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New Antimatter Gravity Tests with Muonium*

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A longstanding question in physics is whether antimatter falls up or down. The equivalence principle of general relativity tells us it falls down; however, if it falls up, a simpler cosmology, with no inflation or baryon asymmetry, and no need for dark matter and energy, may be possible. Alternatively, it may fall down at nearly the same rate as matter, violating the equivalence principle only slightly, and pointing towards a future quantum theory of gravity. For these reasons, several experiments at CERN seek to manufacture antihydrogen and measure its gravitational acceleration. We explore the possibility of similar experiments on muonium, a hydrogen-like atom whose nucleus is an antimuon rather than a proton. The short muon lifetime imposes stringent limits on the required interferometer technology. Meeting them may be feasible using nanotechnology and modern laser feedback techniques. The measurement may thus be feasible using muonium sources at J-PARC, RAL, TRIUMF, or PSI. If so, the outcome could point to a new and better cosmology and theory of gravity. Or it could confirm the equivalence principle in a new realm, at long last laying the question to rest.

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1. Antimatter Gravity

Experiments on antimatter gravity have been pursued for several decades [1, 2] but have yet to yield a statistically significant direct measurement.[1] Attempts to use positrons [1] and antiprotons [2] were abandoned due to confounding effects of stray fields, but studies using (electrically neutral) antihydrogen [3] and positronium [4] are ongoing. We report work toward a measurement with muonium (Mu), a hydrogen-like atom in which a μ^+ replaces the proton. While indirect tests, based on the expected contributions of virtual antimatter to the nuclear binding energy of various elements, imply stringent limits[2] on the gravitational acceleration, $\overline{g}$, of antimatter on earth ($\overline{g}/g - 1 < 10^{-7}$ [5]), a direct test of the gravitational interaction of antimatter with matter seems desirable on quite general grounds [6] and is of interest whether viewed as a test of general relativity or a search for a fifth force. Candidate quantum gravity theories suggest the possibility of differing matter–antimatter and matter–matter forces [6], and recent work on gravity in the SME framework emphasizes the importance of 2nd-generation measurements [7]. The short lifetimes of 2nd- and 3rd-generation particles make Mu the only practical approach beyond the 1st generation.

While physicists generally expect the equivalence principle to hold equally for antimatter as for matter, theories in which antimatter has negative gravitational charge have attracted interest [8] as potentially solving six cosmological mysteries (Why is the cosmic microwave background radiation so isothermal? Why is the universe so flat? Why are galactic rotation curves flat? What happened to the antimatter? Why does $\Lambda = 0$ cosmology give the age of the universe as younger than the oldest stars, and Type IA supernovae dimmer than predicted?) with no need for cosmic inflation, dark matter, or dark energy. This tantalizing possibility provides more than sufficient motivation relative to the required level of experimental effort and expense.[3]

2. Testing Antimatter Gravity with Muonium

The measurement requires a precision three-grating atom-beam interferometer (Fig. 1, left) that determines $\overline{g}$ via the phase observed upon traversal by a slow Mu beam. The atoms' gravitational acceleration causes an interferometric phase shift, measured using the sinusoidal modulation of the Mu-decay counting rate as a grating is scanned vertically. The RMS statistical precision is estimated [9] as $\delta g = d/(2\pi C\sqrt{N}t^2)$, $d \approx 100\,\text{nm}$ being the grating pitch, $C \approx 0.1$ the fringe contrast, N the number of events detected, and t the muonium transit time between gratings. At the anticipated rate of 10^5 Mu/s incident on the interferometer, the statistical precision is about $0.3g$ per $\sqrt{N_d}$, with N_d the exposure time in days, determining $\overline{g}$ to 10% of g in about a month of beam time (assuming a typical 30% overall efficiency). The novel, monoenergetic Mu beam concept, under development at Switzerland's Paul Scherrer Institute [10], relies on muonium formation when a cooled μ^+ beam stops in a μm-thick layer of superfluid He (SHe). An alternative design using a thicker SHe layer may allow an ultimate Mu intensity $\sim 10^2$ higher and enable a sub-1% measurement. A first test using the existing thermal-muonium beam-formation technique [12] is also of interest and could potentially provide the first determination of the sign of $\overline{g}$.

[1]The only published limit, $-65 < \overline{g}/g < 110$, is from the ALPHA Experiment at the CERN AD [3].
[2]The extent to which such limits apply to muonium is far from obvious.
[3]See ref. [11] for a more thorough discussion and more complete list of references.

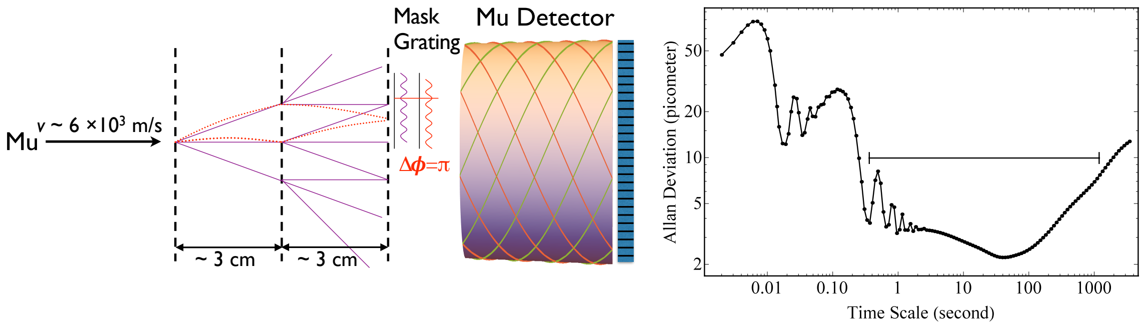

Figure 1: (left) Three-grating interferometer for measurement of $\overline{g}$ with slow muonium beam (not to scale; phase shift $\Delta\phi = \pi$ shown for purposes of illustration); (right) Allan deviation observed in 2-TFG test at IIT.

Interferometer development, including Si_3N_4 grids nanofabricated using *e*-beam lithography and reactive-ion etching at the ANL Center for Nanoscale Materials, is underway using teams of IIT undergraduates and donated equipment and facility time [13]. Given the $\sim 10^2$ pm gravitational deflection (limited by measurement time $\lesssim 3\tau_\mu$), a key challenge is the need to translate a grating with at least 10 pm precision in order to scan the interference pattern. Using two semiconductor-laser tracking frequency gauges (TFGs) [14] we have demonstrated position measurement to ≈ 3 pm, with work ongoing to reduce residual noise. The 10 pm requirement is seen (Fig. 1, right) to imply a need for geometric stability over at least 0.3 s, and calibration (with X-rays) at least every 1000 s. Thus the technique appears to be feasible.

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