PHYSICAL REVIEW D, VOLUME 63, 111101(R)

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

D. F. Phillips, M. A. Humphrey, E. M. Mattison, R. E. Stoner, R. F. C. Vessot, and R. L. Walsworth
Harvard–Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138

(Received 27 August 2000; published 12 April 2001)

We present a new measurement constraining Lorentz and CPT violation of the proton using a hydrogen maser double resonance technique. A search for hydrogen Zeeman frequency variations with a period of the sidereal day (23.93 h) sets a limit on violation of Lorentz and CPT symmetry of the proton at the 10^{-27} GeV level, independent of nuclear model uncertainty, which improves significantly on previous bounds.

DOI: 10.1103/PhysRevD.63.111101 PACS number(s): 11.30.Cp, 06.30.Ft, 11.30.Er, 32.60.+i

Experimental investigations of Lorentz symmetry provide important tests of the standard model of particle physics and general relativity. While the standard model successfully describes particle phenomenology, it is believed to be the low energy limit of a fundamental theory that incorporates gravity. This underlying theory may be Lorentz invariant, yet contain spontaneous symmetry breaking that could result at the level of the standard model in small violations of Lorentz invariance and CPT (symmetry under simultaneous application of charge conjugation, parity inversion, and time reversal).

Clock comparisons [1,2] provide sensitive tests of rotation invariance and hence Lorentz symmetry by bounding the frequency variation of a given clock as its orientation changes, e.g., with respect to the inertial reference frame defined by the distant stars [3]. Atomic clocks are typically used, involving the electromagnetic signals emitted or absorbed on hyperfine or Zeeman transitions. The simple nuclear structure and well-developed theoretical understanding of hydrogen make it an appealing atom for clock-comparison experiments. Here we report results from a hydrogen (H) maser experiment that sets an improved limit on Lorentz and CPT violation of the proton at the level of 10^{-27} GeV as the H maser rotates with the Earth.

Our H maser measurement is motivated by a standard model extension developed by Kostelecký and others [3–7]. This standard-model extension is quite general: it emerges as the low-energy limit of any underlying theory that generates the standard model and that contains spontaneous Lorentz symmetry violation [4]. For example, such characteristics might emerge from string theory [5]. A key feature of the standard-model extension is that it is formulated at the level of the known elementary particles, and thus enables quantitative comparison of a wide array of searches for Lorentz and CPT violation [6]. The dimensionless suppression factor for such effects would likely be the ratio of the appropriate low-energy scale to the Planck scale, perhaps combined with dimensionless coupling constants [3–7].

Recent experimental work motivated by this standard-model extension includes Penning trap tests by Gabrielse *et al.* on the antiproton and H^- [8], and by Dehmelt *et al.* on the electron and positron [9], which place improved limits on Lorentz and CPT violation in these systems. A reanalysis by Adelberger and co-workers of existing data from the ''Eöt-Wash II'' spin-polarized torsion pendulum [10] sets the most stringent bound to date on Lorentz and CPT violation of the electron: approximately 10^{-29} GeV [11]. A recent search for Zeeman-frequency sidereal variations in a ^{129}Xe/^{3}He maser places an improved constraint on Lorentz and CPT violation involving the neutron at the level of 10^{-31} GeV [12]. Also the KTeV experiment at Fermilab and the OPAL and DELPHI collaborations at CERN have limited possible Lorentz and CPT violation in the K and B_d systems [13]. Tests of Lorentz and CPT symmetries for different particles are valuable since limiting one sector of the standard model does not necessarily constrain others.

The hydrogen maser is an established tool in precision tests of fundamental physics [14]. H masers operate on the $\Delta F=1$, $\Delta m_F=0$ hyperfine transition (the ''clock'' transition) in the atomic hydrogen electronic ground state [15]. Hydrogen atoms in the $F=1$, $m_F=+1{,}0$ states are spatially state selected via a hexapole magnet (Fig. 1) and focused into a Teflon coated cell, thereby creating the population inversion necessary for active maser oscillation. The cell resides in a microwave cavity resonant with the $\Delta F=1$ transition at 1420 MHz. A static magnetic field of ~ 1 mG, directed vertically, is applied by a solenoid surrounding the resonant cavity to maintain the quantization axis of the H atoms. The $F=1$, $m_F=0$ atoms are stimulated to make a

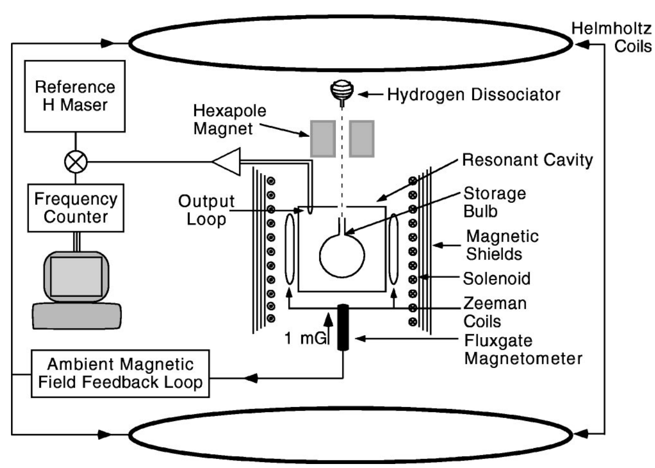

FIG. 1. Schematic of the H maser in its ambient magnetic field stabilization loop. Large Helmholtz coils surround the maser and cancel external field fluctuations as detected by a fluxgate magnetometer placed close to the maser region. Zeeman coils mix the m_F sublevels of the $F=1$ hyperfine state, and allow sensitive measurement of the Zeeman frequency through pulling of the maser frequency [16], as determined by comparison to a reference H maser.

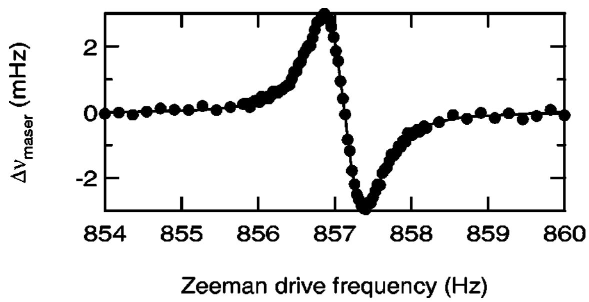

FIG. 2. A double resonance measurement of the Zeeman frequency (ν_Z) in the H maser. The change from the unperturbed maser clock frequency is plotted versus the driving field frequency. (The statistical uncertainty in each point is approximately 50 μHz.) The solid line is the fit of an antisymmetric line shape [16] to the data, yielding $\nu_Z = 857.125 \pm 0.003$ Hz in this example.

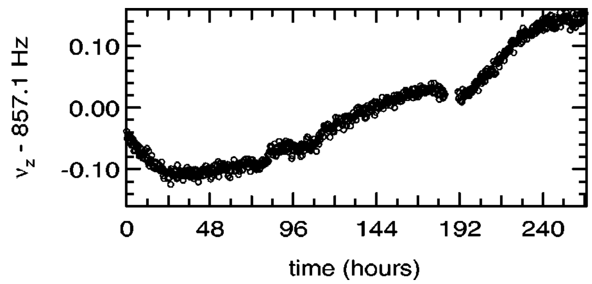

FIG. 3. Zeeman frequency data from 11 days (run 1).

transition to the $F=0$ state by the thermal microwave field in the cavity. The energy from the atoms then acts as a source to increase the microwave field. With sufficiently high polarization flux and low cavity losses, this feedback induces active maser oscillation. H masers built in our laboratory over the last 30 years provide fractional frequency stability on the clock transition of better than 10^{-14} over averaging intervals of minutes to days and can operate undisturbed for several years before requiring routine maintenance.

The $\Delta m_F = 0$ clock transition has no leading-order sensitivity to Lorentz and CPT violation [3,7] because the transition encompasses no change in longitudinal spin orientation. In contrast, the $F=1$, $\Delta m_F = \pm 1$ Zeeman transitions are maximally sensitive to potential Lorentz and CPT violation [7]. Therefore, we searched for a Lorentz-violation signature by monitoring the Zeeman frequency ($\nu_Z \approx 850$ Hz in a static magnetic field of 0.6 mG) as the laboratory reference frame rotated sidereally. We utilized an H maser double resonance technique [16] to measure ν_Z. We applied a weak, oscillating magnetic field perpendicular to the static field at a frequency close to the Zeeman transition, thereby coupling the three sublevels of the hydrogen $F=1$ manifold [17]. This coupling alters the energy of the $m_F=0$ state, shifting the measured maser clock frequency in a manner described by a line shape that is antisymmetric about the Zeeman frequency for sufficiently small static fields (Fig. 2) [16]. We determined ν_Z by measuring the resonant driving field frequency at which the maser clock frequency is equal to its unperturbed value. (The amplitude of the antisymmetric line shape is proportional to the $m_F = \pm 1$ population difference and the strength of the applied Zeeman drive field; the ‘‘zero-crossing’’ value that determines ν_Z is independent of these factors [16].) Because of the excellent frequency stability of the H maser, this double resonance technique allowed the determination of ν_Z with a precision of ~ 1 mHz [18].

In the small-field limit, the hydrogen Zeeman frequency is proportional to the static magnetic field. Four layers of high permeability magnetic shields surround the maser (Fig. 1), screening external field fluctuations by a factor of 32 000. Nevertheless, the residual effects of day-night variations in ambient magnetic noise shifted the measured Zeeman frequency with a 24 hour periodicity which was difficult to distinguish from a true sidereal (23.93 h period) signal in our data sample. Therefore, we employed an active stabilization system to cancel external magnetic field fluctuations (Fig. 1). A fluxgate magnetometer sensed the field near the maser cavity with a shielding factor of only 6 to external magnetic fields due to its location at the edge of the shields. A feedback loop controlled the current in large Helmholtz coils (2.4 m diam.) surrounding the maser to maintain a constant field. This feedback loop effectively reduced the sidereal fluctuations of ν_Z caused by external fields at the location of the magnetometer to below 1 μHz.

We accumulated data in three separate runs over the period Nov., 1999 to Mar., 2000. During data taking, the maser remained in a closed, temperature controlled room to reduce potential systematics from thermal drifts that might have 24 hour periodicities [19]. Each ν_Z measurement required approximately 20 minutes of data (Fig. 2). We also monitored the H maser amplitude, residual magnetic field fluctuations, maser and room temperatures, and the current through the maser solenoid (which sets the static magnetic field). During part of the data taking period, we reversed the direction of the static magnetic field created by the maser's internal solenoid to characterize the double resonance technique [16] and to investigate possible systematic dependence of the diurnal variation of ν_Z on field direction. (As described below, no such dependence was observed as determined by independent measurements of the solenoid current and temperature.) In the field-reversed configuration, the axial magnetic field in the storage bulb was anti-parallel to the field near the exit from the state-selecting hexapole magnet. Thus H atoms traversed a region of magnetic field inversion on their way into the storage bulb, causing loss of atoms from the maser excited state ($F=1$, $m_F=0$) due to Majorana transitions as well as sudden transitions of atoms from the $F=1$, $m_F = +1$ state to the $F=1$, $m_F=-1$ state. In the field reversed configuration, the maser amplitude was reduced by 30% and both the maser clock frequency and Zeeman frequency were less stable [19]. Thus, the constraint on sidereal-period ν_Z variations was weaker in the field-reversed configuration than in the parallel-field configuration.

To identify any sidereal variations in ν_Z, we fit a sidereal-period sinusoid and a slowly varying background to the accumulated ν_Z measurements. (See Fig. 3 for the 11 days of data from run 1.) Two coefficients, $\delta\nu_{Z,\alpha}$ and $\delta\nu_{Z,\beta}$, parametrize the sine and cosine components of the sidereal oscillations. α and β also correspond to non-rotating directions in the plane perpendicular to the Earth's axis of rotation. In

TABLE I. Means and standard errors for $\delta\nu_{Z,\alpha}$ and $\delta\nu_{Z,\beta}$, the quadrature amplitudes of sidereal-period variations in the hydrogen $F=1$, $m_F=\pm1$ Zeeman frequency. Also the number of days of useful and discarded (in parentheses) data, and the maser's internal magnetic field direction are listed.

Run	Useful days (cut days)	Field direction	$\delta\nu_{Z,\alpha}$ (mHz)	$\delta\nu_{Z,\beta}$ (mHz)
1	11(0)	$\Uparrow$	0.43 ± 0.36	-0.21 ± 0.36
2	3(6)	$\Downarrow$	-2.02 ± 1.27	-2.75 ± 1.41
3	5(7)	$\Downarrow$	4.30 ± 1.86	1.70 ± 1.94

addition, we used piecewise continuous linear terms, whose slopes were allowed to vary independently for each day, to model the slow drift of the Zeeman frequency. In the field-reversed configuration (runs 2 and 3), large variations in ν_Z led to days for which this model did not successfully fit the data. Large values of the reduced χ^2 and systematic deviation of the residuals from a normal distribution characterized such days, which we cut from the data sample. Thus, while all the data from run 1 were used in the data analysis, only 8 out of 21 days were used from runs 2 and 3. For each run, the fit determined the components $\delta\nu_{Z,\alpha}$ and $\delta\nu_{Z,\beta}$ of the sidereal sinusoidal variation (see Table I). The total weighted means and uncertainties for $\delta\nu_{Z,\alpha}$ and $\delta\nu_{Z,\beta}$ were then formed from all three data sets, yielding the measured value $A\equiv\sqrt{(\delta\nu_{Z,\alpha})^2+(\delta\nu_{Z,\beta})^2}=0.49\pm0.34$ mHz (1-σ level). This result is consistent with no observed sidereal variation in the hydrogen $F=1$, $m_F=\pm1$ Zeeman frequency, given reasonable assumptions about the probability distribution for A [20].

Systematic sidereal-period fluctuations of ν_Z were smaller than the 0.34 mHz statistical resolution. The current in the main solenoid typically varied by less than 5 nA out of 100 μA over 10 days, corresponding to a change in ν_Z of ~50 mHz. We corrected the measured Zeeman frequency for this solenoid current drift. The sidereal component of the current, for both orientations of the solenoidal field, was typically 25 ± 10 pA, corresponding to a sidereal-period variation of $\nu_Z\approx0.16\pm0.08$ mHz. Also for both field orientations, sidereal temperature variations at the solenoid were less than 25 μK, corresponding to ν_Z variations of less than 1 μHz due to thermomechanical changes in the solenoid. The temperature immediately inside the maser's outer enclosure had a sidereal component below 0.5 mK, corresponding to a sidereal-period modulation of ν_Z of less than 0.1 mHz. Potential Lorentz-violating effects acting directly on the electron spins in the fluxgate magnetometer's ferromagnetic core could change the field measured by the magnetometer and mask a potential signal from the H maser experiment. However, any such effect would be greatly suppressed by a factor of $E/kT\sim10^{-16}$ below the $\lesssim1$ nG sensitivity of the magnetometer, where E is the Lorentz-violating shift of the electron spin energy (known to be $\lesssim10^{-29}$ GeV [10]) and T is the equilibrium temperature of the spins. Also, the magnetic shielding reduces field fluctuations at the magnetometer by a factor of only 6 whereas fluctuations at the storage bulb are reduced by 32 000. Therefore, any shifts of the measured magnetic field induced by Lorentz or CPT violating effects in the magnetometer were negligible in the present experiment. Spin-exchange collisions between the H atoms shift the zero crossing of the double resonance from the true Zeeman frequency [21]. Hence, the measured ν_Z varies with H density. We monitored the atomic density by measuring the output maser power, with the relation to ν_Z being $\lesssim0.8$ mHz/fW. The average maser power drifted less than 1 fW per day. The sidereal component was typically less than 0.05 fW, corresponding to a 0.04 mHz variation in ν_Z. Combining these systematic errors in quadrature with the statistical uncertainty produces a final limit on a sidereal variation in the hydrogen $F=1$, $\Delta m_F=\pm1$ Zeeman frequency of 0.37 mHz (1-σ level), which expressed in energy units is 1.5×10^{-27} GeV.

The hydrogen atom is directly sensitive to Lorentz and CPT violations of the proton and the electron. Following the notation of Refs. [3,7], one finds that a limit on a sidereal-period modulation of the Zeeman frequency ($\delta\nu_Z$) provides a bound on the following parameters in the standard model extension of Kostelecký and co-workers:

$$|\tilde{b}_3^p+\tilde{b}_3^e|\leqslant2\pi\delta\nu_Z \tag{1}$$

for the low static magnetic fields at which we operate. (Here we have taken $\hbar=c=1$.) The parameter $\tilde{b}^{p,e}$ represents the strength of the Lorentz-violating coupling of the proton (p) or electron (e) to possible background expectation values of tensor fields [3,7]. The subscript 3 in Eq. (1) indicates the direction along the quantization axis of the apparatus, which is vertical in the laboratory frame.

As in Refs. [3,9], we can re-express the time varying change of the hydrogen Zeeman frequency in terms of parameters expressed in a non-rotating inertial frame as

$$2\pi\delta\nu_{Z,J}=(\tilde{b}_J^p+\tilde{b}_J^e)\sin\chi, \tag{2}$$

where J refers to either of two orthogonal directions perpendicular to the Earth's rotation axis and $\chi=48°$ is the colatitude of the experiment.

As noted above, a re-analysis of existing data from a spin-polarized torsion pendulum [10] sets the most stringent bound to date on Lorentz and CPT violation of the electron: $\tilde{b}_J^e\lesssim10^{-29}$ GeV [11]. Therefore, the H maser measurement reported here constrains Lorentz and CPT violations of the proton: $\tilde{b}_J^p\leqslant2\times10^{-27}$ GeV at the 1-σ level. This is the first direct experimental bound on $\tilde{b}_J^p$. A previous theoretical re-analysis [3] of the ^{199}Hg/^{133}Cs clock comparison experiment of Hunter, Lamoreaux, and co-workers [2] involved substantial uncertainties due to the complex nuclei used in the experiment. No such uncertainties affect the interpretation of the H-maser experiment because the H nucleus is only a proton. Thus the present work provides improved sensitivity, probably of an order of magnitude or more, to Lorentz and CPT violation of the proton and to $\tilde{b}_J^p$ in particular [3].

To our knowledge, no search for sidereal variations in the hydrogen Zeeman frequency has been performed previously. Nevertheless, implicit limits of ~1 Hz can be set from a widely practiced H-maser characterization procedure in which the Zeeman frequency is measured [15,22]. Our result improves upon such constraints by over two orders of magnitude.

In conclusion, precision comparisons of atomic clocks provide sensitive tests of Lorentz and CPT symmetries [3–7]. A new measurement with an atomic hydrogen maser provides a limit on Lorentz and CPT violation involving the proton that is consistent with no effect at the 10^{-27} GeV level, independent of nuclear model uncertainty. Further details of this work will be found in Ref. [23].

We gratefully acknowledge the encouragement and assistance of Alan Kostelecký. Financial support was provided by NASA grant NAG8-1434 and ONR grant N00014-99-1-0501. M. A. H. acknowledges financial support from the NASA Graduate Student Researchers Program.

[1] V.W. Hughes, H.G. Robinson, and V. Beltran-Lopez, Phys. Rev. Lett. **4**, 342 (1960); R.W.P. Drever, Philos. Mag. **6**, 683 (1961); J.D. Prestage *et al.*, Phys. Rev. Lett. **54**, 2387 (1985); S.K. Lamoreaux *et al.*, Phys. Rev. A **39**, 1082 (1989); T.E. Chupp *et al.*, Phys. Rev. Lett. **63**, 1541 (1989).

[2] C.J. Berglund *et al.*, Phys. Rev. Lett. **75**, 1879 (1995); L.R. Hunter *et al.*, in *CPT and Lorentz Symmetry*, edited by V.A. Kostelecký (World Scientific, Singapore, 1999).

[3] V.A. Kostelecký and C.D. Lane, Phys. Rev. D **60**, 116010 (1999); J. Math. Phys. **40**, 6245 (1999).

[4] V.A. Kostelecký and S. Samuel, Phys. Rev. Lett. **63**, 224 (1989); Phys. Rev. D **40**, 1886 (1989); Phys. Rev. Lett. **66**, 1811 (1991).

[5] V.A. Kostelecký and S. Samuel, Phys. Rev. D **39**, 683 (1989); **40**, 1886 (1989); V.A. Kostelecký and R. Potting, Nucl. Phys. **B359**, 545 (1991); Phys. Lett. B **381**, 89 (1996); V.A. Kostelecký, M. Perry, and R. Potting, Phys. Rev. Lett. **84**, 4541 (2000).

[6] V.A. Kostelecký and R. Potting, in *Gamma Ray–Neutrino Cosmology and Planck Scale Physics*, edited by D.B. Cline (World Scientific, Singapore, 1993), hep-th/9211116; Phys. Rev. D **51**, 3923 (1995); D. Colladay and V.A. Kostelecký, *ibid.* **55**, 6760 (1997); **58**, 116002 (1998).

[7] R. Bluhm, V.A. Kostelecký, and N. Russell, Phys. Rev. Lett. **82**, 2254 (1999).

[8] G. Gabrielse *et al.*, Phys. Rev. Lett. **82**, 3198 (1999).

[9] R.K. Mittleman *et al.*, Phys. Rev. Lett. **83**, 2116 (1999); H. Dehmelt *et al.*, *ibid.* **83**, 4694 (1999).

[10] E.G. Adelberger *et al.*, in *Physics Beyond the Standard Model*, edited by P. Herszeg *et al.* (World Scientific, Singapore, 1999), p. 717; M.G. Harris, Ph.D. thesis, University of Washington, 1998.

[11] B. Heckel, presented at the International Conference on Orbis Scientiae 1999, Fort Lauderdale, Florida, 1999.

[12] D. Bear *et al.*, Phys. Rev. Lett. **85**, 5038 (2000).

[13] KTeV Collaboration, presented by Y.B. Hsiung at the KAON 99 conference, Chicago, 1999; OPAL Collaboration, R. Ackerstaff *et al.*, Z. Phys. C **76**, 401 (1997); DELPHI Collaboration, M. Feindt *et al.*, DELPHI 97-98 CONF 80, 1997.

[14] R.F.C. Vessot *et al.*, Phys. Rev. Lett. **45**, 2081 (1980); J.P. Turneaure *et al.*, Phys. Rev. D **27**, 1705 (1983); R.L. Walsworth *et al.*, Phys. Rev. Lett. **64**, 2599 (1990).

[15] D. Kleppner, H.M. Goldenberg, and N.F. Ramsey, Phys. Rev. **126**, 603 (1962); D. Kleppner *et al.*, Phys. Rev. **138**, A972 (1965).

[16] H.G. Andresen, Z. Phys. **210**, 113 (1968); M.A. Humphrey *et al.*, Phys. Rev. A **62**, 063405 (2000); erratum (to be published).

[17] The weak driving field ($\sim$35 nG at $\sim$850 Hz) caused very small reductions in maser output power ($<2\%$) and line-Q (2%).

[18] At 0.6 mG the differential splitting of the $m_F=\pm 1$ levels is <1 mHz, and is included in the fit model for ν_Z.

[19] Between the data-taking runs, modifications were made to the maser to ready it for other projects.

[20] When both $\delta\nu_{Z,\alpha}$ and $\delta\nu_{Z,\beta}$ have mean zero and variance σ^2, the probability distribution for A is $P(A)=\sigma^{-2}A\exp(-A^2/2\sigma^2)$, and σ is the most probable value.

[21] J.Y. Savard *et al.*, Can. J. Phys. **57**, 904 (1979).

[22] J. Vanier and C. Audoin, *The Quantum Physics of Atomic Frequency Standards* (Adam Hilger, Bristol, 1989).

[23] M.A. Humphrey *et al.*, physics/0103068.