A low-energy muonium source in superfluid helium

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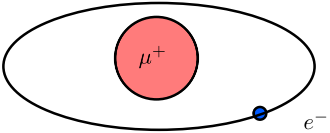
Overview

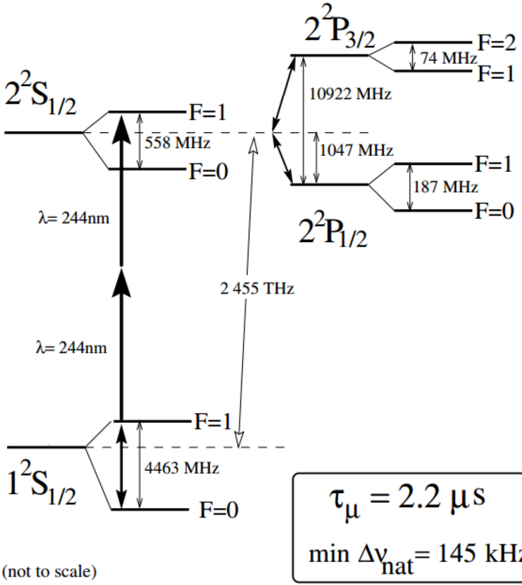
What is muonium?

- Muonium (Mu) is a hydrogen-like bound state of an antimuon μ^+ and an electron e^-
- Purely leptonic
- Lifetime of 2.2 $\mu\mathrm{s}$ due to antimuon decay
- Experimentally confirmed in 1960[1]



[1] [Hughes]

Motivation



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

min $\Delta\nu_{nat} = 145$ kHz

Testing the Standard Model

1S hyperfine splitting

$$\Delta\nu_{HFS} = \frac{16}{3}(Z\alpha)^2 R_\infty \frac{\mu_\mu}{\mu_B}\left[1+\frac{m_e}{m_\mu}\right]^{-3}(1+\epsilon_{QED}+\epsilon_{\mathrm{rec}}) + \Delta\nu_{\mathrm{weak}} + \Delta\nu_{\mathrm{strong}} + \Delta\nu_{\mathrm{new}}$$

Note![2]

- $\delta\left(\Delta\nu_{HFS}^{exp}(H)\right) \sim 10^{-12}$
- $\delta\left(\Delta\nu_{HFS}^{th}(H)\right) \sim 10^{-6}$
- $\delta\left(\Delta\nu_{HFS}^{exp}(Mu)\right) \sim 10^{-8}$
- $\delta\left(\Delta\nu_{HFS}^{th}(Mu)\right) \sim 10^{-8}$

[2] [Hill, Taylor, Crampton]

Correction sources

Table 1
Various contributions to the energy levels

Contribution	Hydrogen-like electronic atom	Positronium	Hydrogen-like muonic atom
Schrödinger contributions			
• With $M=\infty$	1	1	1
• With m_R (correction)	m/M	1	m/M
Relativistic corrections			
• Dirac equation	$(Z\alpha)^2$	α^2	$(Z\alpha)^2$
• Two-body effects	$(Z\alpha)^2 m/M$	α^2	$(Z\alpha)^2 m/M$
Quantum electrodynamics			
• Self-energy	$\alpha(Z\alpha)^2 \ln(Z\alpha)$	$\alpha^3 \ln\alpha$	$\alpha(Z\alpha)^2 \ln(Z\alpha)$
• Radiative width	$\alpha(Z\alpha)^2$	α^3	$\alpha(Z\alpha)^2$
• Vacuum polarization	$\alpha(Z\alpha)^2$	α^3	$\alpha \ln(Z\alpha m/m_e)$
• Annihilation			
– Virtual	—	α^2	—
– Real	—	α^3	—
Nuclear effects			
• Magnetic moment (HFS)	$(Z\alpha)^2 m/M$ or $\alpha(Z\alpha)m/m_p$	α^2	$(Z\alpha)^2 m/M$ or $\alpha(Z\alpha)m/m_p$
• Charge distribution	$(Z\alpha mcR_N/\hbar)^2$	—	$(Z\alpha mcR_N/\hbar)^2$

The results are in units of $(Z\alpha)^2 mc^2$, where m is the mass of the orbiting particle. Here: M is the nuclear mass and m_p is the proton mass which enters equations if one measures the nuclear magnetic moment in units of the nuclear magneton. A contribution of the nuclear magnetic moment, i.e., the hyperfine structure, appears if the nuclear spin is not zero. R_N stands for the nuclear (charge) radius.

Figure : Corrections to the energy levels obtained from Schrödinger

Production techniques

- Usually by stopping μ^+ in noble gases (He, Ar, ...)
- Free Mu extracted after implanting μ^+ in $\mathrm{SiO_2}$ powders or thin porous films[3]
- **Superfluid helium**: Mu production below 0.5 K, emission into vacuum with quasi-monoenergetic velocity

[3] [Kirch]

μ^+ implantation in He-II

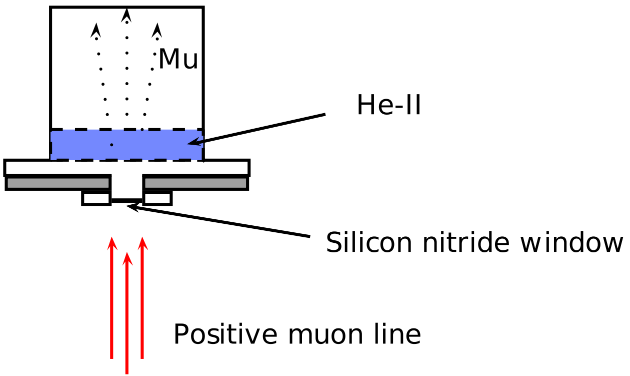


Figure : Sketch of a setup for muonium production in He-II

Design of a test cell

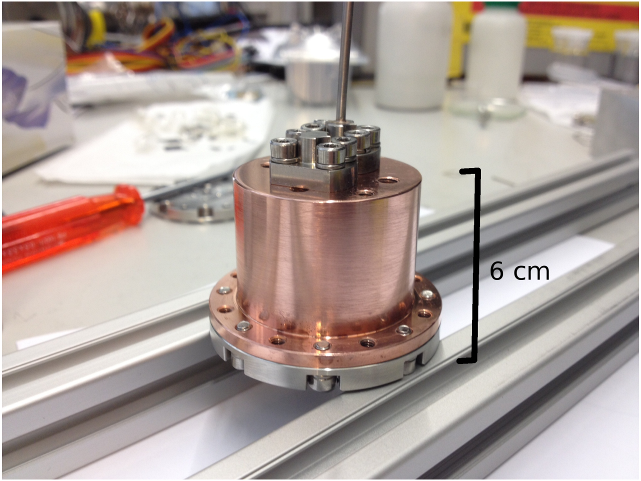


Figure : Test cell with copper container and indium-sealed steel flange.

Sealing of 50 nm-thick silicon nitride windows

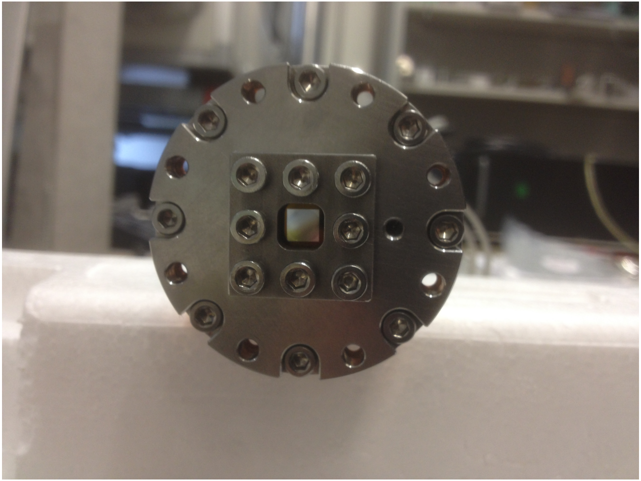


Figure : Indium-foil sealed, 5 x 5 mm^2 silicon nitride window for future antimuon implantation.

Differential pumping

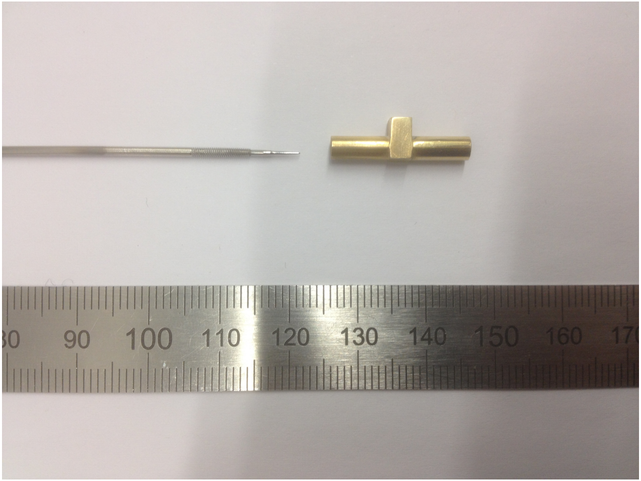


Figure : Custom-made cold valve (brass) with its needle (steel) to allow for differential pumping.

Differential pumping: test pipe

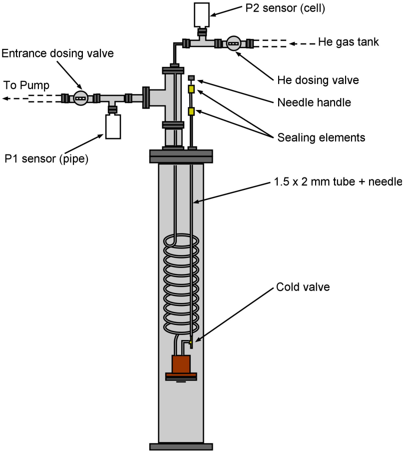


Figure : Principle: the cold valve couples the cell's inside with the outside vacuum during pumpdown.

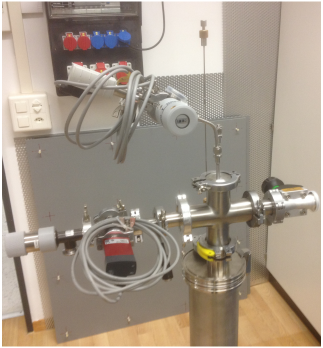
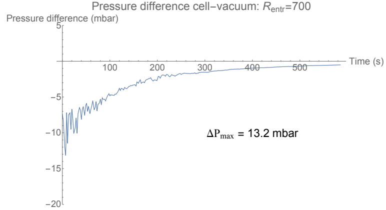
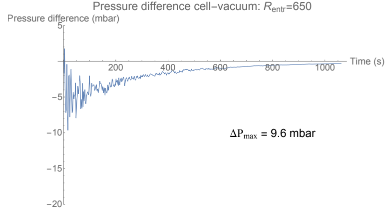


Figure : Test pipe with gauge sensors and dosing valves.

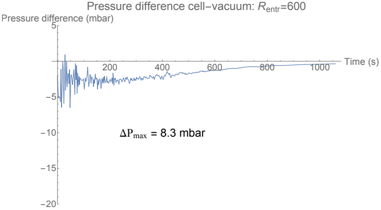
Differential pumping: results



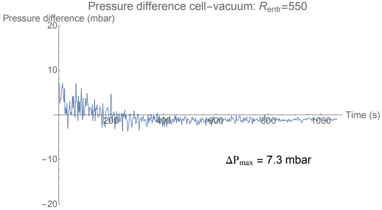
(a) $R_{entr} = 700$



(c) $R_{entr} = 650$



(b) $R_{entr} = 600$



(d) $R_{entr} = 550$

Cryogenic tests I

- Cell is tested at cryogenic temperatures for leaks and mechanical failure of the silicon nitride window
- Cryogen-free, laboratory cryostat based on a pulse-tube cryocooler
- Down to 7.3 K currently (cell temperature)

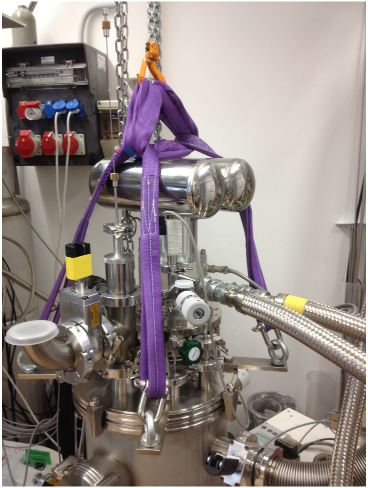


Figure : Laboratory cryostat.

Cryogenic tests II

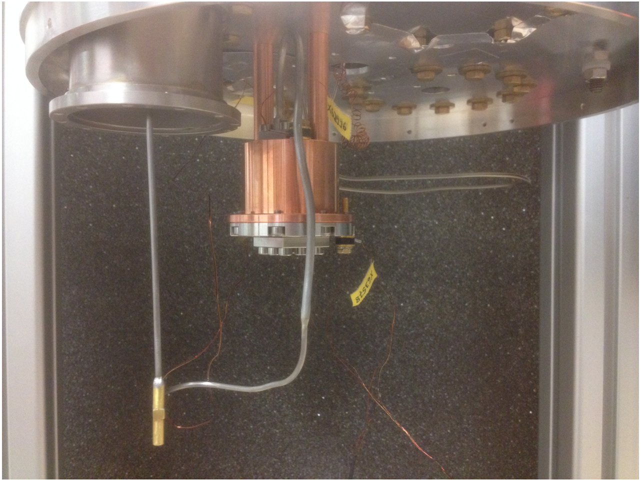


Figure : Test cell attached to the cryostat's second stage.

Cryogenic tests III

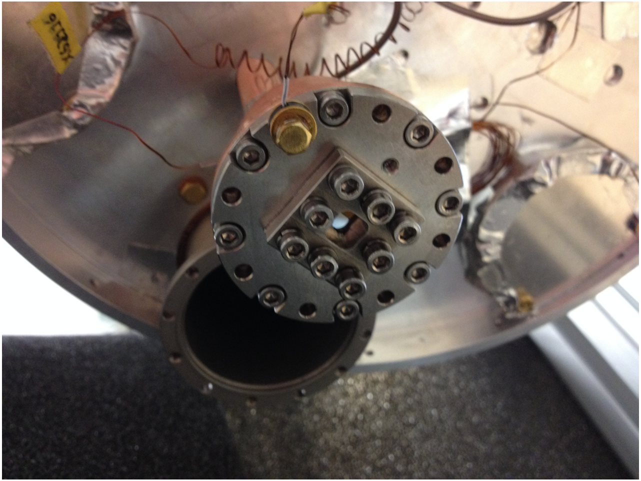


Figure : Test cell with intact window after cooldown.

Conclusion

- Mu is interesting as a tool for testing predictions from the Standard Model, or give better results on BSM constraints.
- It is imperative to extract it into vacuum for clean laser-spectroscopic measurements.

- **The embedding of a 50 nm-thick silicon nitride window for antimuon implantation should be feasible, if used along with a differential pumping mechanism and careful sealing.**

References

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Thank you for your attention