MAGE: Probing Antimatter Gravity with Muons

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Outline

- Motivation: Some history
- Experimental approach
- Required R&D
- Conclusions

Brief History

- 1928: Dirac postulates antielectrons
- 1932: Anderson discovers positron
- 1955: Chamberlain & Segrè discover antiproton
- 1956: M. Goldhaber notes "baryon asymmetry of the universe" (BAU)
  - now generally believed BAU arose through CP violation (discovered 1964)
  - but, pre-1964, more plausible to postulate *gravitational repulsion* between matter and antimatter – "antigravity"!

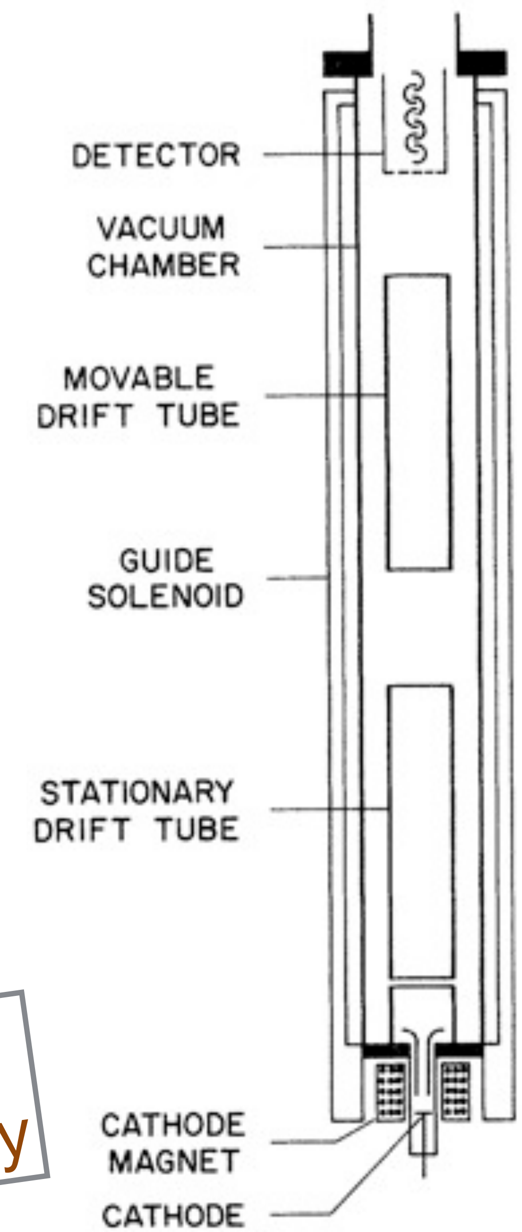
antiparticles a general phenomenon

Brief History

- Led to Witteborn–Fairbank experiment: measure direction of "falling" positrons
  - preliminary e^- test ended inconclusively, e^+ never attempted
- LANL-led team proposed (1986) $\bar{p}$ gravity experiment at LEAR
  - also inconclusive – stray EM forces on charged particles too challenging?
- **Moral**: need *neutral* antimatter
  - $\overline{\mathrm{H}}$ at AD: ALPHA, AEgIS, GBAR
  - Muonium at PSI (FNAL)?

Virtue: No hadronic uncertainty

F. C. Witteborn & W. M. Fairbank, "Experimental Comparison of the Gravitational Force on Freely Falling Electrons and Metallic Electrons," PRL **19**,1049 (1967)



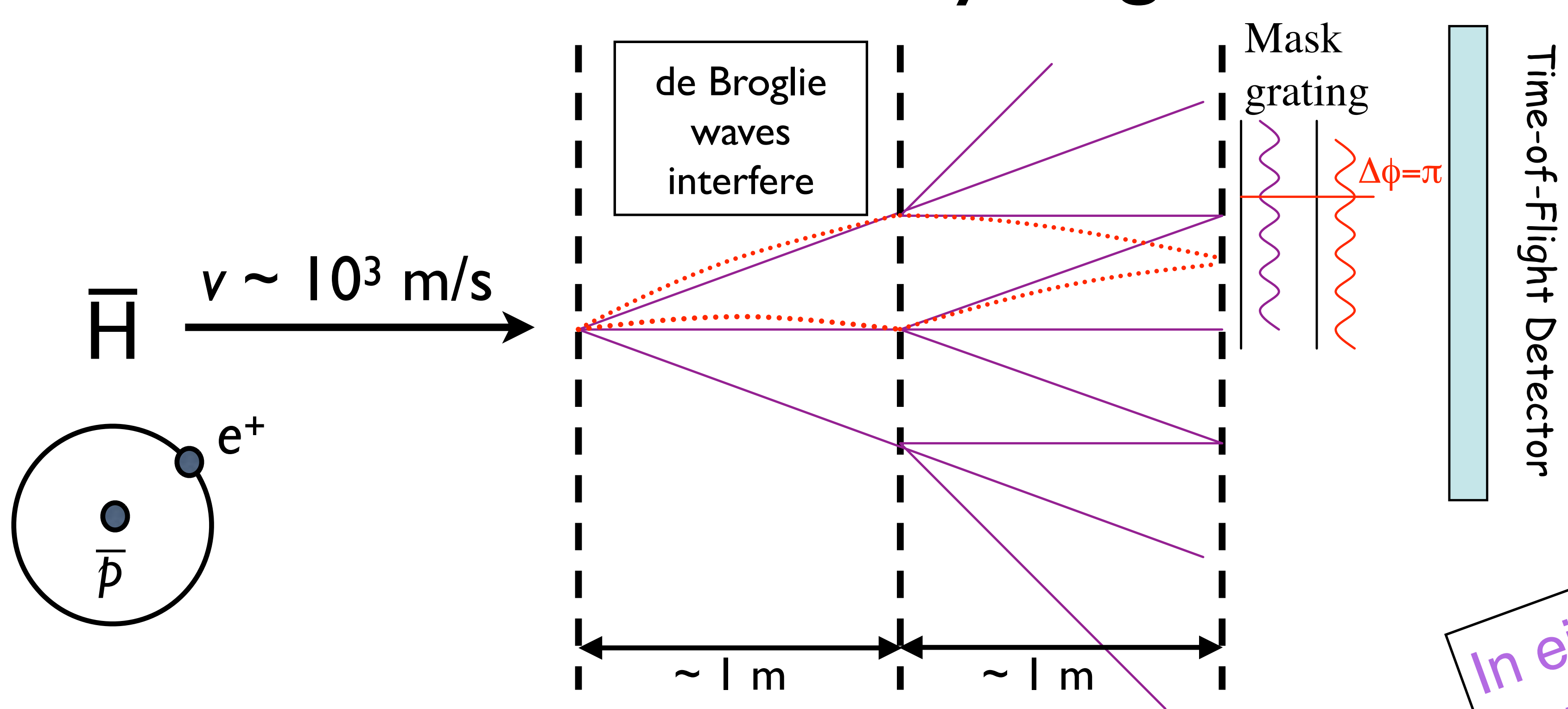
Studying Antimatter Gravity

- Experimentally, *still* unknown if antimatter falls up or down! Or whether $\bar{g} - g = 0$ or ε

C. Amole et al., "Description and first application of a new technique to measure the gravitational mass of antihydrogen," Nature Comm. **4** (2013) 1785: $-65 < \bar{g}/g < 110$

  - in principle a simple interferometric measurement with slow antihydrogen beam:

T. J. Phillips, "Antimatter gravity studies with interferometry," Hyp. Int. **109** (1997) 357



$\frac{1}{2} g t^2 = 5\ \mu m$

  - well within interferometry state of the art

In either case, Equivalence Principle must be modified!

  - if $\bar{g} = -g$, antigravity as discussed above
  - if $\bar{g} = g \pm \varepsilon$, need to modify theory of gravity (scalar + vector + tensor), or add "5th force" to the known 4

Studying Antimatter Gravity

- Besides antihydrogen (and maybe positronium), only *one other* antimatter system conceivably amenable to gravitational measurement:
- Muonium (M or Mu) —
  - hydrogenic atom with μ^+ replacing the proton
    - easy to produce but hard to study!
- Measuring muonium gravity — if feasible — could be *1st* (only?) gravitational measurement of a
  - lepton
  - 2nd-generation particle

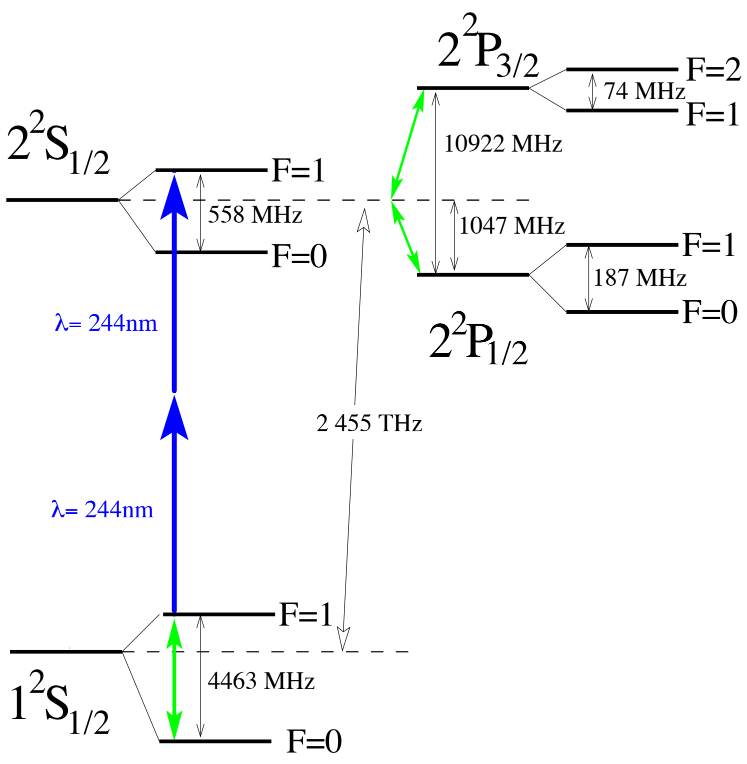
Muonium

- Much is known about muonium...
  - a *purely leptonic atom*, discovered 1960

V. W. Hughes et al., "Formation of Muonium and Observation of its Larmor Precession," Phys. Rev. Lett. **5**, 63 (1960)

$$\tau_M = \tau_\mu = 2.2\ \mu s$$

  - readily produced when μ^+ stop in matter
  - chemically, almost identical to hydrogen
  - atomic spectroscopy well studied
  - forms certain compounds (MuCl, NaMu,...)
  - "ideal testbed" for QED, search for new forces, precision measurement of muon properties, etc.



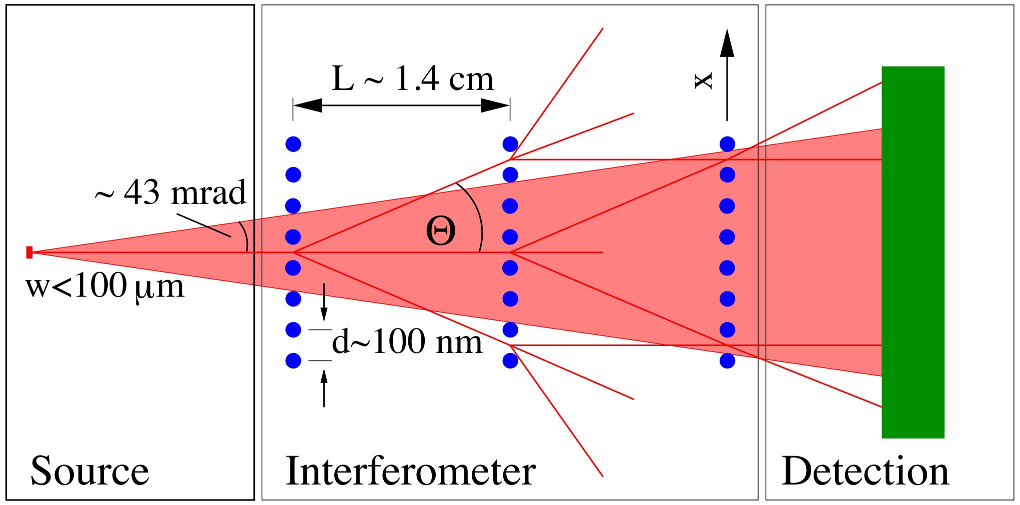
Studying Muonium Gravity

arXiv:physics/0702143v1 [physics.atom-ph]

Testing Gravity with Muonium

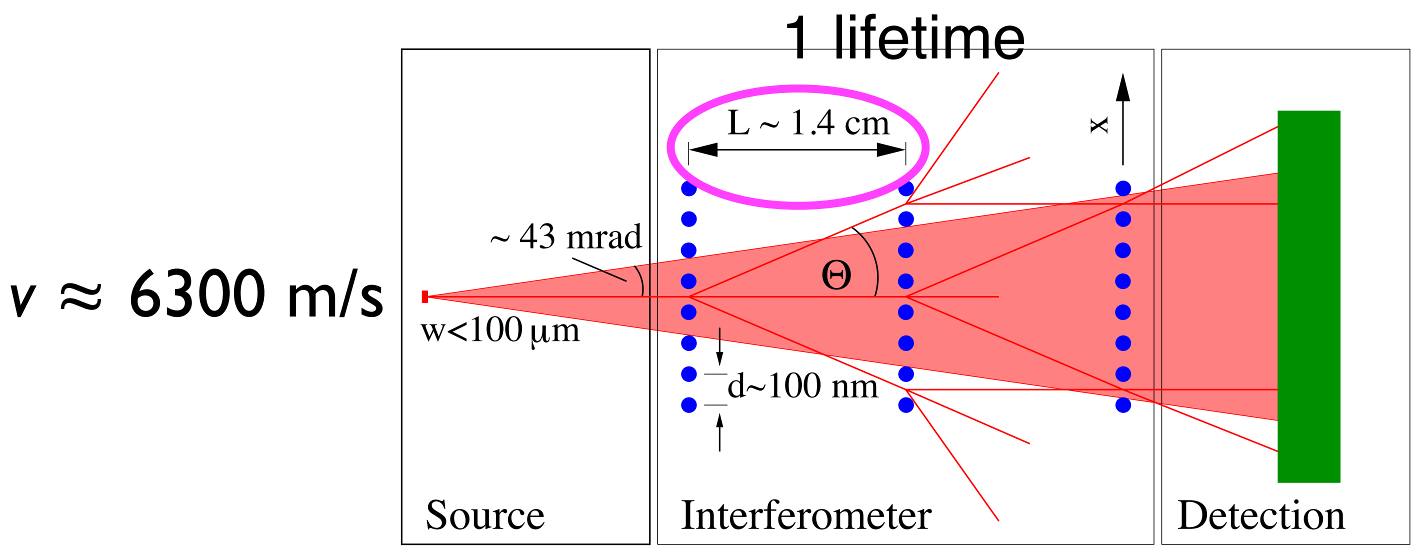
K. Kirch*
Paul Scherrer Institut (PSI), CH-5232 Villigen PSI, Switzerland
(Dated: February 2, 2008)

Recently a new technique for the production of muon (μ^+) and muonium (μ^+e^-) beams of unprecedented brightness has been proposed. As one consequence and using a highly stable Mach-Zehnder type interferometer, a measurement of the gravitational acceleration $\bar{g}$ of muonium atoms at the few percent level of precision appears feasible within 100 days of running time. The inertial mass of muonium is dominated by the mass of the positively charged - antimatter - muon. The measurement of $\bar{g}$ would be the first test of the gravitational interaction of antimatter, of a purely leptonic system, and of particles of the second generation.



Studying Muonium Gravity

- Adaptation of T. Phillips' $\overline{\mathrm{H}}$ interferometry idea to an antiatom with a 2.2 μs lifetime!



$\frac{1}{2}\,gt^2 = 24$ pm

Smaller than an *atom*!

but grows as $t^2 \Rightarrow$ easier problem with *old* muonium

- "Same experiment" as Phillips proposed — only harder!
- Is it feasible? How might it be done?

Studying Muonium Gravity

Part of the challenge: M production method:

- want *monoenergetic* M for uniform flight time
  - otherwise, interference patterns of different atoms have differing relative phases,
    - so signal could be washed out

      (probably not a problem in practice, since interference phase so small…)
- want narrow, *parallel* M beam for good interferometer acceptance

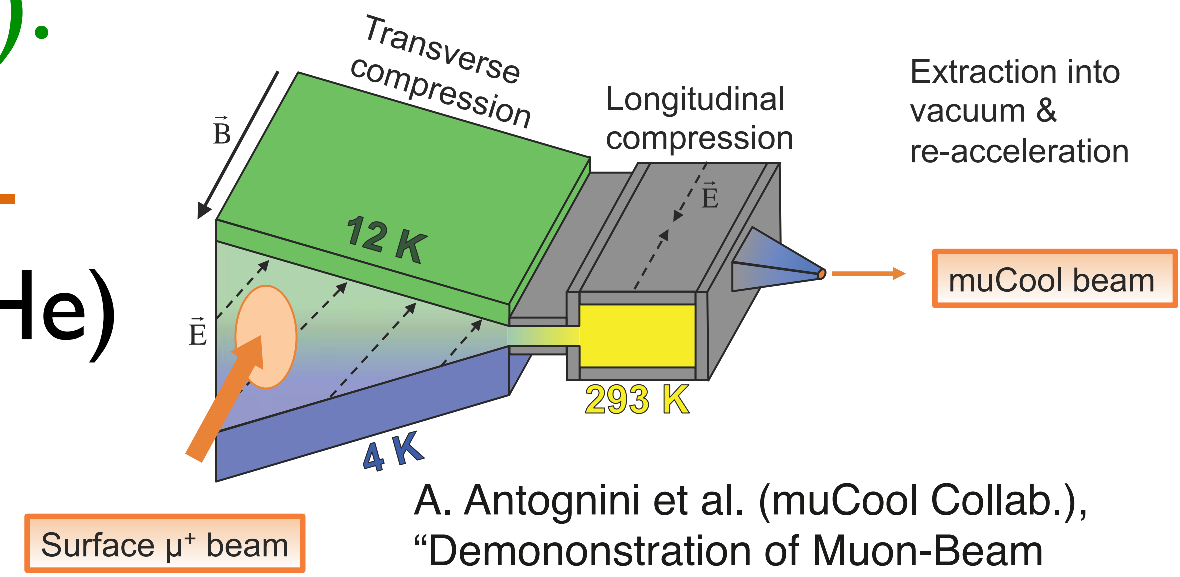
Monoenergetic Muonium?

- Proposal by D. Taqqu of Paul Scherrer Institute (Switzerland):
  - stop slow (keV) muons in ~ μm-thick layer of superfluid He (SFHe)

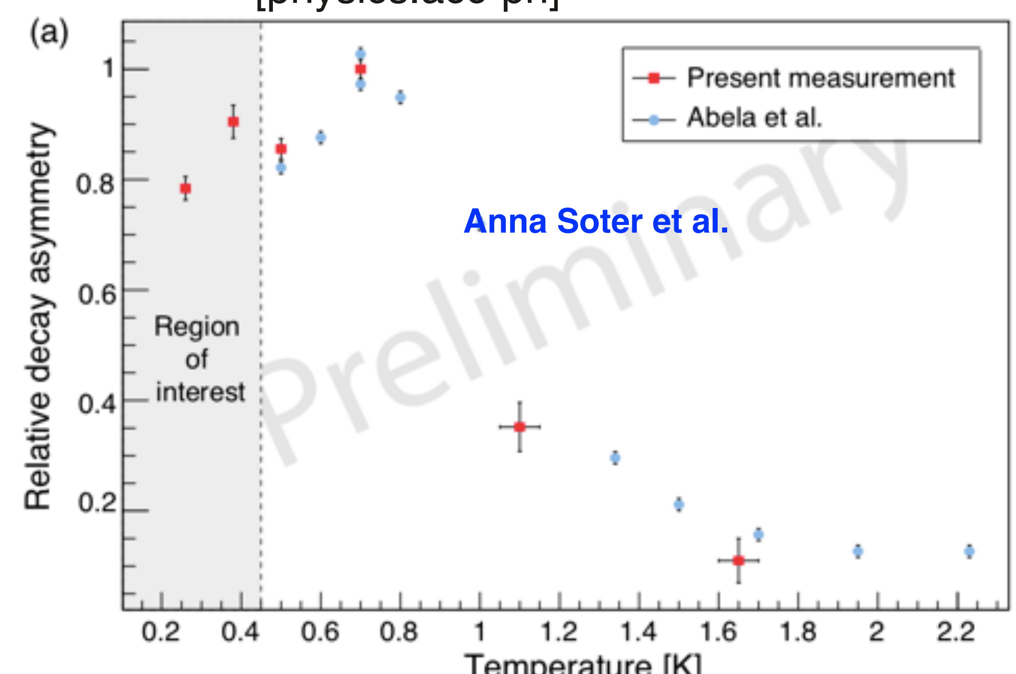
    ⇒ need "muCool" μ^+ beam upgrade
  - chemical potential of M in SFHe will eject M atoms at 6,300 m/s, ⊥ to SFHe surface
    - makes ≈ monochromatic, || beam!

      $\Delta E/E \sim 0.1\%$
- Or (Phillips) ~100 μm SFHe layer → ~10^2 ↑ intensity

D. Taqqu, "Ultraslow Muonium for a Muon beam of ultra high quality," Phys. Procedia **17** (2011) 216

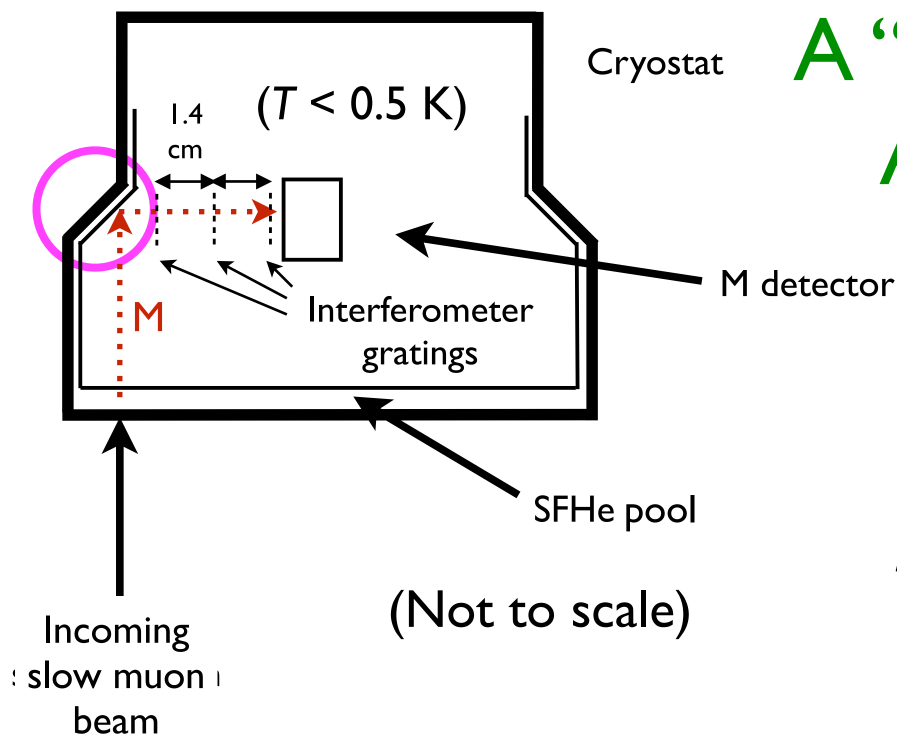


A. Antognini et al. (muCool Collab.), "Demononstration of Muon-Beam Transverse Phase-Space Compression," arXiv:2003.11986 [physics.acc-ph]



Experiment Concept

- One can then imagine the following apparatus:



A "desktop" experiment
A "ship in a bottle!"

Sensitivity estimate @ 100 kHz:

$$S = \frac{1}{C\sqrt{N_0}} \frac{d}{2\pi} \frac{1}{\tau^2}$$

$$\approx 0.3\,\mathrm{g\ \ per}\ \sqrt{\#\mathrm{days}}$$

- Well known property of SFHe to coat surface of its container
- So 45° angled section of cryostat serves as reflector to turn vertical M beam emerging from SFHe surface into horizontal

Experiment Concept

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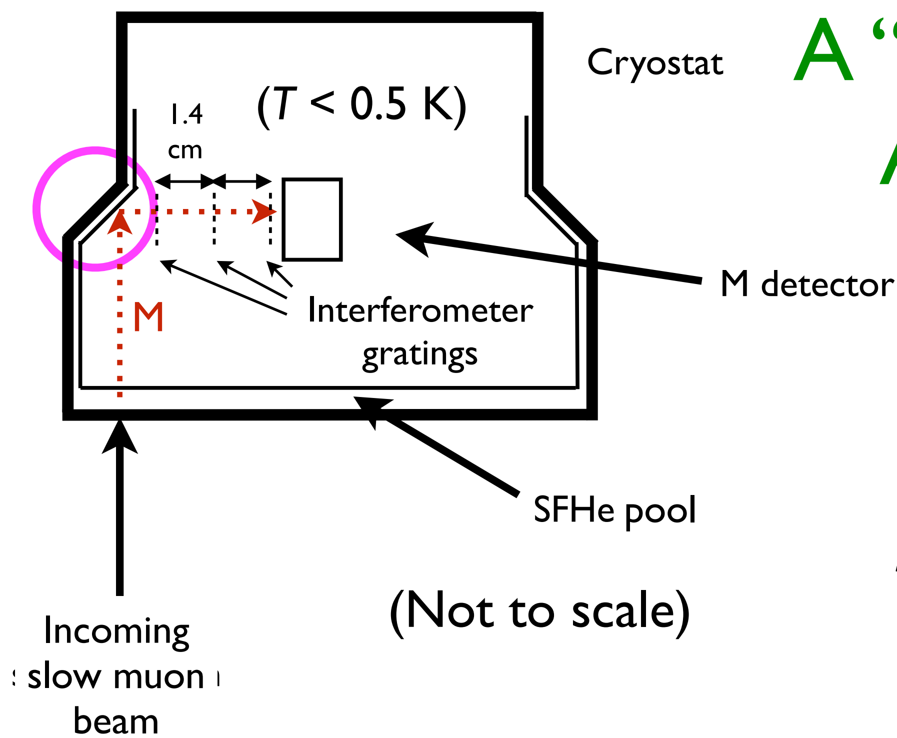

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$$S = \frac{1}{C\sqrt{N_0}}\frac{d}{2\pi}\frac{1}{\tau^2}$$
$$\approx 0.3\,\mathrm{g\ \ per}\sqrt{\#\mathrm{days}}$$

where
C = 0.3 (est. contrast)
N_0 = # of events
d = 100 nm (grating pitch)
τ = M lifetime

➡ Muonium Antimatter Gravity Experiment (MAGE)

VOLUME 71, NUMBER 15 PHYSICAL REVIEW LETTERS 11 OCTOBER 1993

Focusing a Beam of Ultracold Spin-Polarized Hydrogen Atoms with a Helium-Film-Coated Quasiparabolic Mirror

V. G. Luppov
*Randall Laboratory of Physics, University of Michigan, Ann Arbor, Michigan 48109-1120
and Joint Institute for Nuclear Research, Dubna, Russia*

W. A. Kaufman, K. M. Hill,* R. S. Raymond, and A. D. Krisch
Randall Laboratory of Physics, University of Michigan, Ann Arbor, Michigan 48109-1120
(Received 7 January 1993)

We formed the first "atomic-optics" beam of electron-spin-polarized hydrogen atoms using a quasi-parabolic polished copper mirror coated with a hydrogen-atom-reflecting film of superfluid ^{4}He. The mirror was located in the gradient of an 8-T solenoidal magnetic field and mounted on an ultracold cell at 350 mK. After the focusing by the mirror surface, the beam was again focused with a sextupole magnet. The mirror, which was especially designed for operation in the magnetic field gradient of our solenoid, increased the focused beam intensity by a factor of about 7.5.

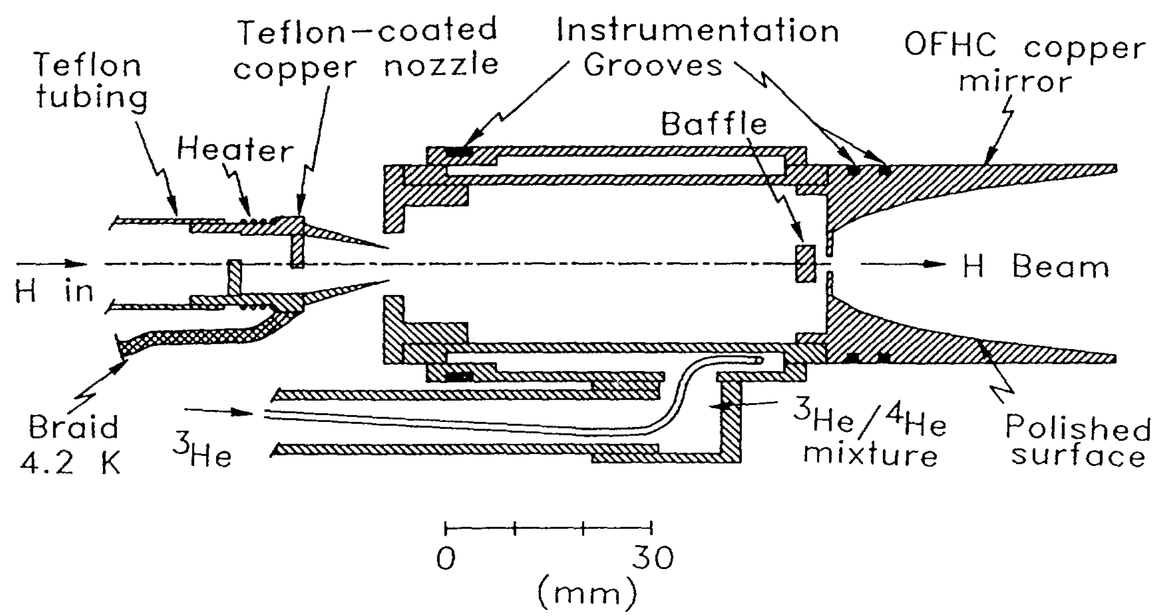


FIG. 2. Schematic diagram of the stabilization cell and mirror. The Teflon-coated copper nozzle is also shown.

- SFHe H mirror an established technique

Muonium Gravity Experiment

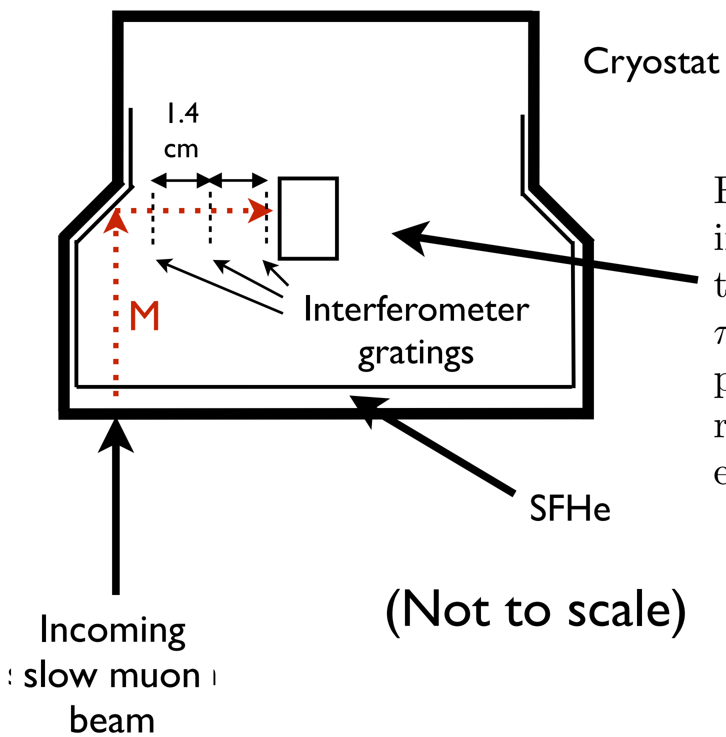
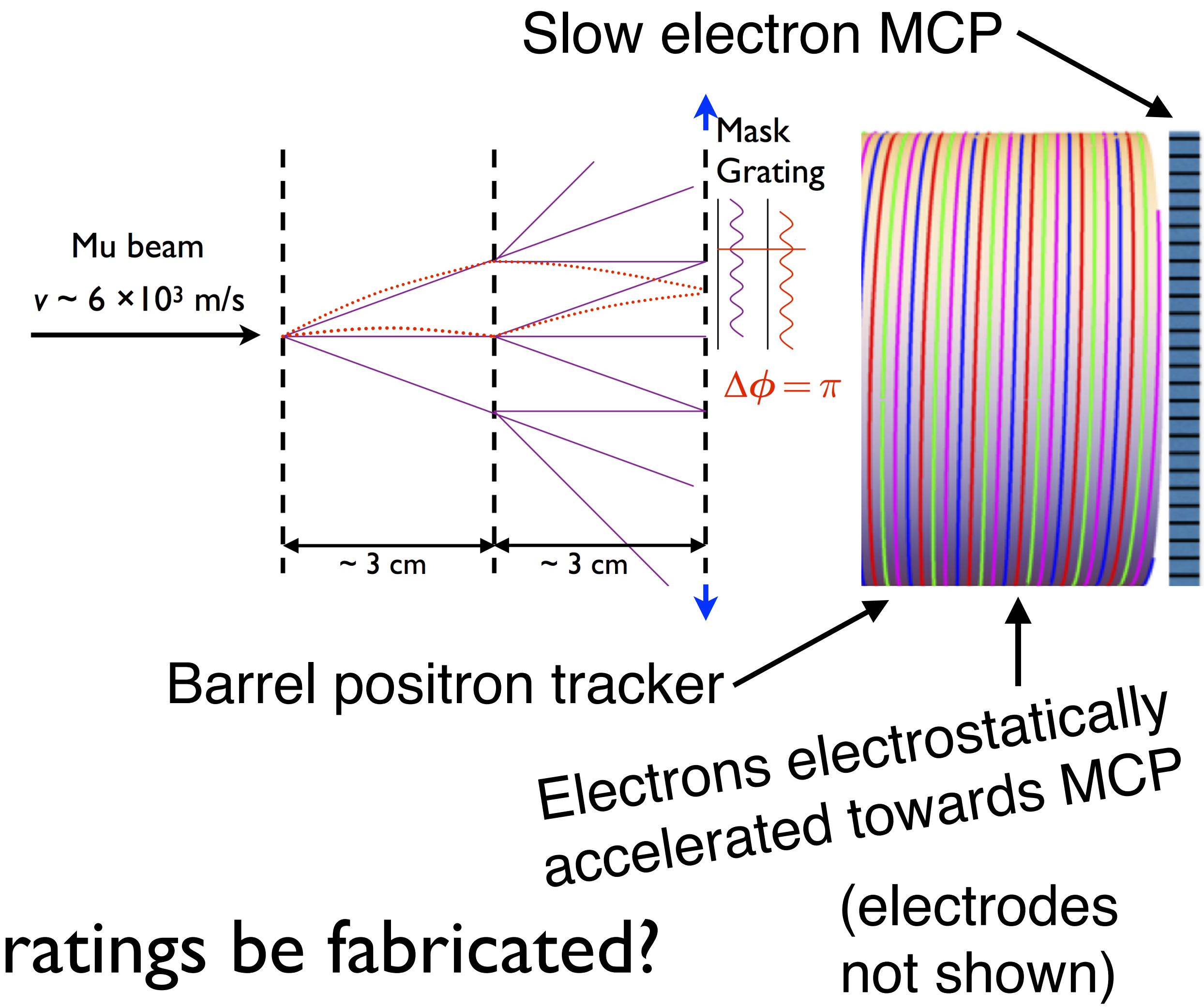


Figure 1: Principle of muonium interferometer, shown in elevation view (phase difference $\Delta\phi = \pi$ shown for illustrative purposes); Mu-decay detectors (barrel SciFi positron tracker and electron MCP) shown at right.

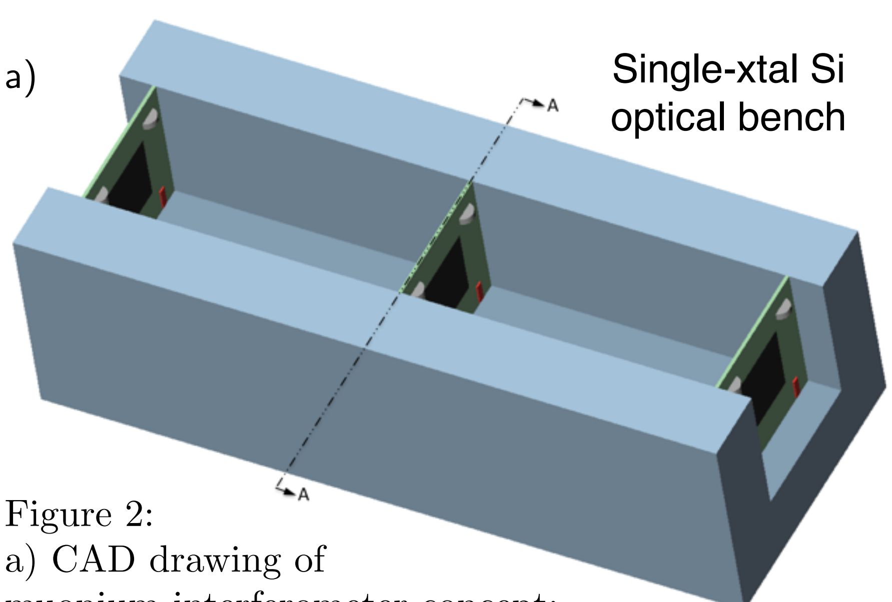


- **Some important questions:**

1. Can sufficiently precise diffraction gratings be fabricated?
2. Can interferometer be aligned to a few pm and adequately stabilized against vibration?
3. Can interferometer and detector be operated at cryogenic temperature?
4. How determine zero-degree trajectory?
5. Does Taqqu's scheme work?

Answering the Questions:

1. Can sufficiently precise diffraction gratings be fabricated?
   - MAGE collaborator Derrick Mancini (a founder of ANL Center for Nanoscale Materials), thinks so (CNM has sub-nm precision) – proposal approved at CNM to try it
2. Can interferometer be aligned, and stabilized against vibration, to several pm?
   - needs R&D, but LIGO & POEM do much better than we need
   - we are operating a POEM distance gauge (TFG) at IIT



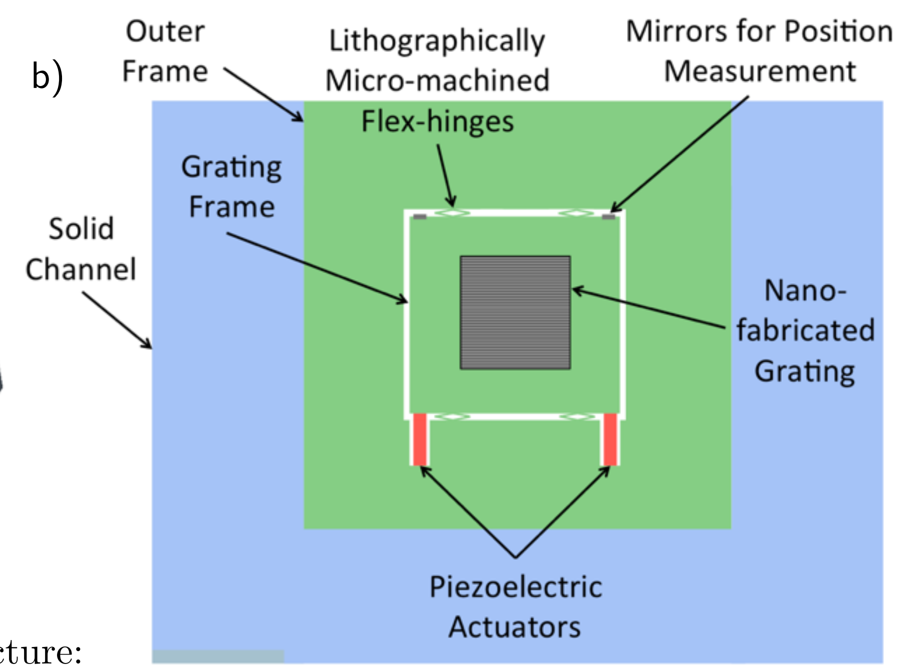


Figure 2:
a) CAD drawing of muonium interferometer concept;
b) Section A-A. In blue-gray is grating support structure: a U-channel machined out of a single-crystal silicon block. Each grating is mounted in a silicon frame connected to an outer frame by flex-hinges; piezo-actuator pair permits small rotations to align the gratings precisely in parallel, as well as scanning of grating 3. Grating frames have mirrors or corner-cube retroflectors at top corners that form part of the laser distance gauges (TFGs) used to measure their position.

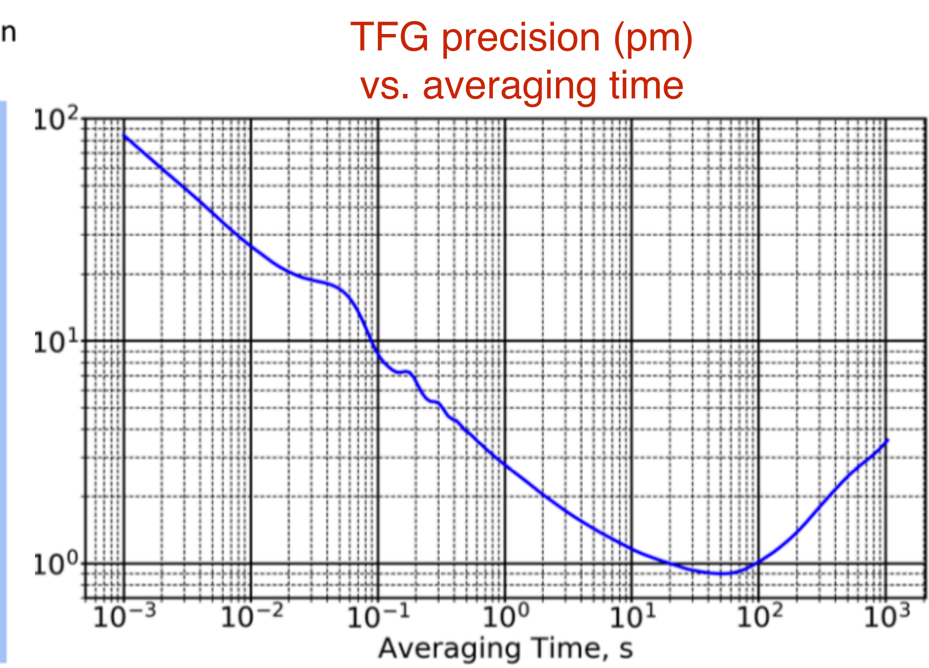


Figure 3. Allan deviation indicating TFG incremental-distance precision vs averaging time.

Answering the Questions:

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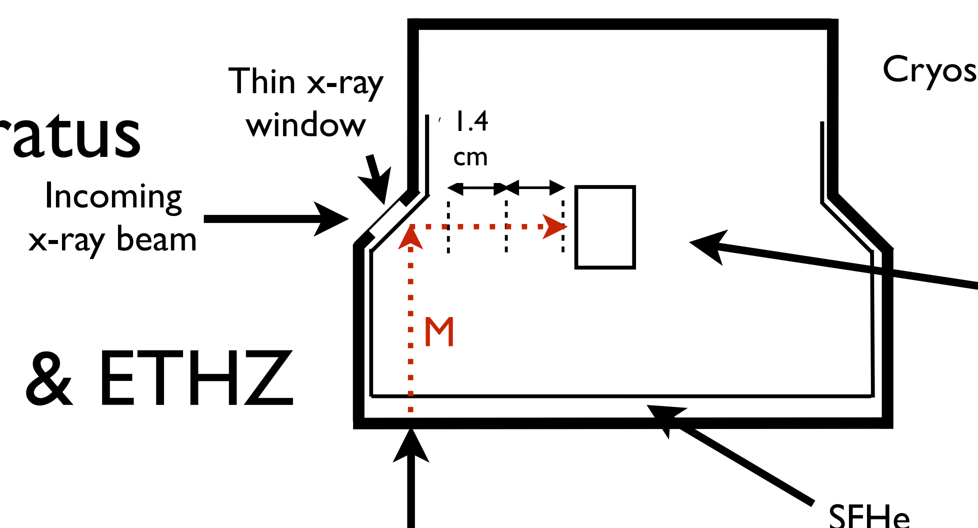
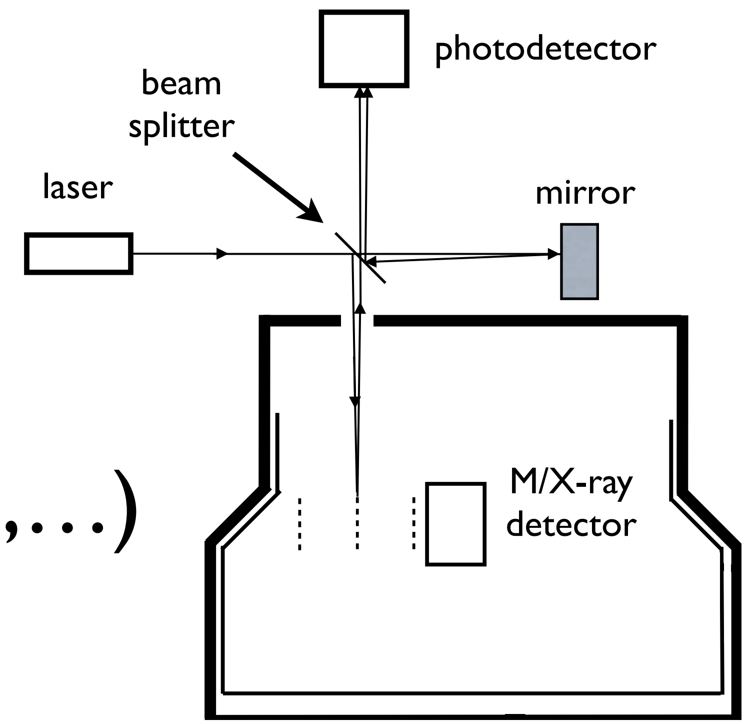
2. Can interferometer be aligned, and stabilized against vibration, to several pm?
   - needs R&D, but LIGO & POEM do much better than we need
   - we are operating a POEM distance gauge (TFG) at IIT
3. Can interferometer and detector be operated at cryogenic temperature?
   - needs R&D; at least piezos OK; material properties favorable
4. How determine zero-degree trajectory?
   - use cotemporal X-ray beam; invert apparatus
5. Does Taqqu's scheme work?
   - needs R&D; we're working on it with PSI & ETHZ



Interferometer Alignment

- Concept: 2 laser interferometers per grating



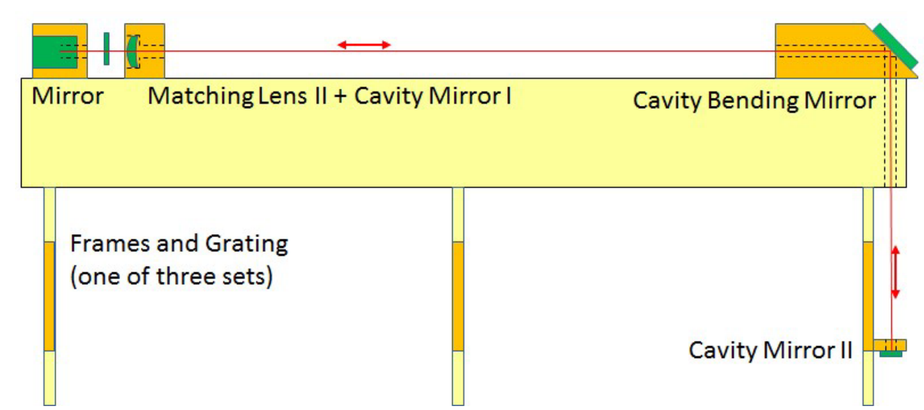
  - using λ = 1560 nm, need ~ 3 pm sensitivity ⇒ ~ 10^{-6} λ
    - use PDH locking à la LIGO (resonance, interferometer null, heterodyne detection,…)
      – shot-noise limit (@ 1 μW) = 0.04 pm
      – <1 pm demonstrated (averaging over 100 s)

"Tracking Frequency Gauge" (TFG)

[D. M. Kaplan et al., "Improved performance of semiconductor laser tracking frequency gauge," JINST 13 (2018) P03008]

[R. Thapa et al., "Subpicometer length measurement using semiconductor laser tracking frequency gauge," Opt. Lett. **36**, 3759 (2011)]

    - To do:
      – reduce laser power (~ mW to ~ μW)
      – demonstrate in miniaturized geometry
      – use TFG to show structural stability of muonium interferometer…

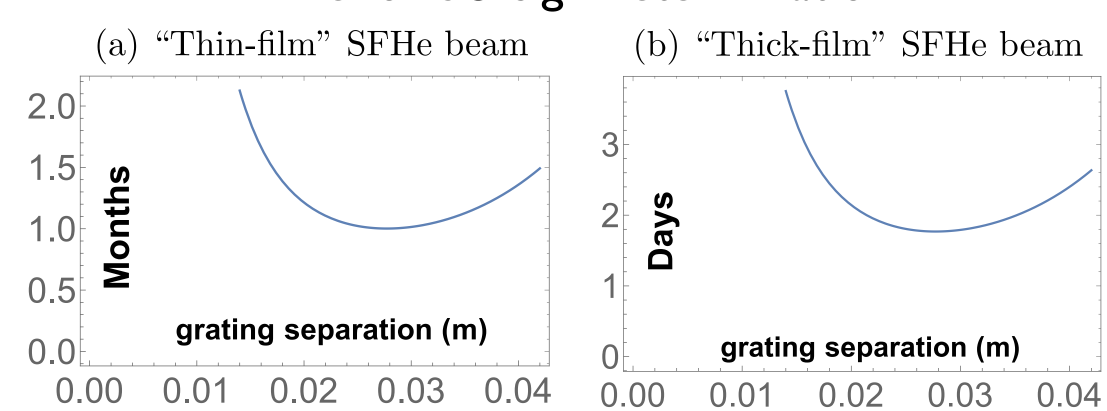


Additional Considerations

- Optimal muonium pathlength?
  - say muonium interferometer baseline doubled: costs $e^{-2} = 1/7.4$ in event rate, gains x 4 in deflection
    - a net win by $4\ e^{-1} \approx 1.5$ → Statistically optimal!
  - OTOH, tripling baseline → x 1.2 improvement
    - still better than 1 lifetime, though returns diminishing
    - but 9x bigger signal ⇒ easier calibration, alignment, & stabilization

Time for 5σ sign determination

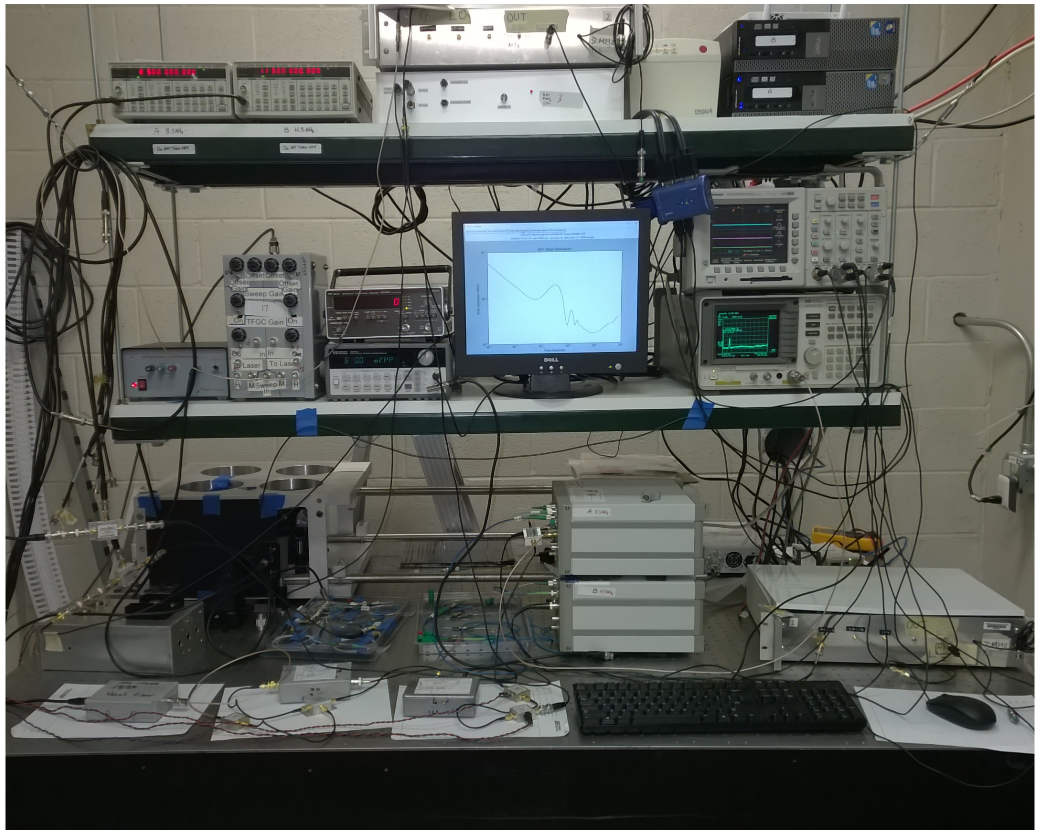
Figure 4: Representative MAGE sensitivity estimates vs. grating separation for beam options described in text, with $0.5\,\mu$m-thick gratings of 100 nm pitch, assuming 10% contrast and that the dominant error is statistical; shown is beam time required for 5σ determination of the sign of $\bar{g}$ (i.e., $\delta\bar{g}/g = 0.4$).[5]



- Need thorough simulation study to identify *practical* optimum, taking all effects into account

Prospects

- To design the experiment, we need a grant!
  - we're the beneficiaries of the POEM program at Harvard–Smithsonian CfA
    - including 2 TFGs
  - developing MAGE slowly with teams of undergrads (thanks to IIT IPRO program)



- Plausible Fermilab venue would help!
  - and another team working on challenging beam issues

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Journal of Instrumentation

Improved performance of semiconductor laser tracking frequency gauge

D.M. Kaplan[a], T.J. Roberts[a], J.D. Phillips[a] and R.D. Reasenberg[b]

Published 14 March 2018 • © 2018 IOP Publishing Ltd and Sissa Medialab
Journal of Instrumentation, Volume 13, March 2018

Article PDF

MAGE Collaboration

+ Article information

Abstract

We describe new results from the semiconductor-laser tracking frequency gauge, an instrument that can perform sub-picometer distance measurements and has applications in gravity research and in space-based astronomical instruments proposed for the study of light from extrasolar planets. Compared with previous results, we have improved incremental distance accuracy by a factor of two, to 0.9 pm in 80 s averaging time, and absolute distance accuracy by a factor of 20, to 0.17 μm in 1000 s. After an interruption of operation of a tracking frequency gauge used to control a distance, it is now possible, using a nonresonant measurement interferometer, to restore the distance to picometer accuracy by combining absolute and incremental distance measurements.

Export citation and abstract BibTeX RIS

Atoms **2018**, *6*(2), 17; doi:10.3390/atoms6020017 (registering DOI) Open Access Feature Paper Article

Studying Antimatter Gravity with Muonium

Aldo Antognini [1,2], Daniel M. Kaplan [3,*], Klaus Kirch [1,2], Andreas Knecht [1], Derrick C. Mancini [3], James D. Phillips [3], Thomas J. Phillips [3], Robert D. Reasenberg [4,5], Thomas J. Roberts [3] and Anna Soter [1]

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(This article belongs to the Special Issue Measuring Gravity in the Lab)

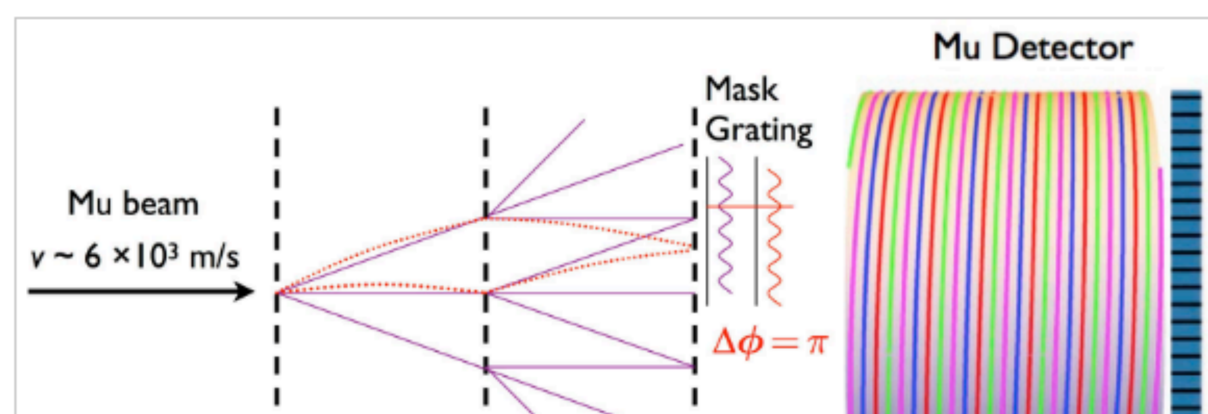
View Full-Text | Download PDF [2742 KB, uploaded 9 April 2018] | Browse Figures

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. These could constitute the first gravitational measurements of leptonic matter, of 2nd-generation matter, and possibly, of antimatter. View Full-Text

Keywords: gravity; antimatter; muonium; atom interferometer; tracking frequency gauge

▼ Figures



Conclusions

- Antigravity hypothesis might neatly solve several vexing problems in physics and cosmology*
  - or $\bar{g} = g \pm \varepsilon$? – clue to a new, QM theory of gravity
- In principle, testable with antihydrogen, positronium, or muonium
  - if possible, *all* 3 should be measured — *especially* if $\bar{H}$ found anomalous

➡ First measurement of muonium gravity would be a milestone!

- But 1st must determine feasibility — in progress!
- FNAL venue would help!

*(but no time to explain in detail)

Final Remarks

- These measurements are a required homework assignment from Mother Nature!

- Whether $\overline{g} = -g$ or not, if successfully carried out, the results will certainly appear in future textbooks.