# Towards Improving the Precision of the Negative Muon Mass via Muonic Helium HFS Spectroscopy

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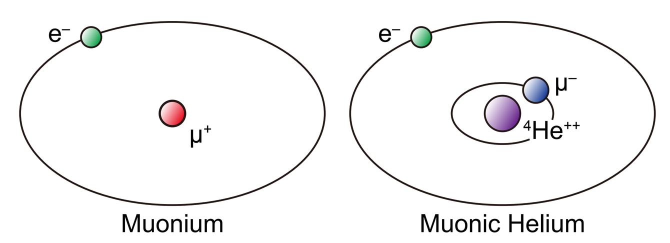
On behalf of the MuSEUM Collaboration

## Introduction

Muonic helium (μHe) is composed of a helium atom with one of its two electrons replaced by a negative muon ($\mu^-$).




- Hydrogen-like atom similar to muonium
- Ground-state hyperfine structure (HFS) nearly equal to that of muonium but inverted

Motivation for new precise muonic helium HFS measurements:

- **Determine fundamental constants: Negative Muon Mass and Magnetic Moment**
- **Test and improve the theory of 3-body Atomic System and Bound-State QED**
- **Test of CPT invariance with second-generation leptons**

The world's most intense pulsed negative muon beam at J-PARC MUSE allows for improving previous measurements by nearly 2–3 orders of magnitude for the HFS interval and almost 50 for the negative muon mass. Complementary measurements both at zero and high magnetic fields are in progress.

## Previous Measurements

Previous measurements were performed in the early 1980s at PSI and LAMPF with experimental uncertainties mostly dominated by statistical errors.

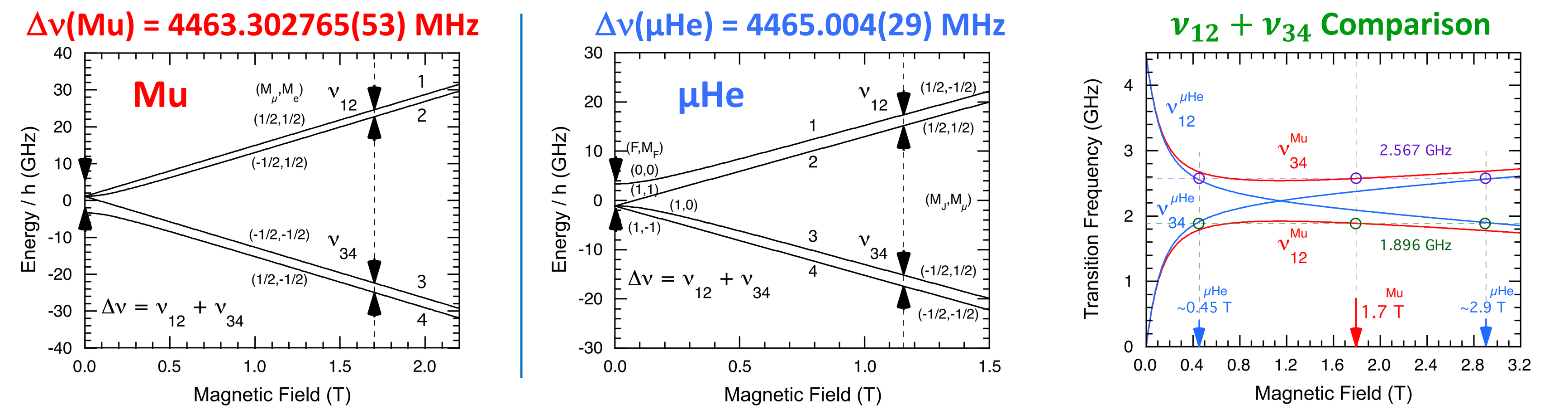
| | condition | Δν | $\mu_{\mu^-}/\mu_p$ |
|---|---|---|---|
| Helium-4 | weak field [1] | 4464.95(6) MHz (13 ppm) | |
| Helium-4 | high field [2] | 4465.004(29) MHz (6.5 ppm) | 3.18328(15) (47 ppm) |
| Helium-3 | weak field [3,4] | 4166.41(5) MHz (12 ppm) | |

- Positive muon mass experimentally determined by muonium ground-state HFS measurements through $\mu_{\mu^+}/\mu_p$ to 120 ppb [5].
- Negative muon mass most accurate experimental value only determined to 3.1 ppm from muonic X-ray studies using a bent-crystal spectrometer [6].
- The negative muon magnetic moment $\mu_{\mu^-}$ obtained with the same accuracy provides a test of CPT invariance through $\mu_{\mu^+}/\mu_{\mu^-}$ at a level of 3 ppm [7].

[1] H. Orth *et al.*, Phys. Rev. Lett. **45** (1980) 1483
[2] C. J. Gardner *et al.*, Phys. Rev. Lett. **48** (1982) 1168
[3] V.W. Hughes and G. zu Putlitz, in *Quantum Electro- dynamics*, ed. T. Kinoshita, World Scientific, (1990) 822
[4] M. Gladish, At. Phys. **8** (1983) 197-211
[5] W. Liu *et al.*, Phys. Rev. Lett. **82** (1999) 711
[6] I. Beltrami *et al.*, Nucl. Phys. A **451** (1986) 679
[7] X. Fei, Phys. Rev. A **49** (1994) 1470

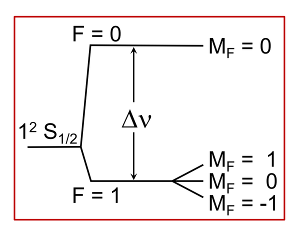
## Muonic Helium Atom HFS

Breit-Rabi energy level diagrams




The ${}^4$Heμ⁻e⁻ ground-state energy levels in an static magnetic field $\vec{H}$ are given by the Hamiltonian:

$$\mathcal{H}_{HFS} = -h\Delta\nu \vec{I}_\mu \cdot \vec{J} + g_J\, \mu_B^e \vec{J}\cdot\vec{H} + g'_\mu \mu_B^\mu \vec{I}_\mu \cdot \vec{H}$$




with Δν the HFS interval, $\vec{J}(\vec{I}_\mu)$ the spin operator, $\mu_B^e(\mu_B^\mu)$ the Bohr magneton, $g_J(g'_\mu)$ the gyromagnetic ratio bound in ${}^4$Heμ⁻e⁻ for electron (muon), respectively. Magnetic field $H$ measured by the free proton NMR precession frequency $\nu_p$ ($h\nu_p = 2\mu_p H$).

We can show that: $\Delta\nu = \nu_{12} + \nu_{34}$ ⇒ **3-body & QED Test**

with $r'_e = g_J \mu_B^e / 2\mu_p$

$$\frac{\mu_{\mu^-}}{\mu_p} = \frac{2\nu_{12}\nu_{34} + r'_e \nu_p(\nu_{34} - \nu_{12})}{\nu_p\left(2r'_e\nu_p - (\nu_{34} - \nu_{12})\right)} \frac{g_\mu}{g'_\mu}$$

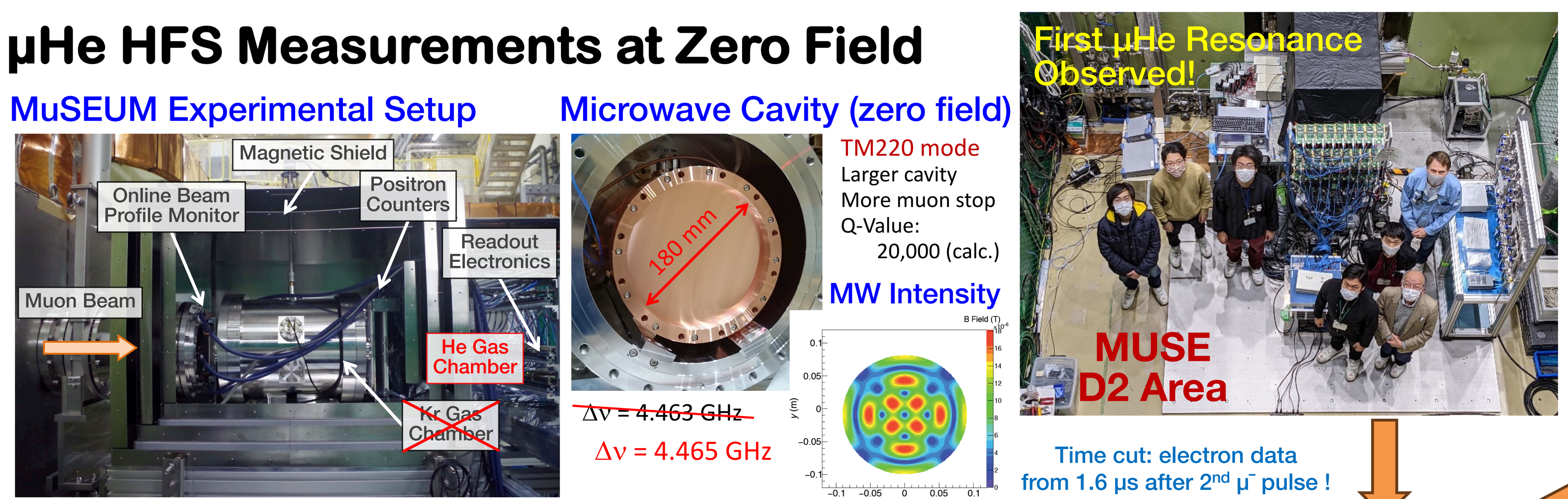
⇒ **Negative Muon Mass & Magnetic Moment**

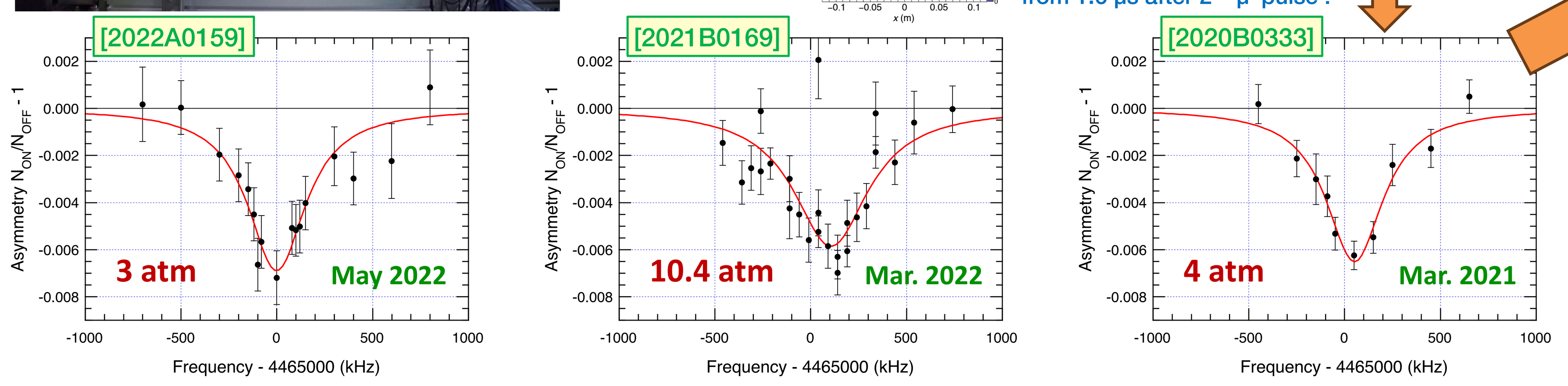
$g_J$ and $g'_\mu$ are theoretically calculated with high accuracy up to the third order.

[S. G. Karshenboim *et al.*, Eur. Phys. J. D **73** (2019) 210]

## μHe HFS Measurements at Zero Field

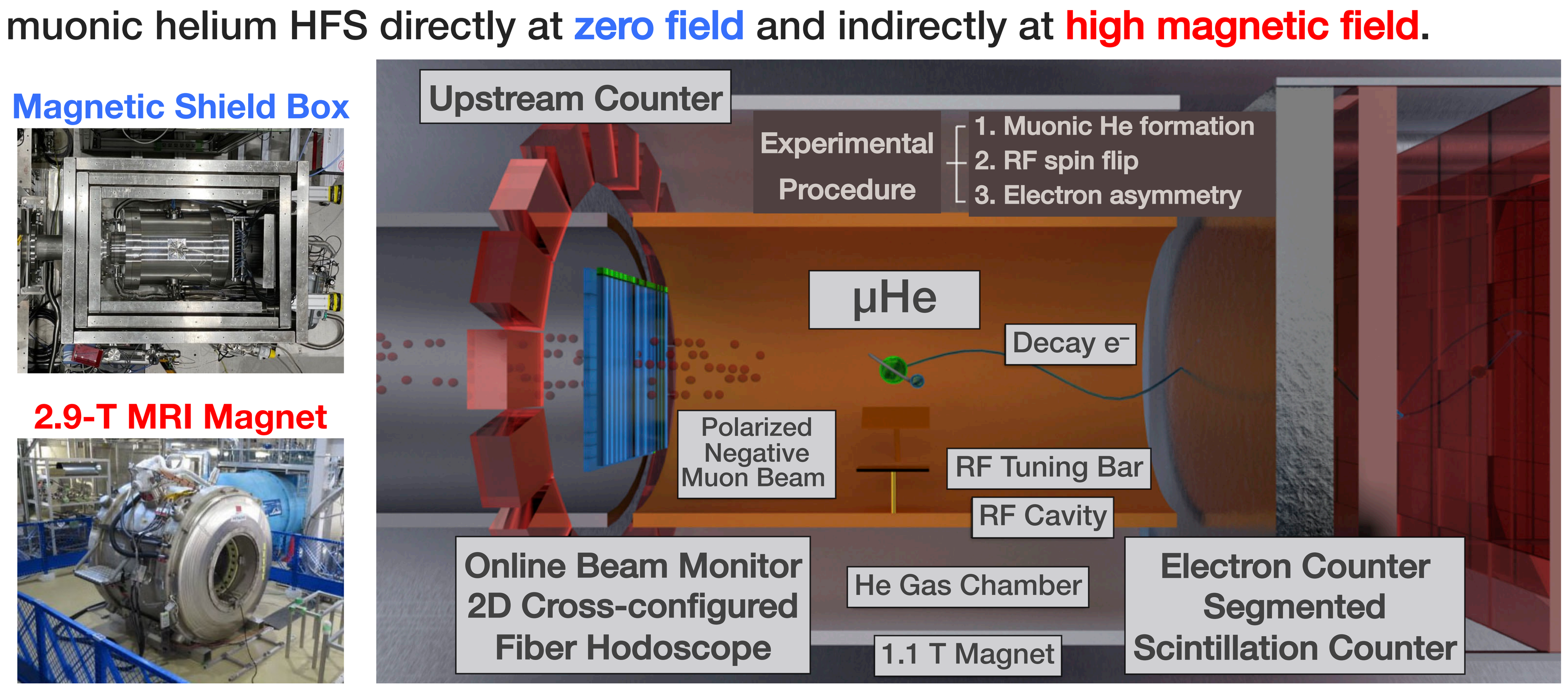
MuSEUM Experimental Setup — Microwave Cavity (zero field)



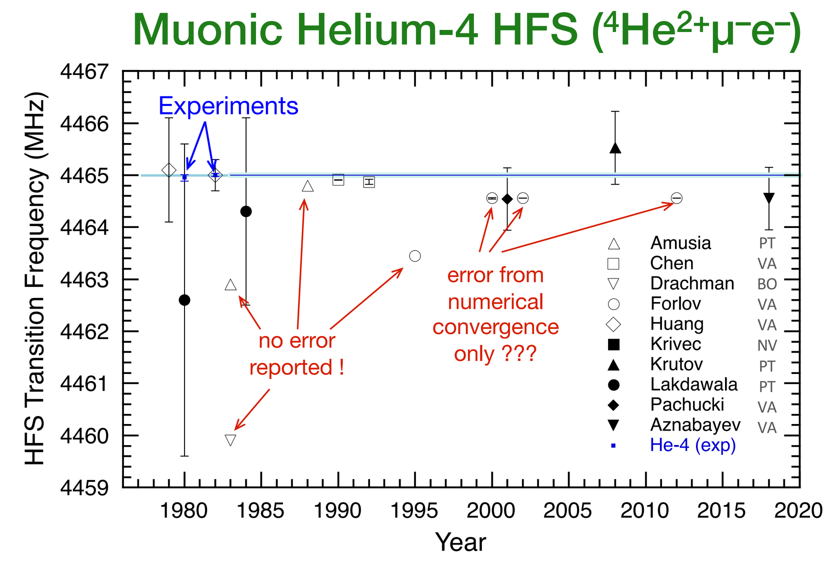

## Experimental Procedure

Same microwave magnetic resonance technique as with muonium used to measure muonic helium HFS directly at zero field and indirectly at high magnetic field.




## Experiment vs. Theory

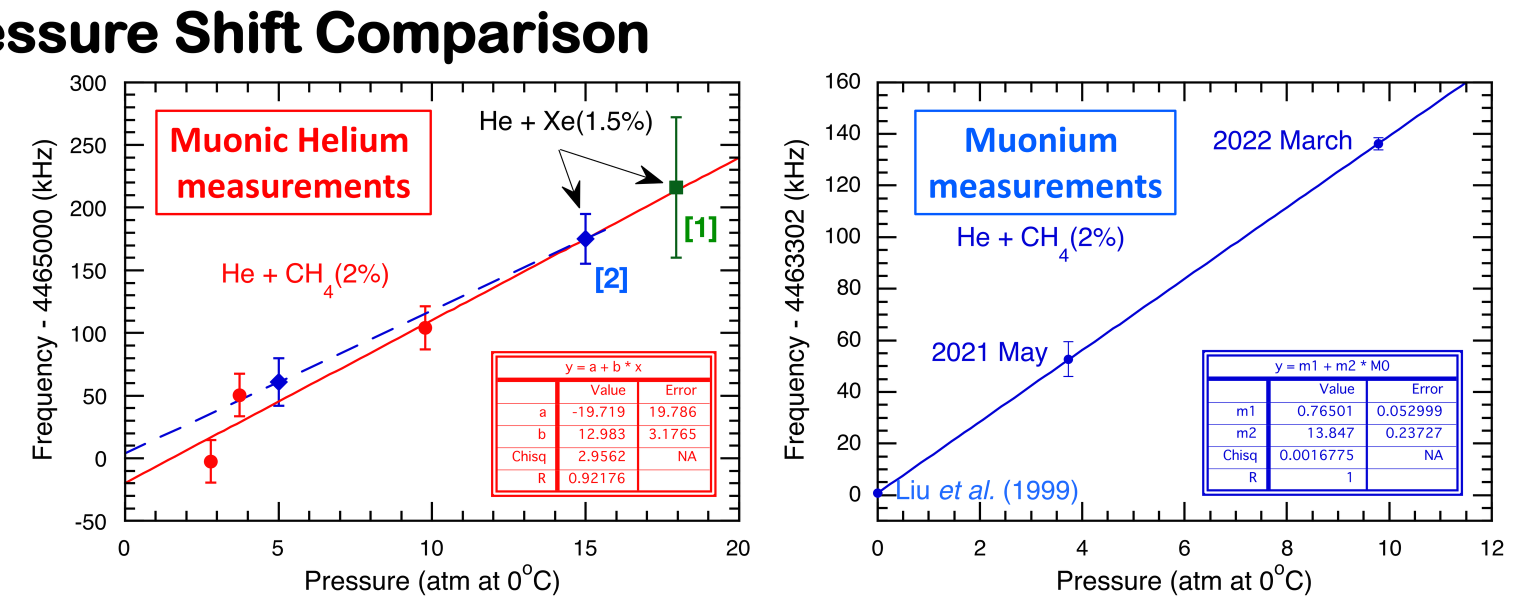
- Ground-state HFS of muonic helium very similar to muonium; however…
- In reality complicated because three-body interactions need to be considered; thus theoretical approach was limited.
- Calculations performed since the late 1970s mainly based on the perturbation theory (PT), variational approach (VA), and Born-Oppenheimer (BO) theory.




⇒ **Need ways of theoretical improvement to test QED !** *possibly …*

- Pachucki suggested QED effects in 3-body systems could be calculated more precisely in higher orders of perturbation theory. [K. Pachucki, Phys. Rev. A **63** (2001) 032508]

## Pressure Shift Comparison




| | He + $CH_4$(2%) | He + Xe(1.5%) | Pure He |
|---|---|---|---|
| Mu | 13.8 ± 0.2 kHz/atm | 14.7 ± 0.9 kHz/atm [1] | 17.0 ± 1.6 kHz/atm [6] |
| H | – | 15.0 ± 0.3 kHz/atm [3,4] | 16.3 ± 0.3 kHz/atm [3] |
| μ⁴He | 13.0 ± 3.2 kHz/atm | 11.4 ± 2.7 kHz/atm [2] | – |

Δν(0 atm) = 4464.980(20) MHz (4.5 ppm) **New World Record**

Pressure shift in noble gases: no isotopic effect observed for H, D, T [3,4] & Mu [5].

[1] H. Orth *et al.*, Phys. Rev. Lett. **45** (1980) 1483
[2] C. J. Gardner *et al.*, Phys. Rev. Lett. **48** (1982) 1168
[3] F. M. Pipkin *et al.*, Phys. Rev. **127** (1962) 787
[4] E. S. Ensberg *et al.*, Phys. Lett. **28A** (1968) 106
[5] D. E. Casperson *et al.*, Phys. Lett. **59B** (1975) 397
[6] S. Seo (The University of Tokyo) (unpublished)

## μHe Spin Exchange Optical Pumping (SEOP) Experiment

Difficult experiment because of low μHe residual polarization: — *Asymmetry Signal*

- Depolarization during muon cascade: → μHe ~ 5% (muonium: 50%) → SMALL
- Re-polarization of μHe by Spin Exchange Optical Pumping → LARGER (~ 10x)

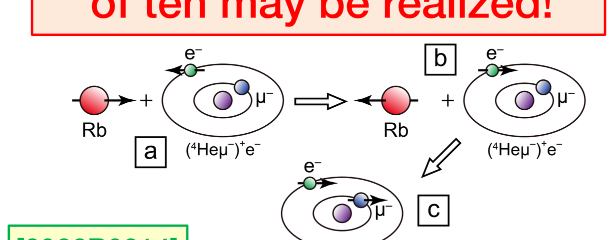
[A. S. Barton et al., Phys. Rev. Lett. **70** (1993) 758]

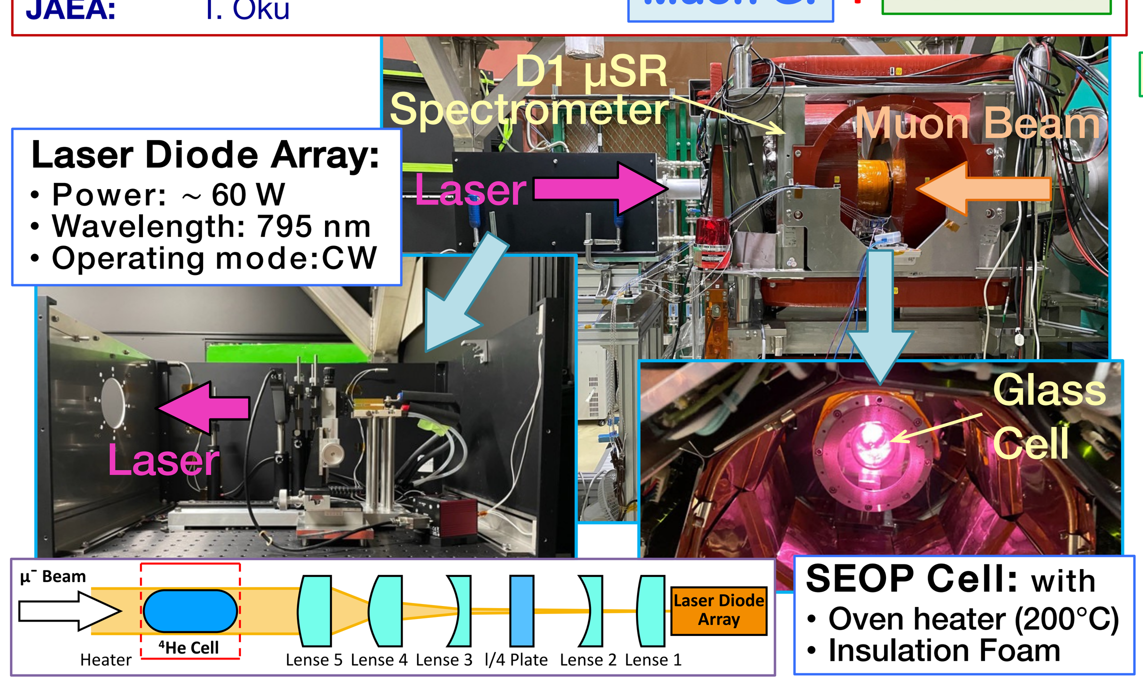
➢ Improvement by a factor of ten may be realized!

**New MuSEUM-SEOP collaboration:**

**KEK:** T. Ino, S. Kanda, S. Nishimura, K. Shimomura, P. Strasser
**Nagoya U:** S. Fukumura, Y. Goto, T. Okudaira, M. Kitaguchi, H. M. Shimizu
**Tohoku U:** M. Fujita, Y. Ikeda (glass cell)
**JAEA:** T. Oku

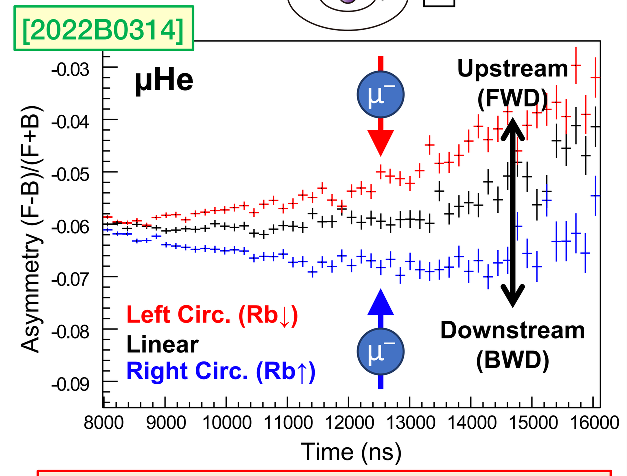
Muon G. + Neutron G.




**Laser Diode Array:**
- Power: ~ 60 W
- Wavelength: 795 nm
- Operating mode: CW

**SEOP Cell:** with
- Oven heater (200°C)
- Insulation Foam




➢ First laser experiment at D1 area!
➢ First μHe SEOP results!