Improved Limits for Violations of Local Position Invariance and Local Lorentz Invariance from Atomic Clock Comparisons

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Searches for violations of Einstein's equivalence principle, such as tests of local Lorentz invariance and local position invariance, have become one of the leading applications of low-energy, high-precision experiments with laser-cooled atoms. In our laboratory, we operate microwave atomic clocks based on the ground state hyperfine splitting frequency of Caesium, and optical clocks based on both an electric quadrupole (E2) and an electric octupole (E3) transition of single trapped Ytterbium ions. The E3 reference transition realized by two independent Yb^+ clocks has been compared and an agreement within the combined relative frequency uncertainty of 4.2×10^{-18} has been found [1]. The comparison has been evaluated in terms of a Lorentz violation for electrons, improving previous limits by two orders of magnitude.

Using two Caesium fountain clocks, we measured the E3 transition frequency at 642 THz with 80 mHz uncertainty, the most accurate determination of an optical transition frequency to date. The frequency ratio of E2 and E3 transition has been determined with 3×10^{-17} fractional uncertainty, improving upon previous measurements by an order of magnitude. Repeated measurements of both the E3 transition frequency and the E2/E3 frequency ratio over several years are analyzed for potential violations of local position invariance that would lead to a variation of fundamental constants and affect the atomic transition frequencies [2]. From the observed agreement and consistency of the clock data, we improve by factors of about 20 and 2 the limits for fractional temporal variations of the fine structure constant to $1.0(1.1) \times 10^{-18}$/yr and of the proton-to-electron mass ratio to $-8(36) \times 10^{-18}$/yr. Using the annual variation of the Sun's gravitational potential at Earth, we improve limits for a potential coupling of both constants to gravity.

[1] C. Sanner, N. Huntemann, R. Lange, Chr. Tamm, E. Peik, M. S. Safronova, and S. G. Porsev, Nature **567**, 204 (2019).

[2] R. Lange, N. Huntemann, J. M. Rahm, C. Sanner, H. Shao, B. Lipphardt, Chr. Tamm, S. Weyers, and E. Peik, Phys. Rev. Lett. **126**, 011102 (2021).