SEARCHES FOR ANOMALOUS INTERACTIONS USING TRAPPED IONS [a]

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The sensitivity of searches for CPT and/or local Lorentz invariance violating interactions using spectroscopic measurements on trapped ions is discussed.

1 Introduction

Certain elementary particles, atoms, and atomic ions can be studied under relatively benign conditions allowing differences in their energy levels to be measured with high precision. This has enabled searches for various anomalous interactions by looking for shifts in energy levels after varying some experimental parameter which otherwise would not cause a shift. In the context of these proceedings, it is therefore possible to constrain parameters in the theory of A. Kostelecký and collaborators by looking for a CPT violating and/or local-Lorentz-invariance (LLI) violating interaction.

Most of the tests we are interested in are sensitive to an anomalous interaction which depends on the angle between the angular momentum **J** of a particle (for example, an atom or its nucleus) and a vector **A** which denotes a preferred vector for the anomalous interaction (for example, the velocity of the laboratory relative to the fixed stars). For example, the interaction might take the form

$$H_A = C_A \mathbf{J} \cdot \mathbf{A}, \tag{1}$$

where C_A is a proportionality constant which can be derived from the theory. In all practical cases, the angular momentum has an associated magnetic moment $\boldsymbol{\mu} = g_J \mu_0 \mathbf{J}$ (g_J is a proportionality constant and here we take μ_0 to be the Bohr magneton), so that in a magnetic field **B** the particle has energy

$$H = -\boldsymbol{\mu} \cdot \mathbf{B} + H_A \equiv H_M + H_A. \tag{2}$$

In this case, the objective is to vary **A** relative to **B** and look for a change in the energy differences described by the normal magnetic interaction H_M.

The spectrum of H_M is measured using magnetic resonance. The particle is subjected to an oscillating magnetic field (angular frequency ω) which, when tuned to resonance ($\omega = |g_J|\mu_0|\mathbf{B}|/\hbar$), causes a change in the orientation of **J** relative to **B**, which can then be detected.

1.1 Measurement Sensitivity

The measurement sensitivity to changes in resonance frequency can be expressed as

$$\Delta\omega = \Delta\omega_{syst} + \Delta\omega_{meas}, \tag{3}$$

where $\Delta\omega_{syst}$ represents uncontrolled frequency fluctuations due to fluctuations in system parameters (such as the magnetic field) and $\Delta\omega_{meas}$ represents the statistical uncertainty, which is ultimately limited by the quantum fluctuations in the number of atoms which make the transition. For the latter we can write

$$\Delta\omega_{meas} = \frac{1}{\epsilon_{det}\sqrt{NT\tau}} \tag{4}$$

where ϵ_{det} (≤ 1) is the efficiency of quantum-state detection,[1] N is the number of particles in the sample, T is the time the radiation is applied before each state measurement, and τ is the total averaging time (total number of measurements $\simeq \tau/T$). The goal is to make $\Delta\omega$ as small as possible.

1.2 Previous Experiments at NIST

Some examples of previous experiments at NIST are cited here; related experiments by other groups are highlighted in other contributions to this conference. The workhorse of the previous NIST search experiments has been the ion $^9Be^+$. Spectroscopy of a relatively large number of ions can be carried out on ions in Penning traps, which require a relatively large externally-applied magnetic field ($|\mathbf{B}| \simeq 1$ T) for trapping. To avoid fluctuations in H_M caused by fluctuations in **B**, we have used a transition in $^9Be^+$ which is "field independent" at an applied field of 0.82 T. This transition is between atomic ground hyperfine states which are approximately given by $|m_I, m_J\rangle = |-3/2, 1/2\rangle$ and $|-1/2, 1/2\rangle$, where m_I and m_J are the components of nuclear spin (I) and electron spin (S) along the applied magnetic field direction (taken to be the z direction). This transition is therefore primarily sensitive to changes in nuclear spin orientation, but due to slight admixtures of other states, $\langle S_z \rangle$ changes by about 2×10^{-4}. At the operating field, the transition frequency depends on changes in magnetic field only in second order and is therefore nearly field independent.

One NIST experiment sought to look for LLI violations within the context of the $TH\epsilon\mu$ formalism[2] by looking for changes in the transition frequency as A varied with the sidereal day[3] (A was taken to be the velocity of the earth relative to the fixed stars). This and related experiments were summarized by Haugen and Will.[2] A second type of experiment used the same transition to test certain mechanisms for nonlinear quantum mechanics; this and related experiments were summarized by Bollinger, *et al.*[4] A third type of experiment used the same transition to test for anomalous spin-scalar and spin-spin interactions.[5] All of these experiments were sensitive to changes in transition frequency due to nuclear spin reorientation ($|\Delta m_I| = 1$) at a level of between 10 and 100 μHz . However, the standard of comparison is currently set by the neutral-atom experiments of Hunter *et al.*,[6] which are about two to three orders of magnitude more sensitive.

2 Atomic Ions vs. Neutral Atoms

Trapped-ion (as well as neutral-atom) experiments gain their strength from the relative immunity of certain transitions to external perturbations which give rise to $\Delta\omega_{syst}$ fluctuations. For this reason they have been developed by a number of laboratories for use as atomic clocks.[7,8] However, for atomic clocks, we want to minimize $\Delta\omega/\omega_0$ where ω_0 is the transition frequency. In this case, it is therefore desirable to also make ω_0 as large as possible. This usually makes $\Delta\omega_{syst}$ larger, a situation exemplified by the time-dilation shift caused by the atoms' or ions' motion. This shift is proportional to the kinetic energy times ω_0; therefore, having ω_0 too large will cause uncontrolled fluctuations in $\Delta\omega_{syst}$, which may exceed $\Delta\omega_{meas}$ given by Eq. (4). In spite of this limitation, "clock" tests, where we are interested in detecting small fractional changes in frequency, are useful in experiments such as measurements of the gravitational-red shift, time variation of the fundamental constants,[9] or anomalous shifts of mass ratios or g-factors.[10]

To make $\Delta\omega_{meas}$ small, trapped-ion experiments are able to achieve $\epsilon_{det} \simeq 1$ and very large values of T ($T > 10$ minutes in some cases[7,8]). Typically however, the number of ions is less than 10^6 because the Coulomb repulsion between ions limits the densities to values which are small compared to the case for neutral atoms. Since it is usually desirable to confine the particles to small volumes to control $\Delta\omega_{syst}$, N can be many orders of magnitude larger in neutral-atom experiments; this has resulted in a sensitivity to absolute energy shifts which significantly exceeds that of the ion experiments. Thus, tighter constraints on CPT- and/or LLI-violating interactions are currently established by neutral-atom experiments.[11] Nevertheless, since the earlier atomic ion experiments were performed, some advances which promise to significantly reduce $\Delta\omega$ in these kinds of tests have been made.

3 Possible Future Atomic Ion Experiments

Smaller values of $\Delta\omega$ could be obtained in ion experiments with much larger values of N. In rf-Paul ion traps, the largest values of N (around 10^6) have been obtained in linear or racetrack type traps.[8,9,12,13] The smallest values of $\Delta\omega$ have so far been obtained in clock experiments.[8,9] Here, since ω_0 was in the microwave region of the spectrum, long term fluctuations in $\Delta\omega_{syst}/2\pi$ (at around 10 μHz) were limited, in part, by fluctuations in the time-dilation shifts. If rf-trap experiments are adapted to very low values of ω_0, by looking at Zeeman transitions in very low magnetic fields, for example, smaller values of $\Delta\omega$ could be obtained.

In Penning trap experiments, the required large magnetic field precludes low values of ω_0. In previous $^9Be^+$ experiments, long-term fluctuations in $\Delta\omega_{syst}/2\pi$ were limited to about 30 μHz.[14] This was dominated by pressure shifts from background gas. At a level of about 1 μHz, fluctuations in the time-dilation shift occurred due to fluctuations in the frequency of the overall rotation of the ion "cloud."

Both of these effects can be substantially reduced in future experiments. Shifts due to background gas collisions can be made negligible by operating the trap apparatus at liquid helium temperature.[15,16] Recently, it has been possible to precisely control the rotation frequency of an ion cloud and the accompanying time-dilation shift by applying a rotating electric field distortion to the ion cloud at the desired frequency.[17] Since the magnitude of the time-dilation frequency shift goes through a minimum as a function of rotation frequency,[18] stabilizing to this condition minimizes the effects of fluctuations in this shift. The minimum values and systematic fluctuations in $\Delta\omega/\omega_0$ for a few ions have been estimated previously.[18] The example of $^{67}Zn^+$ ($\omega_0/2\pi \simeq 1$ GHz for $|\mathbf{B}| \simeq 8$ T) is instructive to consider since $\Delta\omega$ (Eq. (3)) could be quite small. For $N = 10^6$, $T = 100$ s, $\epsilon_{det} = 1$, and assuming that the time-dilation shift is controlled to 1%, we would achieve a limit on $\Delta\omega/2\pi$ limited by time-dilation fluctuations of 25 nHz. This would take an averaging time τ of about 5 days. We think these numbers are somewhat conservative, and N and T could be increased and the fluctuations in the time-dilation shift further reduced.

4 Other possibilities

Alternate tests using trapped ions are discussed in other contributions to this conference. We conclude with a few additional possibilities using laser-cooled and trapped atomic ions.

A measurement of the proton/antiproton magnetic moment ratio and the possible dependence of this ratio on A has been discussed at this conference. Experimentally, it is difficult to detect spin flips in the proton or antiproton because of the smaller change in energy as compared to electron spin flips. (As opposed to the case of atomic ions, where efficient laser fluorescence detection allows detection of single spin flips in individual ions, this method is precluded for elementary particles.) A method for detection of many sequential spin flips has been proposed by Quint and Gabrielse.[19] However, it might be possible to detect a single spin flip of a single proton or antiproton by coupling these particles to a simultaneously trapped "transfer" ion[20,21] such as $^{9}Be^{+}$.

The limit on $\Delta\omega_{meas}$ could be fundamentally lowered by using entangled states.[22] If the desired states could be achieved on N ions, $N^{-1/2}$ would be replaced by N^{-1} in Eq. (4) thereby reducing the time τ to reach a certain precision $\Delta\omega_{meas}$ by N. However, to accomplish this for large numbers of ions will be technically very difficult.[21]

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