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

Smithsonian Astrophysical Observatory

Hydrogen maser basics

The hydrogen maser is among the most stable atomic frequency standards available today. Its 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

In a hydrogen maser, a beam of state selected hydrogen atoms is focused into a storage bulb centered inside a TEM$_{00}$ mode microwave cavity. The cavity is tuned near the hyperfine frequency of 1420 MHz.

The microwave cavity field $B_1$ 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.

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:
- Lorentz invariance? CPT symmetry?
- Lorentz invariance. CPT symmetry.

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:

$$ L = \mathcal{L}_{\text{Standard}} + \mathcal{L}_{\text{LCPT}} $$

$$ \mathcal{L}_{\text{LCPT}} = \mathcal{L}_{\text{antisymmetric maser shift}} $$

This framework predicts a modification of the F=1, $|\Delta m|=1$ Zeeman frequency in hydrogen given by:

$$ \Omega = \mathcal{L}_{\text{Standard}} + \mathcal{L}_{\text{antisymmetric maser shift}} $$

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:

$$ \omega(t) = A_0 + A_1 \sin (2\pi t/T) $$

This initial data set was combined with two additional runs with reversed solenoid current to improve the sidereal uncertainty.

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:

<table>
<thead>
<tr>
<th>Effect</th>
<th>Amplitude (mHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient magnetic field</td>
<td>0.4 mHz</td>
</tr>
<tr>
<td>Maser cabinet temperature</td>
<td>0.0005 °C</td>
</tr>
<tr>
<td>Average maser power</td>
<td>0.1 mHz</td>
</tr>
<tr>
<td>Solenoid current</td>
<td>10 pA</td>
</tr>
</tbody>
</table>

Results

We measure the hydrogen Zeeman frequency using a double resonance technique. A transverse magnetic field $B_2$ is first applied across the atomic ensemble:

$$ F = 1 $$

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, $|\Delta m|=1$ Zeeman frequency can be measured with a resolution of approximately 3 mHz.

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:

$$ d J / d \sigma < 0.4 \text{ mHz} $$

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

$$ d J / d \sigma < 0.4 \text{ mHz} $$