Testing Gravity with Muonium

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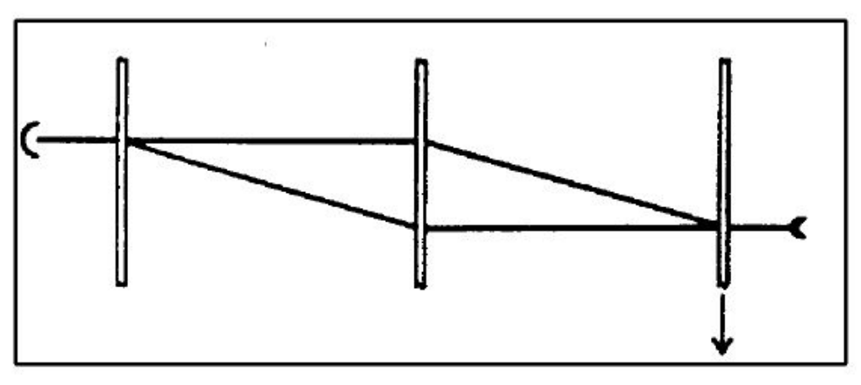
What is muonium ?

- **Hydrogen-like atom of a positive muon and an electron ($M=\mu^+e^-$).**
- **The inertial mass of the M-atom is to 99.5% given by the μ^+, i.e. an antimatter lepton of the 2nd generation.**

How to produce muonium ?

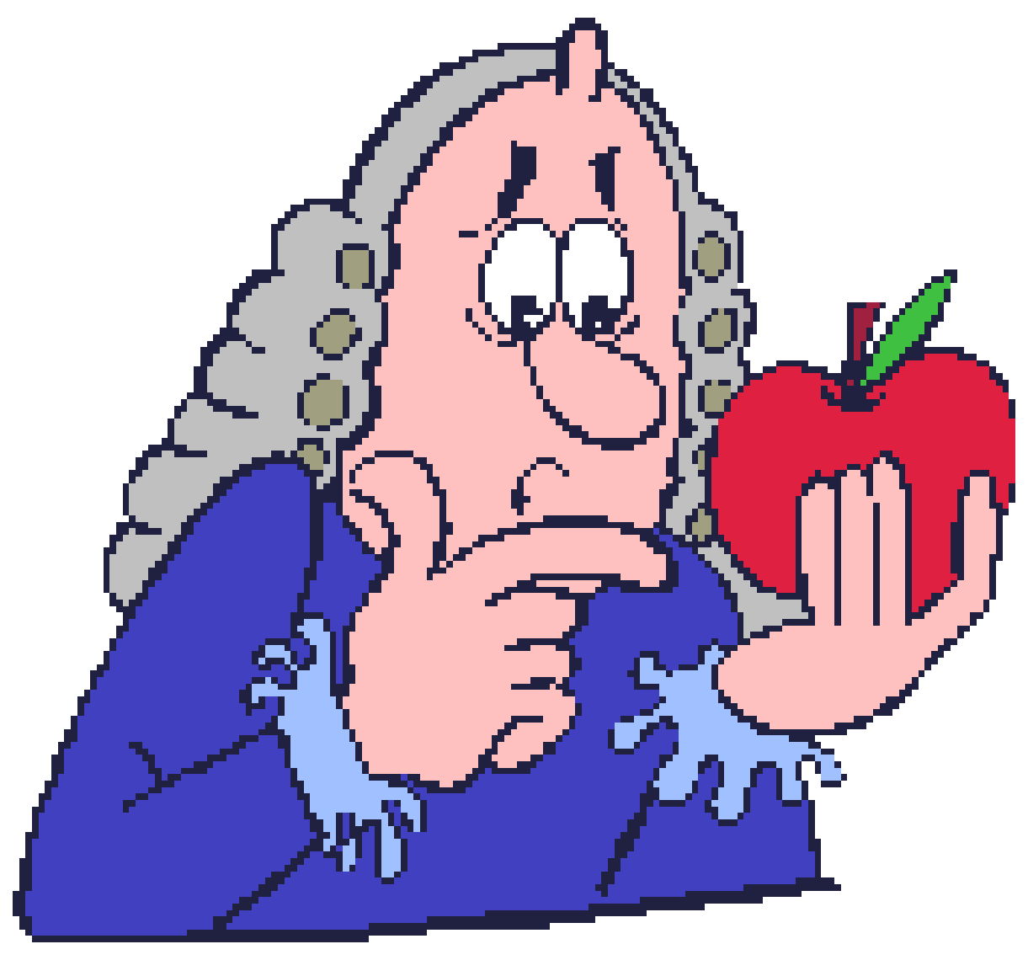
- **Positive μ^+ stop in ordinary matter, attract e^- and form M-atoms.**
- **Some materials are more suitable for M extraction into vacuum.**
- **New technique for production of M-beam of unprecedented brightness using a 10keV μ^+ beam and superfluid helium as M production target (Taqqu [2006, 2007], see his poster!)**

A Mach-Zehnder type matter interferometer



- **Equally spaced transmission line gratings with identical line spacing.**
- **Split beams at 1st grating, diffraction at 2nd grating, interference at 3rd grating. Fringe pattern has same period as gratings and is independent of beam divergence and velocity spread.**
- **Scan 3rd grating → detect intensity pattern behind the grating.**
- **Different beam paths can cause phase shift.**
- **If the split beams run through different gravitational potentials a gravitational phase is accumulated and shifts interference pattern.**

Will antimatter fall just as matter does ?
Will leptons fall as baryons do ?
Will the 2nd generation do the same ?



… probably yes*, but …

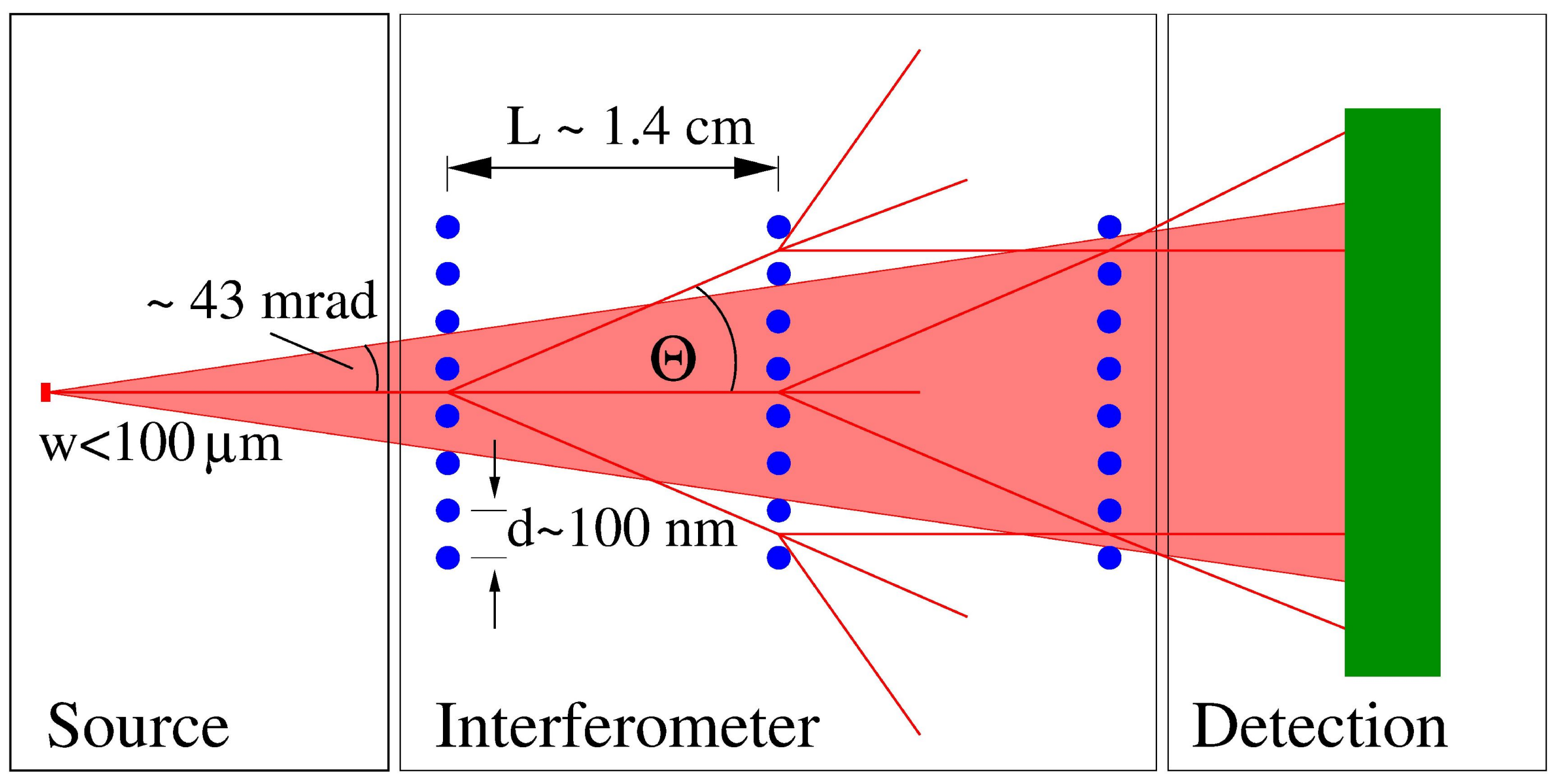
… this has never been tested successfully in the laboratory because of non-availability of neutral systems.

- **Witteborn and Fairbank [1967] tried e^- (having e^+ in mind, too), Holzscheiter et al. [1993] tried antiprotons. Problem: E-fields could not be sufficiently shielded.**
- **Today, effort goes into production of (ultra)cold antihydrogen, also for gravitational studies (see e.g. Holzscheiter et al. [2004]).**
- **Positronium was considered (Oberthaler [2002], Mills[2002]) as well, but in the end muonium might provide the first direct test of gravity for antimatter, for purely leptonic systems and for particles of the 2nd generation.**

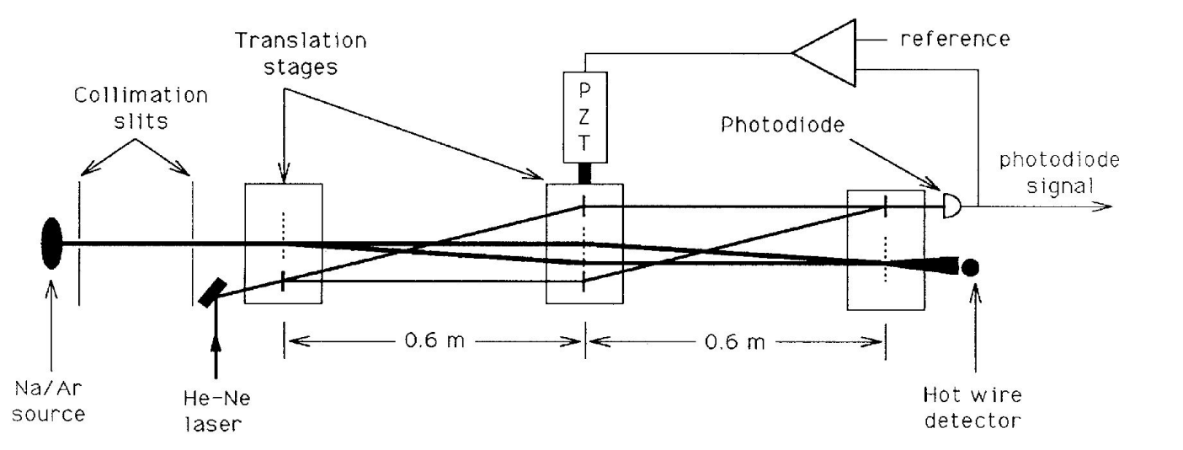
(* see e.g. Adelberger et al. [1991, …], Nieto&Goldman [1991], …)

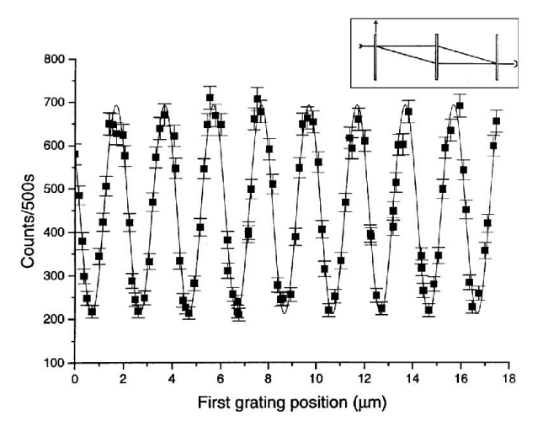
Concept of the muonium gravity experiment

- **Muonium source (Taqqu [2006,2007]): 100μm diameter, 10^5 s^{-1} M atoms, monoenergetic ($\Delta E/E \sim 0.002$), velocity: 6300m/s, 1-dim divergence: 40-50 mrad.**
- **Mach-Zehnder type interferometer accepts full beam divergence.**
- **100nm period transmission gratings → diffraction angle $\Theta \sim 5.6$mrad.**
- **One muon decay length is L~1.4cm, the distance source – detector about 6cm.**
- **Gravitational phase shift 0.003 → 50pm shift of fringes at 3rd grating.**
- **The Sagnac effect (due to earth rotation) is one order of magnitude smaller.**
- **200s^{-1} detected M atoms and fringe visibility of 30%.**
- **Statistical sensitivity: 30% per day for a measurement of the gravitational acceleration g, i.e. 3% in 100 days.**

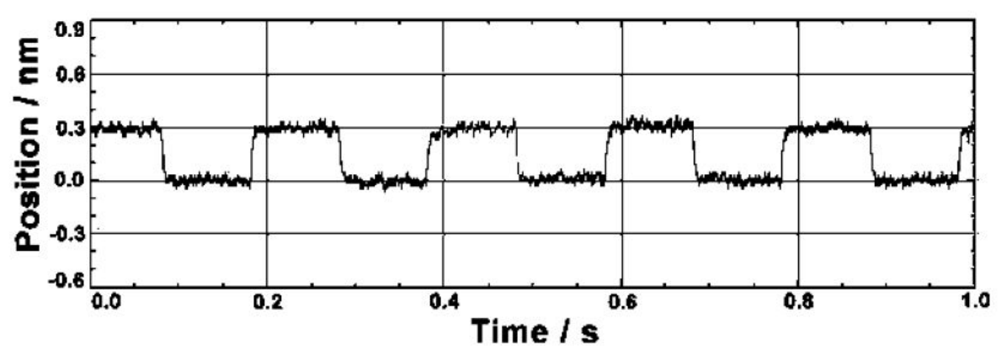


Interferometer issues



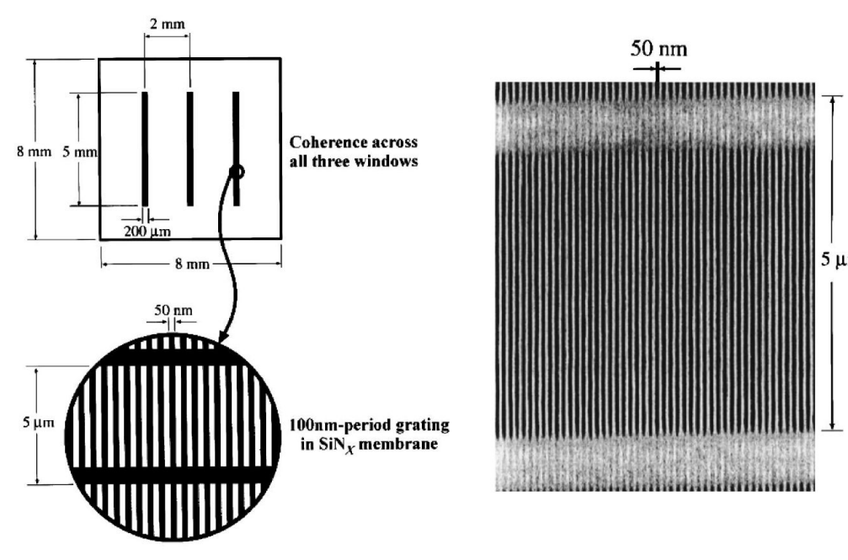


Laser interferometry stabilizes the M-atom interferometer. **This was similarly applied by Keith, …, Pritchard [1991] and by van der Zouw, …, Zeilinger [2000] for Na atoms and very cold neutrons, respectively.**



Picometer piezo positioning of gratings with ≤50pm resolution. Capacitive measurements complement lasers.

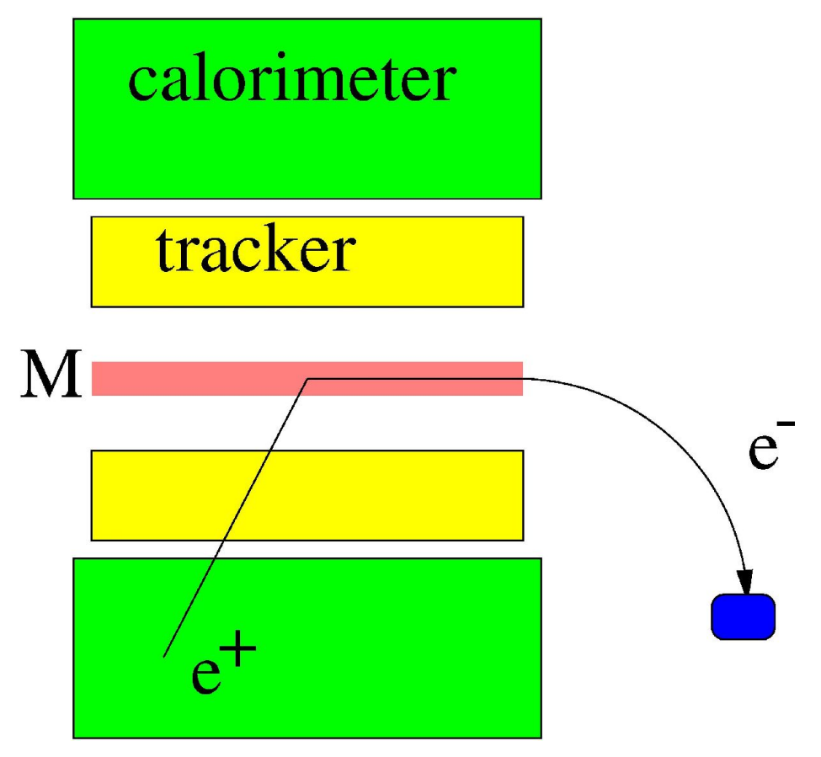
Savas et al. [1996,2006] already fabricated large, free-standing, 100nm period diffraction gratings.



Most relevant know-how in principle available at PSI.

Detector

- **Detect muonium behind the third grating by detecting the decay positron.**
- **Background can be efficiently suppressed by:**
  - **e^+ detection in active, small M-stop volume and calorimeter.**
  - **Or coincident e^- detection (M decay in flight) and/or e^+ tracking.**



Acknowledgements

- **I would like to thank L.M. Simons for many fruitful and inspiring discussions, not only but also, on this *matter*. Following Colella-Overhauser-Werner [1975] and other neutron interferometry experiments, L.M. Simons presented the idea of an antimatter gravity experiment with a Mach-Zehnder type interferometer at a workshop in the late 1980s. An experiment as described here was, however, pure science fiction because appropriate beams seemed out of reach. The idea was, therefore, not put into print. The first printed publication on antimatter (antihydrogen, antineutron, positronium) interferometry is by Phillips [1997].**
- **I am grateful to D. Taqqu for discussions about his new production technique for muon and muonium beams.**

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