Summary of
"Muonium and other experiments" || session

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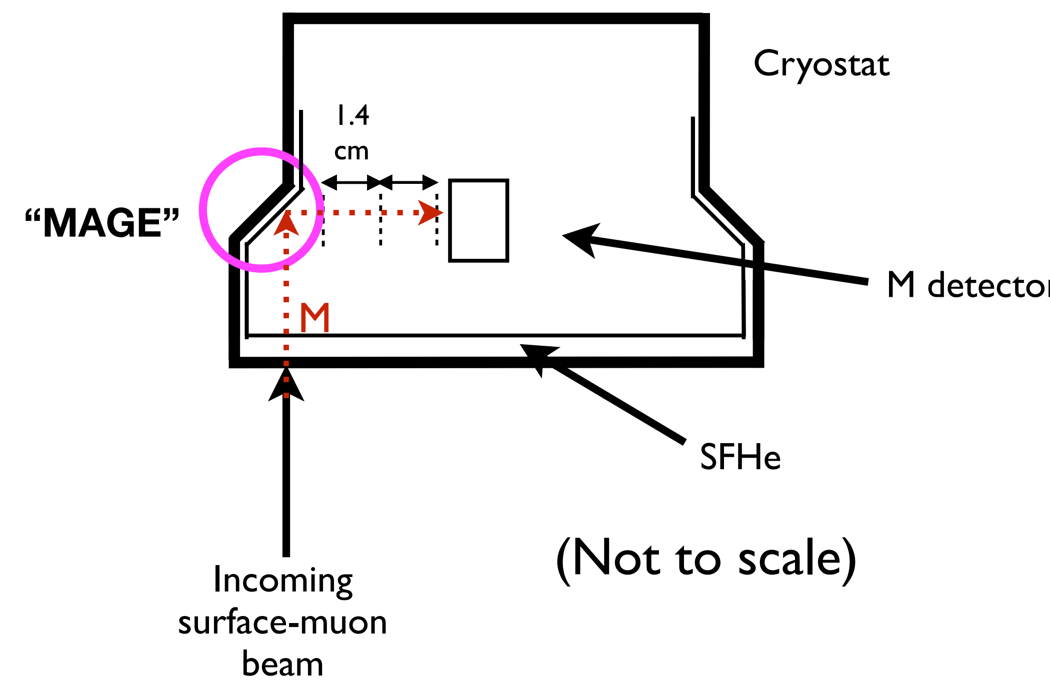
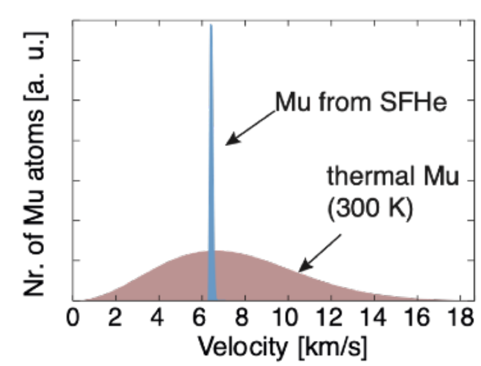
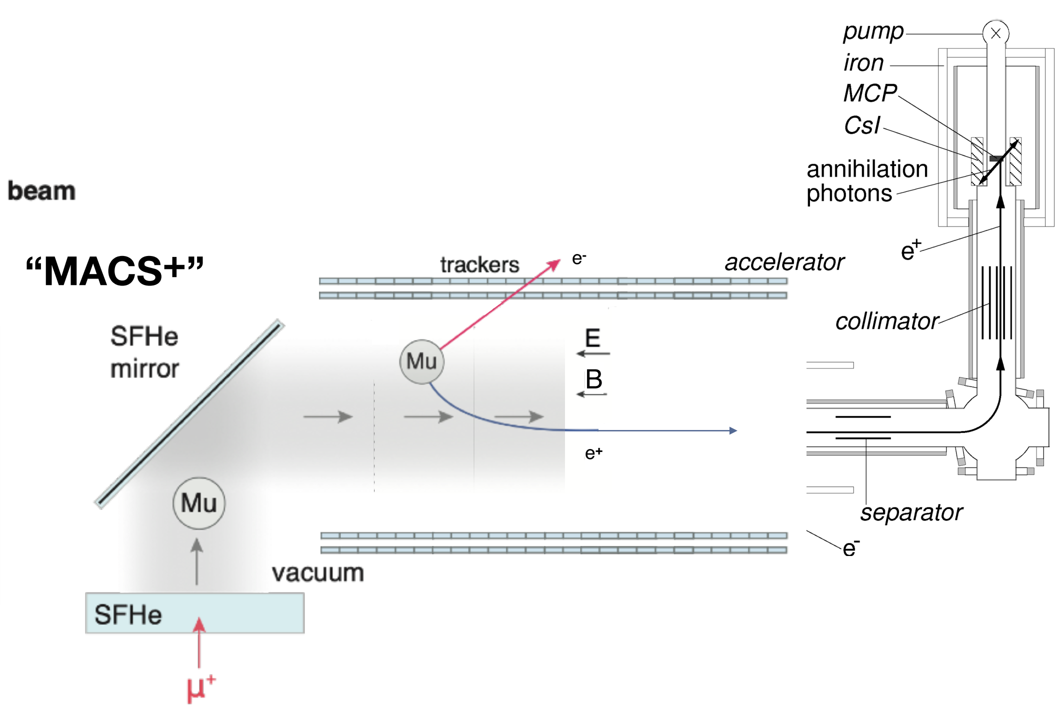
BU Arts & Sciences Physics



Cold beam





Workshop on Future Muon Program at Fermilab

Caltech

29 March 2023

Session Agenda

- Tuesday afternoon, 3/28:

	Muonium overview	*Daniel Kaplan*	*469, Lauritsen*	13:30 - 13:55
14:00	**M-Mbar mixing**	*Alexey Petrov*	*469, Lauritsen*	13:55 - 14:30
	Proposed MACE M-Mbar experiment	*Mr Shihan Zhao*	*469, Lauritsen*	14:30 - 14:55
15:00	**Muonium spectroscopy**	*David Kawall*	*469, Lauritsen*	14:55 - 15:30
16:00	**Low-energy muons at Fermilab**	*Carol Johnstone*	*469, Lauritsen*	16:00 - 16:25
	Making muonium with superfluid hel	*Thomas Phillips*		
	Muonium gravity	*Daniel Kaplan*	*469, Lauritsen*	16:50 - 17:10
17:00	**Discussion, other physics, & summa…**	*All*		

Nutshell Summary

- Muonium (M): $\mu^{+}e^{-}$ atom
  - M-$\overline{\text{M}}$ oscillation search
  - M precision spectroscopy
  - M antimatter gravity
- Fermilab advantages
- Discussion

Nutshell Summary

- Muonium (M): μ^+e^- atom
  - M-$\overline{\text{M}}$ oscillation search
    - Double CLFV; differently sensitive than Mu2e to CLFV new physics
    - New experiment due
    - Goal: 10^{-3}–10^{-4} x PSI 1999 MACS limit
  - M precision spectroscopy
  - M antimatter gravity
- Fermilab advantages
- Discussion

Petrov: M-$\overline{\text{M}}$ mixing

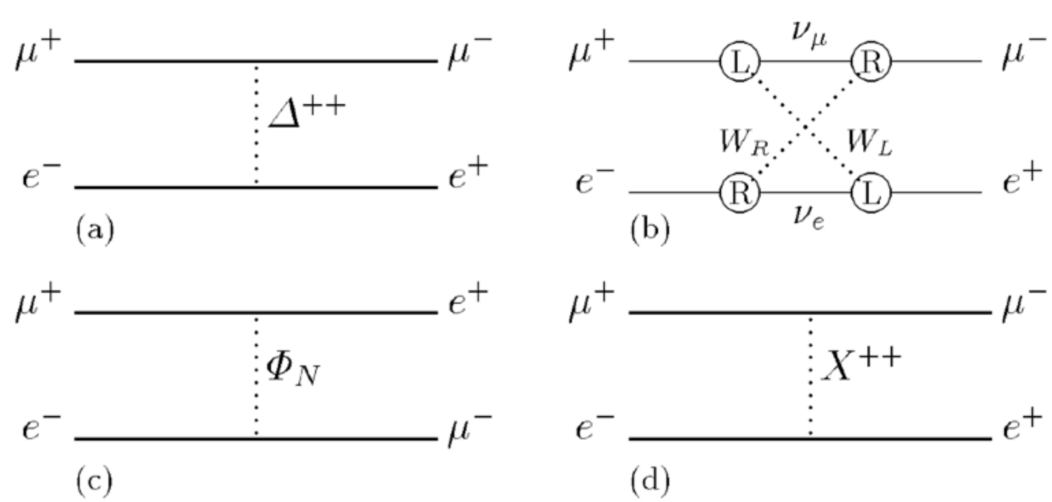
Muonium oscillations: just like $B^0\bar{B}^0$ mixing, but simpler!

★ Lepton-flavor violating interactions can change $M_\mu \to \overline{M}_\mu$

Pontecorvo (1957)
Feinberg, Weinberg (1961)

- Such transition amplitudes are tiny in the Standard Model
  - … but there are plenty of New Physics models where it can happen

Clark, Love; Cvetic et al,
Li, Schmidt; Endo, Iguro, Kitahara;
Fukuyama, Mimura, Uesaka; …



$\sim (\bar{\mu}\Gamma e)\,(\bar{\mu}\Gamma e)$

effective operator

  - theory: compute transition amplitudes for ALL New Physics models!
  - experiment: produce M_μ but look for the decay products of $\overline{M}_\mu$

Alexey A Petrov (U of South Carolina) 18 Future muon program at Fermilab, Caltech, 27-29 March 2023

- Illustrative diagrams of NP models contributing to M-$\overline{\text{M}}$ mixing

Petrov: M-$\bar{M}$ mixing

Conclusions and things to take home

- There is no indication from high energy studies where the NP show up
  - this makes indirect searches the most valuable source of information
- Muonium is the simplest atom: atomic physics
  - level splitting (Lamb shift): probe NP w/out QCD complications

MuSEUM experiment (J-PARC)

- Muons are ideal tools to probe fundamental physics
  - flavor-conserving quantities (g-2, EDM)
  - flavor-changing neutral current decays
  - flavor oscillations (muonium-antimuonium conversion)
  - muon transitions already probe the LHC energy domain and can do better!

Prospects for precise predictions of a_μ in the Standard Model
G. Colangelo, et. al., arXiv:2203.15810 [hep-ph]

- New experimental facilities: MACE at CSNS
  - similar domestic experiment at SNS (Oak Ridge)?
  - possible muonium oscillation experiment at J-PARC (Japan)?

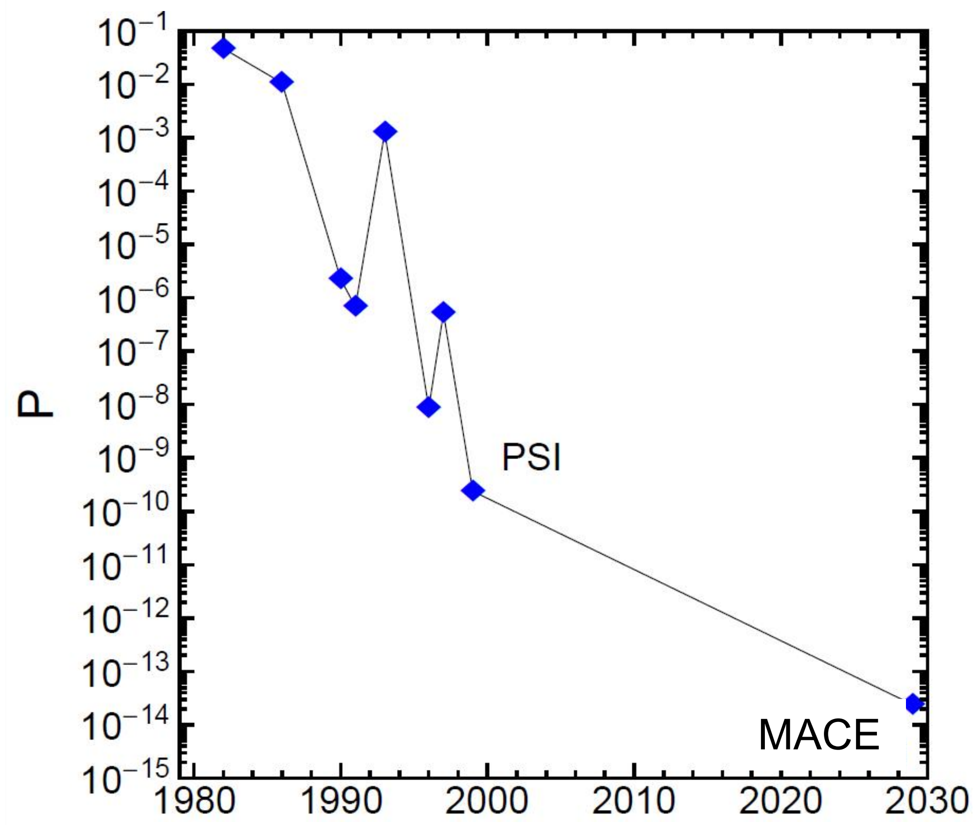
Snowmass2021 Whitepaper: Muonium to antimuonium conversion
A.-Y. Bai, …, AAP, …, arXiv:2203.11406 [hep-ph]

Alexey A Petrov (U of South Carolina) 1 Future muon program at Fermilab, Caltech, 27-29 March 2023

Zhao: Proposed M-$\bar{\text{M}}$ exp't

- Proposal to Chinese SNS:

MACE: Shed light on new physics



- **MACE**: The first proposed muonium-to-antimuonium conversion experiment since 1999, we plan to improve the sensitivity by more than two orders of magnitude.
- Together with other flavor and collider searches, MACE will shed light on the mystery of the neutrino masses.

MACE: Muonium-to-Antimuonium Conversion Experiment

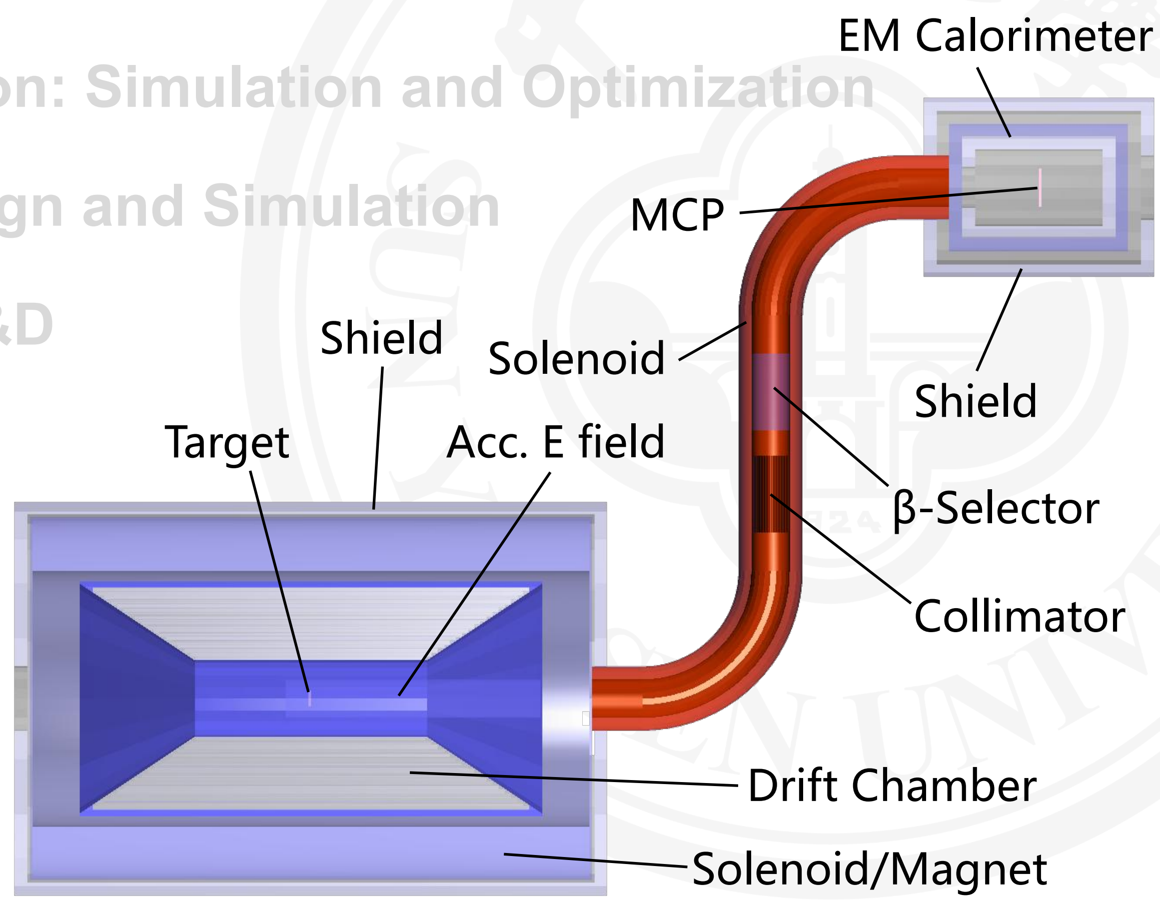
2023-03-28 Shihan Zhao (Sun Yat-sen University) 8

Zhao: Proposed M-M̄ exp't

- Proposal to Chinese SNS:

Content

- Motivation
- **Conceptual Design of MACE**
  - ➢Muonium Production: Simulation and Optimization
  - ➢Drift Chamber Design and Simulation
  - ➢Offline Software R&D
- Preliminary analysis
- Summary



2023-03-28 Shihan Zhao (Sun Yat-sen University) 9

Nutshell Summary

- Muonium (M): μ^+e^- atom
  - M-$\overline{\text{M}}$ oscillation search
  - M precision spectroscopy
  - M antimatter gravity

Precision QED test (~~strong~~, ~~finite-size~~):
M 1S-2S, hyperfine, Lamb shift

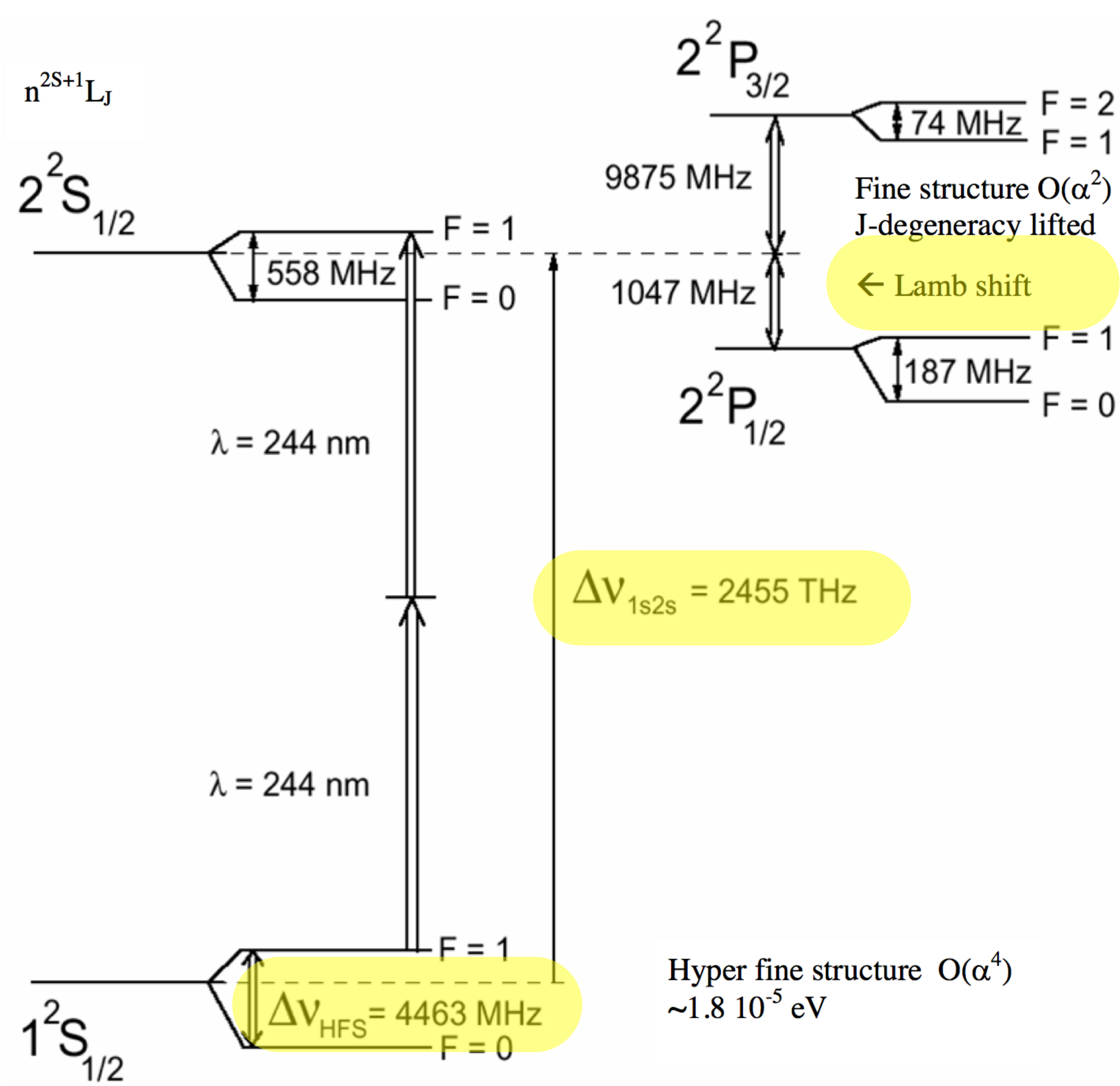
New experiments in progress:
(MuSEUM, Mu-MASS) @ (J-PARC, PSI)

World-leading sensitivity with AMF

- Fermilab advantages
- Discussion

Kawall: M spectroscopy

Muonium Energy Levels



- Hydrogen-like, but purely leptonic, free of nuclear size effects
- Can produce nearly 10^8/s
- Live 2.2 μs, linewidth 145 kHz
- Amenable and interesting for precision spectroscopy
- Extract important constants
- Test bound state QED, search for new physics

$$a_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

Muonium Spectroscopy, D. Kawall, UMass Amherst Workshop on a Future Muon Program at Fermilab, Mar 27-29 2023, Caltech 2

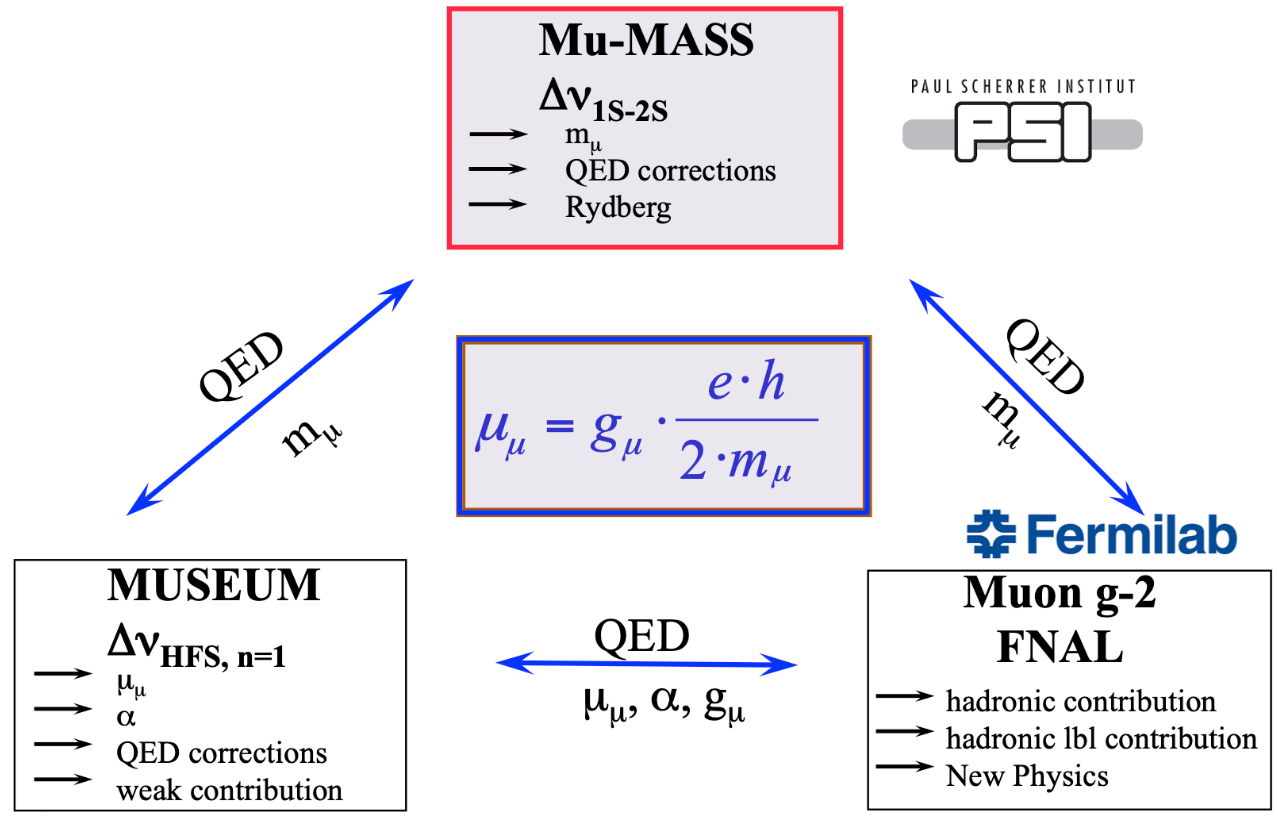
Kawall: M spectroscopy

Mu-MASS: Measure 1S-2S interval to 10 kHz, determine m_{μ}/m_{e} to 1 ppb

Mu-MASS: Measure **1S-2S transition** with Doppler free laser spectroscopy
GOAL: improve by 3 orders of magnitude (10 kHz, 4 ppt)

OUTPUT

- → **Muon mass @ 1 ppb**
- → Ratio of q_e/q_μ @ 1 ppt
- → Search for New Physics
- → **Test of bound state QED (1×10^{-9})**
- → Input to muon g-2 theory
- → **Rydberg constant @ ppt level**
- → New determination of α @ 1 ppb



- Technique: Make M inside microwave cavity, or probe with lasers

Nutshell Summary

- Muonium (M): μ^+e^- atom
  - M-$\overline{\text{M}}$ oscillation search
  - M precision spectroscopy
  - M antimatter gravity
    - Never measured; 5th-force search, test of GR
    - New experiments in progress/proposed using SFHe M production: (LEMING, MAGE) @ (PSI, FNAL)
    - World-leading sensitivity with AMF
- Fermilab advantages
- Discussion

Kaplan: Muonium Gravity

Muonium Gravity Experiment

- Some important feasibility questions:

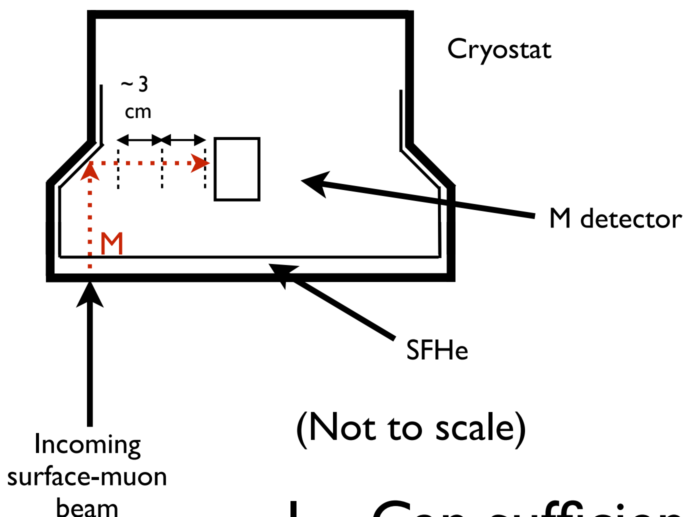
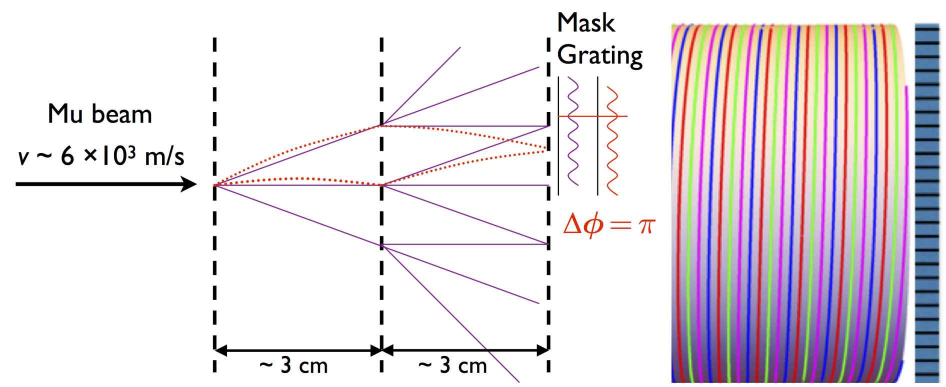


Figure 1: Principle of muonium interferometer, shown in elevation view (phase difference $\Delta\phi = \pi$ shown for illustrative purposes); Mu-decay detectors (barrel SciFi positron tracker and electron MCP) shown at right.



1. Can sufficiently precise diffraction gratings be fabricated?
2. Can interferometer and detector be aligned to a few pm and stabilized against vibration?
3. Can interferometer and detector be operated at cryogenic temperature?
4. How determine zero-degree line?
5. Does SFHe M production work?

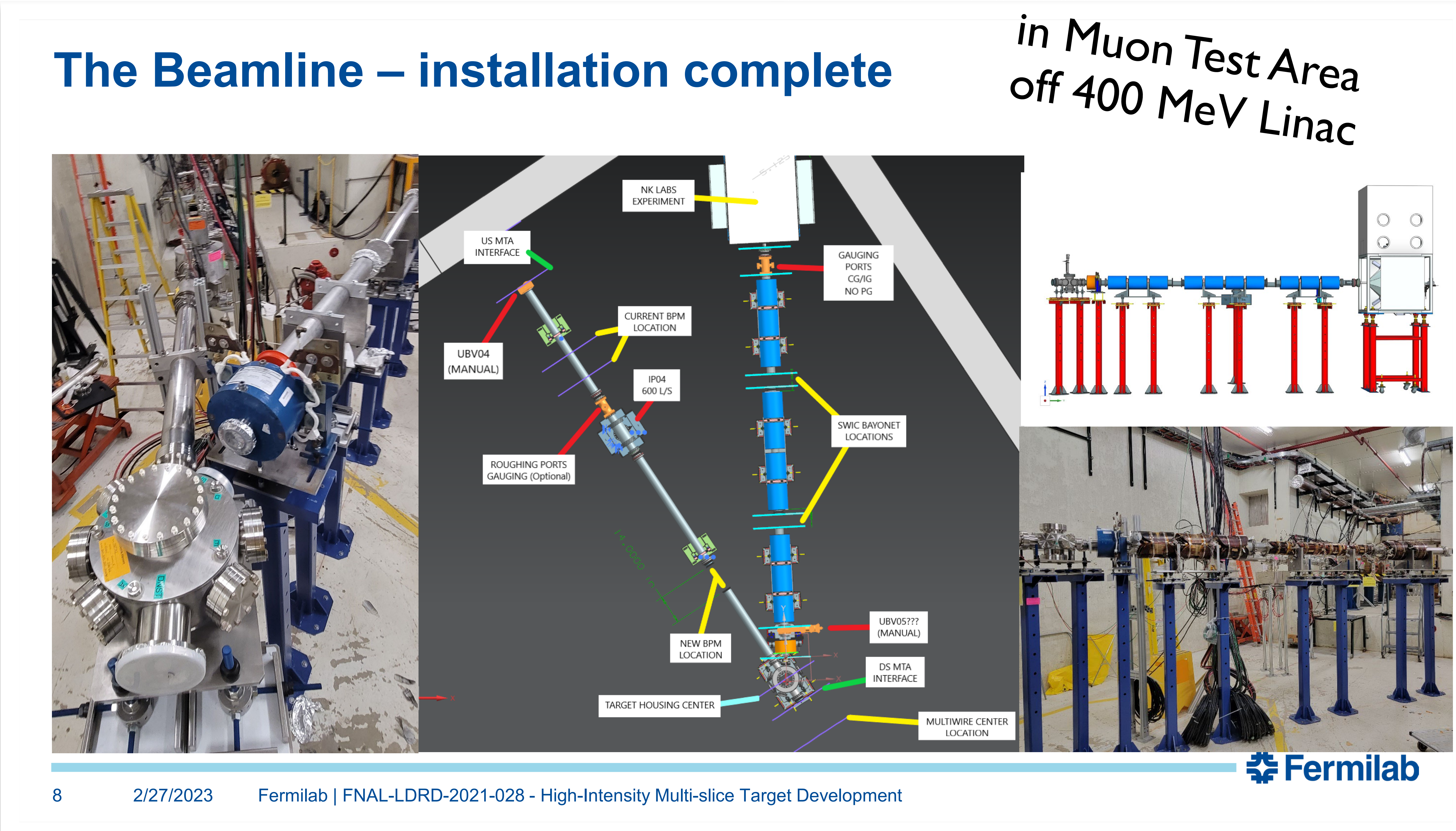
D. M. Kaplan, IIT Future Muon Workshop | Muonium Gravity 3/28/23 13/21

- Atom-beam interferometer for ~ pm precision
- Techniques seem feasible based on past experience
- Need SFHe M production:
  - thick SFHe film → higher rate than PSI thin-film approach
  - needs R&D

Nutshell Summary

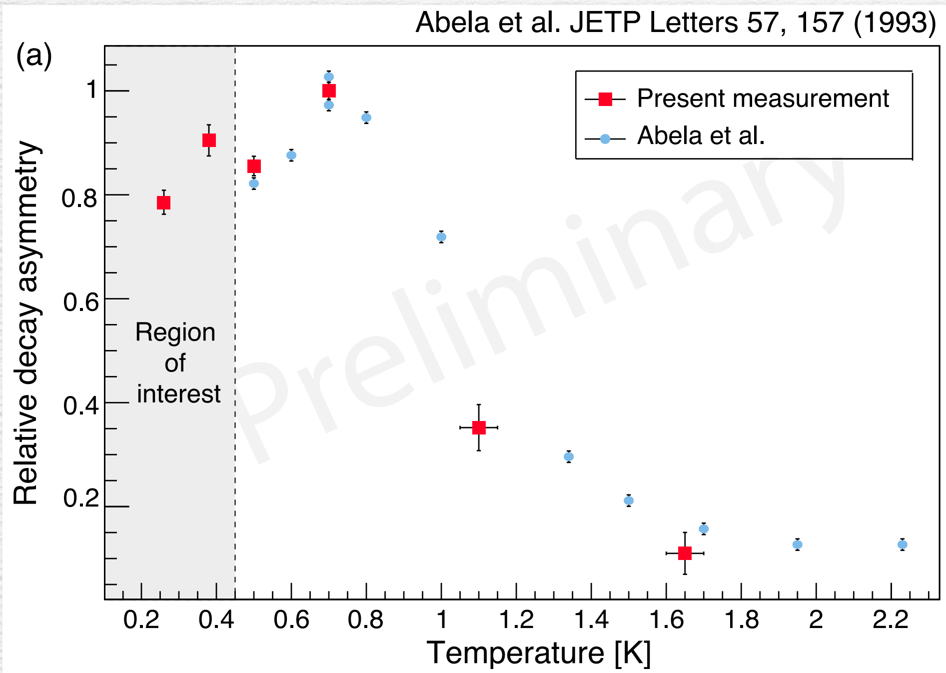
- Muonium (M): μ^+e^- atom
  - M-$\overline{\text{M}}$ oscillation search
  - M precision spectroscopy
  - M antimatter gravity
- Fermilab advantages
  - R&D possible with existing 400 MeV Linac
  - Possibly competitive with PSI for e.g. M gravity
  - World-leading sensitivity with AMF
- Discussion

Johnstone: Low Energy Muons at Fermilab

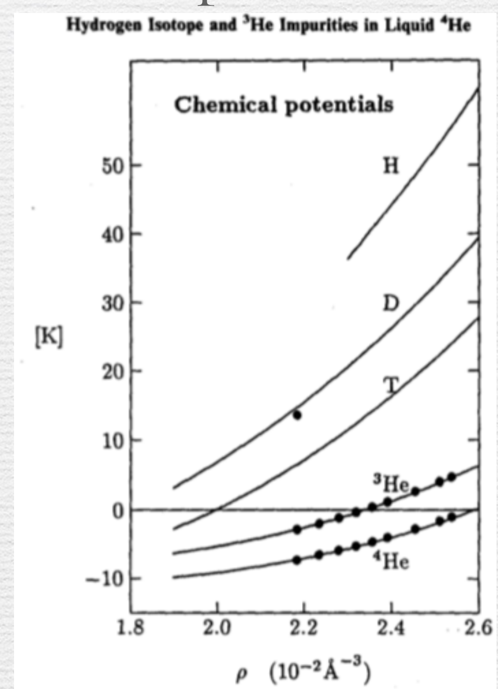


- MTA beamline installed for μCF experiment (μ^-); also transmits μ^+
- Available for R&D until long shutdown (FY27)

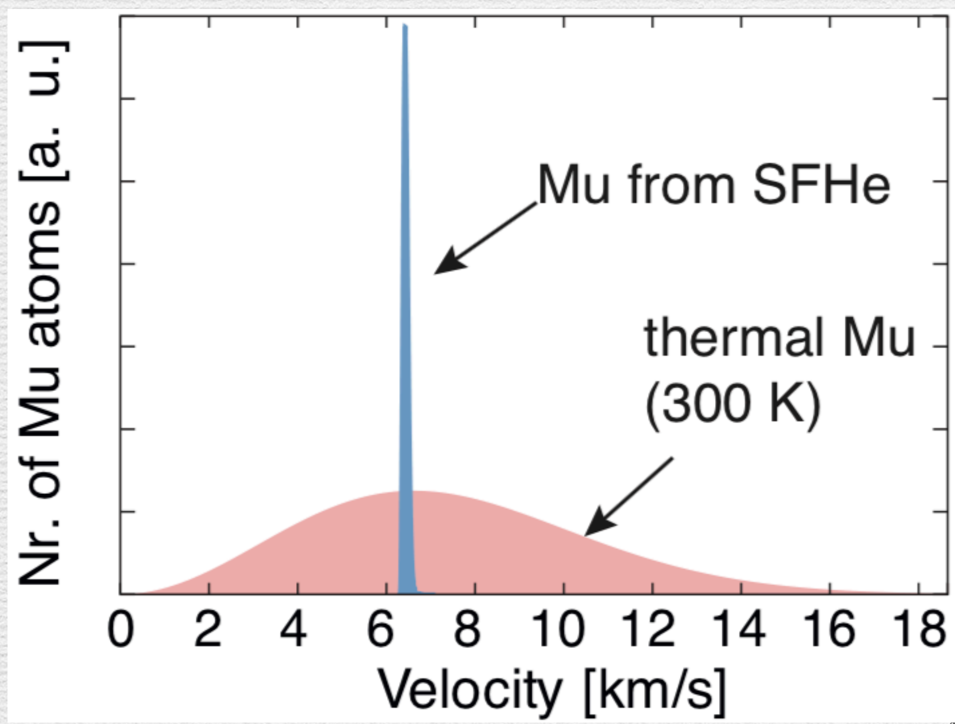
Phillips: Muonium in Superfluid Helium



- Mu produced with high efficiency for T < 1K
- As a light isotope of hydrogen, Mu does not dissolve in SFHe (calculated potential: 270 K)



Saarela and Krotscheck, J. Low Temp. Phys. 90, 415 (1993)



- ✦ if Mu reaches surface it is ejected perpendicular to surface at 6.3mm/μs
- ✦ nearly mono-energetic and uni-directional!

T.J Phillips IIT Workshop Future Muon Program @ FNAL 3/28/23

- Stopped $\mu^+ \to$ M ~100% efficient in SFHe @ $T \leq 0.8$ K
- Makes quasi-monoenergetic, low-divergence beam in vacuum
- Ideal for M gravity
- Game-changer for other meas'ts too?
- Needs R&D
  - uses QIS technique of electrons on SFHe surface

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  - M antimatter gravity
- Fermilab advantages
- Discussion
  - Can SFHe M prod. improve oscillation, spectroscopy exp'ts?
  - Possible to seek rare double-CLFV decays: M → $\nu\bar{\nu}$, e^+e^- ? (μw cavity?)

Kaplan: Overview

arXiv:2212.04897 [physics.ins-det]

Letter of Intent: Muonium R&D/Physics Program at the MTA

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* Spokesperson †Also at Zurich Instruments

December 5, 2022

1 Introduction

There is a need for a high-efficiency source of muonium (M $\equiv \mu^+ e^-$, chemically a light isotope of hydrogen), traveling as a beam in vacuum, for fundamental muon measurements, sensitive searches for symmetry violation, and precision tests of theory [1]. Currently PSI in Switzerland is the world leader for such research. With PIP-II Fermilab has the potential to eclipse PSI and become the new world leader. It is prudent to begin the R&D now in order to be ready when PIP-II comes online. Fermilab's MeV Test Area (MTA) at the 400 MeV H^- Linac has a low-energy muon beamline suitable for this R&D, with the potential to compete with PSI for this physics in the pre-PIP-II near term as well.

Key muonium measurements include the search for M-$\overline{\text{M}}$ conversion, precision measurement of the M atomic spectrum, and the study of antimatter gravity using M. Furthermore, the J-PARC $g-2$ experiment proposes to use a low-energy μ^+ beam produced by photo-ionizing a slow beam of muonium, but the needed high-intensity muonium beam has yet to be demonstrated. The technique we propose may form a suitable muonium source for such a $g-2$ measurement as well as for other applications of slow muon beams.

M-$\overline{\text{M}}$ conversion is a double charged-lepton flavor-violating (CLFV) reaction, allowed (albeit at an undetectably small rate) via neutrino mixing. It may be no less likely — and in some models, *more* likely — than μ to e conversion [1]. Thus in a thorough CLFV research program it should be

- More collaborators welcome!
- Hope for 1st (~10%) gravity meas't as well as R&D

In Summary,

- Stimulating session!
- New ideas raised:
  - applying SFHe M production to M-$\overline{\text{M}}$ mixing, M spectroscopy?
  - detecting rare M decays?
- Great promise for M physics at Fermilab
  - hope to follow up with further discussions!
  - please contact us if interested: kaplan-at-iit.edu, awje-at-bu.edu