Pulsed laser spectroscopy of Muonium 1S-2S transition in J-PARC

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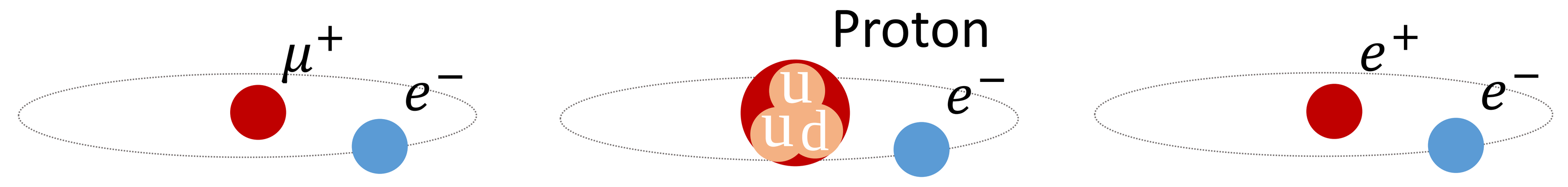
Introduction: Spectroscopy Mu1S-2S for determining muon mass

Mu(Muonium)

- Consists of a positive muon and an electron
- **Purely leptonic system**
- No concerns of the charge radius of the nucleus
- **Long life time** among exotic atoms



Mu
τ= 2.2 μs

Hydrogen

Positronium
τ= 142 ns (ortho)

Validation of the Standard Model with muon

- e.g.1)Muon g-2 experiment[1]

$$a_\mu = \frac{\omega_a}{\omega_p}\frac{\mu_\mu}{\mu_e}\frac{m_e}{m_\mu}\frac{g_e}{2}$$

- e.g.2)MuSEUM experiment[2]

$$\Delta\nu_{HFS} = \frac{16}{3}\alpha^2 R_\infty \frac{\mu_\mu}{\mu_e}\left(1+\frac{m_e}{m_\mu}\right)^{-3}$$

The improvement of the muon mass accuracy Enables more strong verification of SM.

Physical constant	Relative uncertainty [ppb]
Muon mass: m_μ	22
Electron mass: m_e	0.3
Fine-structure constant : α	0.15
Muon magnetic moment : μ_μ	22
Electron magnetic moment: μ_e	0.3

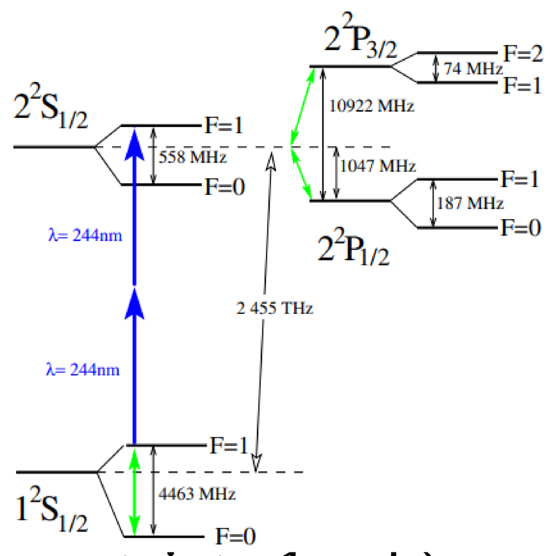
ppb=10^{-9}
※2018 CODATA

[1]B. Abi *et al.*, Phys. Rev. Lett. 126, 141801 (2021)
[2] S. Nishimura *et al.* , Phys. Rev. A 104, L020801 (2021)

Mu1S-2S spectroscopy

Purpose: Determine muon mass from Mu $\Delta\nu_{1S-2S}$

$$h\Delta\nu_{1S\_2S} \approx \frac{3\alpha^2 m_e c^2}{8}\left(1+\frac{m_e}{m_\mu}\right)^{-1}$$

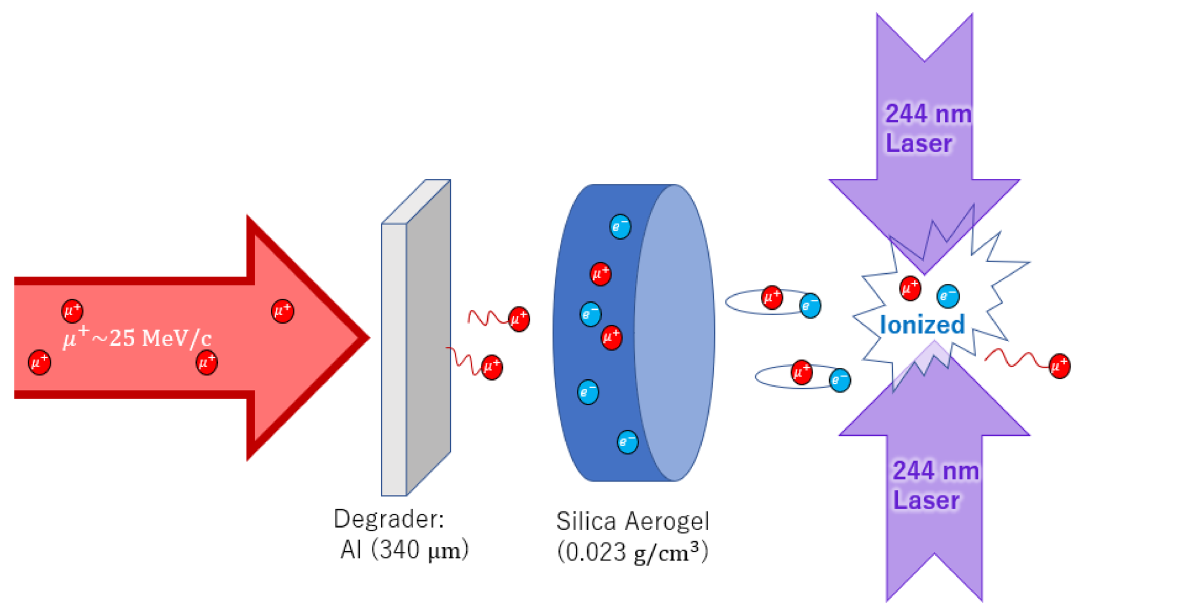


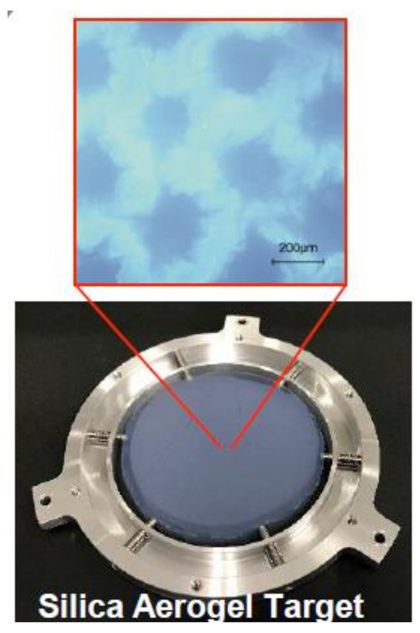
- Precise calculation of the $\Delta\nu_{1S-2S}$ is possible.
- Objective $\Delta\nu_{1S\_2S}$ uncertainty: 10 kHz (= m_μ uncertainty 1 ppb)

→impact on verification of the Standard Model

[3]K. P. Jungmann J. Phys Soc. Jpn. 85, 091004 (2016)

Production of Mu

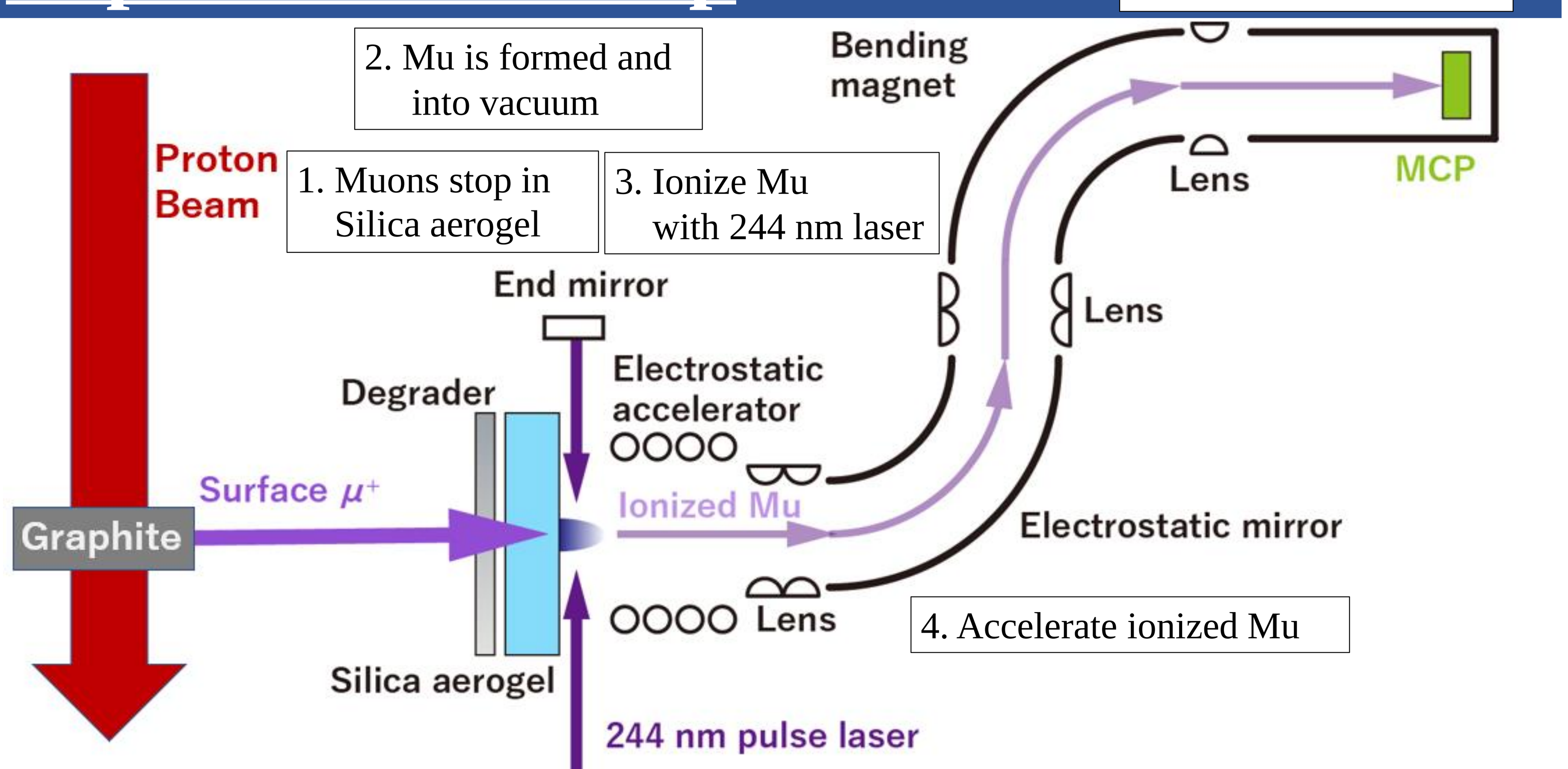




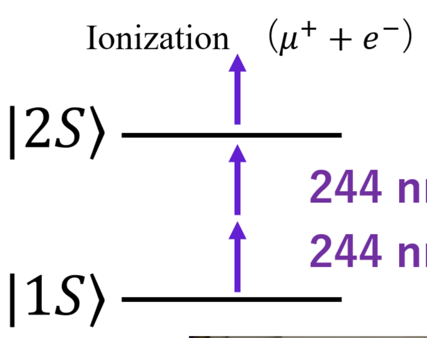
- Productivity of Muonium is improved by laser ablation of aerogel target[5].
- ~2.4% of muon yield into vacuum as Mu.(Simulation[6])

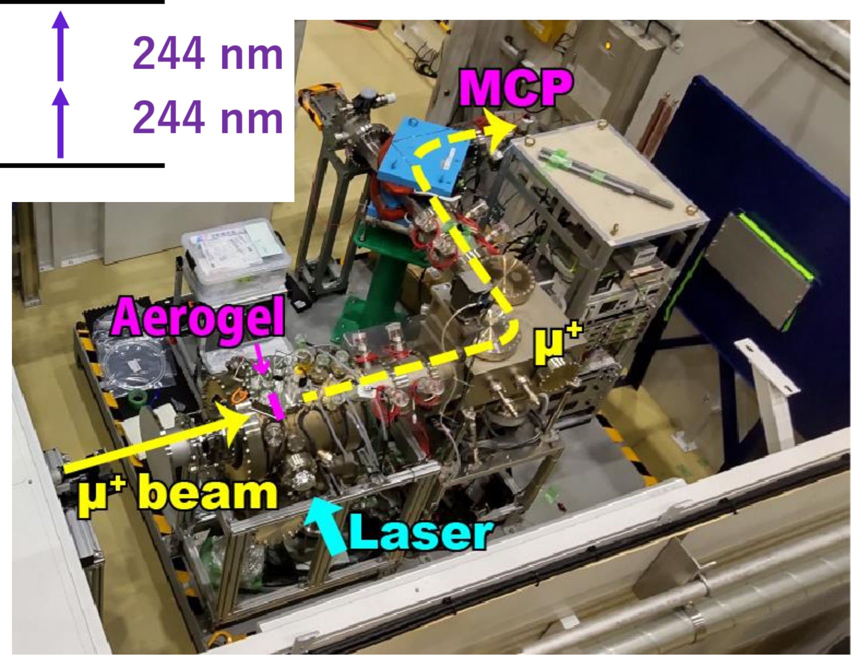
[5] G. A. Beer *et al.*, Prog. Theor. Exp. Phys. 2014, 09C01
[6]Ce. Zhang *et al.* ,JPS Conf Proc. 33, 011125 (2021)

Experimental Setup



- Mu ionization process is two-photon + one-photon transition
- Laser is counterpropagating with an end mirror
- Operated at J-PARC MLF, Japan



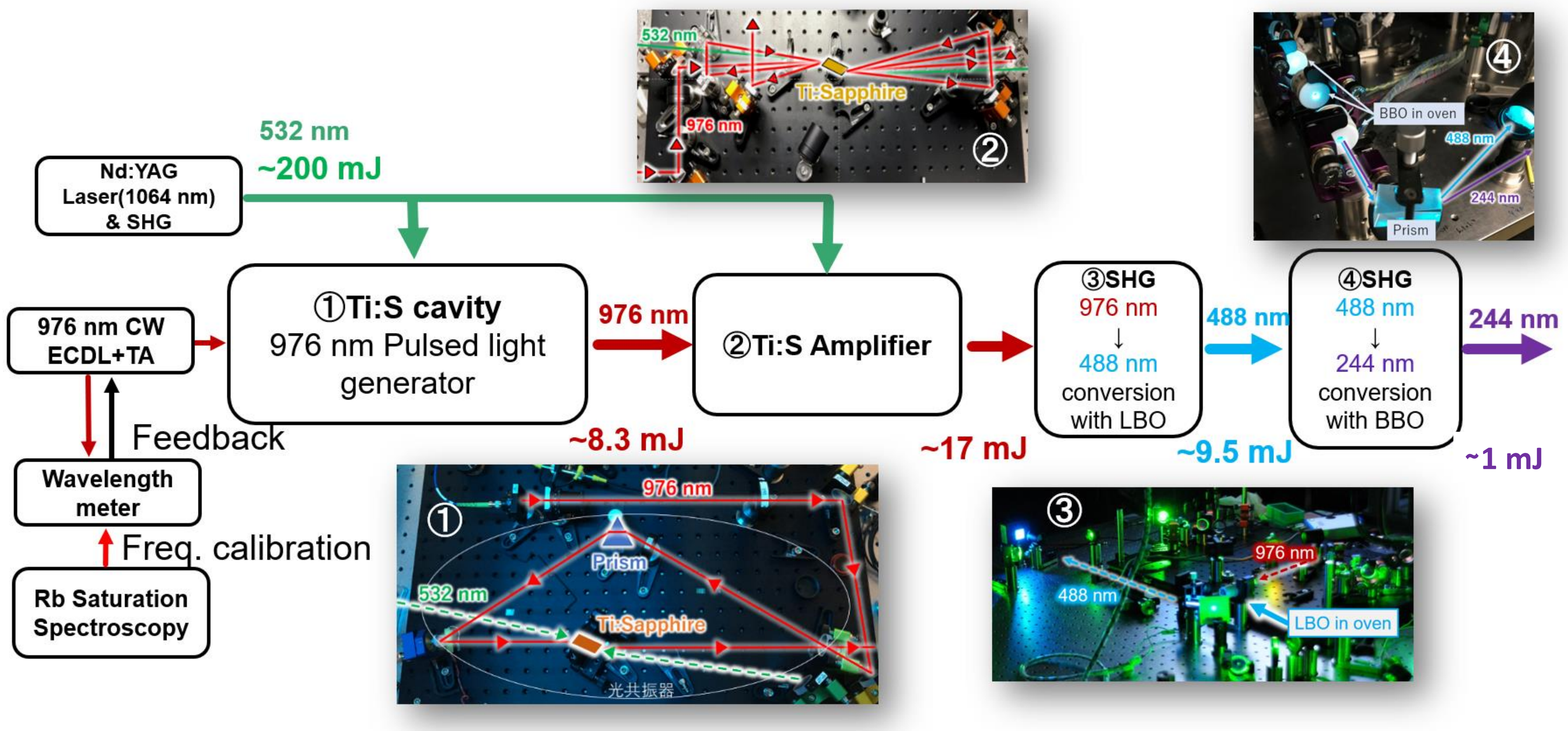


at J-PARC MLF S-line S2 area, Japan

J-PARC MLF

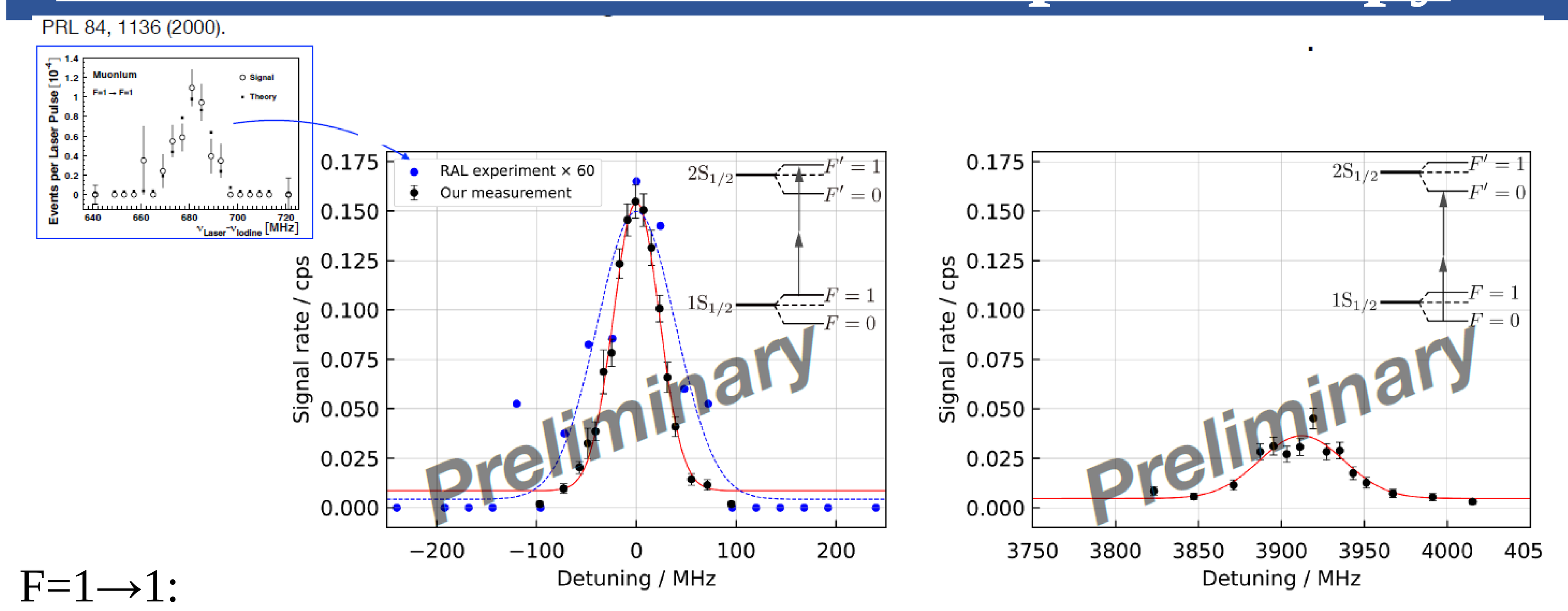
- World's highest intensity pulsed muon beam source
- ~6.8×10^4 μ/pulse beam is available at S2 area. (0.35×10^4 μ/pulse at RAL in 2000[4])

244 nm Laser Status



- Generate 976 nm pulsed light from Ti:Sapphire crystal
- Convert the wavelength to 244 nm by two SHGs
- Pulse duration : ~ 57 nsec
- Linewidth : ~ 6 MHz at 976 nm (close to Fourier transform limit)

Recent result of Mu1S-2S Spectroscopy



F=1→1:

- Ionized Mu signal rate: >0.15/sec, more than **60** times higher than a previous result in RAL(2000)
- Resonance width is a factor of **1/2** narrower

F=0→0:

- **First observation** due to the higher signal rate

Prospects

- Aiming to determine the transition frequency at **1 MHz** accuracy.

Uncertainty		RAL(2000)	
Stat.		9.1 MHz	< 1 MHz is achievable owing to high signal rate
	Frequency calibration	0.8 MHz	<0.1 MHz w/ a Fiber comb
	Stability of lock	0.5 MHz	<0.1 MHz w/ a Fiber comb
Syst.	Residual doppler	3.4 MHz	<0.1 Optical cavity
	Line shape	1.2 MHz	×1/2 narrower linewidth

Summary

- 1S-2S transitions both of F=1 and F=0 have been observed
- Pulsed laser spectroscopy of 1 MHz precision will be performed

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