

IMPROVED TESTS OF LORENTZ AND CPT SYMMETRY USING NOBLE-GAS MASERS

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We discuss recent improvements of the $^{129}\text{Xe}/^3\text{He}$ Zeeman maser used to make measurements constraining Lorentz and CPT violation. Experimental investigations of Lorentz and CPT symmetry provide important tests of the framework of the Standard Model of particle physics and theories of gravity. Previous measurements using the $^{129}\text{Xe}/^3\text{He}$ Zeeman maser set stringent limits on rotation- and boost-dependent Lorentz and CPT violation involving the neutron, consistent respectively with no effect at the level of 10^{-31} GeV and 10^{-27} GeV. Recent upgrades to the system should lead to an order-of-magnitude improvement in sensitivity to Lorentz and CPT violation.

1. Introduction

Lorentz symmetry is a fundamental feature of modern descriptions of nature. Lorentz transformations include both spatial rotations and boosts. Therefore, experimental investigations of rotation and boost symmetry provide important tests of the framework of the Standard Model of particle physics and single-metric theories of gravity.

Clock comparisons¹ provide sensitive tests of these symmetries by bounding the frequency variation of a given clock as its orientation changes, e.g., with respect to the fixed stars. In practice, the most precise limits are obtained by comparing the frequencies of two co-located clocks as they rotate with the Earth and as they revolve with the Earth around the Sun. Atomic clocks are typically used, involving the electromagnetic signals emitted or absorbed on hyperfine or Zeeman transitions.

Here we discuss recent upgrades to our two-species $^{129}\text{Xe}/^3\text{He}$ Zeeman maser to enable an improved test of Lorentz and CPT symmetry. Using a previous version of this device we placed a limit on rotation-dependent Lorentz and CPT violation involving the neutron of 10^{-31} GeV,² improving by more than an order of magnitude on the best previous measurement.^{3,4}

With the same device we performed the first clean test for the fermion sector of the symmetry of spacetime under boost transformations, placing a limit on boost-dependent Lorentz and CPT violation involving the neutron of 10^{-27} GeV.⁵

2. Motivation

Our atomic clock tests of Lorentz and CPT symmetry are interpreted in terms of the Standard-Model Extension (SME) developed by Kostelecký and others.⁷ The SME parameterizes arbitrary coordinate-independent Lorentz violation. Since violation of CPT symmetry (the product of Charge conjugation, Parity inversion, and Time reversal) must come with Lorentz violation,⁸ the SME also parameterizes general CPT violation. Observable Lorentz and CPT violation could be a remnant of Planck-scale physics. One attractive origin is spontaneous Lorentz breaking in a fundamental theory,⁹ but other sources are possible.¹⁰

The SME provides a widely-accepted formalism for the interpretation and comparison of experimental searches for Lorentz and CPT violation, and has been applied to many systems, including mesons, photons, and leptons. For example, the SME admits Lorentz-violating couplings of noble-gas nuclei to expectation values of tensor fields. (Some of these couplings also violate CPT.) Each of the tensor fields may have an unknown magnitude and orientation in space, to be limited or detected by experiment. Our atomic-clock comparisons using the $^{129}\text{Xe}/^3\text{He}$ Zeeman maser have provided the most stringent laboratory tests of Lorentz and CPT symmetry (and hence rotation and boost invariance) in any system.^{2,5}

3. $^{129}\text{Xe}/^3\text{He}$ maser upgrades for Lorentz/CPT tests

We provide here a brief review of the design and operation of the two-species $^{129}\text{Xe}/^3\text{He}$ maser, and an overview of recent upgrades that should enable an order-of-magnitude improvement in sensitivity to violations of Lorentz and CPT symmetry of the neutron. A schematic of the $^{129}\text{Xe}/^3\text{He}$ maser is shown in Fig. 1. Co-located ensembles of ^{129}Xe and ^3He atoms at pressures of hundreds of mbar are held in a double-chamber glass cell placed in a homogeneous magnetic field of ~ 6 G. Both species have spin-1/2 nuclei and the same sign nuclear magnetic dipole moment, but no higher-order electric or magnetic nuclear multipole moments. In one chamber of the glass cell, the pump bulb, the noble gas atoms are nuclear-spin-polarized into a population inversion by spin-exchange collisions with optically-pumped

SME fields should be the same for both noble gas species to leading order. We also assume that the SME fields are static and homogenous on scales of at least as long as a year and large as the solar system so that we can detect modulations in the maser frequencies as the Earth rotates and orbits the Sun.

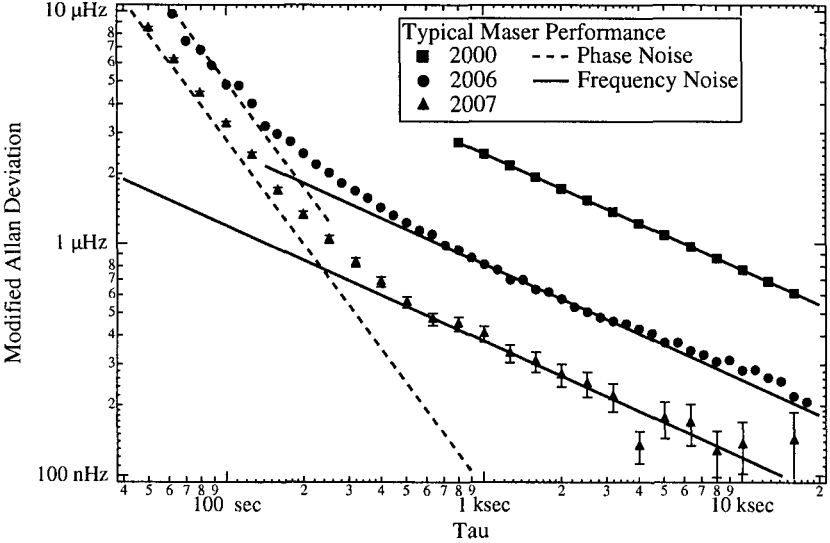


Figure 2. Examples of Allan deviation plots from the last several years, showing improvements in frequency stability of the $^{129}\text{Xe}/^3\text{He}$ Zeeman maser due to increased maser amplitudes (hence lower phase noise), longer coherence times (extends phase-to-frequency-noise crossover), and reduced long-term drift in system parameters.

To make a sensitive measurement of a Lorentz violating background field, the noble-gas masers must have excellent absolute frequency sensitivity, which requires narrow absolute linewidths (i.e., long atomic coherence times) and high signal-to-noise. They also need long term frequency stability to realize that sensitivity on the time scale of the rotation of the apparatus through the Lorentz violating background field. (In our experiments this has been performed using the Earth's rotation.) Very narrow absolute linewidths are possible due to the generally weak interactions of noble gas atoms with the walls and during atomic collisions. The ^3He and ^{129}Xe ensembles can have long Zeeman coherence (T_2) times of hundreds of seconds in magnetic fields of a few gauss with high absolute homogeneity.

Recent optimizations of the noble gas pressures and double bulb cell geometry to maximize maser amplitudes and coherence times as well as an increase in Zeeman frequency (i.e., applied magnetic field) to increase maser power led to significant improvements in frequency stability, as shown in Fig. 2. Importantly, the upgraded $^{129}\text{Xe}/^3\text{He}$ maser now regularly provides frequency stability on timescales of a day that is free of $1/f$ drift, with a modified Allan deviation that continues to decrease as $\tau^{-0.5}$ for consecutive measurement intervals τ . Thus no advantage would be gained by rotating the apparatus for tests of Lorentz symmetry (and problems associated with rotation can be avoided).

The frequency stability of the $^{129}\text{Xe}/^3\text{He}$ maser can be degraded by frequency shifts not corrected for by comagnetometry: including intra- and inter-noble gas species magnetization, noble gas collisions with polarized Rb, collisions with the cell wall, cavity pulling, imperfect spatial overlap of the masing ensembles, and the extended nature of the masing ensembles. All of these frequency shifts are temperature sensitive and hence good control of local environmental temperatures as well as heating power delivered by the optical pumping laser are critical for long term frequency stability. To improve the temperature stability of the double bulb cell we redesigned the oven in which the cell is contained (i) to use separate boron nitride (high thermal conductivity and mass) ceramic blocks around each bulb of the cell; and (ii) to heat and cool each block with blown air not directly in contact with the cell. With this system we achieved thermal stability of 1 m $^\circ\text{C}$ per day for each temperature-controlled region. In addition, we added thermal stabilization to both the laser (an array of free running diodes) and the optics to stabilize the heat load from the absorbed optical pumping light.

Several systematic frequency shifts have been greatly reduced in the upgraded maser system. For example, the pump bulb (see Fig. 1) must be at a high temperature (~ 130 $^\circ\text{C}$) with high Rb density to enable rapid noble gas population inversion; however, the upgraded temperature control system allows the maser bulb and transfer tube between the two bulbs to be up to 80 $^\circ\text{C}$ cooler with low Rb density and no laser light and hence negligible loss of polarization and Zeeman frequency shifts due to Rb-noble gas collisions. Also, the use of a spherical geometry maser bulb and optimization of noble gas pressures through systematic variation has greatly reduced frequency shifts due to intra-noble gas species magnetization (which is exactly eliminated for a sphere with uniform magnetization).

Although the double bulb geometry separates the pumping and masing actions, atoms in the pump bulb can still weakly couple to the inductive coil

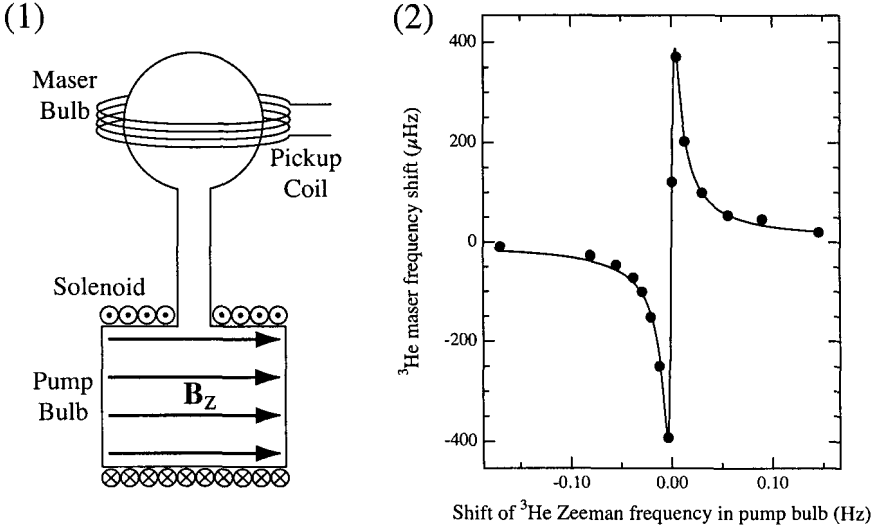


Figure 3. (1) A solenoid wrapped around the pump bulb is used to locally shift the noble gas Zeeman frequency away from that in the maser bulb. (2) Measurements of ^3He maser frequency as a function of ^3He Zeeman frequency in the pump bulb (shifted by the solenoid magnetic field). Detuning the Zeeman frequency in the pump bulb from that in the maser bulb by several linewidths prevents atoms in the pump bulb from participating in the maser ensemble.

surrounding the maser bulb, and thereby contribute to the maser ensemble and overall maser frequency (see Fig. 3). This effect is unwanted for several reasons: collisional frequency shifts due to polarized Rb in the pump bulb can affect the maser frequency; also small magnetic field gradients would lead to large frequency shifts given the distance between bulbs. To avoid these systematic effects we added a local magnetic field to the pump bulb (as shown in Fig. 3) to detune the noble gas Zeeman frequencies in the pump bulb many linewidths away from the maser bulb Zeeman frequencies so that the pump bulb atoms are not part of the masing ensembles.

Improved frequency stability of the $^{129}\text{Xe}/^3\text{He}$ maser requires stringent stability of the tuned circuit resonant frequencies to avoid cavity pulling of the maser frequencies. Improvements in coil design and construction greatly reduced the parasitic capacitance of the coil and the stray capacitive couplings of the coil to other parts of the circuit and environment; temperature stabilization of the double-tuned resonator was also significantly improved. As shown in Fig. 4, cavity-pulling shifts from the double-tuned resonator should not limit maser frequency stability on timescales of hours to a day.

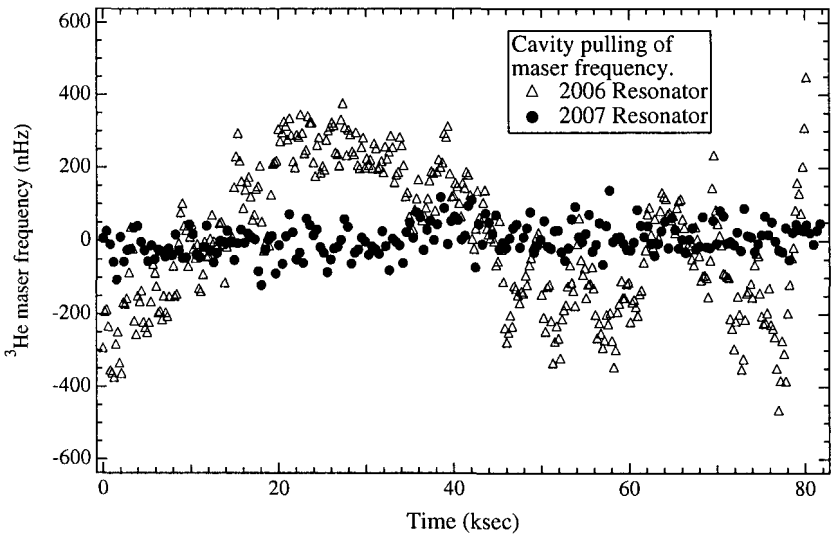


Figure 4. Upgraded stability of the double-tuned resonator has enabled improved long-term maser frequency stability, as illustrated in this comparison of one day’s worth of data for the 2006 and 2007 resonators..

4. Conclusions

Precision comparisons of atomic clocks provide sensitive tests of Lorentz and CPT symmetry, thereby probing extensions to the Standard Model in which these symmetries can be spontaneously broken. Previous measurements using the two-species $^{129}\text{Xe}/^3\text{He}$ Zeeman maser constrain rotation-violation of the neutron at the 10^{-31} GeV level and boost-dependent violations at the 10^{-27} GeV level. We expect about an order of magnitude improvement in sensitivity to Lorentz/CPT violation of the neutron using an upgraded $^{129}\text{Xe}/^3\text{He}$ maser. Improved temperature control of the pump and maser regions, optimized noble gas pressures and cell geometry, increased Zeeman frequency, proper spatial definition of masing ensembles, and improved stability of the double-tuned resonator should enable this goal to be achieved over the next couple of years.

Acknowledgments

We gratefully acknowledge our collaborators on the maser upgrade work described above: Federico Canè, Matthew Rosen and Marc Browning. Support for the $^{129}\text{Xe}/^3\text{He}$ maser upgrade was provided by NASA and NSF.

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