Why test gravitational acceleration of antimatter?

Why muonium and how to test gravity with it?

Requirements for such experiments

Technical challenges

Slow muon beam program at PSI

Slow muonium production at PSI

Conclusions & Outlook
Why testing antimatter gravity and why muonium?
Why antimatter gravity?

- \( g \) for matter measured to very high precision
- No direct measurement of antimatter yet
- Test of weak equivalence principle (WEP) for antimatter
- Input for constructing theories of quantum gravity
- Insights to dark matter and dark energy
Why muonium (Mu) and how to test gravity with it?

- Pure leptonic bound-state of $\mu^+$ and $e^-$, 2.2 $\mu$s lifetime
- 1S-2S transition frequency and HFS measured to very high precisions (4 ppb and 12 ppb)
- Well studied and can be produced at high rates
- Test of Mu's gravitational interaction possible in 2 ways
  #1 - Annual modulation of 1S-2S transition frequency
  #2 - Mach Zehnder three-grating atom interferometer
Muonium spectroscopy and interferometry

STRATEGIES
#1: 1S-2S spectroscopy

- Measure the gravitational redshift when the earth revolves around the sun \( (dH = 5 \times 10^6 \text{ km}) \)
  \[ \frac{[dU(r_{\text{max}})-dU(r_{\text{min}})]}{c} \approx 3.2 \times 10^{-10} \]
- Precision level of about 0.1 ppb is needed (current = 4 ppb) → 40 times improvement!
- This improvement will require:
  - high slow \( \mu^+ \) rate (4000/s at LEM@PSI, T. Prokscha et al.)
  - high \( \mu^+ \) → slow Mu conversion rate (Porous silica)
  - high power CW laser (Ps 1S-2S at ETH, P. Crivelli)
  - a better reference line (I\(_2\) at Taiwan, frequency comb)

S.G. Karshenboim, arXiv/0811.1008
#2: Mach-Zehnder interferometer

- Established in neutron and neutral atom interferometry also for gravity measurements

- To have enough statistics and measurable deflection
  - separation between gratings $\geq 2.2 \, \mu$s
  - grating pitch $\sim 100$ nm
  - $10^5$ monoenergetic Mu/s
  - precision $\sim 0.3g/\sqrt{\text{#days}}$

L.M. Simons, priv. comm., 1995
T. Philipps, Hyp. Int. 109(1997)357
D. Kaplan et al., arXiv:1308.0878
Phase space compression of muon beam

SLOW MUON BEAMLINE
Use position-dependent $\mu^+$ drift direction in helium gas

Achieve phase space compression ($10^{10}$)

Ultra slow $\mu^+$ beam with sub-mm size and sub-eV energy for re-acceleration

3 stages of compression: transverse compression, longitudinal compression and extraction of the $\mu^+$ beam

Estimated efficiency of about 0.1% (lifetime limited)
Feasibility test done at $\pi E1$ at PSI ($2 \times 10^4 \mu^+ / s @ 10$ MeV/c)

Implemented low energy $\mu^+$ elastic collision physics and Mu formation in He gas into GEANT4

Good agreement between MC and data

Compression of the 16 cm wide muon swarm into 0.5 cm width occurs in much less than 2 $\mu$s $\rightarrow$ feasible!
Helium gas density gradient

- Cylinder made of copper (top, bottom) and stainless steel (sides)
- Resistors to heat the cell and sensors to measure temperatures
- Helium gas pressure varied from 0.01 mbar to 50 mbar
- Copper plate temperatures varied from 3 K to 50 K
- Good agreement between COMSOL simulation and experimental data
Muonium from porous silica and superfluid helium
Muonium production – Porous silica

- Bulk silica - high Mu production rate but no emission from the target (Mu in vacuum is needed!)
- Silica with structured pore-network (porous silica) - high fraction of Mu diffuses out into vacuum

- Measurements done at LEM@PSI with 4000/s $\mu^+$ on sample
- Muon spin rotation technique to extract Mu formation rate
- Positron shielding technique (PST) to extract Mu yield in vacuum

K. Kirch, WAG Bern, Nov 13, 2013
Muon spin rotation technique (μSR)

- Decay positrons emitted preferentially in direction of μ⁺ spins due to parity violation of weak interaction
- Monitor evolution of μ⁺ spin after implantation in external B-field
- Larmor precession frequency of Mu ~100 times that of μ⁺
- Can distinguish unbound μ⁺ from Mu
- With segmented positron detectors, Mu formation rate can be determined from the precession amplitude
Positron shielding technique (PST)

- No Mu emission into vacuum $\rightarrow$ exponential decay
- Mu emission into vacuum $\rightarrow$ deviation from exponential function for the downstream detectors
- Increase in count rate when Mu decay outside of the sample
- GEANT4 simulation for 0\% ($F_0$) and 100\%(F$_{100}$)
- Fit the data with $F_{\text{fit}} = aF_{100} + (1-a)F_0$
Muonium yield in vacuum

- Optimization of Mu yield in vacuum
  - measurements with different pore sizes and temperatures
  - extract yields and velocity distributions
  - best results so far (5 nm pore size, 20% at 100 K and 40% at 250 K, Boltzmann velocity distribution)

- Can improve Mu 1S-2S by factor of 10 with available technology (μ+ beam, Mu yield in vacuum, CW laser)
Muonium production in superfluid helium

- Stop slow $\mu^+$ in superfluid helium at $\leq 0.5$K
- Production of Mu measured but not yet the vacuum yield
- Expect quasi-monoenergetic Mu emission ($v\approx 6300$ m/s) from the surface chemical potential of $270$K (M. Saarela and E. Krotscheck, JLTP90(1993)415; D. Taqqu, E. Krotscheck priv. comm.)
- Beam and interferometer R&D started and ongoing
Collaboration

muon beam, muonium production and spectroscopy:


Mach-Zehnder interferometer

- UMich: R. Gustafson
Conclusions & Outlook

- Mu gravity measurement within coming years
  - Annual modulation of 1S-2S transition frequency
  - Mach-Zehnder interferometer

- Several technical challenges
  - high rate slow $\mu^+$ beam
  - high intensity of slow Mu in vacuum
  - high power CW laser for 1S-2S
  - high rate Mu beam for interferometer
  - highly stable Mach-Zehnder interferometer

- The technology is available for a Mu 1S-2S measurement at tenfold improved precision.
Thank you for your attention

Special thanks for discussions in connection with this talk to Kim-Siang Khaw, Aldo Antognini, Paolo Crivelli and David Taqqu

Group at ETHZ
The High Intensity Muon Beam HiMB project: gain factor 100 in surface muon intensity at PSI

- Use SINQ target window as surface muon source
- Transport $\mu^+$ with extraction solenoid and conventional channel via existing cellar and short tunnel out of SINQ.

Realistic MCNP-X predicts $\geq 7 \times 10^{10}$/s surface muons at 1.68 mA passing a surface within the beam pipe 25 cm below SINQ target.

A feasibility study will check on all issues within the next two years.
Mu 1S-2S Status

*LEM beam @ PSI – 4500 $\mu^+$/$\text{s}$*
*Detection efficiency – 0.95*
*Transportation losses – 0.61 (TOF = 1.1 $\mu\text{s}$)*
*Mu yield in vacuum – 0.3 (only triplet – 0.4 x 75% = 0.3)*
*Total efficiency – 0.17*
*On resonance 30 events/day expected with 2.5 BG/day*
*10 times improvement readily with current “technology”*

**Photo-ionization Probability**

- $T_{\text{Mu}} = 100$ K
- $P_0 = 8$ W
- $w_0 = 100$ $\mu$m
- $\sigma_{\text{beam}} = 1.7$ mm

**FWHM ≈ 2 MHz**

*Simulation*

*Courtesy: Paolo Crivelli*
Mu $1S-2S$ old vs new

Pulsed laser

FWHM $\approx 20$ MHz

V. Meyer et al., PRL84(2000)1136

CW laser

FWHM $\approx 2$ MHz

simulation
FIG. 1 (color online). Density gradient compression in helium gas for muon trajectories starting 10 mm away from the left target wall. The drift time up to the throat is given in ns near the starting point of each muon trajectory. Constant density lines are shown together with the density scale. The magnetic field is $B_z = 5$ T, the electric field $|\vec{E}| = 1800$ V/cm, and the pressure 4.6 mbar. For a 50 cm long target, 1 liter/hour liquid helium is consumed for cooling the lower wall.

D. Taqqu, PRL97(2006)194801