Limit on CPT and Lorentz violation of the proton using a hydrogen maser

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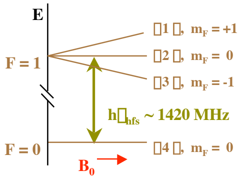
Hydrogen maser basics

The hydrogen maser is among the most stable atomic frequency standards available today. It's applications include:

1. Astronomy (VLBI, deep space tracking)
2. Local oscillators for absolute time standards (for atomic fountain clocks)
3. Precision tests of fundamental physics
4. Precision tests of atomic physics

Hydrogen hyperfine structure

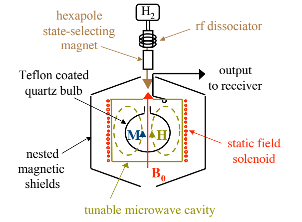


In a hydrogen maser, a beam of state selected |1⟩and |2⟩ hydrogen atoms is focused into a storage bulb centered inside a TE_{011} mode microwave cavity. The cavity is tuned near the hyperfine frequency of 1420 MHz.

The microwave cavity field **H** stimulates hyperfine transitions in the atomic ensemble, and the coherently radiating atoms build up a macroscopic magnetization **M** which acts to increase the microwave field.

This positive feedback between the field and the atoms leads to self-sustained maser oscillation at a frequency near 1420 MHz.

Hydrogen maser schematic



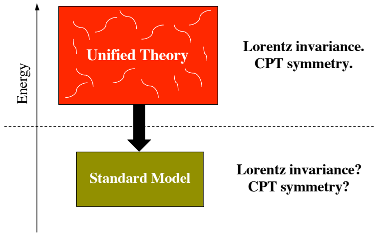
The output oscillation frequency is extremely stable. This stability is attributed to:

1. Long atomic storage time (~1 s)
2. Minimal wall relaxation
3. No first-order Doppler effects
4. No first-order Zeeman effects
5. Significant shielding from environment (thermal, magnetic, vacuum)
6. Low intrinsic noise, set by:
    - **thermal** microwave field → **incoherent transitions**
    - **thermal** noise in receiver

(Items 1–2: → **narrow resonance line**)

Lorentz and CPT symmetry in the standard model

While there may exist a unified theory which incorporates gravity and the standard model and preserves Lorentz and CPT symmetry, the low energy limit of this theory may exhibit violations of these symmetries:



An extension to the standard model has been developed which includes Lorentz and CPT violating effects in the constituent particles of atoms. For example, the modified, Lorentz and CPT violating Lagrangian density of the electron is given by:

$$\mathcal{L} = \tfrac{1}{2} i \bar{\psi} \Gamma_\nu \overleftrightarrow{\partial^\nu} \psi - \bar{\psi} M \psi + \mathcal{L}^{QED}_{\text{int}}$$

$$\Gamma_\nu = \gamma_\nu + \left(c_{\mu\nu}\gamma^\mu + d_{\mu\nu}\gamma_5\gamma^\mu\right)$$

$$M = m + \left(a_\mu\gamma^\mu + b_\mu\gamma_5\gamma^\mu + \tfrac{1}{2}H_{\mu\nu}\sigma^{\mu\nu}\right)$$

Lorentz-violating couplings

*Kostelecky and Lane, Phys. Rev. D, **60,** 116010 (1999)*

This framework predicts a modification of the F=1, Δm_F=1 Zeeman frequency in hydrogen given by:

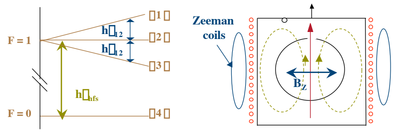
$$\boxed{\left|\Delta\nu_{12}\right| = \frac{1}{h}\left|\left(b_3^{e^-} - d_{30}^{e^-} m_e - H_{12}^{e^-}\right) + \left(b_3^{p} - d_{30}^{p} m_p - H_{12}^{p}\right)\right|}$$

Since the subscripts denote the projection of vector and tensor expectation values onto the laboratory frame, the Zeeman frequency could exhibit sidereal variation as the earth rotates relative to fixed stars.

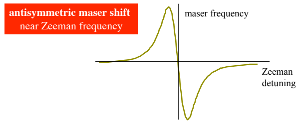
*Bluhm, Kostelecky and Russell, PRL, **82**, 2254 (1999)*

H maser double resonance

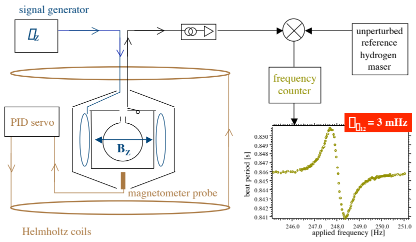
We measure the hydrogen Zeeman frequency using a double resonance technique. A transverse magnetic field $\mathbf{B_Z}$ is first applied across the atomic ensemble:



As the transverse field frequency is swept through the hydrogen Zeeman frequency, the maser oscillation frequency is shifted antisymmetrically:

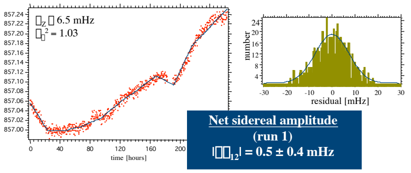


Using this procedure, the F=1, Δm_F=1 Zeeman frequency can be measured with a resolution of approximately 3 mHz:



Long-term Zeeman data

The Zeeman frequency was monitored for multiple sidereal days. The resulting data were fit to a piecewise-continuous linear function (to account for long-term drift) plus a sidereal sinusoid of arbitrary amplitude and phase.



Net sidereal amplitude
(run 1)
$|\delta\nu_{12}|$ = 0.5 ± 0.4 mHz

This initial data set was combined with two additional runs with reversed static solenoid field for a total of 21 days of data over 5 months:

1-sigma limit: $|\delta\nu_{12}| < 0.4$ mHz

This limit results in a very clean bound on Lorentz-violating terms:

$$\boxed{\left|\tilde{b}_J^{e^-} + \tilde{b}_J^{p}\right| \le 2 \times 10^{-27}\ GeV}$$

$$\tilde{b}_J^w = b_J^w - m_w d_{J0}^w - \tfrac{1}{2}\varepsilon_{JKL} H_{KL}^w$$

*Phillips et al., Phys. Rev. D, **63,** 111101 (2001)*

Systematic effects

The following systematic effects were characterized and monitored during the long-term Zeeman frequency measurements. The sidereal variation in these effects led to corresponding variations below our bound on the Zeeman frequency sidereal variation:

Ambient magnetic field

Sidereal varying amplitude: 1 nG → 0.2 μHz

Maser cabinet temperature

Sidereal varying amplitude: 0.0005 °C → 100 μHz

Average maser power

Sidereal varying amplitude: 0.05 fW → 40 μHz

Solenoid current *(subtracted directly from Zeeman data)*

Sidereal uncertainty: 10 pA → 80 μHz

Results

We compare our bound with previous experimental bounds on Lorentz and CPT violation in the electron, proton and neutron. Our experiment with hydrogen places bounds directly on the electron and proton. Therefore, this work places a new, clean bound on Lorentz and CPT violation of the proton:

Experiment	$\tilde{b}_J^e$ [GeV]	$\tilde{b}_J^p$ [GeV]	$\tilde{b}_J^n$ [GeV]
anomaly frequency of electron in Penning trap (Dehmelt et al.)	10^{-25}	--	--
^{199}Hg and ^{133}Cs precession frequencies (Hunter, Lamoreaux et al.)	10^{-27}	10^{-27}	10^{-30}
spin-polarized torsion pendulum (Adelberger et al.)	10^{-29}	–	--
dual ^{129}Xe/^{3}He maser (Bear et al.)	–	--	10^{-31}
this work	**10^{-27}**	**10^{-27}**	–