Letter of Interest for a Muonium Gravity Experiment at Fermilab

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Abstract

The gravitational acceleration of antimatter, $\bar{g}$, has yet to be directly measured; an unexpected outcome of its measurement could change our understanding of gravity, the universe, and the possibility of a fifth force. Three avenues are apparent for such a measurement: antihydrogen, positronium, and muonium, the last requiring a precision atom interferometer and novel muonium beam under development. The interferometer and its few-picometer alignment and calibration systems appear feasible. With 100 nm grating pitch, measurements of $\bar{g}$ to 10%, 1%, or better can be envisioned, and are the goal of the MAGE collaboration. These could constitute the first gravitational measurements of leptonic matter, of 2nd-generation matter, and possibly, of antimatter. The coming PIP-II and Booster accelerator upgrades could make Fermilab the world's best venue for such an experiment.

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1 Introduction

The question of antimatter gravity, first raised in the 1950s [1], is of continuing interest [2,3]. In the (perhaps counterintuitive, and controversial) "antigravity" scenario, antimatter is predicted to repel matter [1,4–16], potentially solving several problems in cosmology [17]; while in a field-theory-motivated framework, the gravitational acceleration of antimatter by matter could differ slightly from that of matter [2], contrary to expectations from general relativity, and perhaps provide clues to the correct quantum theory of gravity. Decades of experimental effort have yet to yield a statistically significant direct measurement. Antimatter gravity studies using antihydrogen ($\overline{\mathrm{H}}$) are ongoing [18–21], and experiments with positronium have been discussed [22]. We here consider a possible measurement with muonium (M or Mu), an exotic atom consisting of an electron bound to an antimuon; unlike the $\overline{\mathrm{H}}$ case, the interpretation of such a measurement has no hadronic uncertainties. This measurement — the goal of the Muonium Antimatter Gravity Experiment (MAGE) collaboration — could potentially be performed at an upgraded Fermilab muon complex [23].

The most sensitive ($\sim 10^{-7}$) limits on antimatter gravity come from *indirect* tests (for example, equivalence principle tests using torsion pendula [24] or masses in Earth orbit [25]), relying on the expected amounts of virtual antimatter in the nuclei of various elements [26]; these are invalid in the antigravity scenario and, in any case, are inapplicable to muonium. Another limit, $|\alpha_g - 1| < 8.7 \times 10^{-7}$ [27], has been derived from the measured cyclotron frequency of magnetically confined antiprotons, compared with that of H^- ions, based on the gravitational redshift due to Earth's gravitational potential in the field of the local galactic supercluster [28–30]; it too need not apply to antimuons.* A *direct* test of the gravitational interaction of antimatter with matter is desirable on quite general grounds [2].† Such a measurement can be viewed as a test of general relativity or as a search for a fifth force and is of interest from both perspectives.

2 Experiment Concept

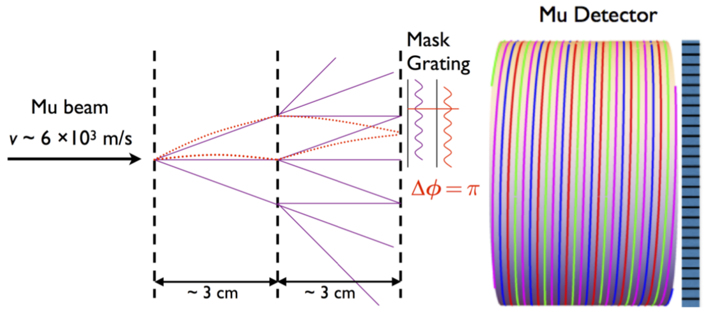
A direct test of antimatter gravity can be performed interferometrically, by passing an intense, high-quality muonium beam in vacuum through precise nanofabricated gratings and measuring the gravity-induced phase shift [17,31,32]. As shown in Fig. 1, a horizontal, parallel, slow muonium beam impinges on a 3-grating, Mach–Zehnder-type interferometer, with the interference pattern following the beam's gravitational acceleration. Mu atoms decaying after the third grating are detected as a coincidence between a fast positron in the barrel detector and a slow electron electrostatically accelerated onto a microchannel plate at the back. The interferometric phase is measured by translating a grating continually up and down and analyzing the resulting changes in detected coincidence rate. The phase is quite small: $\Delta\phi = 2\pi \bar{g} t^2/d \approx 0.01$ (for $\bar{g} = g$), where t is the time for the atom to traverse the distance between gratings and d is the grating pitch (here taken as 100 nm). The required few-picometer alignment system is feasible using laser interferometry [17,33,34]. The zero-deflection phase is determined by periodically illuminating the interferometer with soft X-rays, with a systematic check provided by periodically rotating the interferometer by 90 or 180°.

Preparing the intense, high-quality Mu beam needed for MAGE is a challenge. Beam R&D is currently carried out at Switzerland's Paul Scherrer Institute (PSI) [35] following ideas of Taqqu [36, 37], involving cooling of a surface muon beam in gaseous helium in crossed electric and magnetic fields to reduce its 6D emittance by some 10 orders of magnitude, at a cost of two to three orders of magnitude in muon decay loss. The cooled beam can then be stopped in a $\sim \mu$m-thick layer of superfluid helium (SFHe) at the bottom of a cryostat, efficiently forming muonium, which is then

*And we note that arguments based on absolute gravitational potentials have been critiqued by Nieto and Goldman [2]. Other precise measurements of these cyclotron frequencies [38, 39] have not been interpreted in terms of possible matter–antimatter gravitational differences.

†The only published direct test so far [18] has yielded the limit $-65 < \bar{g}/g < 110$.

Figure 1: MAGE experiment concept (elevation view; gravitational deflection and phase shift $\Delta\phi$ exaggerated for clarity). Muonium beam enters from left, slow-electron detector is at right. Not shown: ring electrodes to accelerate slow electrons onto their detector, starting downstream of grating 3 and continuing within scintillating-fiber-barrel positron detector; hodoscope around positron barrel.



expelled vertically from the upper SFHe surface at a predicted speed of 6.3 mm/μs [37] due to its large, positive chemical potential (270 K) in SFHe [36]. The vertical beam is turned to horizontal, as needed for MAGE, by means of a 45° SFHe-coated deflector [40]. (Because the Mu atoms are in thermal equilibrium with the SFHe prior to expulsion, both the beam energy spread and its angular divergence are determined by the ratio of the $\sim$ 0.2 K SFHe temperature to the Mu chemical potential.) The resulting interferometer acceptance is maximal, leading to a 5σ $\bar{g}$ sign determination with about one month's worth of beam at PSI [17].

Another beam option exploits another idea of Taqqu's [36]: use a 100-times-thicker SFHe layer, thus needing no muon cooling, so potentially providing two orders of magnitude higher intensity than the "muCool" beam discussed above; it could be developed at Fermilab in parallel to the work in progress at PSI. This "thick-film" approach could enable a $\lesssim 10\%$ measurement of $\bar{g}$ in a month of beam time at PSI [17], and potentially a 1% or higher-precision measurement at a future Fermilab facility. Since only Mu atoms formed close to the upper SFHe surface will emerge upwards to form the desired beam, an electric field is maintained in the helium (via a pool of negative charge at the SFHe surface) to cause the stopping μ^+ to separate from their ionization trails and drift to the upper surface before forming Mu. The $\sim$cm-wide beam results in some acceptance loss if cm-wide gratings are employed, thus larger gratings (if feasible) could be beneficial; alternatively, the SFHe deflector could have a curved surface so as to produce some focusing of the beam into the interferometer [40].

Surface muon beams, available at J-PARC and MuSIC in Japan, ISIS in the U.K., TRIUMF in Canada, and PSI, are currently unavailable in the U.S. As the record holder for surface-muon beam intensity, PSI — with up to $\sim 10^9$ Hz surface-muon rate, and an upgrade to 10^{10} under discussion, to be produced using $\sim 10^{12}$ Hz of 590 MeV protons on target — has been the natural venue for muonium-beam R&D. With potentially $\gtrsim 10^{13}$ Hz of protons on target, the coming PIP-II intensity upgrade [41] could make Fermilab the world leader for both fundamental muon experiments and the Muon Spin Rotation community [42]; the novel muonium beams discussed above could be used as-is for MAGE [17] and other muonium experiments, or ionized to serve muon experiments [43].

3 R&D

To enhance beam design progress in the interim period before a new facility can be built, an R&D platform would be extremely useful and, for some applications (e.g., SFHe Mu production), even crucial. This could be provided at the Fermilab "MuCool Test Area" (MTA) [44], or (at lower intensity) using the Fermilab Test Beam Facility (FTBF). Other options may also be available.

4 Conclusion

We propose to study the options for providing competitive muonium beams at Fermilab in the Mu2e and PIP-II "eras." This study can inform proposals for MAGE at Fermilab as well as other future experiments employing muonium, such as the precision determination of the hyperfine and 1S–2S transition frequencies [45–47], the search for Mu–$\overline{\text{Mu}}$ oscillation [48], etc.

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