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BOUNDS ON LLI VIOLATION AND LONG-RANGE SPIN-SPIN INTERACTIONS USING HG, CS, AND THE EARTH

L.R. HUNTER*, S.K. PECK, D. ANG, D.K. KIM , D. STEIN,
D. ORBAKER, A. FOSS, M.T. HUMMON, AND J.E. GORDON

Physics Department, Amherst College
Amherst, MA 01002, USA
**E-mail: lrhunter@amherst.edu*

J.F. LIN

Department of Geological Sciences, Jackson School of Geoscience
Austin, TX 78712, USA

We report bounds from a second generation LLI violation experiment using Hg and Cs magnetometers. The experiment is mounted on a rotating table that has made it possible to reduce experimental noise and to extract the first bounds on $\tilde{b}_z$ for the proton and neutron. The same experiment can be used in conjunction with a polarized electron spin map of the Earth to place bounds on long range spin-spin interactions. For some of the proposed long-range spin-spin interactions, these new bounds are a million times more restrictive than the bounds derived by other methods. Our upper bound on the magnitude of the spin-spin force between an electron and a neutron is nearly a million times smaller than their gravitational attraction.

1. Introduction

In the first CPT conference held here fifteen years ago, we reported bounds from our first test of local Lorentz invariance (LLI).[1] In that work we used optically pumped light-absorption oscillators to make precise measurements of the spin precession frequencies of ^{199}Hg and Cs atoms and searched for changes in their relative precession frequencies as a function of the orientation of our applied magnetic field with respect to the fixed stars.[2] At the time, this experiment established the best bounds on the Standard-Model Extension parameters $\tilde{b}_\perp$ for the electron, neutron and proton. The suggestion that these bounds might actually be probing physics at the Planck scale created a great deal of excitement within the field.

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2. The second generation Hg-Cs LLI experiment

We recently completed a new test of LLI using a Hg-Cs comagnetometer.[3] In this experiment, we have upgraded our ultraviolet light source from a Hg discharge lamp to a 271 nm laser. We have also mounted the entire apparatus on a rotation table so that we can invert the horizontal component of our magnetic field every eight minutes, rather than having to wait for the rotation of the Earth. We collected 12 data runs with this second-generation apparatus over a period of a year, where each run consisted of four or five days of data collection. With the existing bounds on possible electron LLI couplings,[4] we use our data to place the first bounds on $\tilde{b}_z$ for the neutron and the proton: $\tilde{b}_z^n < 7\times10^{-30}$ GeV and $\tilde{b}_z^p < 7\times10^{-29}$ GeV. These bounds are significantly less restrictive than the limits that have been established on $\tilde{b}_\perp$.[5] As such, any signal associated with $\tilde{b}_z$ is likely to be associated with an Earth-bound source. One interesting possibility is that the Earth may provide a source of spin-polarized electrons that might interact with our ^{199}Hg spins via long-range spin-spin interactions.

3. Using our results to limit spin-spin interactions

Long-range spin-spin interactions can arise from a variety of possible extensions beyond the standard model of particle physics. Dobrescu and Mocioiu have enumerated nine possible long range spin-spin interactions that could arise via the virtual exchange of a low mass vector boson such as the Z'.[6] Similarly, the virtual exchange of 'unparticles'[7] has been shown to result in long-range spin-spin interactions.[8] Torsion gravity also quite naturally leads to long-range spin-spin interactions.[9]

If such long-range spin-spin interactions do exist, they would create an interaction between the spin-polarized geoelectrons and the ^{199}Hg nuclear spins in our apparatus. The unpaired electron spins within the Earth acquire a modest polarization in the presence of the geomagnetic field. We have created a model of the polarized geoelectron density throughout the Earth using recent deep-Earth geophysics and geochemistry results. We have combined this model with our experimental results and the results from two other experiments[4,10] to constrain the possible strength of these long-range spin-spin interactions between electrons and electrons, neutrons and protons.[11] For potentials that fall off as 1/r at long range, these new bounds are about a million times more restrictive than those achieved from earlier studies that used spin-polarized laboratory sources.[12–14]

Because of the relatively large velocity of the geoelectrons with respect

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to our apparatus, we have been able to constrain the velocity-dependent spin-spin interactions suggested in Ref. 6.[15] Of the six velocity-dependent potentials only V_8 was previously bounded.[16] In the long-range limit, our constraint on V_8 improves upon this earlier bound by about 30 orders of magnitude.

4. Future prospects

We anticipate further improvement in all of these bounds. The work underway using a Rb-^{21}Ne comagnetometer at the South Pole by the Princeton group (presented at this conference) and a new experimental comparison of ^{85}Rb and ^{87}Rb at Cal State East Bay[17] are likely to result in interesting new experimental bounds.

The sensitivity of our recent ^{199}Hg-Cs comparison was not limited by the intrinsic sensitivity of our magnetometers, but rather by small changes in the AC light shift that occurred upon the rotation of our apparatus. While the 'Mx' optical-pumping scheme we have used in our magnetometers is convenient, it is unfortunately first-order sensitive to AC light shifts. We intend to change to either a 'Bell-Bloom'[18]or a 'pump-then-probe'[17,19] geometry where the AC light shifts should be greatly suppressed. With this change we hope to achieve at least an order of magnitude improvement.

Further improvement in the long-range spin-spin interactions will require that we address two additional possible sources of systematic error. Our ability to subtract off the Earth's gyroscopic effect is limited by how well we know the direction of our magnetic field. A straightforward solution to this issue is to move the rotation apparatus to the equator. At the equator, the misalignment of an applied magnetic field (pointing north or south) with the Earth's rotation axis z will only produce uncertainties in the gyroscopic shifts that are second order in the magnetic field misalignment with z. The second obstacle to further improvement arises from the fact that we currently must use separate cells for the Hg and Cs magnetometers. With a single stack of three cells (say, a single Hg cell sandwiched between two Cs cells), we are unable to subtract off a differential frequency shift that would be associated with a quadrupole moment of the magnetic field at our cell stack that does not rotate with the apparatus. This issue could be addressed by the addition of two more Cs cells to monitor the the magnetic quadrupole moment of the field.

A more radical change that would address all of these issues would be to create a rotating comagnetometer with three nuclear species in the same cell (e.g. ^{3}He, ^{129}Xe, and ^{21}Ne or ^{199}Hg). One species could be used to

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regulate the magnetic field. Forming the difference between the frequencies of the other two species would remove the Earth's gyroscopic effect while retaining sensitivity to both neutron and proton couplings to the spin-polarized geoelectrons. Such an apparatus should be limited only by the intrinsic magnetometer sensitivities and could operate at any geographic location.

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