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TESTS OF CPT INVARIANCE WITH LEPTONS AND BARYONS

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A summary of experimental tests of CPT invariance is provided. The most precise and most recent tests with leptons are discussed. A measurement underway to provide a first high precision test of CPT with baryons is mentioned.

1. INTRODUCTION

A basic assumption in physics is that of CPT invariance, where C represents charge conjugation, P represents a parity transformation and T represents a time reversal operation. This good assumption is based to a large extent upon the difficulty of formulating a relativistic, local field theory which is not invariant under CPT Since CPT transforms a particle to an antiparticle, CPT invariance provides several concrete predictions which can be tested experimentally.

1. Particle and antiparticle have the same magnetic moment except for opposite sign.
2. Particle and antiparticle have the same intertial mass.
3. Particle and antiparticle have the same mean life

Experimental tests of CPT invariance, grouped according to which of these predictions is being tested, are summarized in Fig. 1. The experimental numbers for this figure are taken primarily from the compilation of the Particle Data Group.[1] The electron/positron entries are updated.[2] The fractional accuracy is plotted, and baryons, mesons and leptons are distinguished by the shading. The particle/antiparticle systems are identified on the right.

The neutral kaon system provides a test of CPT invariance of striking precision. Others at this conference are discussing CPT tests with this unique system so I will not discuss it further despite its great importance. Equally striking, however, is that only 3 other tests exceed 1 part per million in accuracy, and these involve leptons only. In fact, there is not even a single test of CPT invariance of this precision with a baryon system. Of the lepton tests, the muon measurements done at CERN some years ago[3] do not require any discussion in this setting Efforts are now underway at Brookhaven to improve the muon measurements. The electron/positron measurements are being continually improved They will be discussed in Sec. 2 Finally, in Sec. 3, a new measurement underway to provide a precise CPT test with baryons is discussed. The unshaded region in Fig. 1 indicates the accuracy with which the inertial masses of the proton and antiproton may eventually be compared

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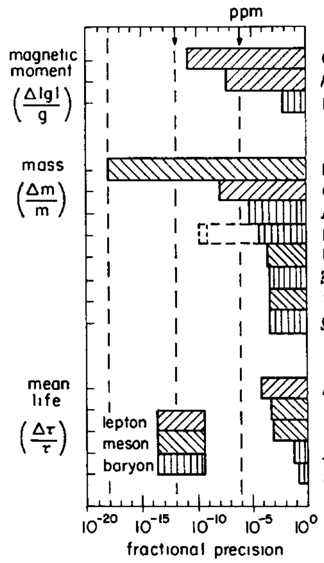

FIGURE 1
Fractional accuracy in experimental tests of CPT invariance.

2. ELECTRON AND POSITRON COMPARISONS

The comparison of the magnetic moments of the electron and positron within a Penning trap is the most precise test of CPT invariance made with leptons. The experiments[2] are very intricate. The highest accuracy is now obtained by comparison with a detailed line shape theory[4] and there are some systematic problems due to the interaction of the electron or positron with the microwave cavity formed by the trap electrodes.[5,6] Because of the high precision achieved, a fairly complete theoretical treatment[7] is not possible here. Instead, I will oversimplify quite a lot to illustrate several central features of the experiments. For example, the Penning trap is essentially a strong, spatially-uniform magnetic field for the purposes of this section.

The g value for a isolated electron confined in a Penning trap is related to the measured spin frequency ν_s, and cyclotron frequency ν_c. An experimenter's definition of the g value is given by

$$\frac{g}{2} = \frac{\nu_s}{\nu_c}. \tag{1}$$

Alternatively, the g value is the dimensionless proportionality constant which relates the spin magnetic moment μ to the spin vector $\mathbf{S}$

$$\mu = g\ \mu_B\ \frac{\mathbf{S}}{\hbar}, \tag{2}$$

where μ_B is the Bohr magneton. Measured g values for the electron and positron are compared. Notice that whereas both the cyclotron and spin frequencies are proportional to the magnetic field, a measurement of both frequencies with the same particle at nearly the same time, greatly reduces the requirements upon the stability and homogeneity of the magnetic field. Nonetheless, field stability and homogeneity remain pressing concerns due to the high precision which can be achieved. A recently developed "self-shielding" superconducting solenoid should greatly facilitate higher precision experiments.[8]

Higher accuracy is actually obtained by a slight variation on the procedure discussed above As is well known, the spin and cyclotron frequencies are not equal primarily because of radiative corrections which can be calculated using quantum electrodynamics (QED). Thus g can be written as

$$g = 2 + a, \tag{3}$$

where the anomaly a is approximately 10^{-3} An experimenter's definition of the anomaly, analogous to Eq. (1), is

$$a = \frac{\nu_a}{\nu_c}. \tag{4}$$

The anomaly frequency ν_a in this definition is given by

$$\nu_a = \nu_s - \nu_c. \tag{5}$$

The advantage of this approach occurs when ν_a can be measured directly rather than being the difference of measured spin and cyclotron frequencies. In the experiments, a fractional accuracy in the measured anomaly a approaching 10^{-9} has been obtained, making it possible to compare the electron and positron g values at the 10^{-12} level

In a Penning trap, slightly shifted cyclotron and anomaly frequencies are actually measured rather than ν_c and ν_a directly. However, the shifts are small and measurable, being simply related to other eigenfreqencies of an electron or positron in a Penning trap which can themselves be measured. Various harmonic motions of the particle in the trap are driven by appropriate radio frequency or microwave fields driving fields. The response of the particle is monitored in general by phase sensitive detection of the current induced in the trap electrodes by the moving particle. A typical set of parameters is a magnetic field of 6 Tesla, cyclotron and spin frequencies near 160 GHz (corresponding to a wavelength of 2 mm) and an anomaly frequency near 200 MHz

The most recent experimental results[2] are

$$a(e^-) = 1\ 159\ 652\ 188.4\ (4.3) \quad 10^{-12} \tag{6}$$

$$a(e^+) = 1\ 159\ 652\ 187.9\ (4.3) \times 10^{-12} \quad (7)$$

The quoted uncertainties are 0.6×10^{-12} due to statistics, 1.3×10^{-12} due to a microwave power shift and 4.0×10^{-12} due to the microwave cavity shift mentioned earlier. However, the microwave cavity shift should be common to both the electron and positron measurements so that the measurements provide a comparison of the magnetic moments at the level

$$\frac{\Delta g}{g} < 1.5 \times 10^{-12}. \quad (8)$$

In the future it may be possible to reduce the first two sources of error by using the relativistic mass shift as a detection technique.[9]

3. COMPARISON OF ANTIPROTON AND PROTON MASSES[10]

Measurements of the inertial mass of the antiproton[11,12,13,14] are represented in Fig. 2, with the proton mass indicated by the dotted line. All of these measurements involve an antiproton orbiting a nucleus. Measured X-ray transition frequencies are compared to calculated transition frequencies, which have a reduced mass factor, to deduce the antiproton mass. No improved measurement has been accomplished in recent years although the antiproton mass is known much less precisely than is the proton mass, to a fractional precision of only 5×10^{-5}. By comparing the cyclotron frequencies of an isolated antiproton and proton in a Penning trap, we hope to eventually get to 10^{-9} based upon precisions achieved with matter particles, perhaps further. This would be an improvement by more than 10^4 and would comprise the first high precision test of CPT invariance with a baryon system. High precision mass spectroscopy in a Penning trap is facilitated by an invariance theorem[15] which makes it possible to minimize otherwise important systematic consequences of the imperfections in a real Penning trap.

Two major challenges must be met before the desired mass spectroscopy with antiprotons is possible. Such mass spectroscopy with matter particles is typically done at energies less than 1 milli-eV. The first challenge is thus to slow antiprotons from the GeV energies at which they are produced. The Low Energy Antiproton Ring (LEAR) at CERN begins the slowing, down to a kinetic energy of 6 MeV. Our TRAP collaboration slowed some of the antiprotons much further,[16] to below 3 keV, via collision with electrons within a thin beryllium window which the antiproton beam passed through. We then captured antiprotons in a simple 3 kV Penning trap, by suddenly switching on the trap potential while the antiprotons were within. This fall we resumed our experiments with a dedicated beam line at LEAR. In fact, a great deal of progress was made shortly after the conference owing to the hard work of my collaborators X. Fei, J. Haas, L. Orozco, R. Tjoelker, H. Kalinowsky, T.A. Trainor and W. Kells. Nearly 10^5 antiprotons were captured into a 3 keV trap at one time. Antiprotons below 3 KeV were held for days. As many as 1/2 to 1/3 of the

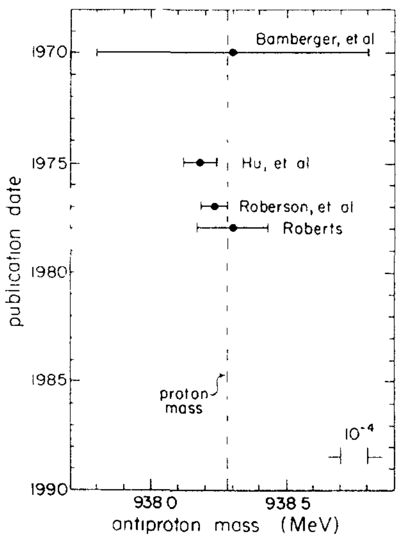

FIGURE 2
Antiproton Mass Measurements

trapped antiprotons were cooled to a kinetic energy below several eV We will try to publish a detailed account as soon as we have completely analyzed our data.

The second major challenge will be to measure cyclotron frequencies precisely in an environment which includes many magnets whose field are being continually adjusted to steer antiproton and proton beams in the proton synchrotron (PS), LEAR itself and various LEAR experiments. The fluctuations of the ambient magnetic field would limit us to a fractional precision of approximately 10^{-6} if nothing were done. For comparison, this is more than 100 times worse than night time fluctuations in my laboratory at Harvard. Fortunately, the "self-shielding" superconducting solenoid mentioned earlier[8] compensates the magnetic field fluctuations by more than 100. For highest precisions, however, it may be necessary to add other shielding as well We will learn as we go.

4. Acknowledgements

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