Publications

6-2016

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Improved Tests of Lorentz Invariance in the Matter Sector using Atomic Clocks

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For the purpose of searching for Lorentz-invariance violation in the minimal Standard-Model Extension, we perfom a reanalysis of data obtained from the ^{133}Cs fountain clock operating at SYRTE. The previous study led to new limits on eight components of the $\tilde{c}_{\mu\nu}$ tensor, which quantifies the anisotropy of the proton's kinetic energy. We recently derived an advanced model for the frequency shift of hyperfine Zeeman transition due to Lorentz violation and became able to constrain the ninth component, the isotropic coefficient $\tilde{c}_{\text{TT}}$, which is the least well-constrained coefficient of $\tilde{c}_{\mu\nu}$. This model is based on a second-order boost Lorentz transformation from the laboratory frame to the Sun-centered frame, and it gives rise to an improvement of five orders of magnitude on $\tilde{c}_{\text{TT}}$ compared to the state of the art.

The ^{133}Cs and ^{87}Rb double fountain (see Fig. 1[1]) was run in Cs mode on a combination of $|F = 3, m_F\rangle \longleftrightarrow |F = 4, m_F\rangle$ hyperfine transitions,[2,3] which have good sensitivity to the quadrupolar energy shift of the proton and a weak dependence on the first-order Zeeman effect. The combined observable ν_c, build by measuring quasi-simultaneously the clock frequency for $m_F = +3, -3, 0$, can be related to a model for hyperfine transitions in the minimal Standard-Model Extension (SME)[5,6] and leads to the laboratory-frame SME model presented in Ref. 4. This observable depends on the proton's laboratory-frame coefficient $\tilde{c}_q^p$, which is a combination of the $c_{\mu\nu}$ tensor components.

To search for a periodic modulation of the clock frequency, the laboratory coefficients must be expressed as functions of the Sun-centered frame

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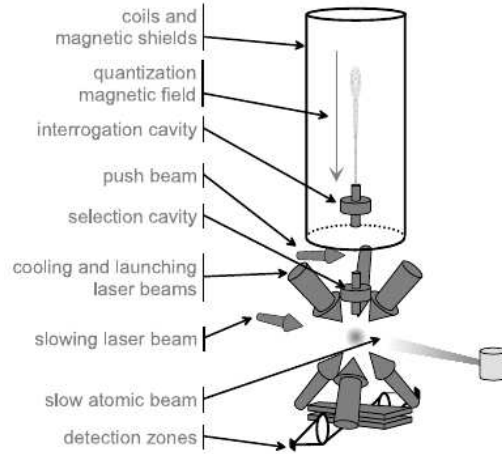
Fig. 1.   Schematic view of an atomic fountain. [1]

coefficients. [7] This transformation is usually done via a first-order ($O(\beta)$) boost Lorentz transformation, [4–6] but for purpose of setting a limit on the isotropic coefficient, $\tilde{c}_{TT}$, which appears in an $O(\beta^2)$ model suppressed by a factor β^2, we develop an improved model using a second-order boost matrix (see also Ref. 8). This contains all the terms up to $O(\beta^2)$, in contrast to Ref. 9 which kept the $O(\beta^2)$ terms exclusively for $\tilde{c}_{TT}$. We also include the annual frequency, previously taken as a constant [4]. The model now exhibits in total 13 frequency components (25 quadratures), instead of 3 frequency components (5 quadratures) for the previous analysis.

We perform a complete least-squares adjustment of the $O(\beta^2)$ model to the data used in Ref. 4. This model is fitted in the SME coefficient basis, which enables us to evaluate simultaneously the nine $\tilde{c}_{\mu\nu}$ coefficients for the proton and their respective correlations. It also avoids additional assumptions on parameter expectation values and underestimation of the uncertainties. [10] The main systematic effects are related to the first- and second-order Zeeman effects. The second-order effect is responsible for an offset of the data from zero, assessed at -2.2 mHz, and the residual first-order Zeeman effect is calibrated via a least-squares fitting of the $O(\beta^2)$ model to the time of flight of the atoms in the fountain. [4,10]

The bounds on $\tilde{c}_{\mu\nu}$ components obtained using the complete $O(\beta^2)$ model are presented in Table 1. They show an improvement by five orders of magnitude on $\tilde{c}_{TT}$ compared to the state of the art. [11] Despite our

Table 1. Limits on SME Lorentz-violation coefficients $\tilde{c}$ for the proton in GeV.

Coefficient	Measured value	Uncertainty			Unit (GeV)
		Statistical	Systematic	Total	
$\tilde{c}_{\mathrm{Q}}$	-0.3	10^{-2}	2.1	2.1	10^{-22}
$\tilde{c}_{-}$	1.4	0.7	8.9	9.0	10^{-24}
$\tilde{c}_{\mathrm{X}}$	-1.5	0.7	5.2	5.3	10^{-24}
$\tilde{c}_{\mathrm{Y}}$	0.8	0.3	1.6	1.6	10^{-24}
$\tilde{c}_{\mathrm{Z}}$	1.0	0.8	3.9	3.9	10^{-24}
$\tilde{c}_{\mathrm{TX}}$	-1.5	0.6	5.7	5.7	10^{-20}
$\tilde{c}_{\mathrm{TY}}$	1.4	0.3	5.9	5.9	10^{-20}
$\tilde{c}_{\mathrm{TZ}}$	-1.1	0.2	3.5	3.5	10^{-20}
$\tilde{c}_{\mathrm{TT}}$	1.6	0.9	6.9	6.9	10^{-16}

advanced model, the correlation matrix still contains large values (up to 0.95), except for the $\tilde{c}_{\mathrm{Q}}$ coefficient, which is almost decorrelated at this sensitivity level. This indicates that our marginalized uncertainties in Table 1 are dominated by those correlations, and could thus be significantly improved with more data spread over the year.

In conclusion, our improved model including $O\left(\beta^2\right)$ terms and annual frequency modulations enables us to improve the present limits on the isotropic coefficient $\tilde{c}_{\mathrm{TT}}$ by 5 orders of magnitude. Furthermore, we expect that an additional data set would reduce the marginalized uncertainties and lead to an improvement by one extra order of magitude on all the limits, bringing the constraint on $\tilde{c}_{\mathrm{TT}}$ near one Planck scale suppresion, i.e. 10^{-17} GeV.

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