Tests of CPT Invariance

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Ph 135c

29 May 2007

Outline

- Theory behind CPT invariance
  - CPT theorem
  - Lorentz Invariance
- Standard Model Extension
- Predictions of Lorentz-Violating Theories
- Experimental tests
  - Atomic Clock
  - Particle Oscillations
  - Electrodynamics
  - g-2
  - Muonium
  - Polarized Electrons
  - Hydrogen Maser
  - EDM
  - Neutrino Astronomy

CPT Invariance

- CPT Invariance was originally proved theoretically by Pauli in 1954, and simultaneously by Luders and Bell
- Stronger symmetry (CP) was thought to be good, but it's violated in weak force

Connection to Lorentz Invariance (CPT=>Lorentz)

- The CPT theorem states that for local QFTs with Lorentz invariance, the field theory will have CPT symmetry
- Standard Model & SUSY all satisfy these properties
- Most experiments seek Lorentz violation rather than CPT violation

CPT and Lorentz-Violating Theories

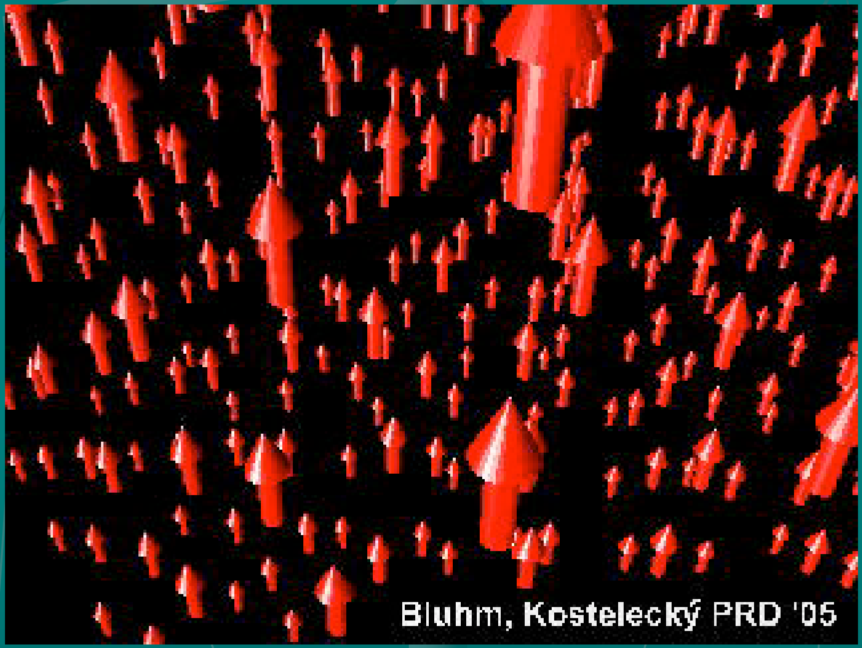
- Most theoretical models are specifically designed to incorporate CPT symmetry
  - Standard Model
  - SUSY
- In 1998, Lorentz-violating extension to the standard model was proposed (SME)
  - Contains gauge-invariance, energy conservation, renormalizability
  - Symmetric under Lorentz transformations of observer
  - Breaks symmetry in boosts and rotations of particle

CPT and Lorentz-Violating Theories cont'd…

- Converse of CPT theorem has been shown:
  If CPT is violated, Lorentz invariance is too
- SUSY can be extended in a similar manner to allow for Lorentz violation
- String theory has small-scale CPT violations
  - Theorists claim to have shown that string theory reduces in some limits to the Standard Model Extension

Manifestations of Lorentz Invariance

- Give inherent spacetime "directionality"
- Lorentz violations may result in:
  - Quantum Gravity
  - Baryogenesis
  - Photons via Nambu-Goldstone modes



Experiments

- Many different experiments for CPT invariance
  - Atomic clock (nuclear)
  - Particle oscillations, g-2 (particle)
  - Photon sector measurements (E&M)
- Experiments set limits on different parameters in the SME
- There is no absolute scale for SME parameters

Experiment 1: Particle Oscillations

- Searching for different particle oscillations
  - B mesons - BABAR, OPAL, Belle
  - Charm (D) mesons - FOCUS
  - Kaons - KTeV
  - Neutrinos - LSND
- Based on rotation of Earth compared to background
  - Sidereal day = 23.93 hours
  - Time for Earth to rotate 360°

Experiment 1: Particle Oscillations

- Neutral meson oscillations
  - B-meson (physical states on left):

$$|B_L\rangle = p\sqrt{1-\mathrm{z}}|B^0\rangle + q\sqrt{1+\mathrm{z}}|\overline{B}^0\rangle$$
$$|B_H\rangle = p\sqrt{1+\mathrm{z}}|B^0\rangle - q\sqrt{1-\mathrm{z}}|\overline{B}^0\rangle$$

$$\mathrm{z} \approx \frac{\beta^\mu \Delta a_\mu}{\Delta m - i\Delta\Gamma/2}.$$

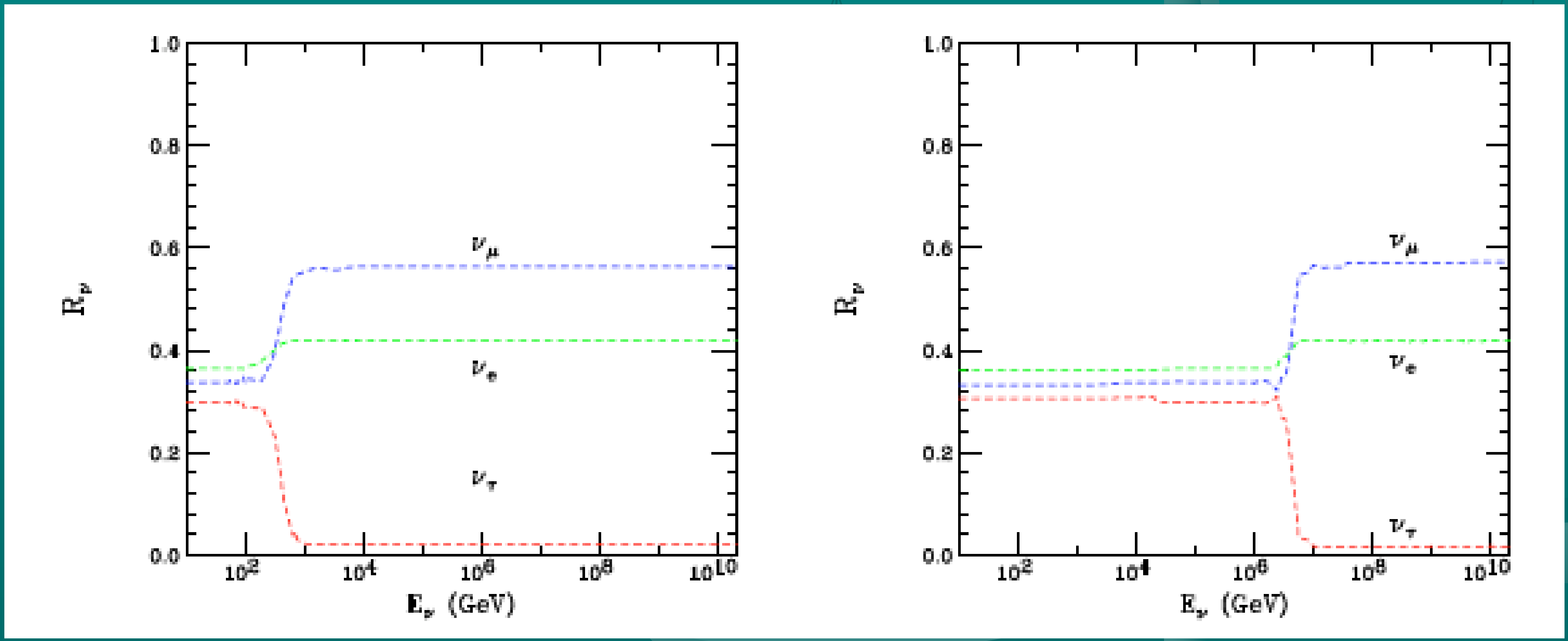
  - β^μ has sidereal time dependence
  - Δa_μ is LV assymetry
  - Mesons produced in B-$\bar{\text{B}}$ decays

Experiment 1: Particle Oscillations

- Neutrino Oscillations
  - LSND
    - Often cited as evidence for sterile neutrinos
    - SME describes neutrino oscillations without requiring sterile neutrino
    - LSND group looked for sidereal dependence (similar to meson oscillations) - found none
    - Also possible to get bounds on parameters of SME from neutrino oscillations
    - LSND paper suggests Planck scale observations

Experiment 2: Neutrino Astronomy

- SME gives energy dependence to ratios of neutrino flavors



Experiment 3: Atomic Clock

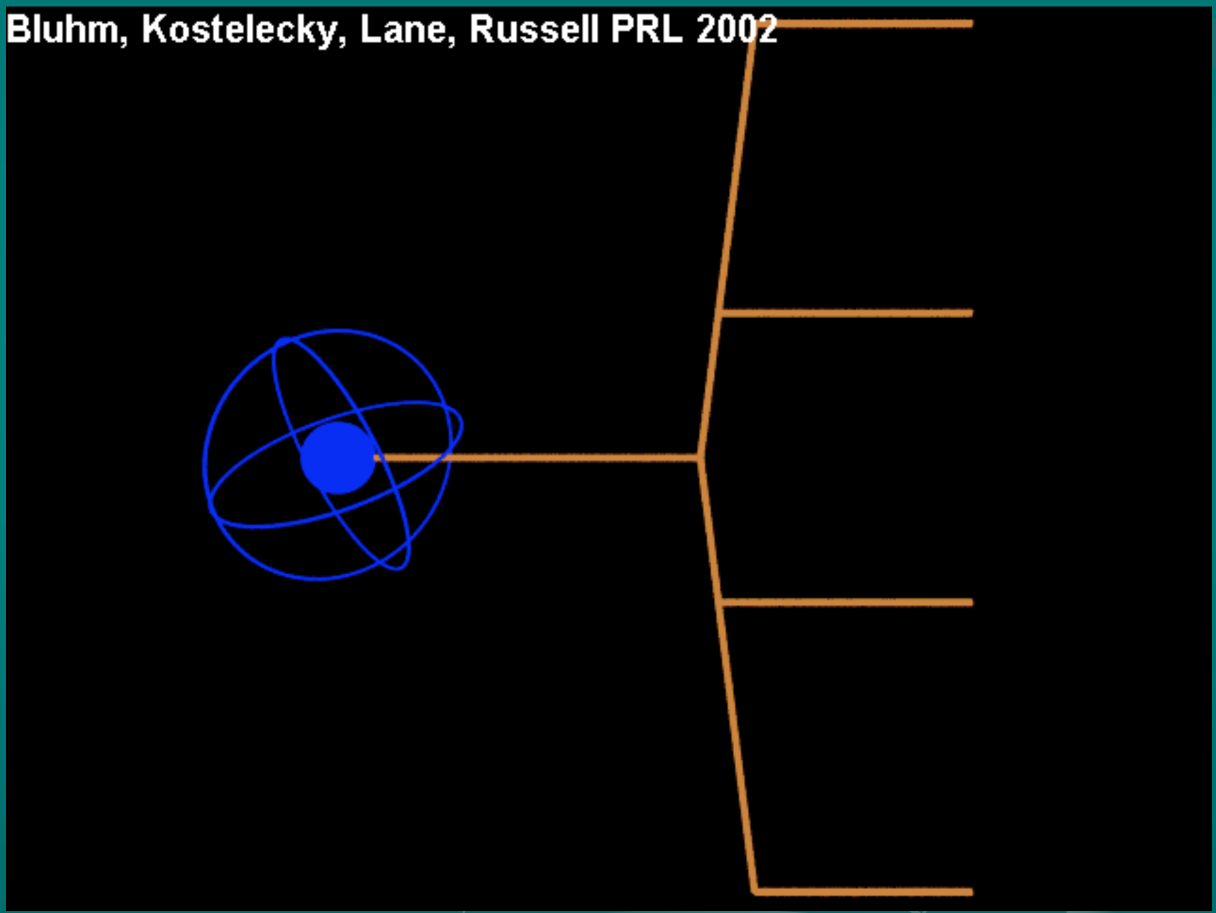
- Cs clock based on F = 3 to F = 4 transitions
- Frequency of clock transition:

Lorentz-Violating

$$\delta\nu = \frac{m_F}{14h}\sum_{w=p,e}\left(\beta_w \tilde{b}_3^w - \delta_w \tilde{d}_3^w + \kappa_w \tilde{g}_d^w\right) - \frac{m_F^2}{14h}\left(\gamma_p \tilde{c}_q^p\right)$$

$$+ m_F K_Z^{(1)} B + \left(1 - \frac{m_F^2}{16}\right) K_Z^{(2)} B^2 \qquad (1)$$

Experiment 3: Atomic Clock

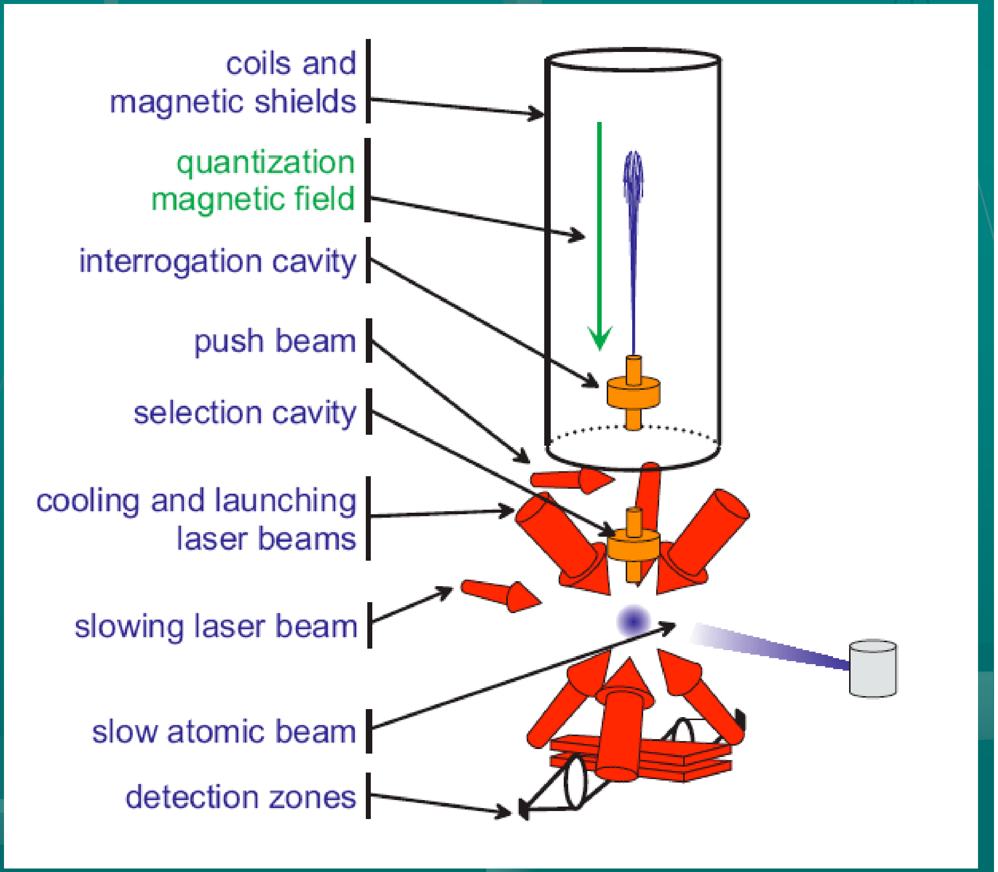


Experiment 3: Atomic Clock

- Measure combined observable that removes first order Zeeman

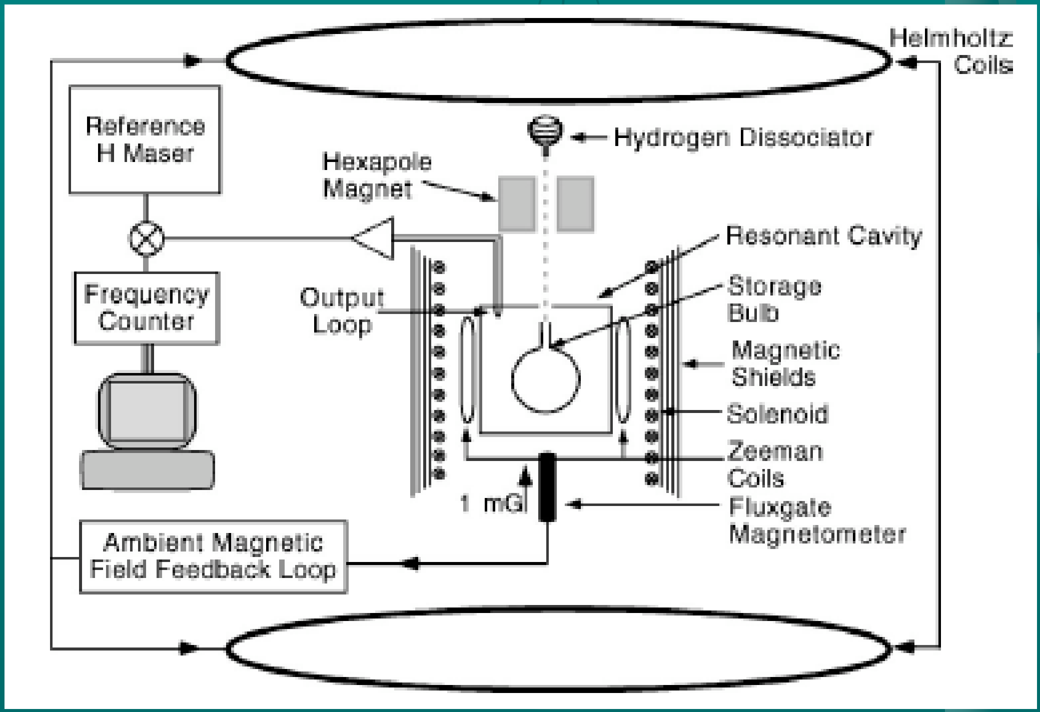
$$\nu_c \equiv \nu_{+3} + \nu_{-3} - 2\nu_0.$$

$$\nu_c = \frac{1}{7h} K_p \tilde{c}_q^p - \frac{9}{8} K_Z^{(2)} B^2$$



Experiment 4: Hydrogen Maser

- Very similar to Cs clock - uses stimulated emission from state transitions
- Unlike Cs, uses atomic transitions



Experiment 5: Muonium

- Again, SME changes energy levels and causes sidereal time-dependence
- Involve muon spin flip
- Possible more sensitive in second-generation lepton regime

Experiment 6: Electrodynamics

- SME gives new Maxwell's equations:

$$\nabla . \boldsymbol{D} = 0$$
$$\nabla . \boldsymbol{B} = 0$$
$$\nabla \times \boldsymbol{E} + \partial \boldsymbol{B} / \partial t = 0$$
$$\nabla \times \boldsymbol{H} - \partial \boldsymbol{D} / \partial t = 0$$

$$\begin{bmatrix} \boldsymbol{D} \\ \boldsymbol{H} \end{bmatrix} = \begin{bmatrix} \varepsilon_0(\overleftrightarrow{\varepsilon}_r + \kappa_{DE}) & \sqrt{\frac{\varepsilon_0}{\mu_0}}\kappa_{DB} \\ \sqrt{\frac{\varepsilon_0}{\mu_0}}\kappa_{HE} & \mu_0^{-1}(\overleftrightarrow{\mu}_r^{-1} + \kappa_{HB}) \end{bmatrix} \begin{bmatrix} \boldsymbol{E} \\ \boldsymbol{B} \end{bmatrix}$$

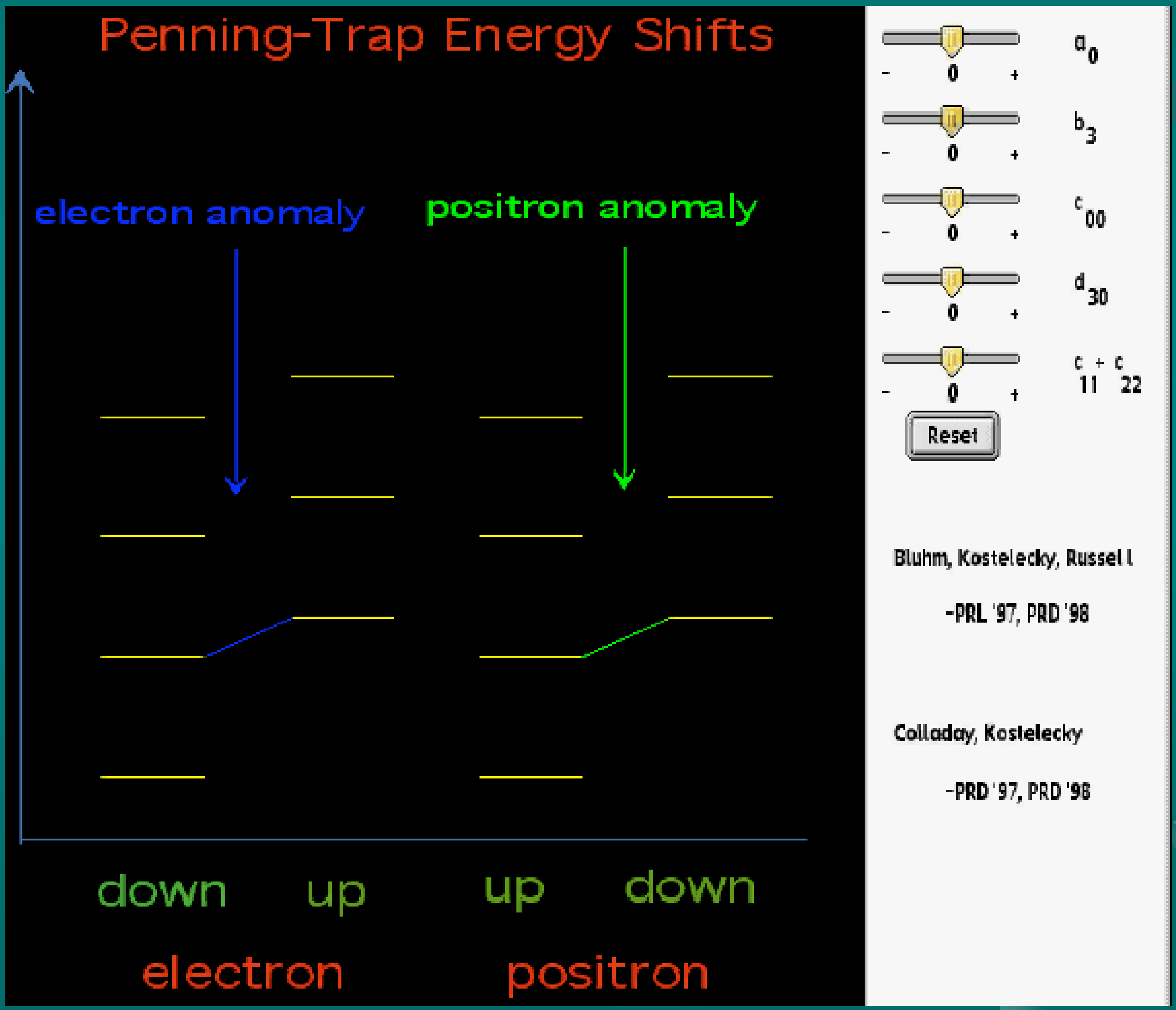
- Changes Doppler Shift (in Li ions)

$$\frac{\nu_p \nu_a}{\nu_0^2} = 1 + \varepsilon_{LV}(t)$$

Experiment 7: Electron g-2

- Actually looks at CPT violation
  - CPT symmetry gives same mass and lifetime for particle and anti-particle
  - g-2 experiments can provide limits on mass difference between electron and positron
  - Looks at frequency difference of electron and positron in Penning traps

Experiment 7: Electron g-2



Experiment Sensitivities

Experiment	Parameter Constraints (GeV)
Particle oscillations	$a_L \sim 10^{-19}$ (neutrino), $\Delta a < 9.2\text{x}10^{-22}$ (kaon)
Atomic Clock	$c < 10^{-25}$ (multiple bounds, see paper)
Maser	$b_\varepsilon < 10^{-29}$, $b_L < 2\text{x}10^{-27}$
Neutrino Astronomy	Not yet complete
Electrodynamics	$\kappa_{Tr} < 2.2\text{x}10^{-7}$ (unitless)
Kaon scattering	$\lvert m_{Kaon} - m_{Antikaon}\rvert / m_{Kaon} < 10^{-18}$
g-2	$\lvert\Delta a\rvert \hbar\omega_c/2m_0c^2 = \lvert 3 \pm 12\rvert \times 10^{-22}$
Muonium	$b^\mu < 2\text{x}10^{-23}$
Polarized Electrons	$b_\varepsilon < 5\text{x}10^{-30}$
EDM	Not complete, expected to improve on pol. elec.

Experiment 8: Polarized Electron Torsion

- Basic idea
  - Torsional pendulum
  - Polarized electrons in the pendulum
  - CP and CPT violating fields create torque on the torsional pendulum
  - Measure the torque
- The problems
  - Separating potentials
  - Designing proper spin pendulum

Experiment 8: Polarized Electron Torsion

- 3 Forces to consider
  - CPT violating potential

$$V_e = \boldsymbol{\sigma}_e \cdot \tilde{\boldsymbol{b}}^e$$

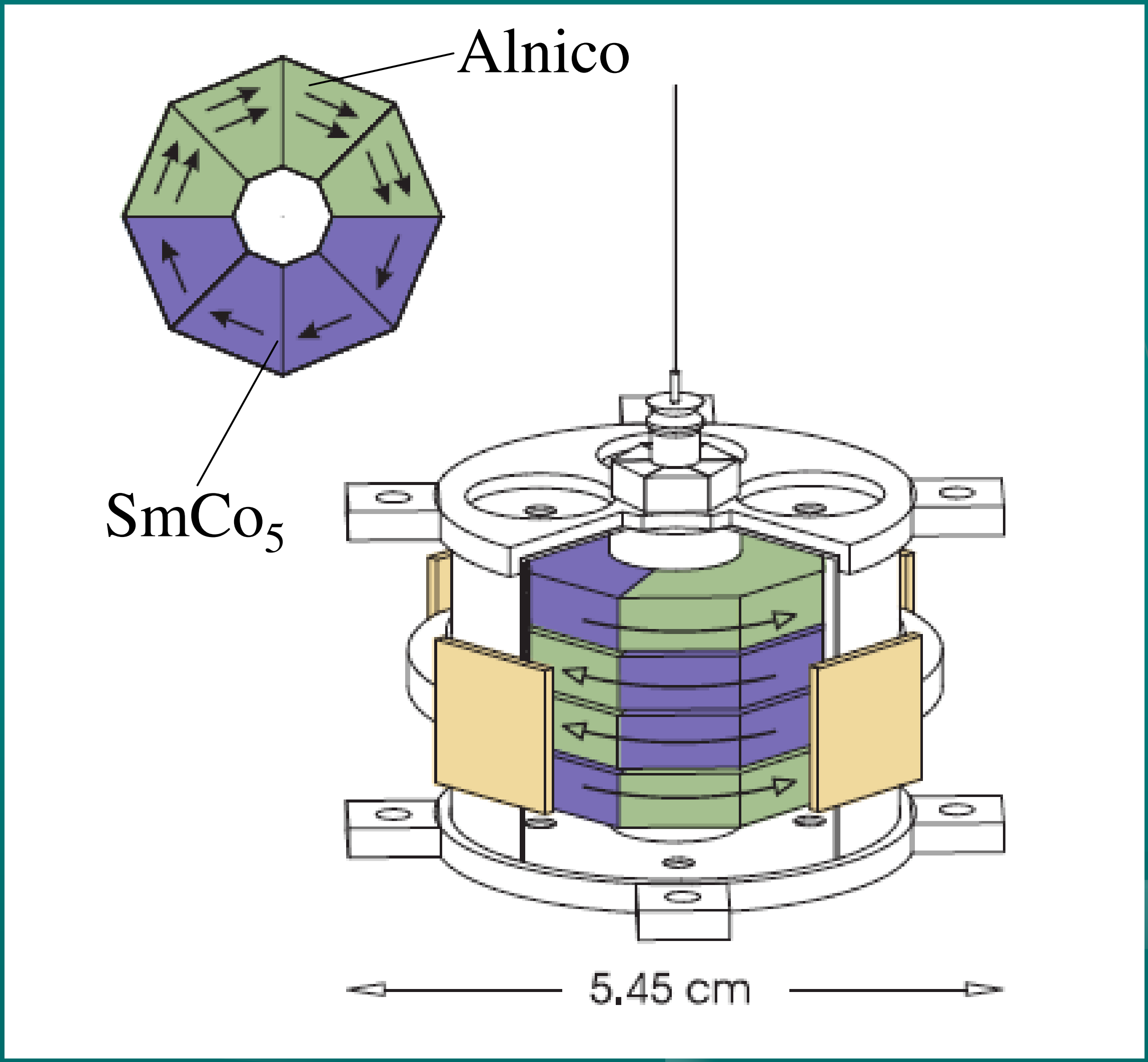
  - CP violating potentials (from hypothetical spin-0 particles)

$$V_{eA}(r) = g_{\mathrm{P}}^{e} g_{\mathrm{S}}^{A} \frac{\hbar}{8\pi m_e c} \boldsymbol{\sigma}_e \cdot \left[\hat{\boldsymbol{r}} \left(\frac{1}{r\lambda} + \frac{1}{r^2} \right) e^{-r/\lambda} \right]$$

$$V_{eN}(r) = \boldsymbol{\sigma}_e \cdot \left[A_\perp \frac{\hbar}{c} \frac{(\tilde{\boldsymbol{v}} \times \hat{\boldsymbol{r}})}{m_e} \left(\frac{1}{r\lambda} + \frac{1}{r^2} \right) + A_v \frac{\tilde{\boldsymbol{v}}}{r} \right] e^{-r/\lambda}$$

Experiment 8: Polarized Electron Torsion

- Alnico
  - Magnetization caused by electron spin
- $SmCo_5$
  - Electron spin in Co, weak field from Sm
- Co cancels Alcino



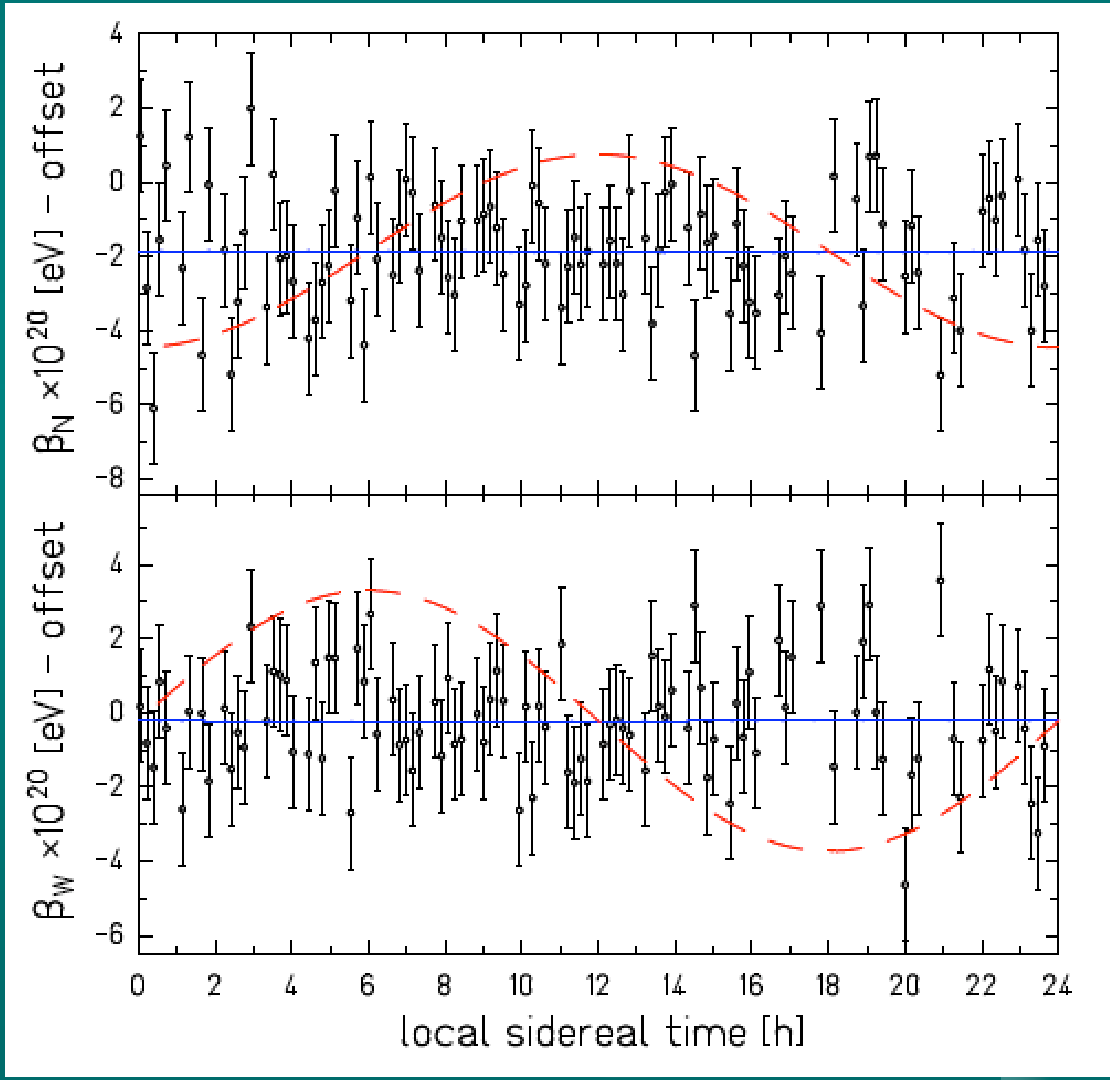
Experiment 8: Polarized Electron Torsion

- Preparation of system
  - Alcino and $SmCo_5$ magnetized via temporarily positioned coils
  - Pendulum suspended on tungsten fiber
    - f_0 = 2.57 mHz, κ = .118 dyne-cm/rad
  - Connected to turntable, spun at frequency f between $3f_0/29$ and $3f_0/20$
  - Turntable placed on "feet-back" system to keep vertical to within 10 nrad

Experiment 8: Polarized Electron Torsion

- Measurements
  - Net spin
    - X-ray scattering gave Co to Sm spin moment ratio of -.23±.04
    - Neutron scattering gave $\mu_{Sm} = 0.04\mu_B$ and $\mu_{Co} = 7.8\mu_B$
    - Gives $N_p = 6x10^{22}$
  - Torque
    - Pendulum rotation measured at 4 angles along it's path
    - Torque extrapolated

Experiment 8: Polarized Electron Torsion



Experiment 8: Polarized Electron Torsion

- Experiment sensitive to β_x and β_y, which are in the normal plane to the Earth's rotation axis
  - $\beta_x = (0.1 \pm 2.4) \times 10^{-22}$ eV
  - $\beta_y = (-1.7 \pm 2.5) \times 10^{-22}$ eV
  - $\beta_z = (-29 \pm 39) \times 10^{-22}$ eV
  - Compare to $m_e^2/M_{planck} = 2 \times 10^{-17}$ eV

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Future Experiments

- EDM measurements
  - Require high-precision magnetometry
  - Difficult to distinguish from CP
- Neutrino Astronomy
- Kaon scattering at CERN
- Most experiments designed to test string theories

Conclusions

We still have no idea if CPT is a good symmetry of nature

References

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