Muonium Atom Interferometry for High-precision Studies of Symmetries and Interactions

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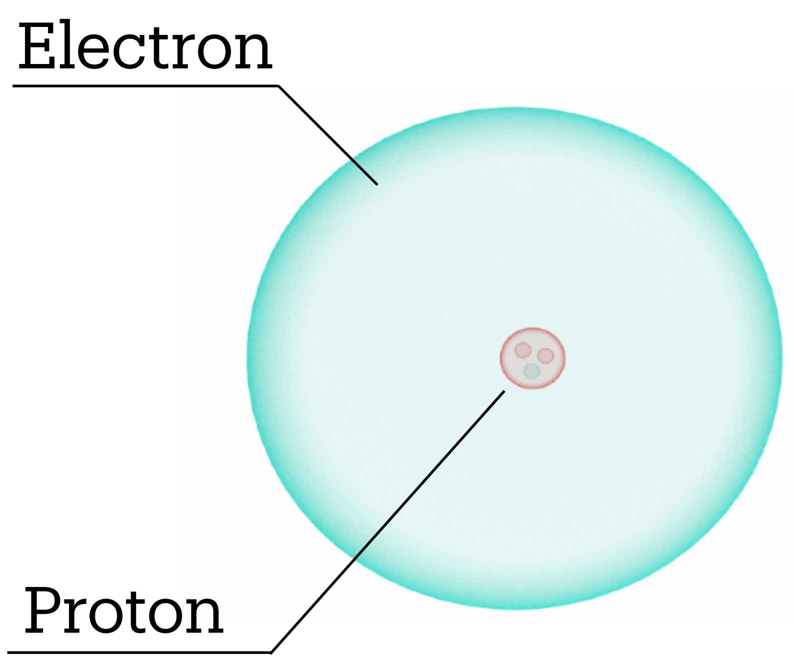
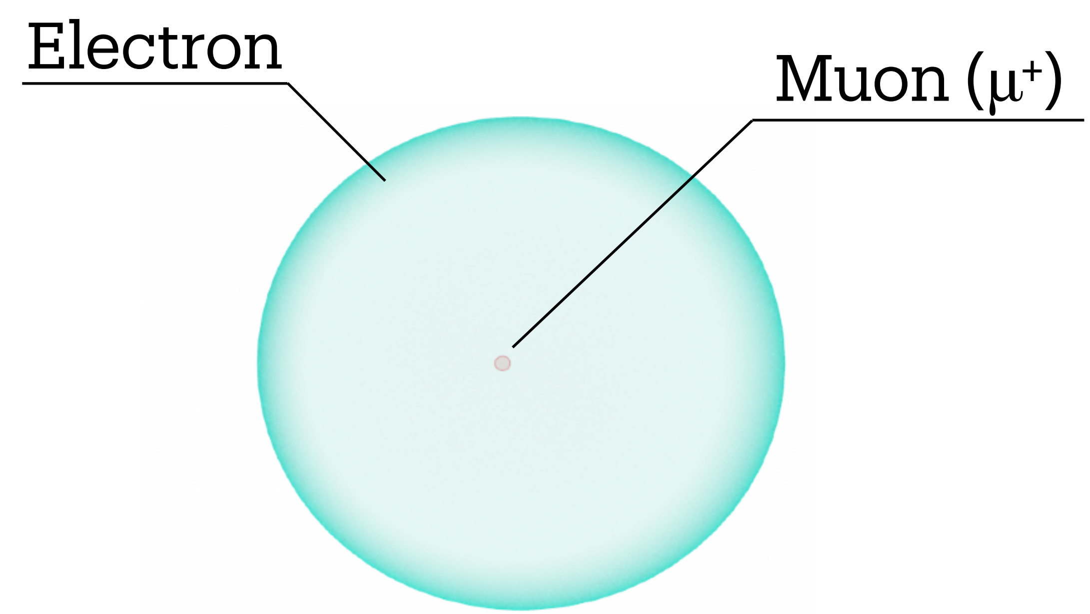
Muonium

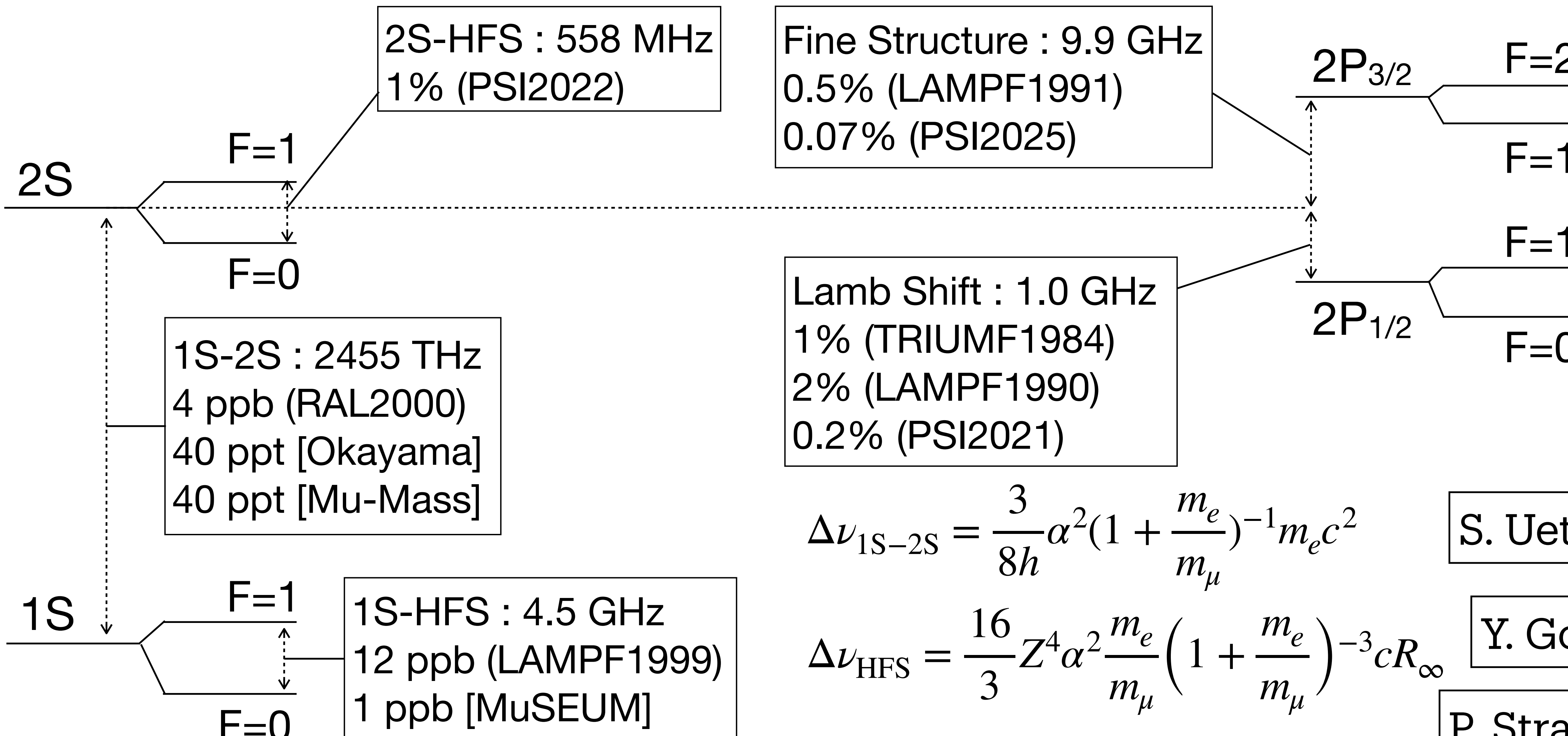




Hydrogen	r_{ep} = 0.53 Å	Muonium	$r_{\mu p}$ = 0.53 Å
938 MeV/c^2	stable	105.7 MeV/c^2	lifetime 2197 ns

- Muons are second-generation charged lepton, with a mass 200 times that of an electron and the lifetime of 2.2 μs.
- Muonium is a hydrogen-like atom composed of a positive muon and an electron, forming a purely leptonic two-body system.
- It serves as an ideal testbed for bound-state quantum electrodynamics.

Muonium Spectroscopy



$$\Delta\nu_{\mathrm{1S-2S}} = \frac{3}{8h}\alpha^2(1+\frac{m_e}{m_\mu})^{-1}m_e c^2$$

$$\Delta\nu_{\mathrm{HFS}} = \frac{16}{3}Z^4\alpha^2\frac{m_e}{m_\mu}\left(1+\frac{m_e}{m_\mu}\right)^{-3}cR_\infty$$

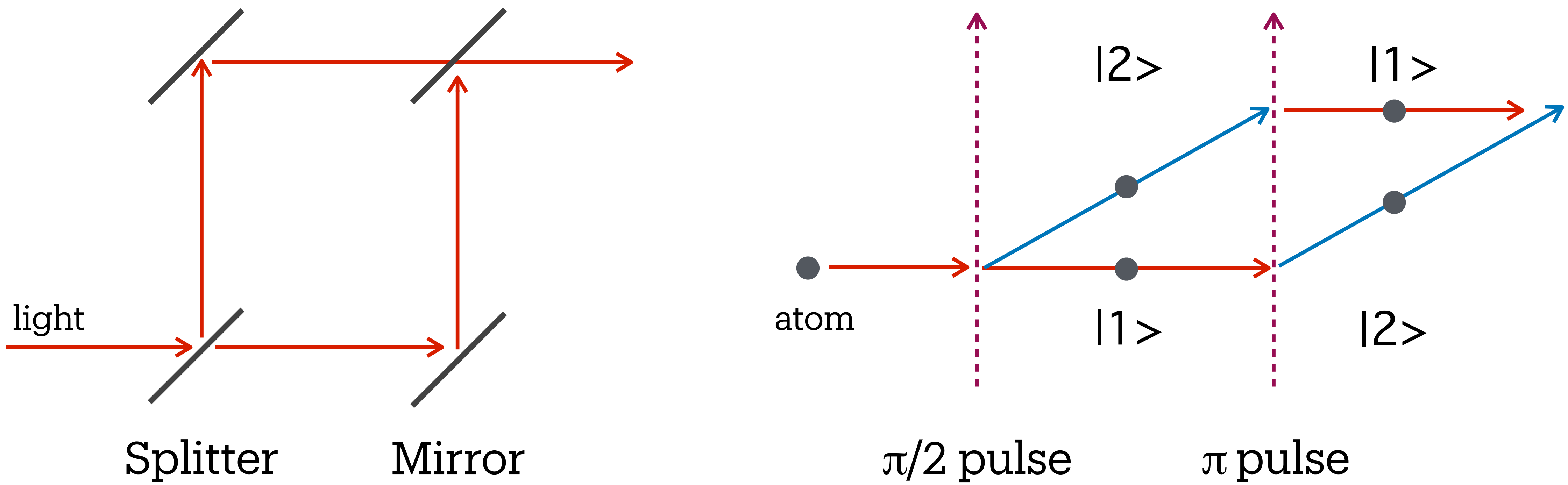
S. Uetake

Y. Goto

P. Strasser

- The spectroscopy of muonium provides a unique gateway for precision tests of the Standard Model and searches for new physics.
- The potential for discovering new physics using muons is constrained by muon mass precision (120 ppb) → Alternative methods for independent determination.

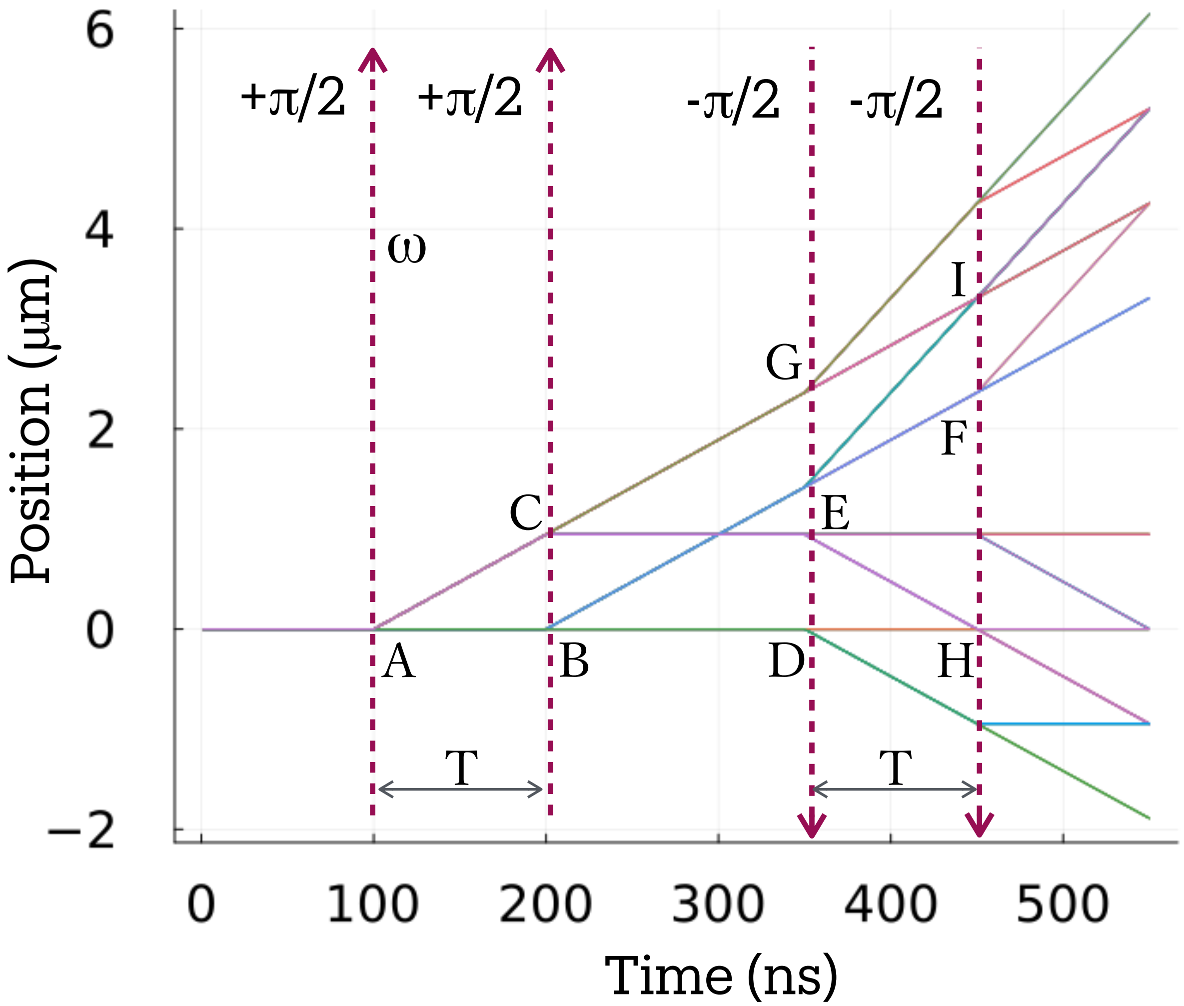
Matter Wave Interferometry

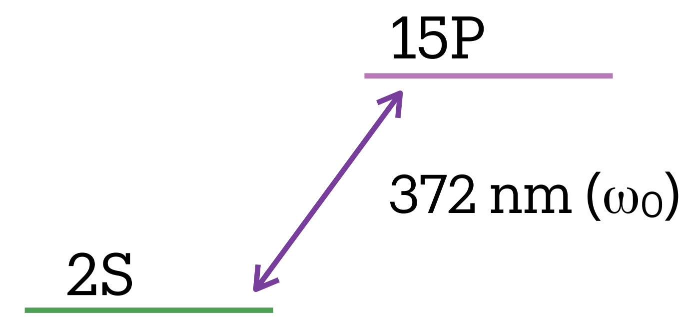


Mach-Zehnder interferometers of lights and atoms

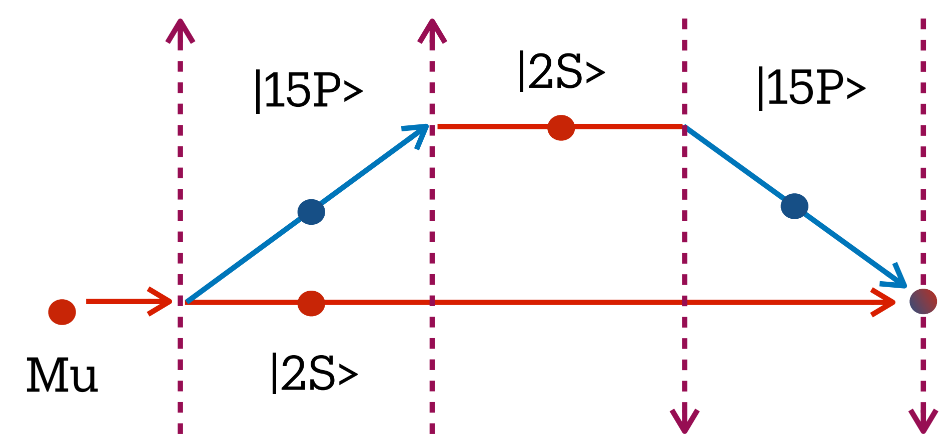
- Matter wave interferometers can be applied to ultra-sensitive measurements.
  - The interaction time is longer than that of an optical interferometer.
- π/2-and π-pulses act as a beam splitter and a mirror for atoms, respectively.
- There is no precedent for matter wave interferometry using muons.
  - Why? → A bright, low-energy muon beam is necessary.
  - See also: Anna Soter's talk on Sunday (LEMING at PSI).
- Atomic parity violation, the parity violating Berry phase, tests of the CPT/Lorentz invariance…

Ramsey-Bordé Interferometry





Irradiating a UV laser on a 2S Mu beam to induce Rabi oscillations between the 2S and 15P states.



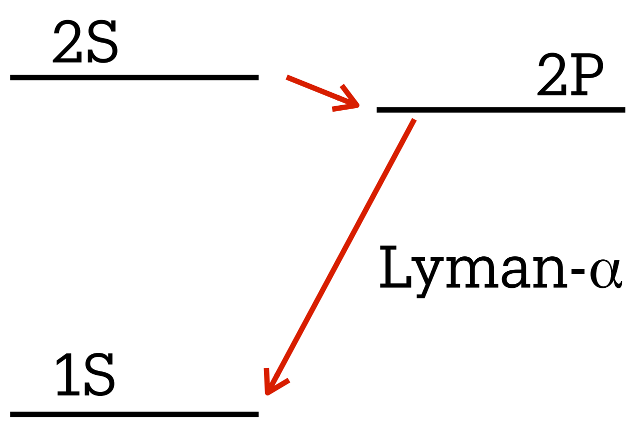
- The atomic mass can be measured via photon recoil shift.
- The phase difference between ACEH and ABDH is $\delta\phi_1 = 2(\omega - \omega_0)T - \hbar k^2 T/2m$.
- Similarly, for the paths ABFI and ACGI, it is $\delta\phi_2 = 2(\omega - \omega_0)T + \hbar k^2 T/2m$.
- By taking the difference, $\Delta\phi = \delta\phi_2 - \delta\phi_1 = \hbar k^2 T/m$.
- By taking the sum, $\Sigma\phi = \delta\phi_2 + \delta\phi_1 = 4(\omega - \omega_0)T$.

$$\frac{\hbar}{m} = \frac{\Delta\phi}{\Sigma\phi} \times \frac{4(\omega - \omega_0)}{k^2}$$

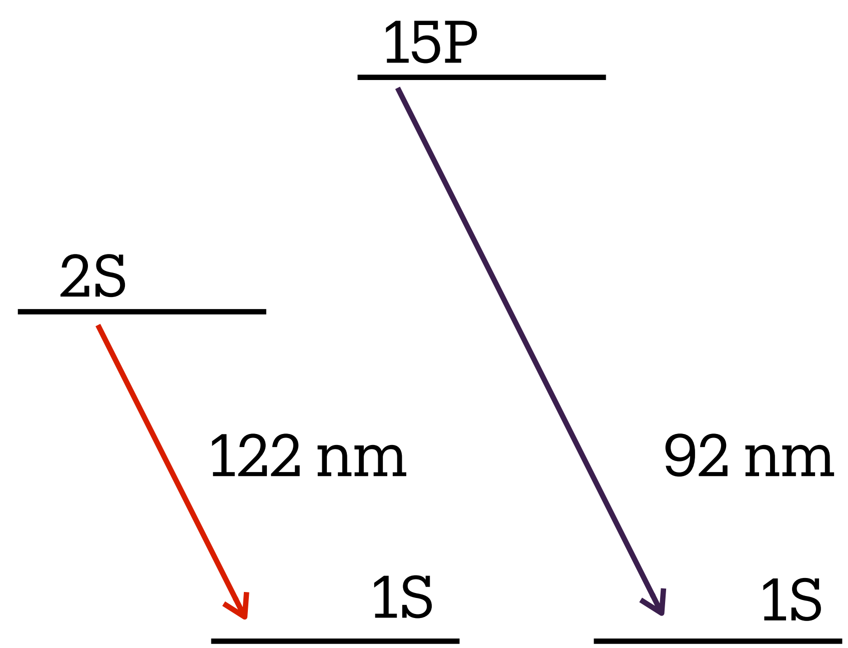
- The goal is O(1 ppb) precision (for Rb atoms, 0.15 ppb precision was achieved).

Rb exp. : L. Morel et al., Nature 588, 7836 (2020).

Signal Detection



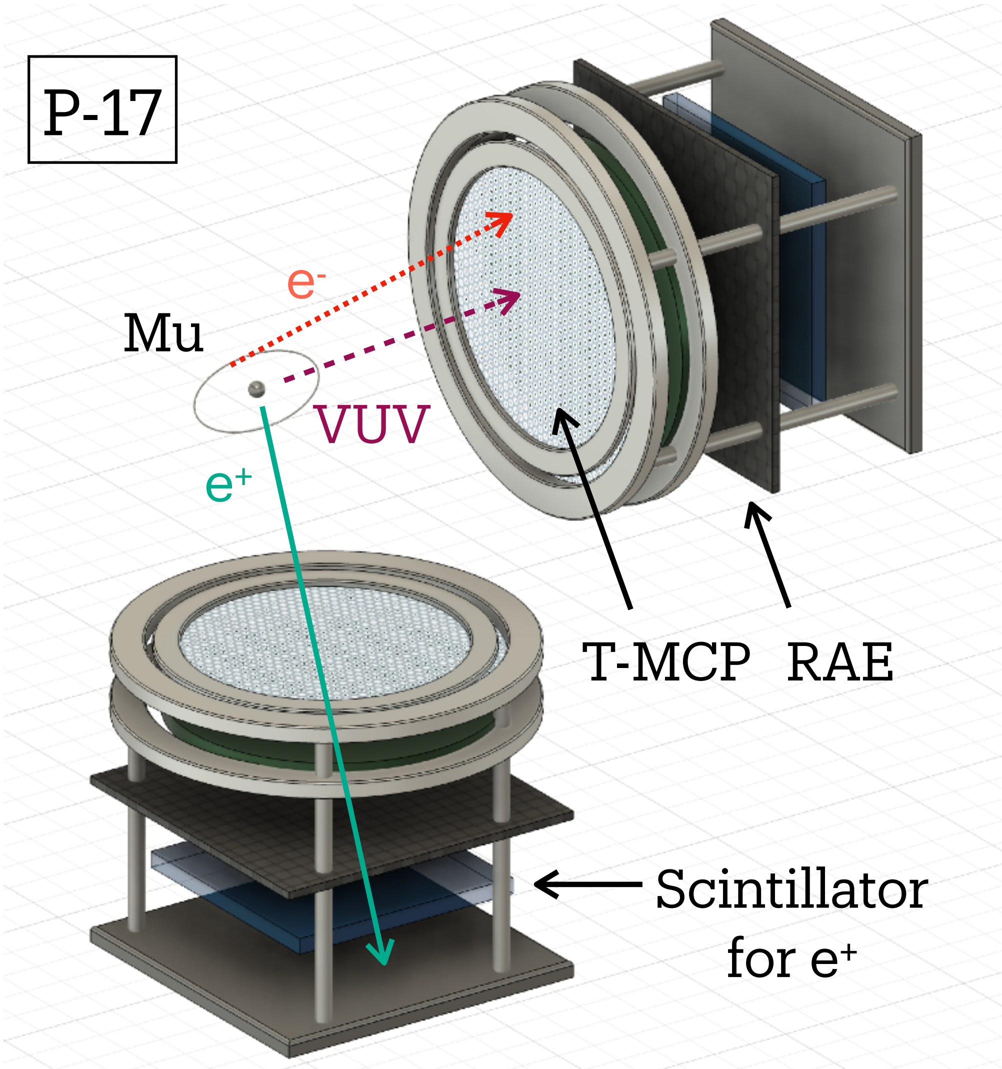
Stark mixing and quenching
2S lifetime 0.2 s
2P lifetime 1.6 ns
15P lifetime 650 ns

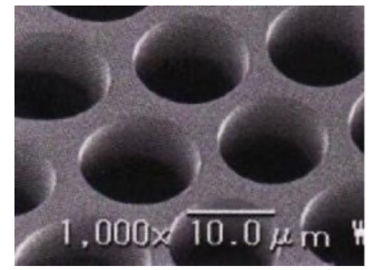


A lithium fluoride filter can distinguish between de-excitation photons from two states because its cut-off is about 105 nm.

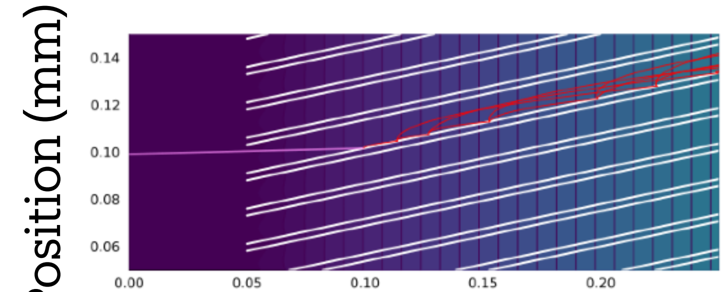
- The interferometry signal is obtained by counting the number of Muonium atoms in a specific state.
  - This is achieved by detecting VUV photons, induced by electric field quenching.
- A suitable filter allows 2S-Mu to be distinguished from 15P-Mu and counted selectively.
- The detection efficiency of VUV light is limited by the device's quantum efficiency (QE), which is on the order of a few percent → Room for improvement.

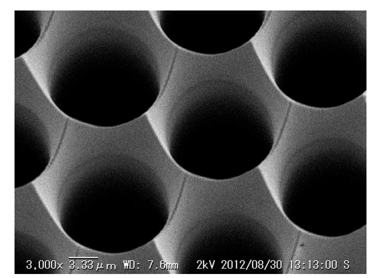
Multi-Particle Imager



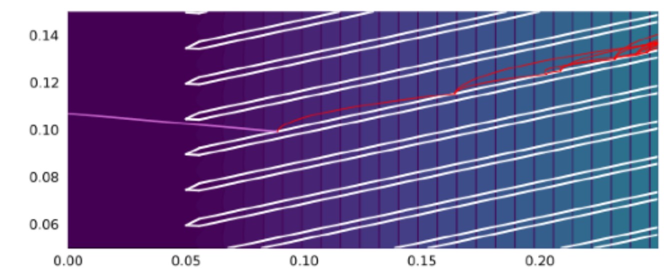


Normal MCP
OAR=50%



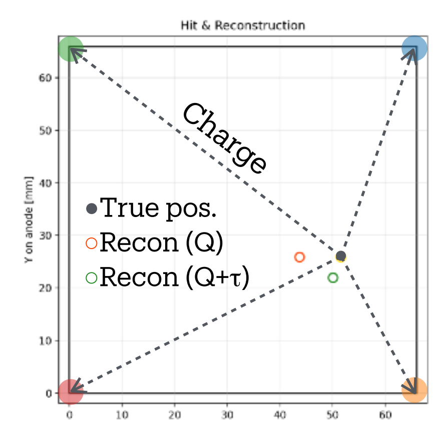


Tapered MCP (T-MCP)
OAR=90%

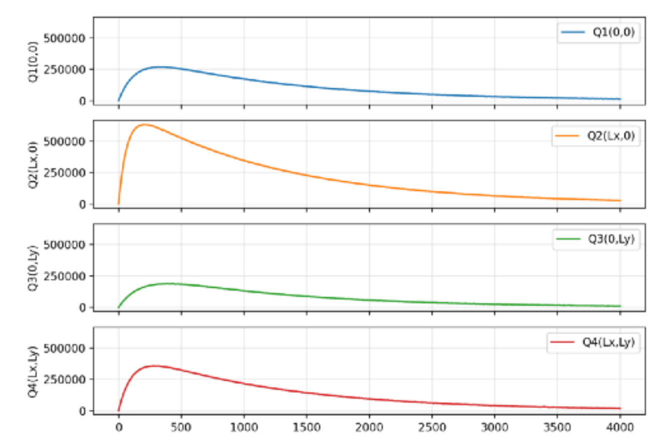


Simulated VUV light detection and electron avalanche

- An imaging device for low-energy particles and VUV photons.
- High detection eff. and resolution.
- ML assisted position reconstruction.
- A testbeam is scheduled for next week.

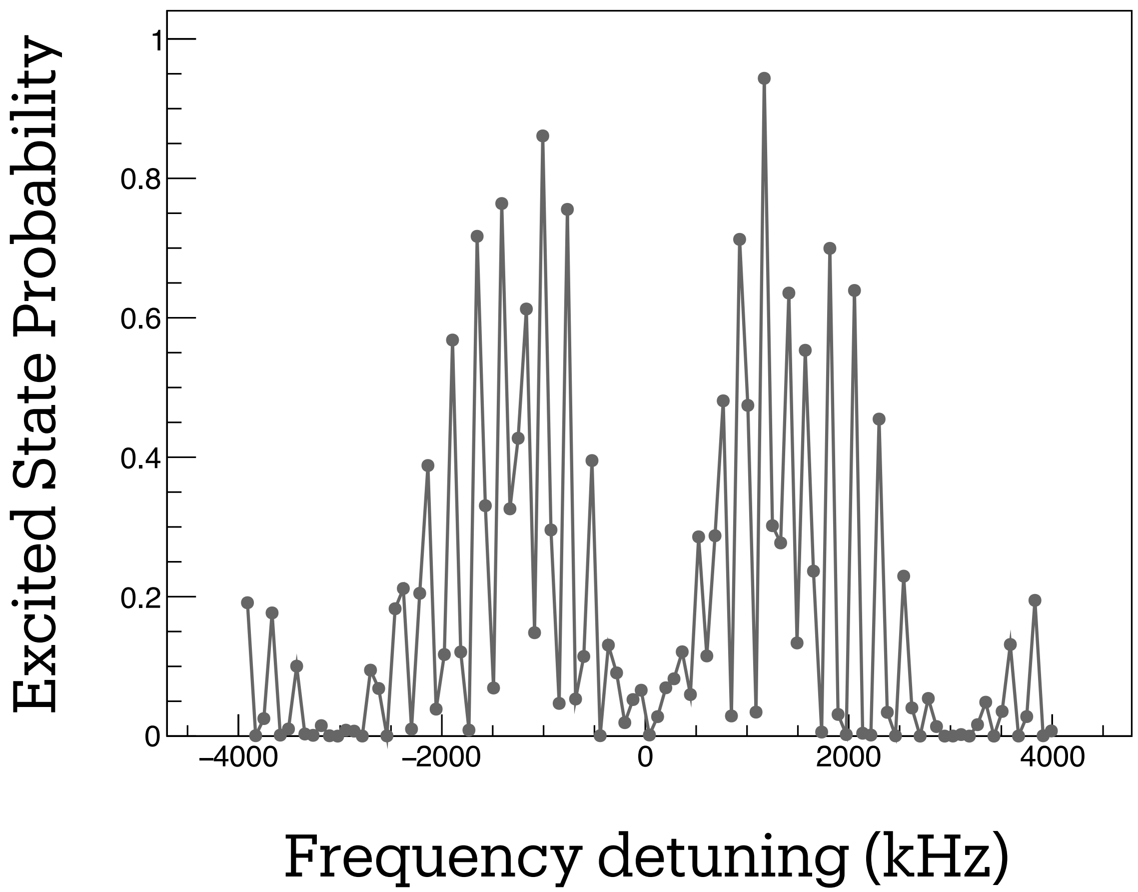


Resistive anode encoder (RAE)

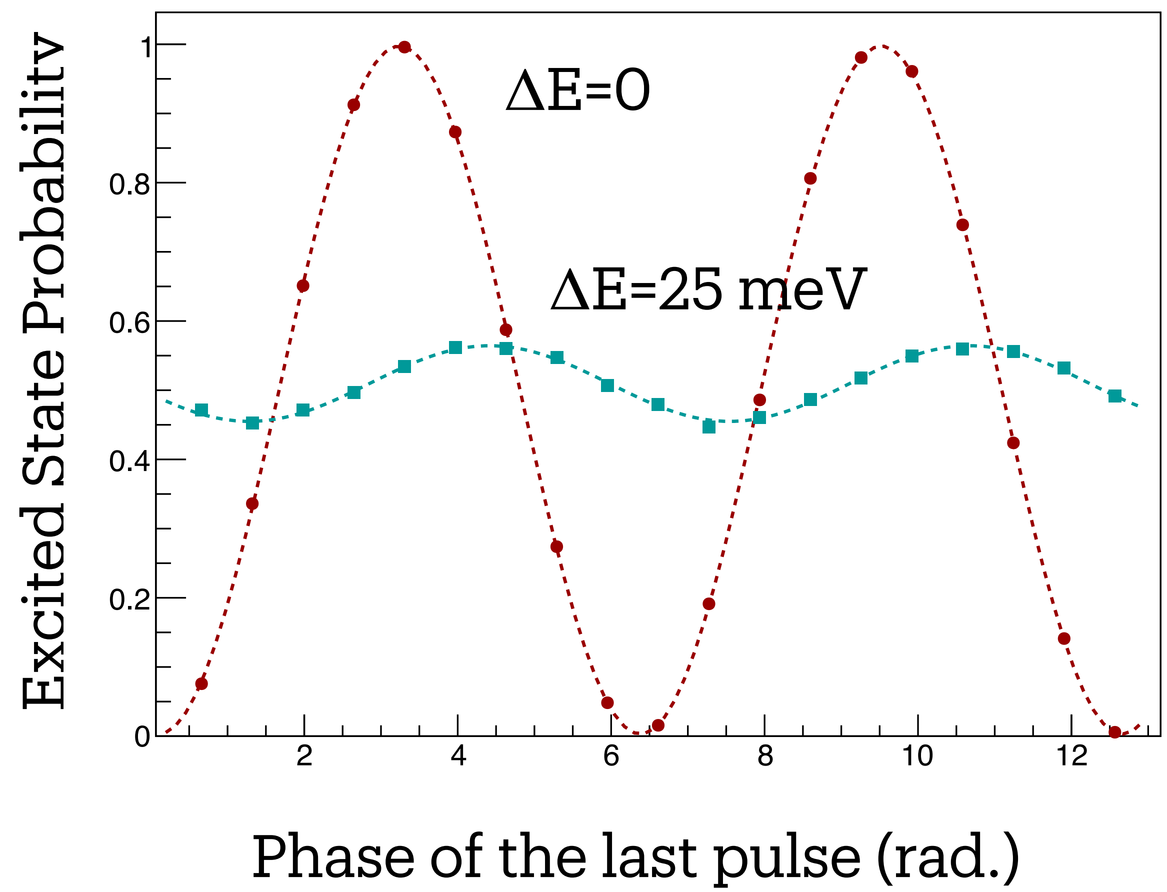


Anode signal waveforms

Simulations of Interferometry



Recoil doublet spectrum (ΔE=0)



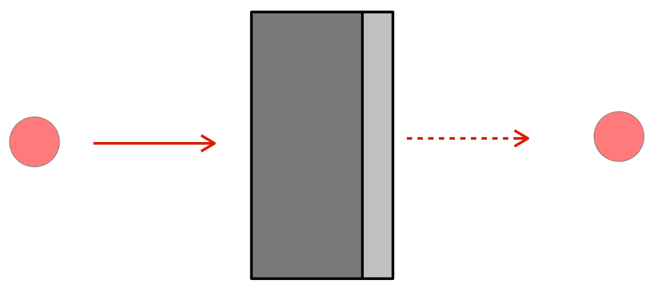
Interference fringes (Δω=0)

- Time evolution of atomic wavepackets was calculated by Monte Carlo simulations.
- Next steps: Addition of π pulses, statistical sensitivity, systematics evaluation, and interferometer optimization.

S. Kanda, submitted to J. Phys. Conf. Proc.

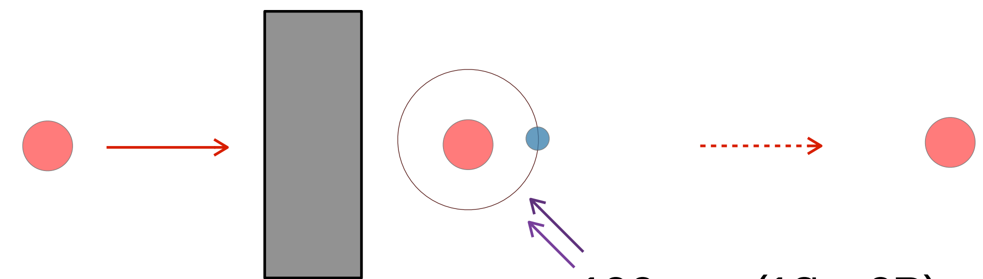
Low-Energy Muons

Cold rare-gas moderator (LEM)



E. Morenzoni et al., PRL 72, 2793 (1994).

Laser ionization of muonium (USM)

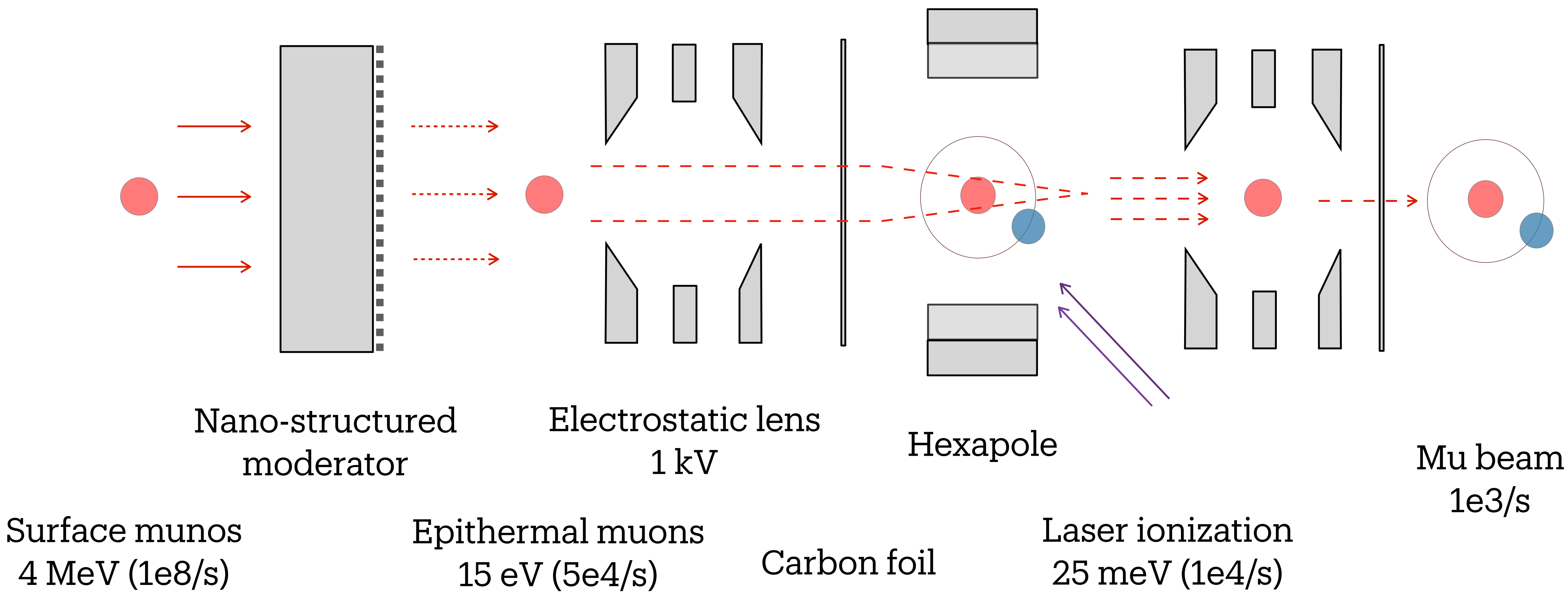


K. Nagamine et al., PRL 74, 4811 (1995).

- Due to the short lifetime of muons, the slowing down and cooling methods for stable atoms are not applicable.
- USM and LEM are promising methods to obtain slow muons.
- The USM technique defines the measurement's time origin using the ionization laser. This makes it possible to achieve high time resolution, even with a pulsed beam.

S. Kanda et al, J. Phys.: Conf. Ser. 2462 012030 (2023).

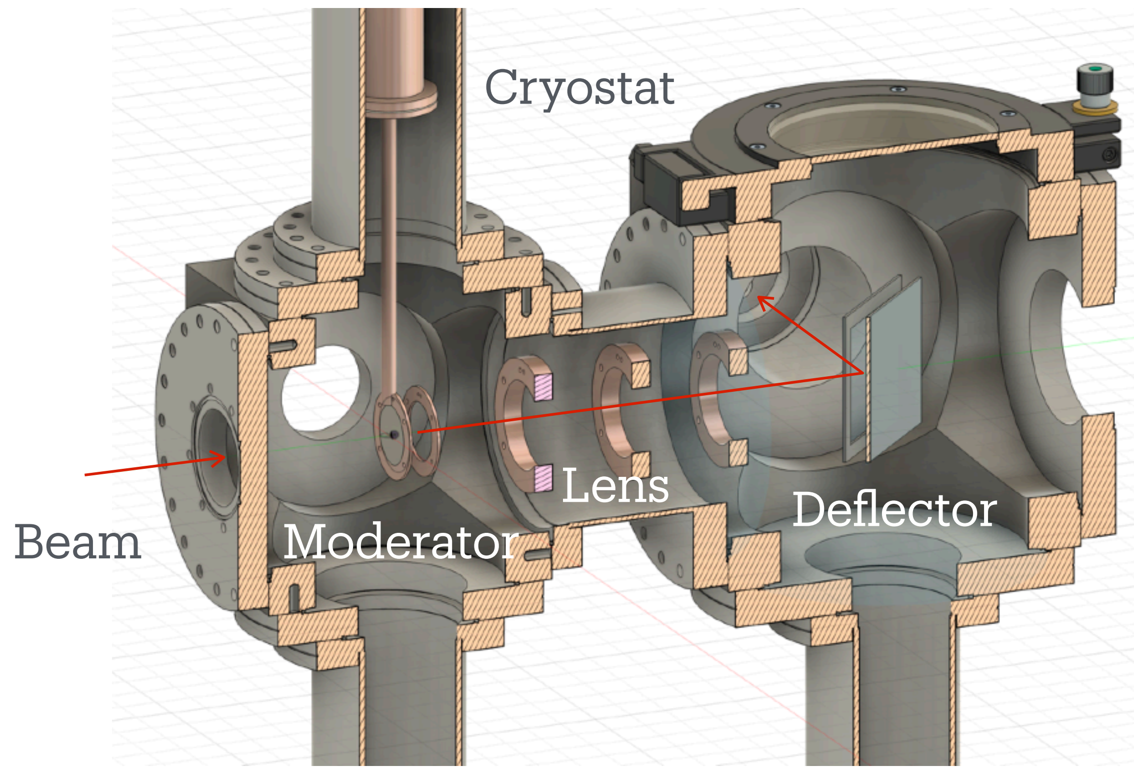
Slow Muonium Beam

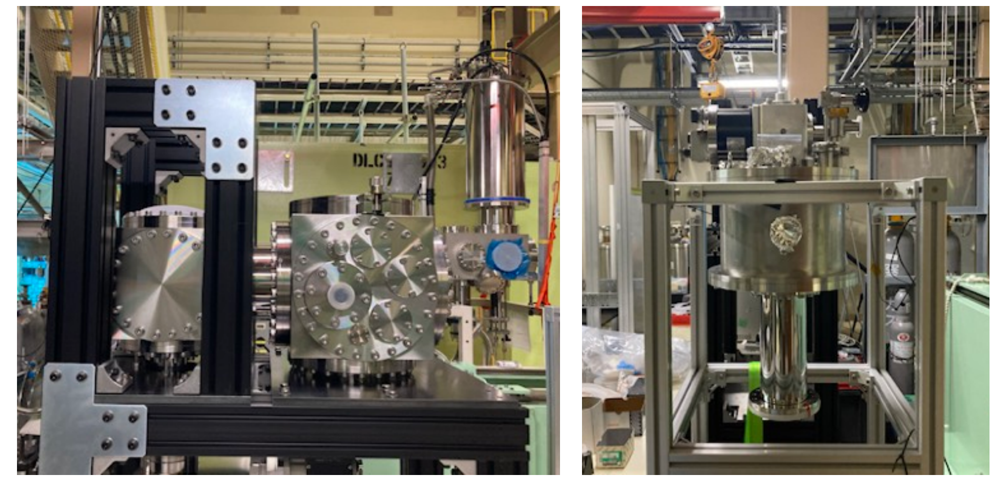


- A two-stage cooling scheme combining LEM and USM improves the brightness of low-energy Mu beam → Target Mu beam flux is 1000/s.
- By inserting LEM before USM, the spatial overlap between the laser beams and the Mu cloud is significantly enhanced.
- An accelerating-type electrostatic lens for muon extraction.
- A hexapole lens for muonium focusing.

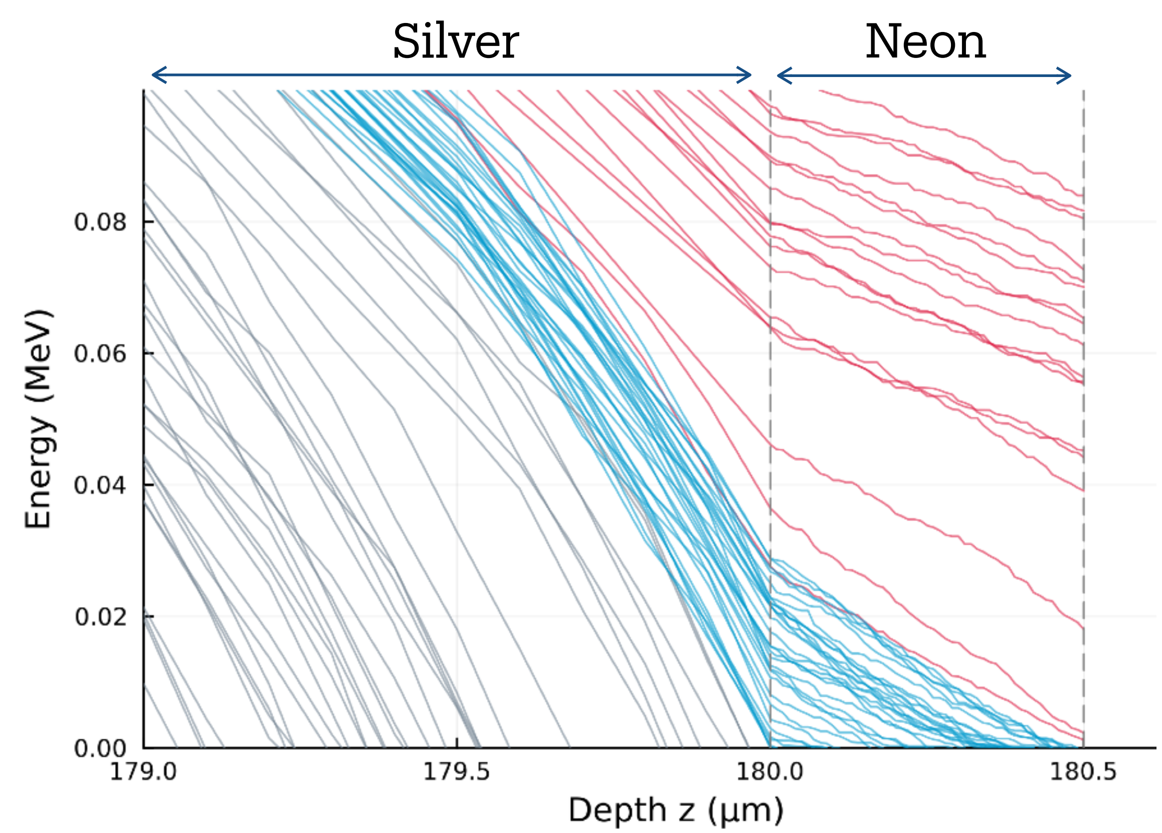
S. Kanda, Interactions 245, 78 (2024).
S. Kanda, accepted for publication in J-PARC2024 proc.

Cryogenic Moderator





The moderator chamber and cryostat



Simulated generation of epithermal muons

- A solid rare-gas moderator for the epithermal muon generation.
- Pulse tube refrigerator for cooling silver foil and cryogenic crystal of neon.
- Extraction and transport optics.
- A test beam is scheduled for this November.

Summary and Outlook

- The muon mass can be precisely determined using a muonium (Mu) atom interferometer.
- A slow, high-brightness Mu atomic beam is being developed through a multi-stage muon cooling.
- A multi-particle imager for high detection efficiency with position resolution is under development.
- Evaluation of the statistical precision and systematic uncertainties in Mu interferometry is in progress.
- We have secured funding for the next five years, during which we aim to demonstrate the proof-of-principle.
- Develop a hydrogen atom interferometer and conduct offline tests of the system.

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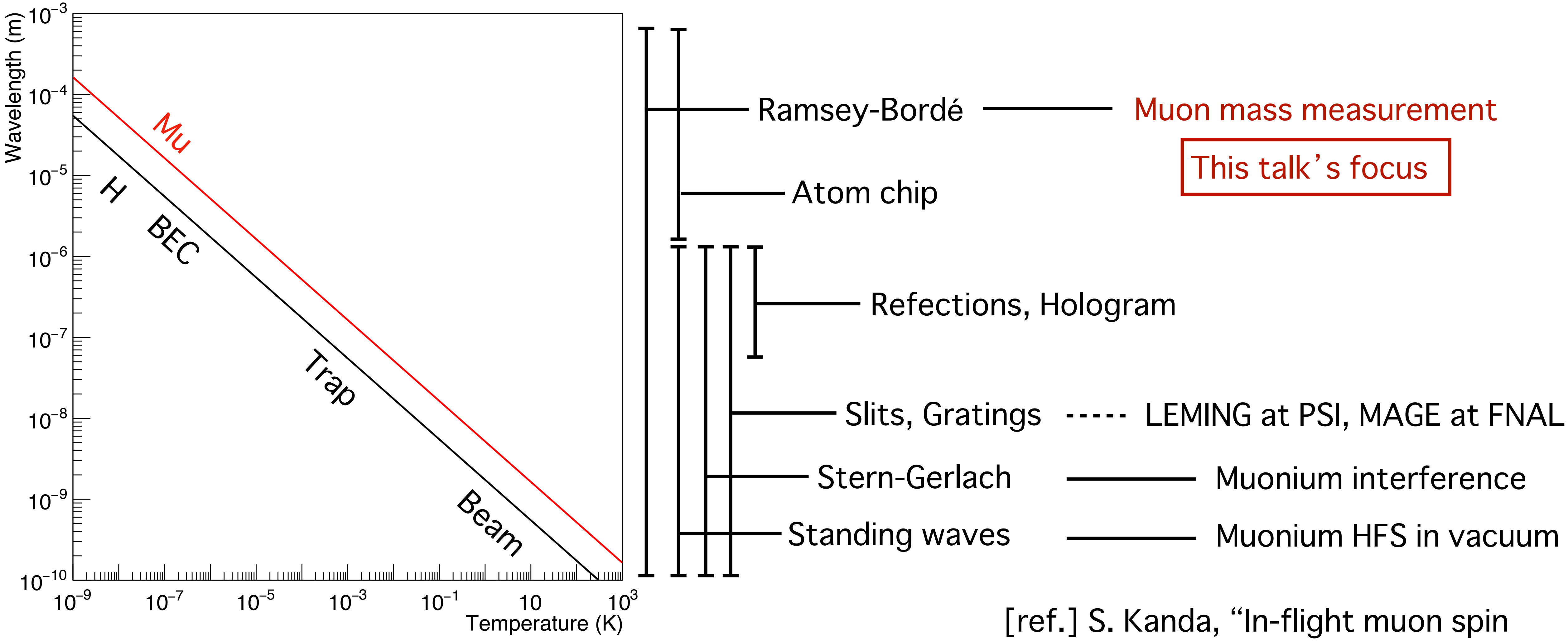
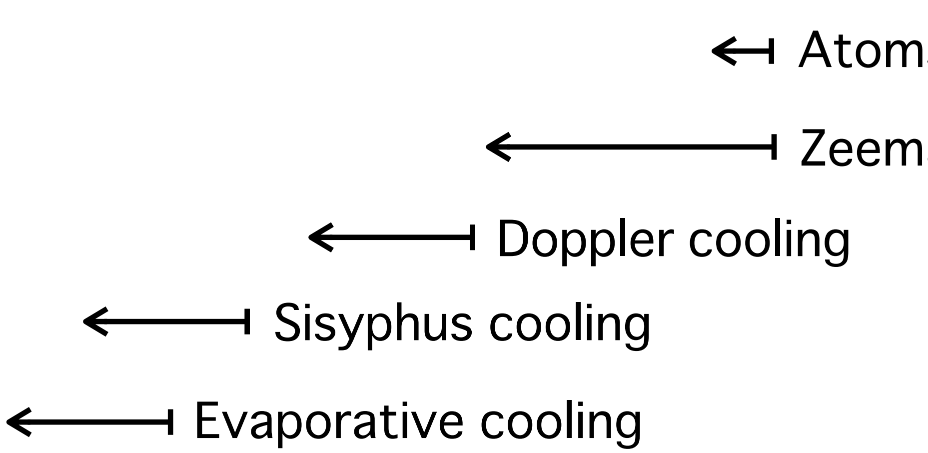
Muonium Interferometry



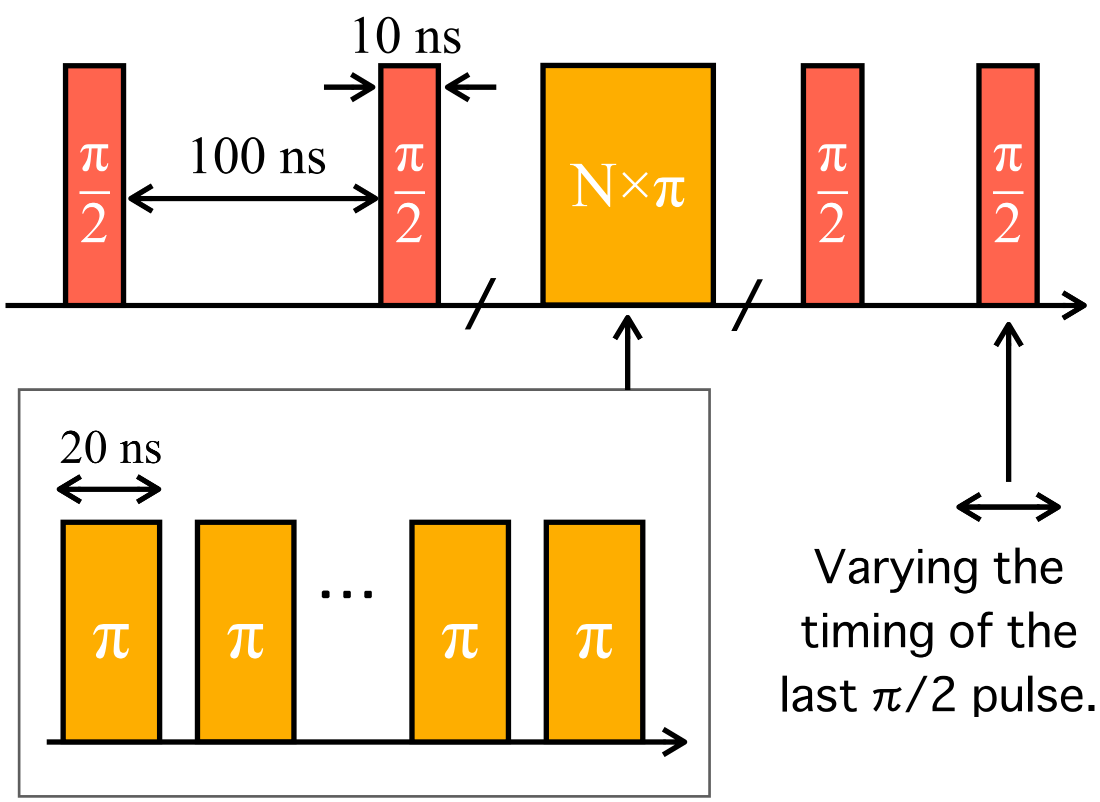
[ref.] S. Kanda, "In-flight muon spin resonance and muonium interferometry", J. Phys.: Conf. Ser. 2462, 012029 (2023).



- Due to the short lifetime of muons, the slowing down and cooling methods for stable atoms are not applicable.

Ramsey-Bordé Interferometry

- The precision of interferometry depends on the beam splitting between two arms.
  - Additional light pulses
  - Multi-photon Bragg diffraction (optical lattice)
  - Bloch oscillations

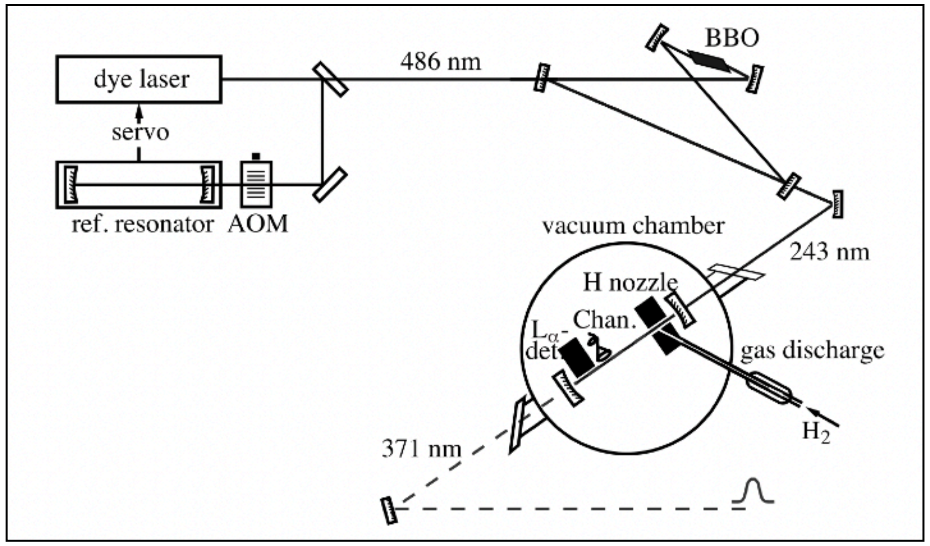


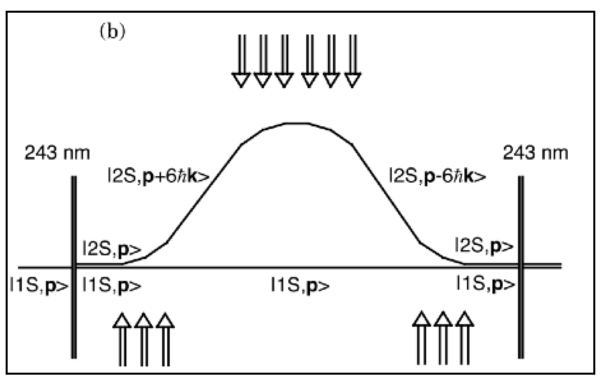
- Applying additional π-pulses can expand the phase difference between trajectories.
- With N sets of π pulses, the phase difference becomes 2N+1 times larger.
- Note: It is not possible to make N infinitely large due to spontaneous emission compromising coherence.
- Lifetime of 15P states: 650 ns.

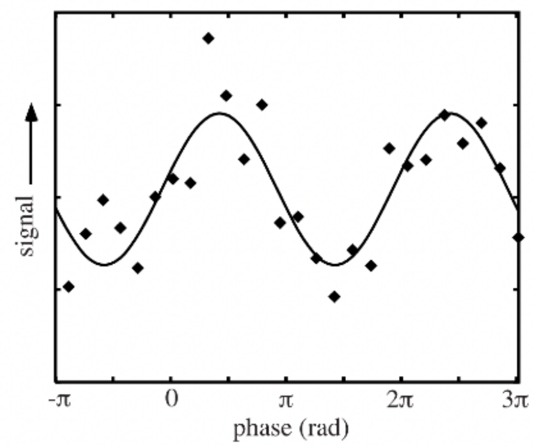
- Goal: 1 ppb precision with 10 π pulses.

Experiments with Atoms

H



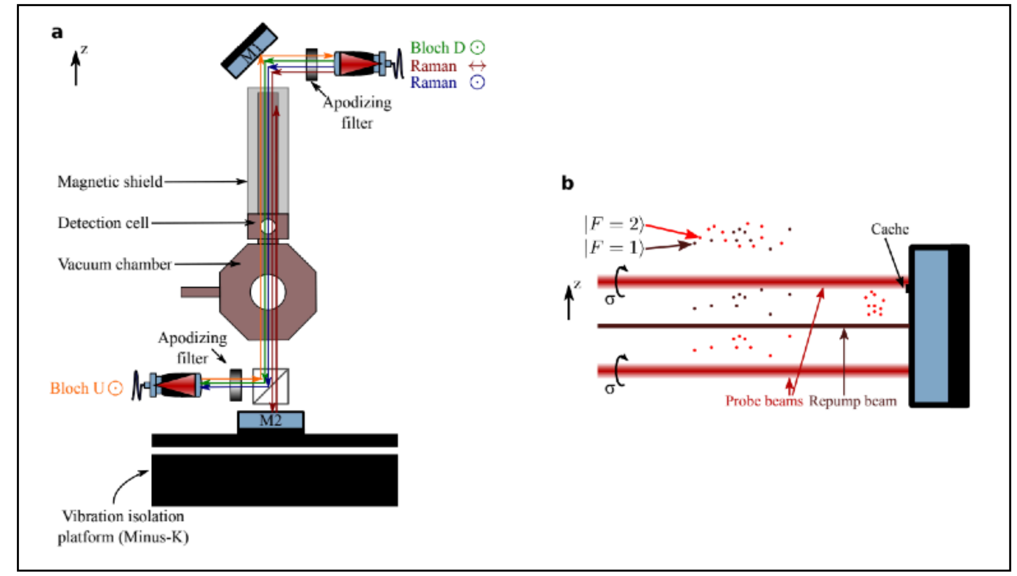


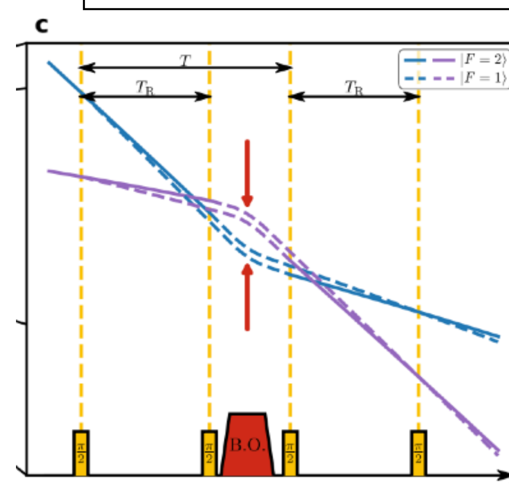


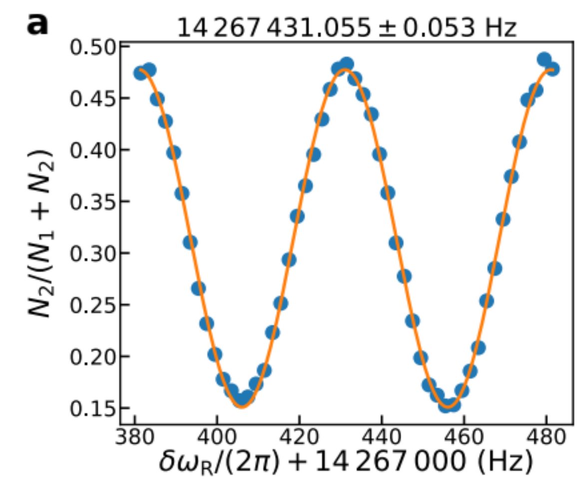
- A $\pi/2$-π-$\pi/2$ pulse sequence was applied to observe photon echo of hydrogen atoms.
- The three light pulses, each 13 ns long and separated by 100 ns. The peak power of the laser pulses at 371 nm was 2 to 5 W typically.
- ppb-level mass determination is possible with 10 π pulses

T. Heupel et al., Europhys. Lett. 57, 158 (2002).

Rb







- Ramsey-Bordé interferometry with Bloch oscillation.
- Determination of the fine-structure constant with an accuracy of 81 ppt.
- The atomic mass of Rb was determined with 0.15 ppb precision.

L. Morel et al., Nature 588, 7836 (2020).

Systematics

- Laser beam geometry (imperfections in the laser wavefront)
  - Gouy Phase: A geometric phase shift occurs as the laser beam propagates through its focus.
  - Wavefront Curvature and Distortion: Atoms at different positions experience different phase shifts.
  - Beam Misalignment: An imperfect overlap or angle between the laser beams.
- Light-atom interactions (shifting in the atom's energy levels)
  - AC Stark Shift: Intensity variations across the expanding atomic cloud lead to position-dependent energy level shifts, creating a bias.
  - Two-Photon Light Shift: Off-resonant, co-propagating Raman transitions cause an AC Stark shift on the atomic ground states.
- External fields (changing in the atom's trajectory and energy levels)
  - Gravity Gradient: The two spatially separated paths of the interferometer experience slightly different gravitational acceleration, causing a phase shift.
  - Coriolis Force: The Earth's rotation induces a velocity-dependent force on the atoms, which systematically shifts the interference phase.
  - Second-Order Zeeman Effect: Inhomogeneous ambient magnetic fields shift the energy levels of the magnetically insensitive states.
- Instrumental effects
  - Phase Shifts in Electronics: Delays and nonlinearities in the electronics used to control the laser frequency.
  - Laser Frequency Uncertainty: Any uncertainty in the absolute frequency of the lasers.