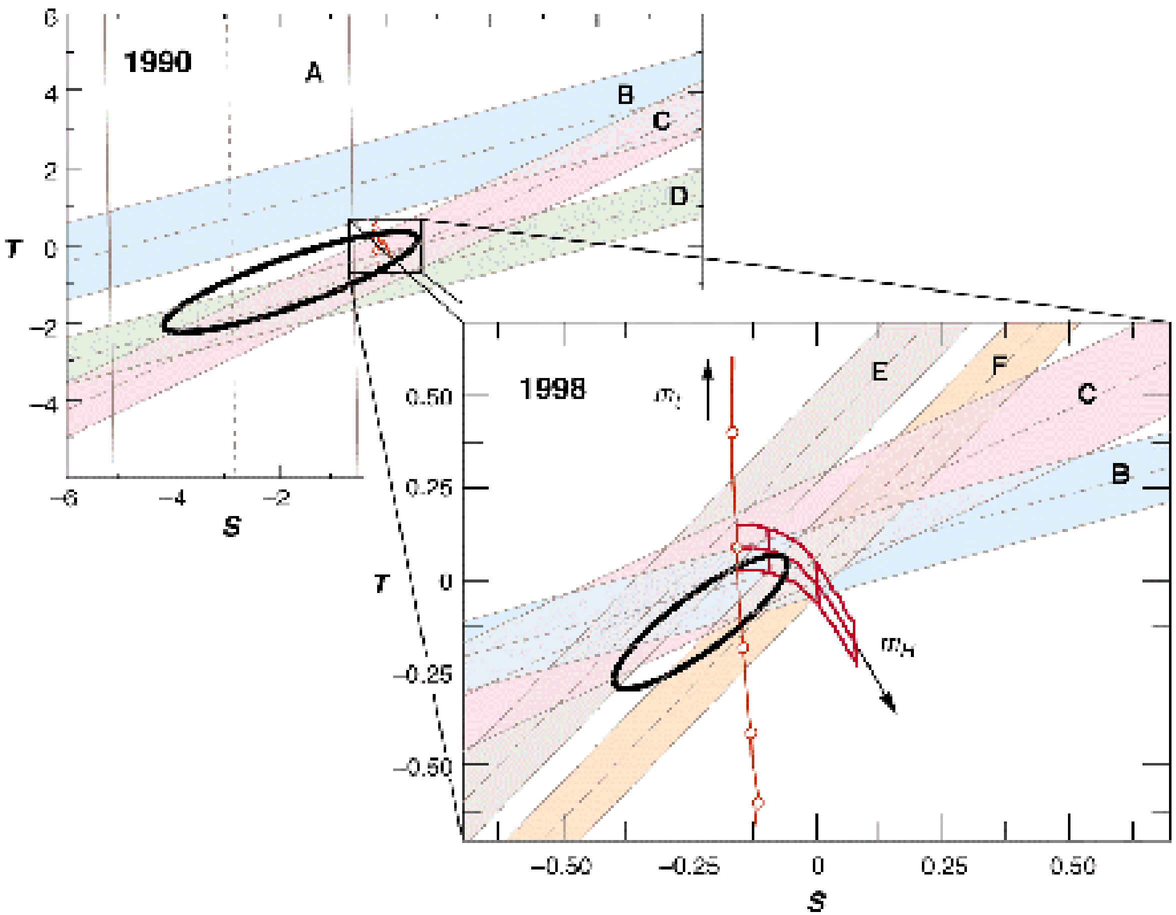
$$\langle \vec{\sigma} \cdot \vec{p} \rangle$$

To align the spins in the external magnetic field and limit the phase space of the spins, cool the sample; make thermal contact with a cerium-magnesium nitrate salt cooled by an adiabatic demagnetizing process.

The 1957 Columbia-NBS experiment. Phys. Rev. 105, 1413 (1957).



PARTICLE PHYSICS: Electroweak Reconciliation, Michael E. Peskin, Science 281, Issue of 21 Aug 1998, pp. 1153 - 1155



Precision fits. Comparison of weak interaction measurements, using the variables S and T (see text). The bands show the most important constraints in each data set, those from (A) atomic parity violation experiments, (B) the total decay rate of the Z^0, (C) the mass of the W, (D) neutrino scattering experiments, (E) the electron spin asymmetry, and (F) the Z^0 decay angular asymmetries.

With these experimental results in hand, we can explore whether the particles already known suffice to give the correct contribution to the vacuum polarization effect. The possible contribution of new heavy particles can be described by two parameters S and T (11, 12). **The parameter S measures the total size of the new set of particles**; **the parameter T measures the extent to which these particles violate the symmetry among the weak bosons**. The top and bottom quarks, for example, provide only one weak-interaction multiplet, but their masses are very asymmetrical; thus, this multiplet gives a small contribution to S and a large contribution to T. The two variables are defined in such a way that a contribution of 1unit to S or T produces a 1% correction to weak interaction observables, a typical size for vacuum polarization effects. Each precision measurement is sensitive to one linear combination of S and T, and so it picks out a band in the S-T plane. The overlap of the various bands tells us the extent to which the size of the vacuum polarization effect is well determined. In the figure, I show the situation as it was in the summer of 1990, when only the first data from SLC, LEP, and the Tevatron were available, and as it is today. The new measurements focus in on a tiny region in the S, T plane.

M. E. Peskin

Work with β decay:

TRIUMF ^{37}K (1.23s) → ^{37}Ar ; and isomeric ^{38m}K

Berkeley ^{21}Na (22.5 s) → ^{21}Ne

Mirror β decay

Los Alamos ^{82}Rb (1.25 min.) [more about it by D. Vieira later]

TRIUMF: MOT to capture; second trap for background and polarization. Has observed β^+ coincident with Ar recoiling. They get $Ar^{1+,2+,3+}$ accelerated into a microchannel plate with uniform electric field.

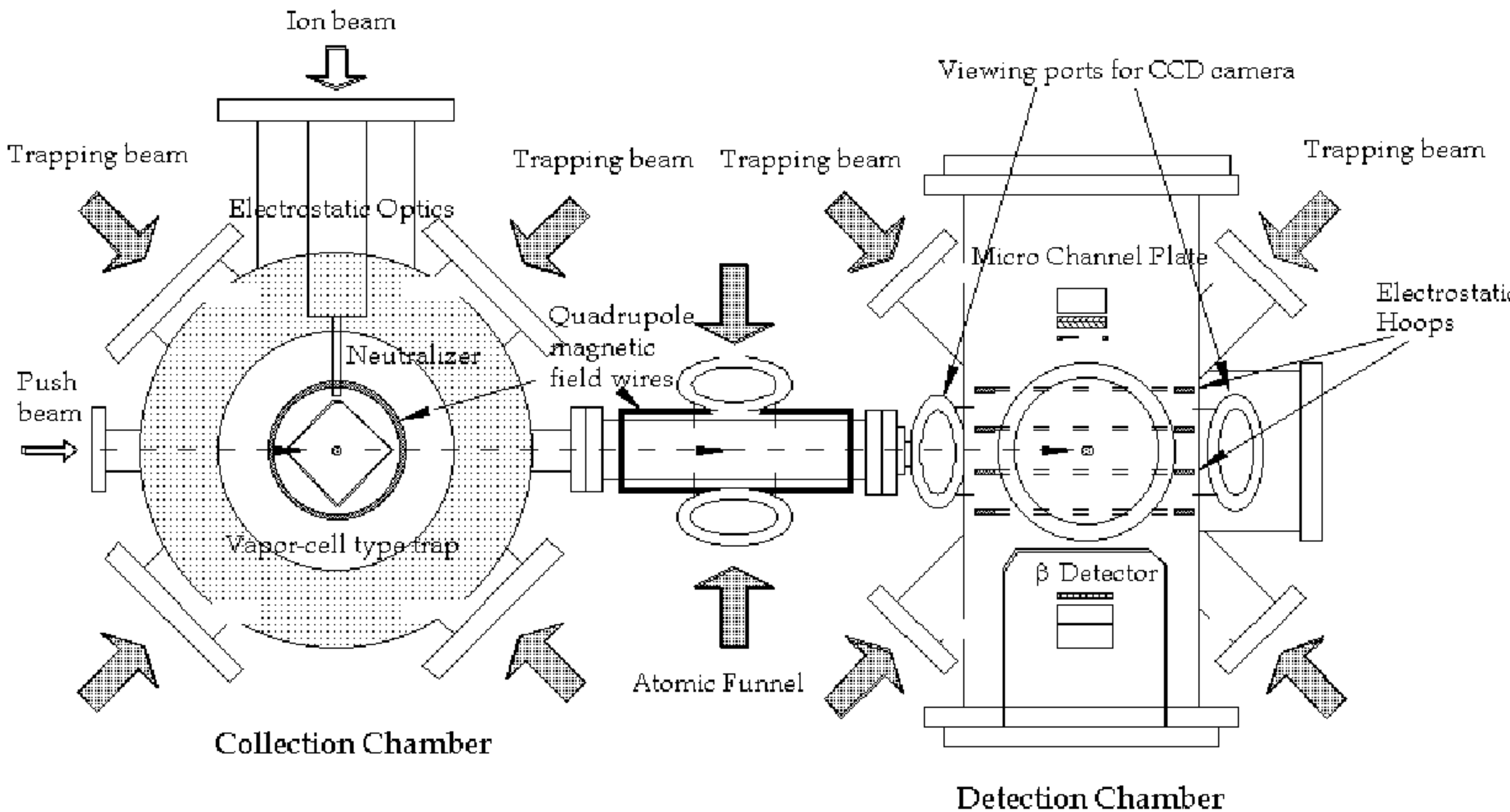
TRIUMF has detected shake-off electrons in coincidence with β^+

May be able to give a full reconstruction of the event but it depends a lot on the atomic physics. How the electron cloud arranges itself when it finds out that the charge of the nucleus has changed.

There should be some very interesting results coming out of this experiment soon.

The work in Berkeley is also making progress

They expect to make a measurement of better than 5% that puts limits to certain types of currents forbidden by the standard model.



TRIUMF apparatus fro trapping and β decay measurements

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