Measurements of Muonic Helium Hyperfine Structure in High Magnetic Field at J-PARC MUSE

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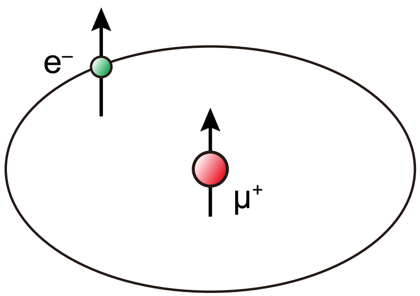
On behalf of the

MuSEUM Collaboration

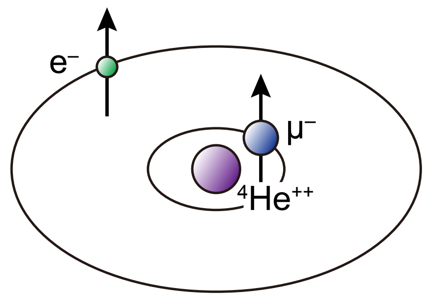
(**Mu**onium **S**pectroscopy **E**xperiment **U**sing **M**icrowave)

International Conference on Precision Physics of Simple Atomic Systems (PSAS 2026)
Austrian Academy of Sciences, Vienna, Austria, May 18-22, 2026

Muonic Helium Atom

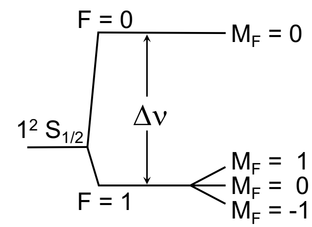


Muonium



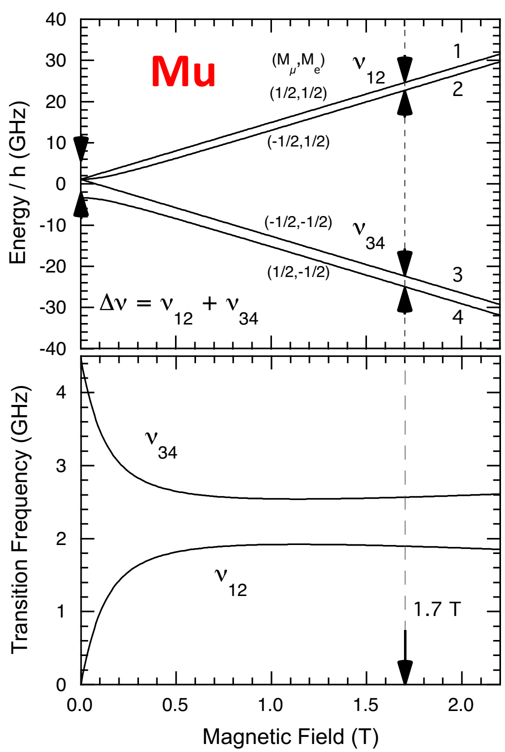
Muonic Helium

- Hydrogen-like atom similar to **muonium**
- Similar ground-state HFS but inverted
- Same technique to measure **μHe** HFS

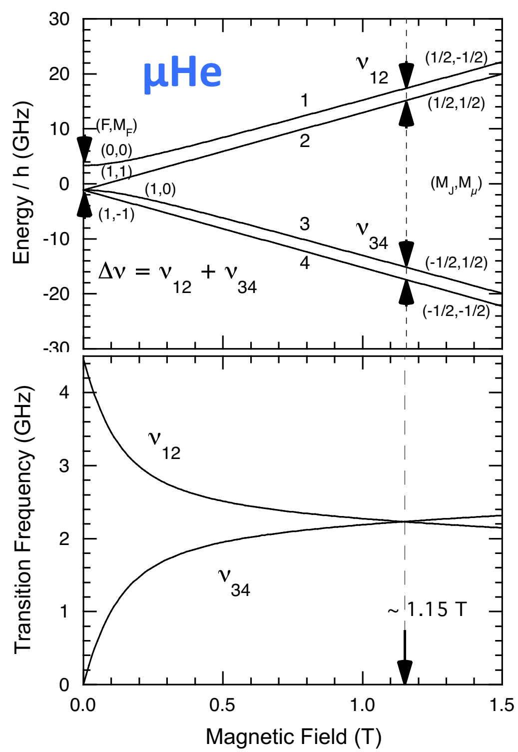


Ground-state muonic helium HFS structure and low-field Zeeman splitting

Δν(Mu) = 4463.302765(53) MHz



Δν(μHe) = 4464.980(20) MHz



Breit-Rabi energy level diagrams

Sensitive tool to …

- test **3-body atomic system** and **bound-state QED**

$$\nu_{12} + \nu_{34} = \Delta\nu$$

- determine **negative muon magnetic moment** and **mass**

$$\frac{\mu_{\mu^\pm}}{\mu_p} = \frac{r_e'\nu_p(\nu_{34} - \nu_{12}) \mp 4\nu_{12}\nu_{34}}{2\nu_p\left(r_e'\nu_p + (\nu_{34} - \nu_{12})\right)}\,\frac{g_\mu}{g_\mu'}$$

- **CPT test with 2nd generation lepton**

Muon Precision Experiments @ J-PARC MLF

Diagram borrowed from Klaus Jungmann

MuSEUM

$\Delta\nu_{HFS,n=1}$

Muonic Helium HFS

Negative muon magnetic moment μ_{μ^-}

Hyperfine structure constant α

CPT Test

$m_{\mu^-} \doteqdot m_{\mu^+}$

Muonium HFS

Muon magnetic moment μ_{μ^+}

Hyperfine structure constant α

NEGATIVE MUON

$$\overrightarrow{\mu_{\mu^-}} = g_{\mu^-} \frac{e\hbar}{2m_{\mu^-} c} \vec{s}$$

$\mu_{\mu^-}, \alpha, g_{\mu^-}$

$\mu_{\mu^+}, \alpha, g_{\mu^+}$

POSITIVE MUON

$$\overrightarrow{\mu_{\mu^+}} = g_{\mu^+} \frac{e\hbar}{2m_{\mu^+} c} \vec{s}$$

m_{μ^+}

MuMass@PSI

$\Delta\nu_{1s-2s}$

FNAL(μ^+)

BNL(μ^-)

Muon $g-2$

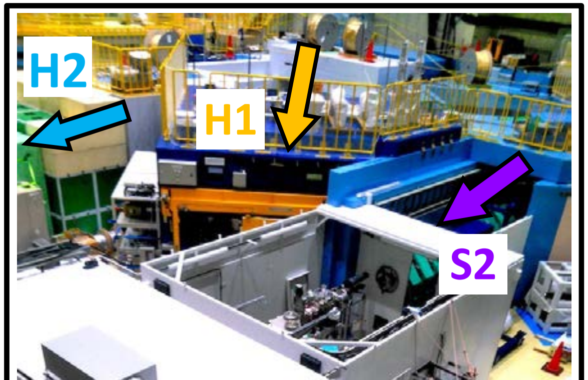
New physics beyond SM

m_{μ^+}

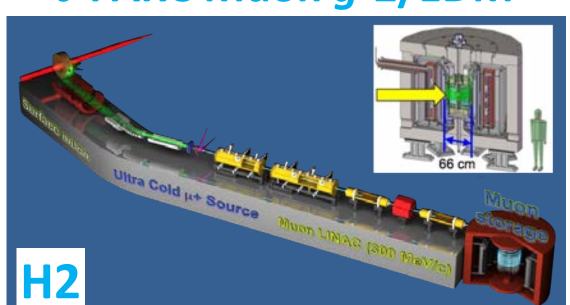
Muonium $1s-2s$

Muon mass m_{μ^+}

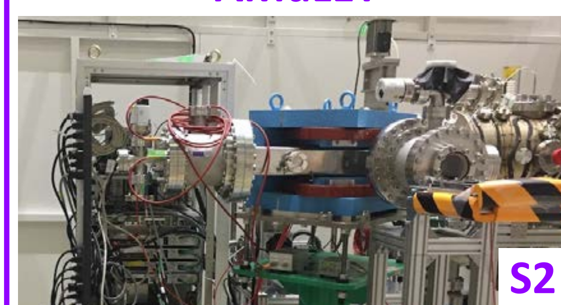
J-PARC MLF



J-PARC Muon *g*-2/EDM



AMuLET



Previous μHe HFS Experiments ('80s)

Zero Field (SIN)

pressure: 20 atm

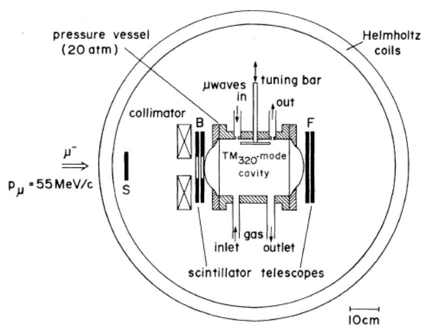
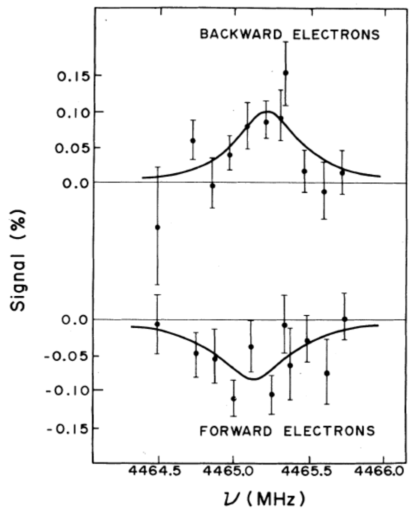
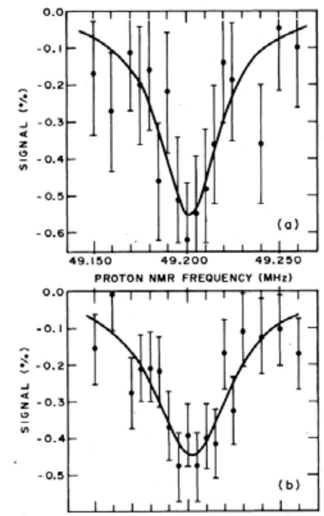


FIG. 2. Schematic view of the apparatus. The Helmholtz coils are used for muon-spin rotation. A cylindrical high-permeability metal shield (diameter 50 cm, length 100 cm) was installed (not shown in the figure) during the microwave magnetic-resonance experiment to reduce the stray magnetic fields.



High Field (LAMPF)



pressure: 5 & 15 atm

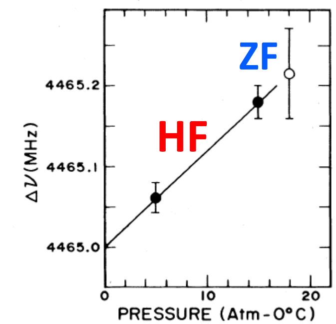


FIG. 2. Δν as a function of He+Xe(1.5%) gas pressure. Closed circles show the results of this experiment; the open circle is the result of Ref. 3. The straight line shows the linear extrapolation used to extract Δν(0).

	Condition	Δν	μ_{μ^-}/μ_p
^{4}He	zero field [1] **ZF**	4464.95(6) MHz [13 ppm]	
	high field [2] **HF**	4465.004(29) MHz [6.5 ppm]	3.18328(15) [47 ppm]
^{3}He	zero field [3,4]	4166.41(5) MHz [12 ppm]	

[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

CPT with Second Generation Lepton

- The **positive muon mass** is experimentally determined by muonium ground state HFS measurement through μ_{μ^+}/μ_p to **120 ppb** [5].

New precise measurements underway:

- **Muonium HFS** by **MuSEUM** (J-PARC)
- **Muonium 1*s* – 2*s*** by **AMuLET** (J-PARC), **Mu-MASS** (PSI) [6]
- **Muon Penning Trap** at J-PARC

Next talk by Takayuki Yamazaki

- The **negative muon mass** is only experimentally determined to **3.1 ppm** from muonic X-ray studies using bent-crystal spectrometer (^{24}Mg, ^{28}Si) [7].

CPT test at a level of **3 ppm** [8].

- μ_{μ^-}/μ_p also needed to determine a_{μ^-} and its g factor g_{μ^-} in the BNL muon g–2 experiment [9].

New precise measurement of the negative muon mass highly desirable !

[5] W. Liu *et al.*, Phys. Rev. Lett. **82** (1999) 711

[6] P. Crivelli, Hyperfine Interact. **239** (2018) 49

[7] I. Beltrami *et al.*, Nucl. Phys. A **451** (1986) 679

[8] X. Fei, Phys. Rev. A **49** (1994) 1470

[9] G. W. Bennett *et al.*, Phys. Rev. A **92** (2004) 161802

$\Delta\nu_{HFS}$: Experiment vs. Theory

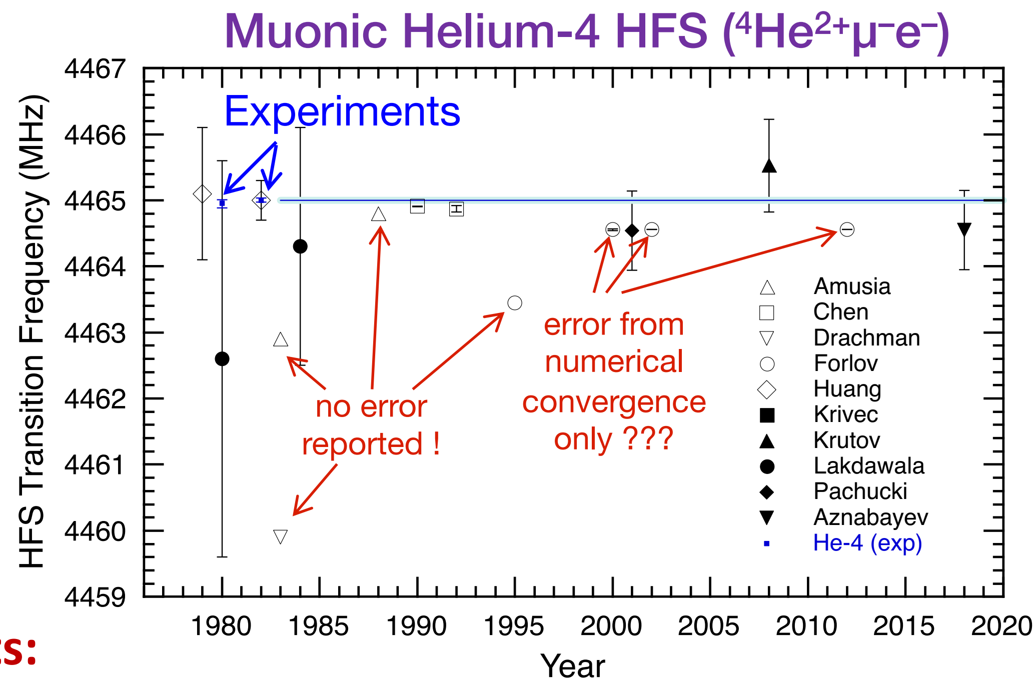
- Ground state HFS of muonic helium is very similar to muonium.
- In reality, however, muonic helium is complicated because three-body interaction has to be considered, thus limiting the theoretical approach.

Calculations performed since the 1970s based on perturbation theory (PT), variational approach (VA), and Born-Oppenheimer (BO) theory.

PT: Amusia, Krutov, Lakdawala, …
VA: Aznabayev, Chen, Forlov, Huang, Pachucki, …
BO: Drachman, …

$\Delta\nu$ = 4464.55(60) MHz (135 ppm)

D. T. Aznabayev *et al.*, Phys. Part. Nucl. Lett. **15** (2018) 236



Possible theoretical improvements:

- QED effects calculation in 3-body systems could be performed more precisely in **higher orders of perturbation theory**. K. Pachucki Phys. Rev. A **63** (2001) 032508
- Recent calculations developed for HFS in ^{3}He (40-fold improvement): could it be applied to muonic helium HFS ? V. Patkos *et al.*, Phys. Rev. Lett. **131** (2023) 183001

Why so difficult compared to Mu?

Muonic helium atom residual polarization

- Depolarization during muon cascade process: **100% → 2–5%**

P. A. Souder *et al.*, Phys. Rev. A **22** (1980) 33: **5.0 ± 0.7%**
H. Orth, Hyperfine Interact. **19** (1984) 829: **2.3 ± 0.5%**

Electron donor

- Helium capturing a muon forms **$(^4He\mu^-)^+$** ion → need an **electron donor !!!**
- Previously 1–2% **xenon** (IP = **12.1 eV**) was used. But **Xe** (**Z=54**) prevents efficient μ^- capture by **He** (**Z=2**) due to Fermi-Teller *Z*-law.
- Recently **methane** (**CH_4**) was found more efficient because of its reduced total charge (**Z=10**) and similar IP of **12.5 eV**. Polarization of **~ 5%** reported.

D. J. Arseneau, *et al.*, J. Phys. Chem. B **120** (2016) 1641

Negative Muon Beam Intensity

- Negative muon beams are generally 10 – 100 times less intense than surface (positive) muon beams

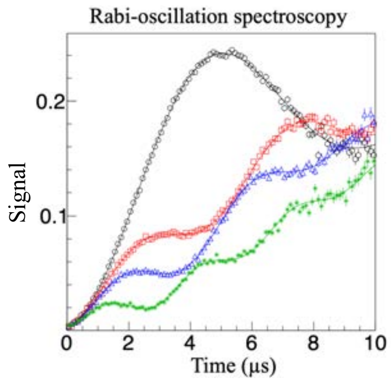
New μHe HFS at J-PARC MUSE

New precise HFS measurements are being planned at the Muon Science Facility (MUSE) of the Japan Proton Accelerator Research Complex (J-PARC).

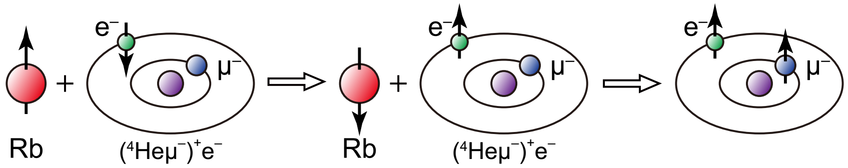
Three key components for improvement:

1) Using **high-intensity negative muon beam** at J-PARC MUSE.

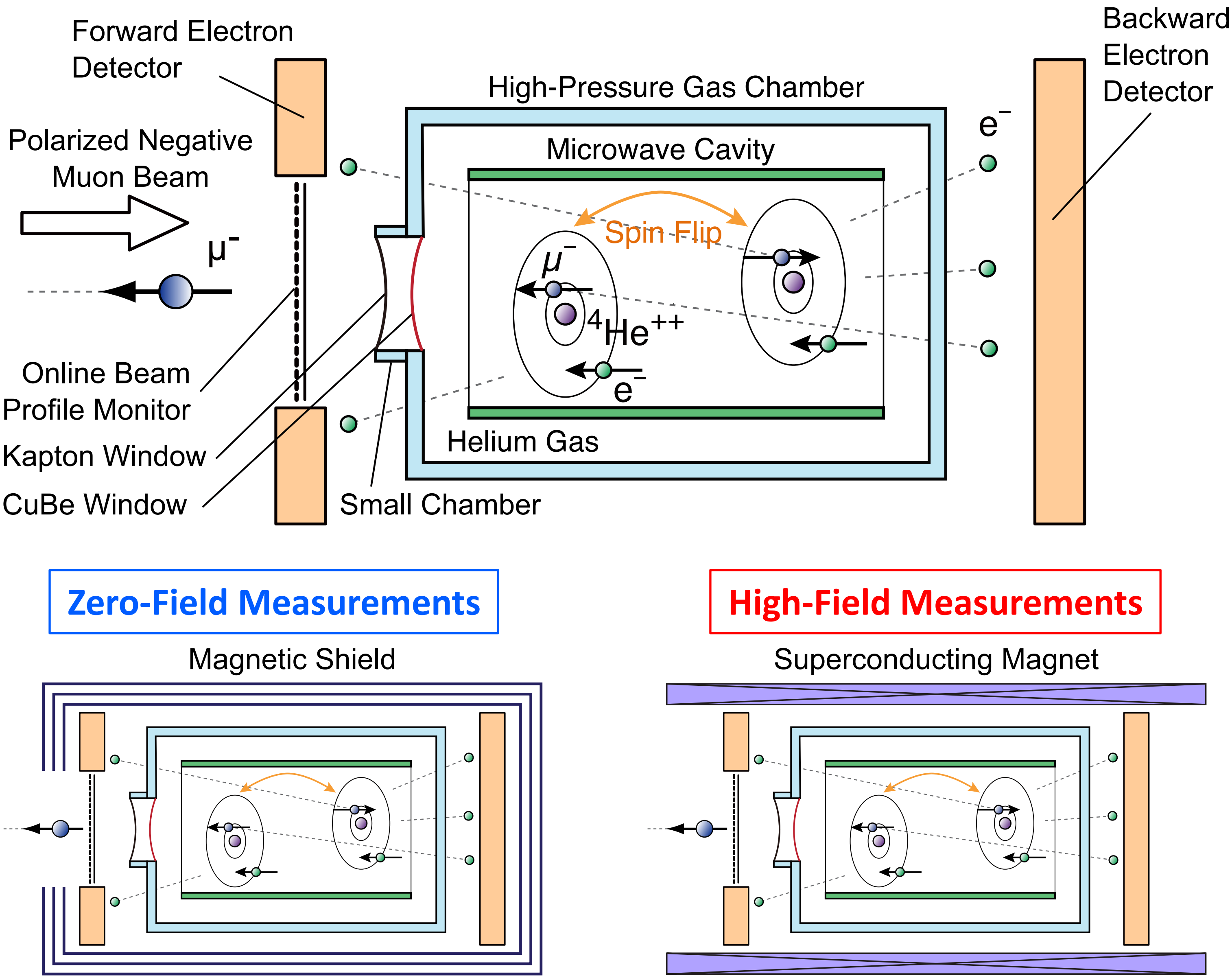
2) Applying **Rabi-oscillation spectroscopy technique** to HFS measurements.



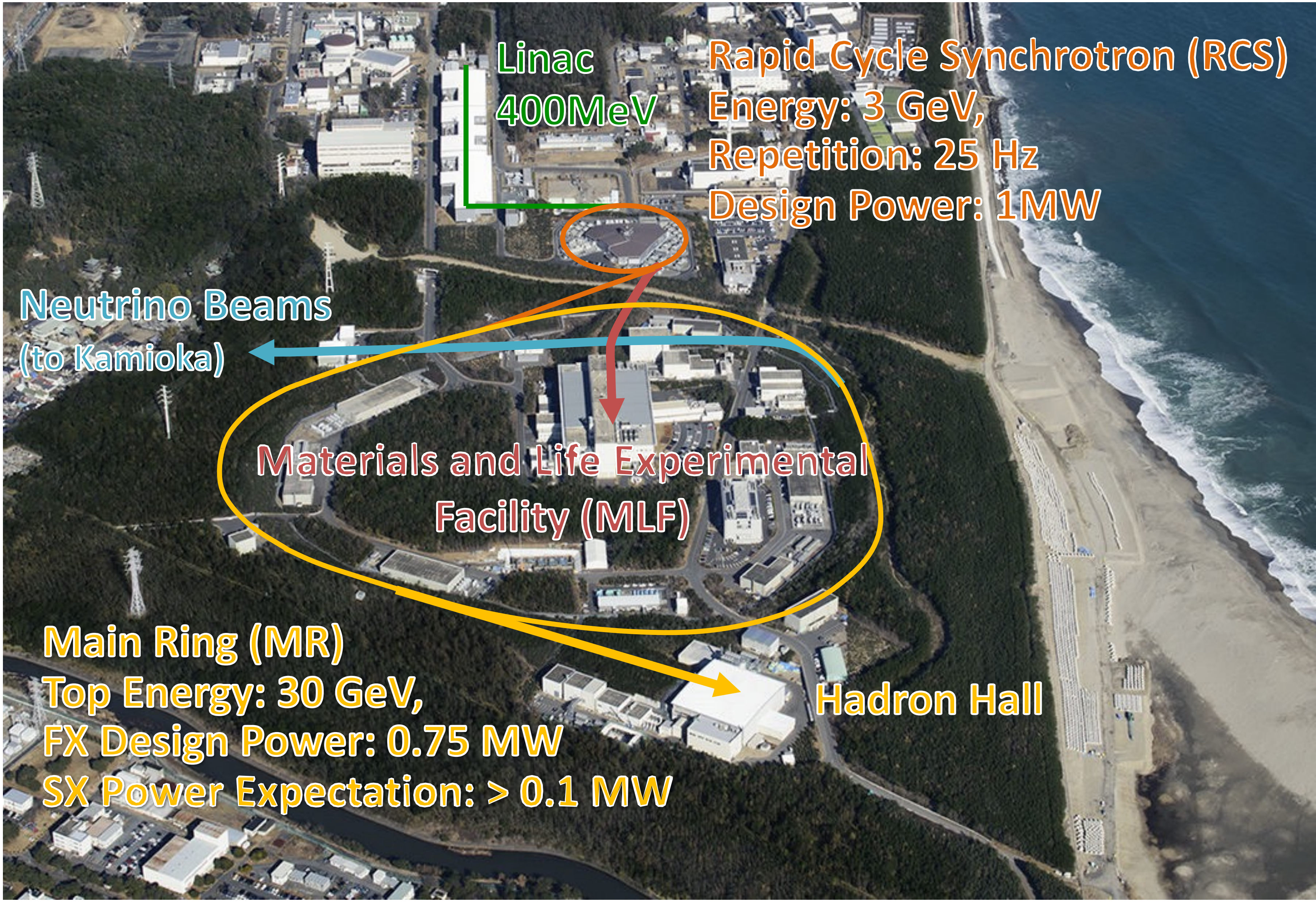
3) Producing **highly-polarized muonic helium atoms** to improve the μ^- residual polarization in helium by Spin Exchange Optical Pumping (SEOP).



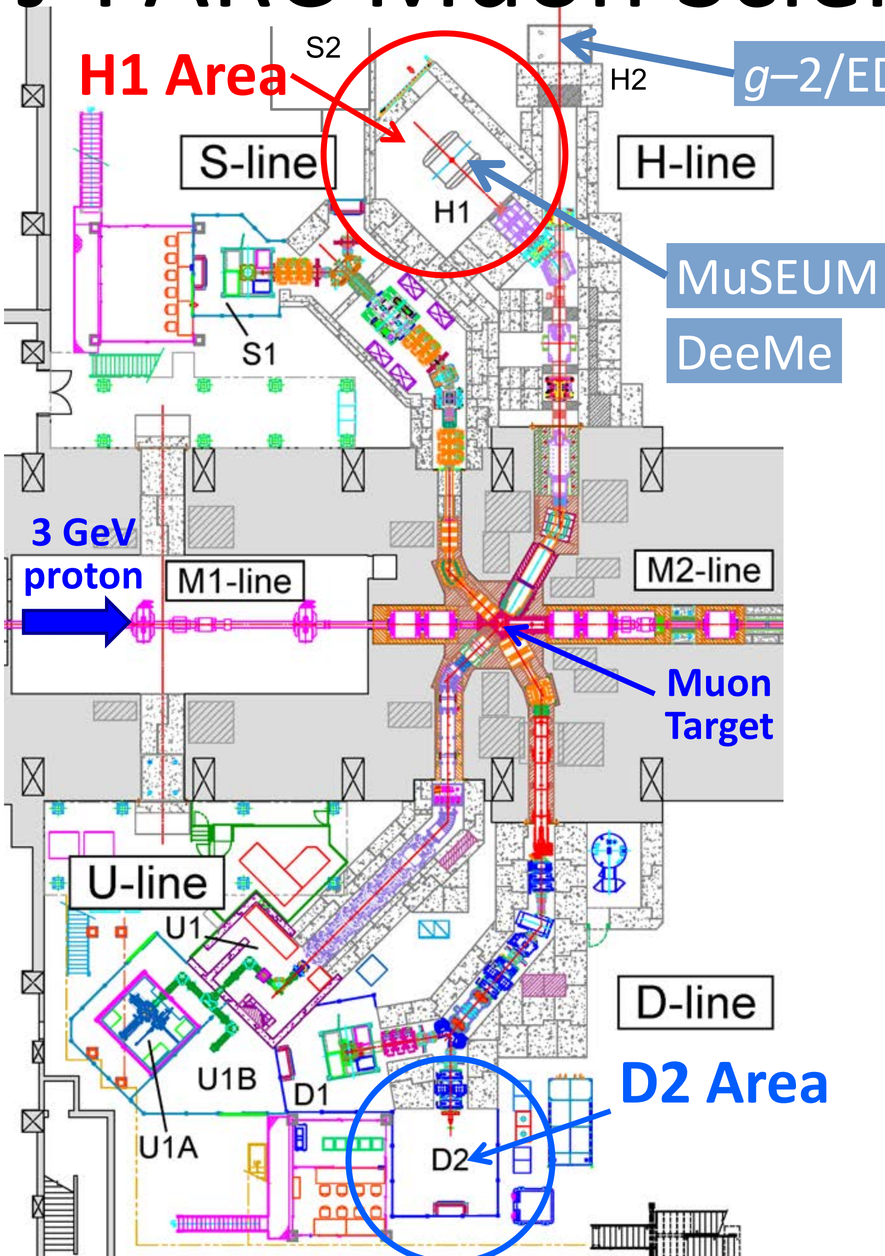
Experimental Arrangement



J-PARC Facility (KEK/JAEA)



J-PARC Muon Science Facility (MUSE)



Under Commissioning

H-Line: for particle and atomic physics large scale experiments, "precision frontier"

Higher intensity tunable (4 – 50 MeV) μ^+ & μ^- beam. (Exp.: MuSEUM, Deeme, *g*–2/EDM, …)

MLF Experimental Hall No. 1 (May 2023)

Beamlines in Operation

S-Line: Surface muon (μ^+)
Slow (4 MeV) beam for condensed matter physics.

D-Line: Decay muon (μ^+ & μ^-)
Slow (50 keV) – fast (50 MeV) beam, general purpose.

U-Line: Ultra-slow muon (μ^+)
Ultra-slow (0.1 – 30 keV) beam for near-surface condensed matter physics, chemistry, etc.

Expected Improvements

Previous experiments: $\delta(\Delta\nu) = 6.5$ ppm, $\delta(\mu_{\mu^-}/\mu_p) = 47$ ppm)

- 5×10^4 μ^-/s at 55 MeV/c (low field), 4×10^4 μ^-/s at 35 MeV/c (high field)

H-line:

- $\sim 10^7$ μ^-/s at 30 MeV/c (at 1-MW proton beam power)
  $\rightarrow \sim 10^4$ times more statistics (intensity $\times \sim 10^3$ & runtime of 100 days)

Statistical Improvement	$\Delta\nu$	μ_{μ^-}/μ_p
10^4 statistics ($\times$100)	100 ppb	1000 ppb
Rabi Spectroscopy ($\times$3)	40 ppb	400 ppb
Highly-Polarized μ^-He ($\times$7)	6 ppb	60 ppb

Very Very Preliminary !!!

Systematic uncertainties:

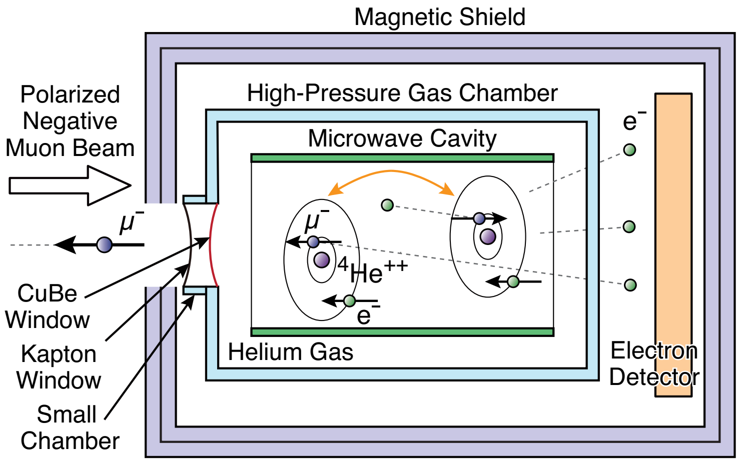
- MuSEUM experiment has similar systematical errors.
- Present estimation: $\sim$2 ppb for $\Delta\nu$ and $\sim$20 ppb for μ_{μ^-}/μ_p.

D-line: (zero field)

$\rightarrow \sim 10^2$ times more statistics (depending on beamtime allocation)

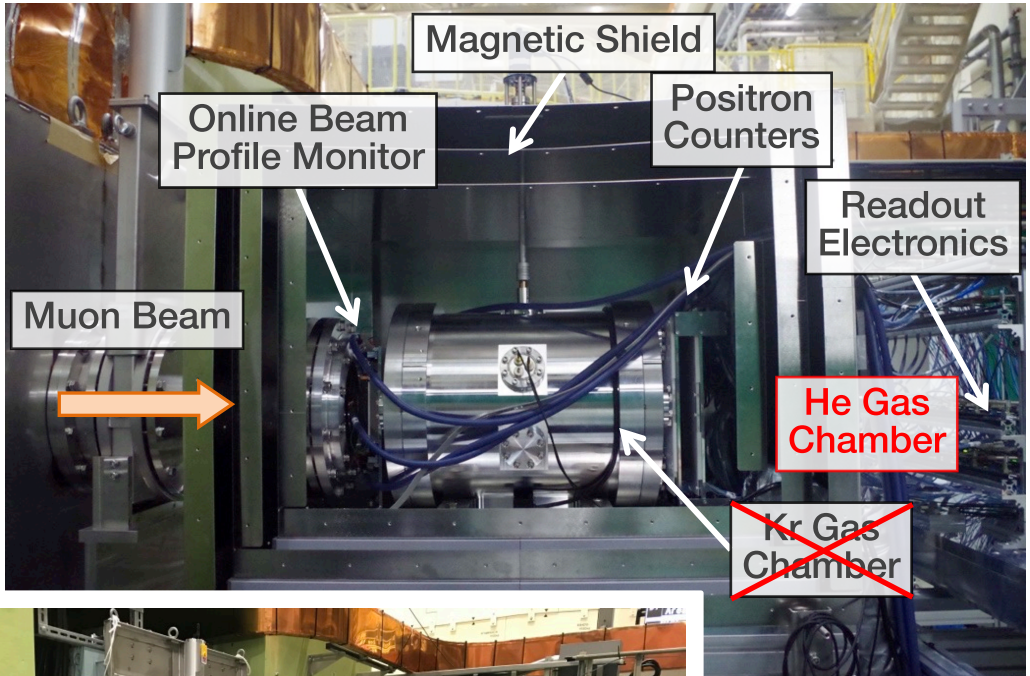
General User Program

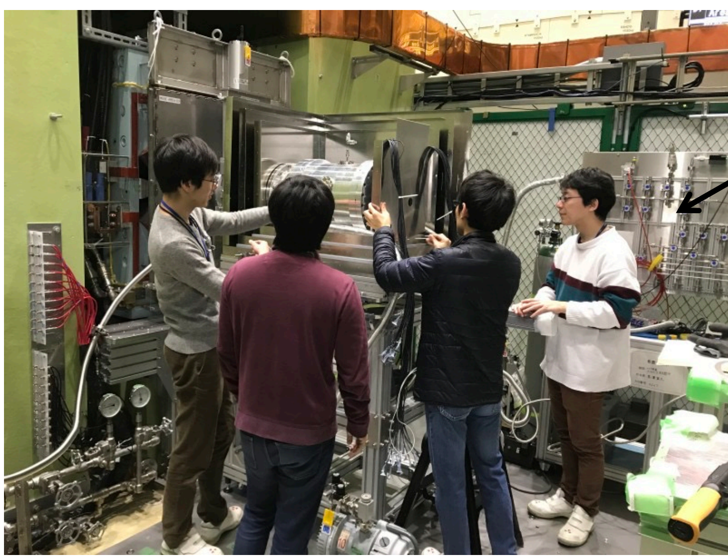
Muonic Helium HFS Measurement at Zero-Field



μHe HFS Measurements at Zero-Field

Experimental Setup





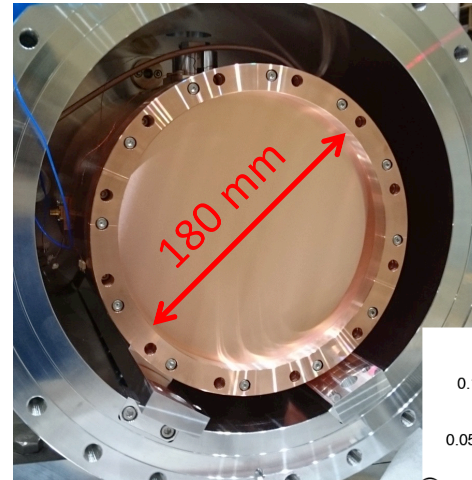
Gas Panel

[2019B0318]

Preparation of MuSEUM apparatus in D2 area

(students from Nagoya University and the University of Tokyo)

Microwave Cavity (zero field)



TM220 mode

Larger cavity

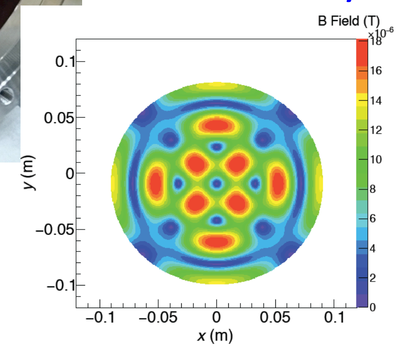
More muon stop

Q-Value:
20,000 (calc.)

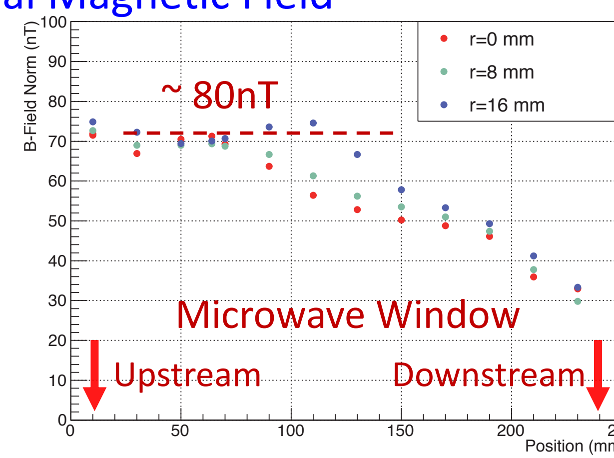
~~$\Delta\nu$ = 4.463 GHz~~

$\Delta\nu$ = 4.465 GHz

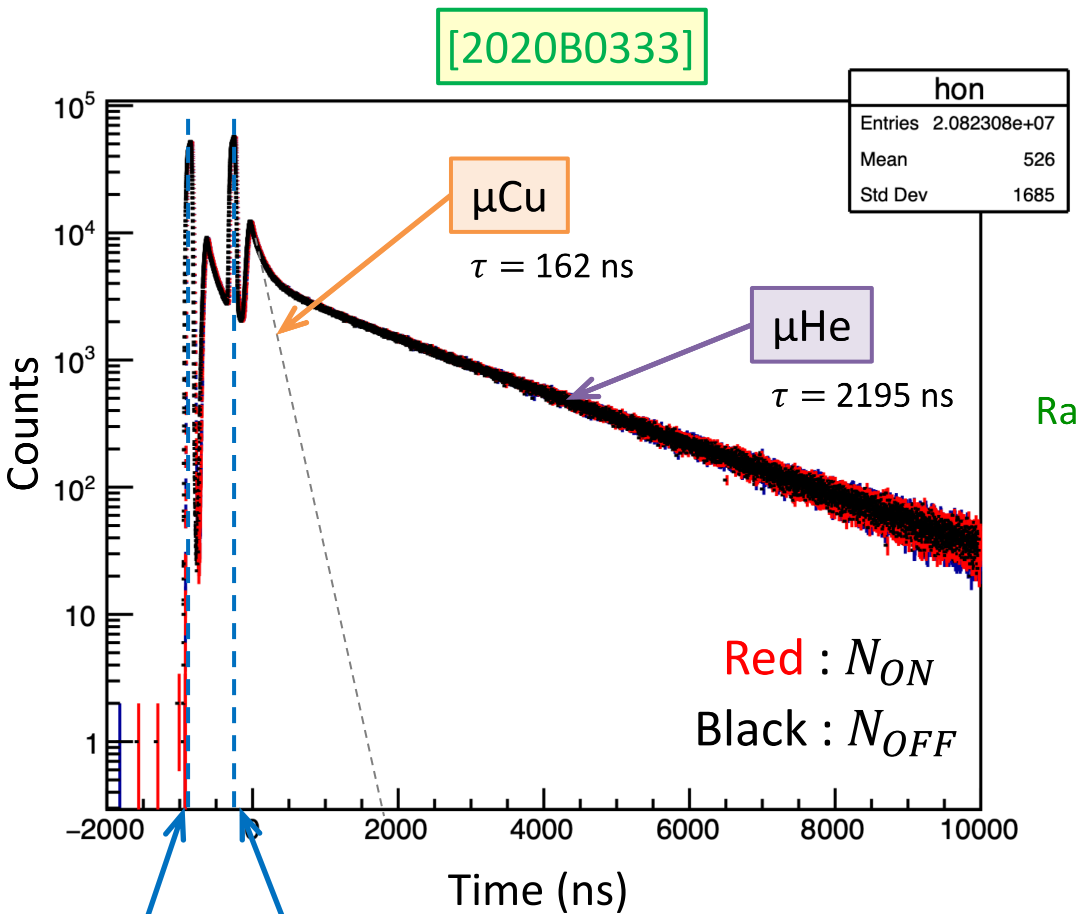
MW Intensity



Residual Magnetic Field

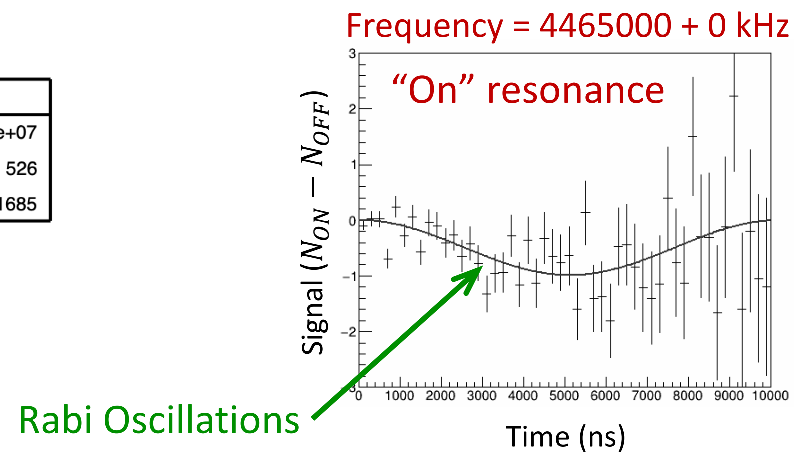


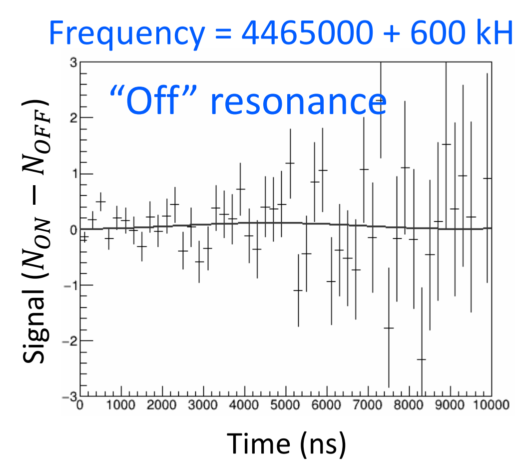
Decay Electron Time Spectra



1st Muon Peak (-600 ns)

2nd Muon Peak (0 ns)

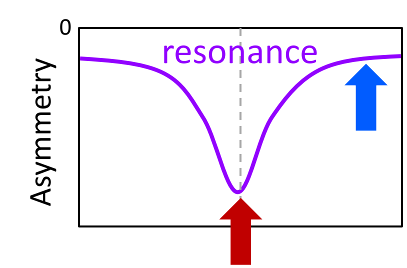




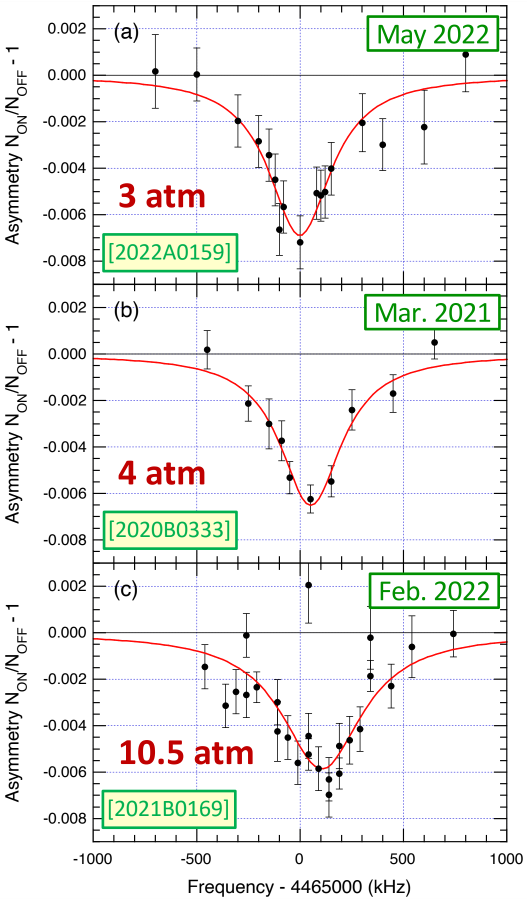
$$\text{Asymmetry} = \frac{N_{OFF}}{N_{ON}} - 1$$

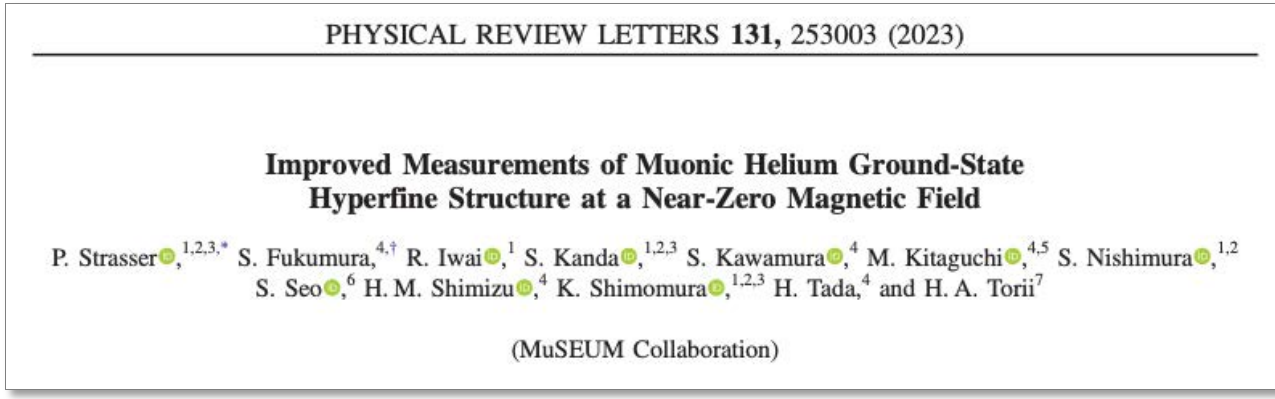
N_{ON} : Number of e⁻ with microwave

N_{OFF} : Number of e⁻ without microwave



μHe HFS Measurement at Zero Field

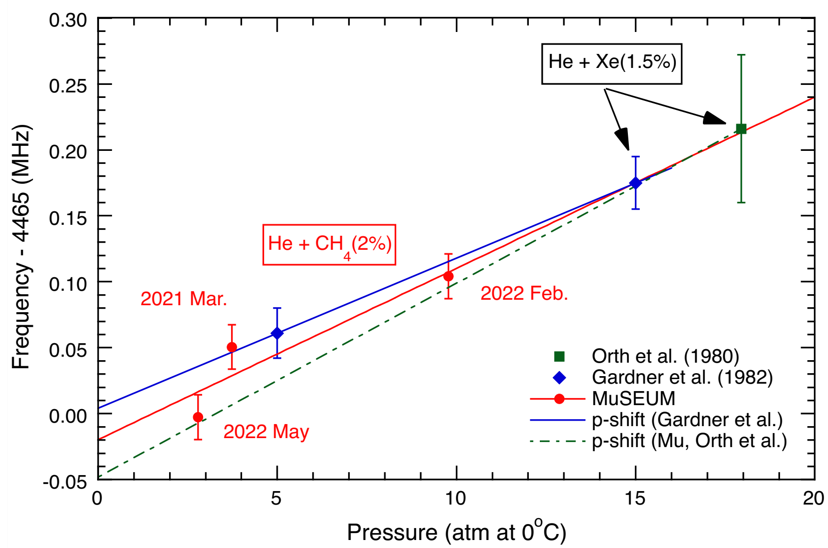


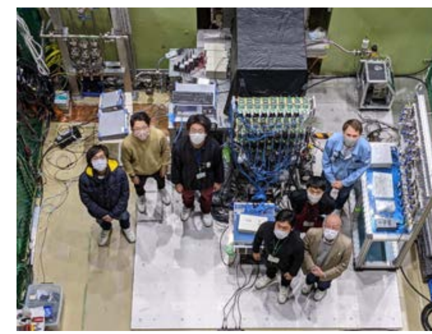

PHYSICAL REVIEW LETTERS **131**, 253003 (2023)

Improved Measurements of Muonic Helium Ground-State Hyperfine Structure at a Near-Zero Magnetic Field

P. Strasser,[1,2,3,*] S. Fukumura,[4,†] R. Iwai,[1] S. Kanda,[1,2,3] S. Kawamura,[4] M. Kitaguchi,[4,5] S. Nishimura,[1,2] S. Seo,[6] H. M. Shimizu,[4] K. Shimomura,[1,2,3] H. Tada,[4] and H. A. Torii[7]

(MuSEUM Collaboration)





After 40 years New World Record!

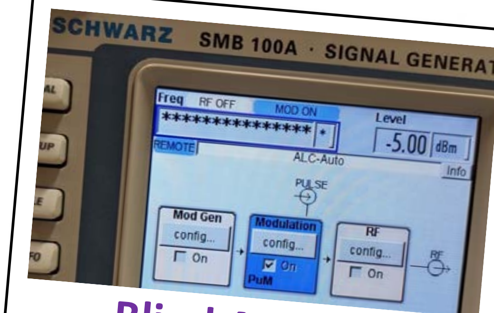
$\Delta\nu$ = 4464.95(6) MHz [13 ppm] zero field (Orth *et al.*, PRL **45** (1980) 1483)

$\Delta\nu$ = 4465.004(29) MHz [6.5 ppm] high field (Gardner *et al.*, PRL **48** (1982) 1168)

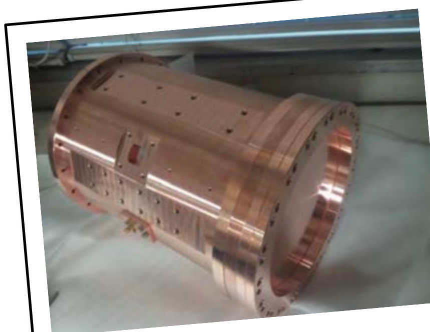
$\Delta\nu$ = 4464.980(20) MHz [4.5ppm] zero field (MuSEUM 2023)

Development for High-Field Experiment

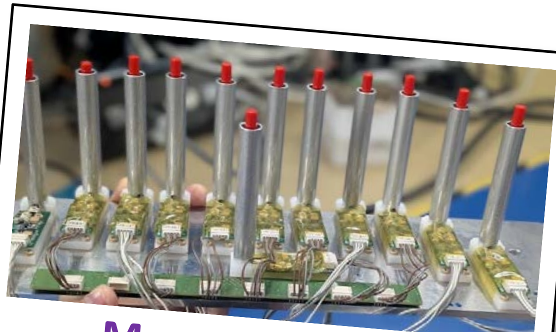
MRI Magnet



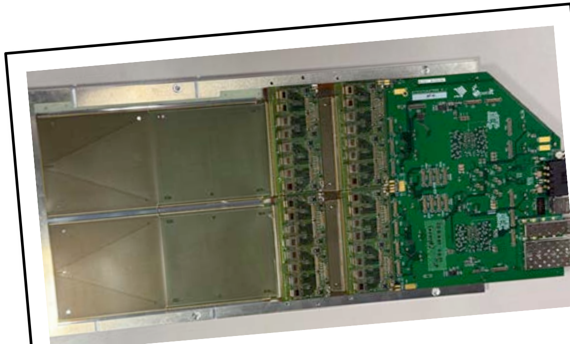
Blind Analysis



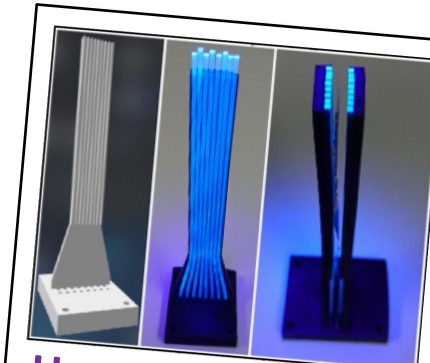
HF Cavity



Magnetic Probes



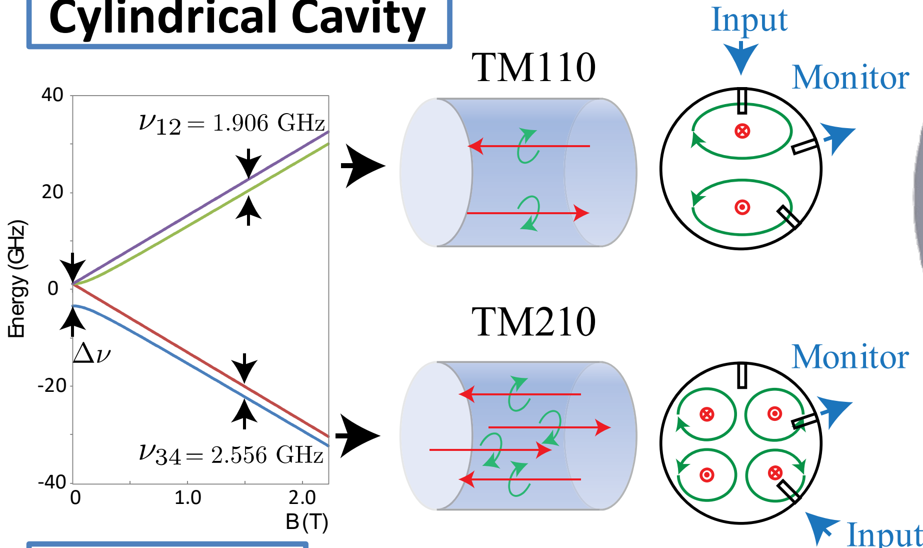
Detectors



Upstream Detector

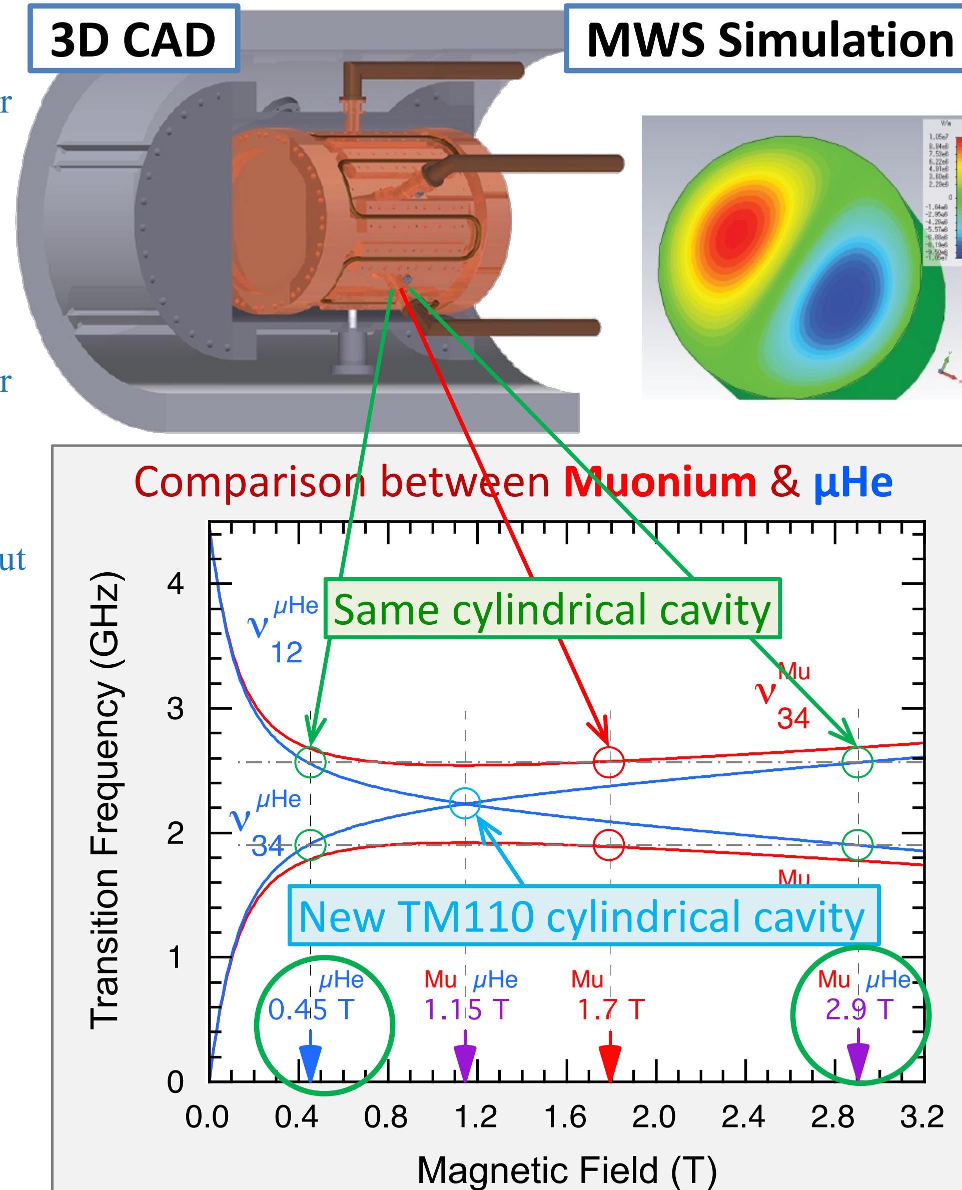
High-Field Microwave Cavity for μHe

Cylindrical Cavity

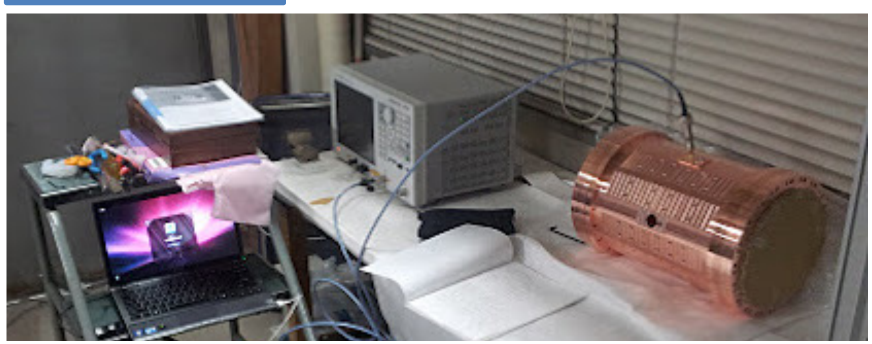


3D CAD

MWS Simulation



Cavity Test



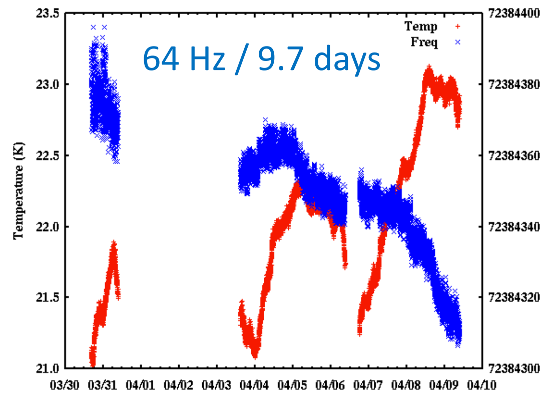
Q Value

Modes	Q (measured)	Q (simulation)
TM110	1.13 x 10^4	2.97 x 10^4
TM210	8.05 x 10^3	2.89 x 10^4

MRI Magnet for High-Field Experiment

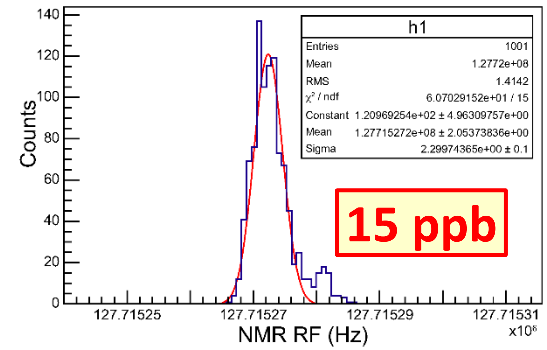
2.9 T MRI magnet

Long Term Stability

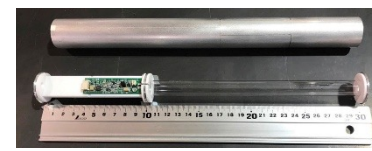


0.003 ppm / h

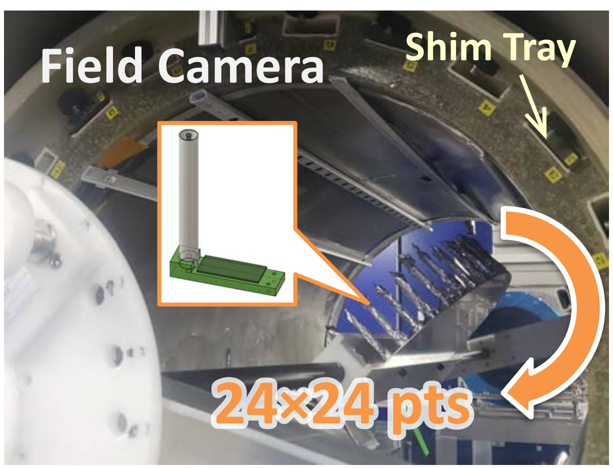
CW-NMR Probe

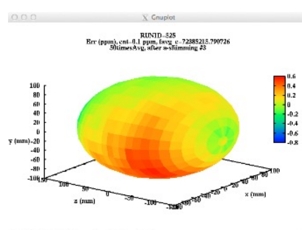


15 ppb



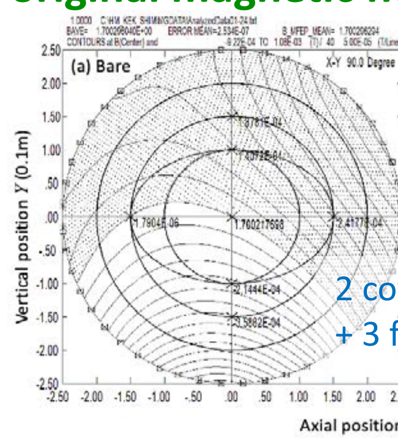
Field Homogeneity (after shimming)





Spheroid :
ø=200 mm
z=300 mm

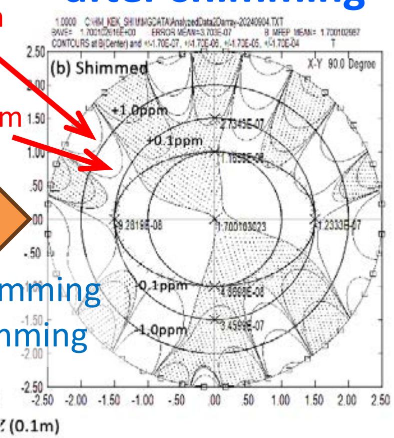
original magnetic field



±1 ppm line

±0.1 ppm line

after shimming



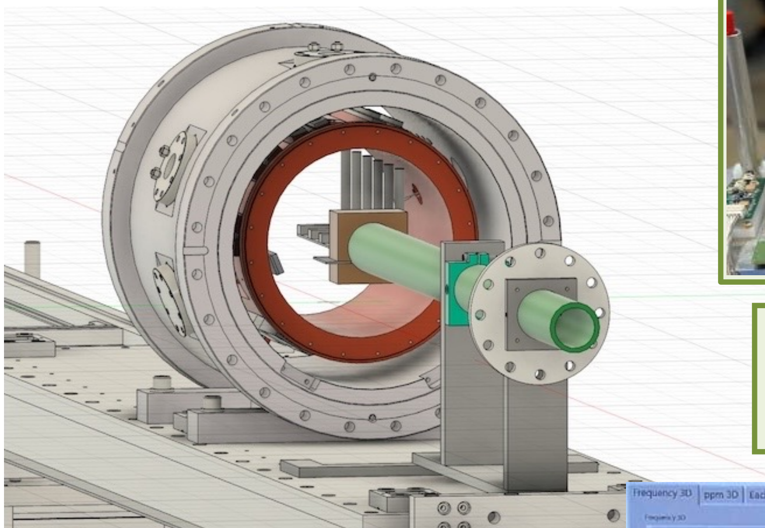
2 coarse shimming
+ 3 fine shimming

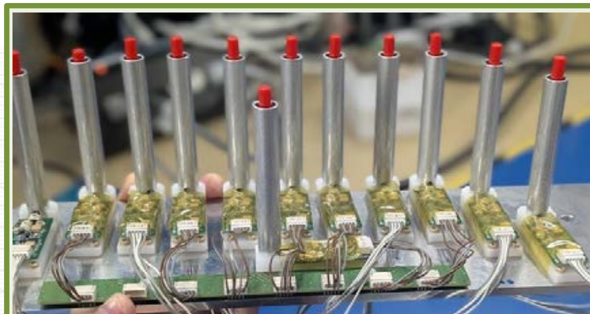
296 ppm (p-p) → 0.203 ppm (p-p)

New Inner Field Camera

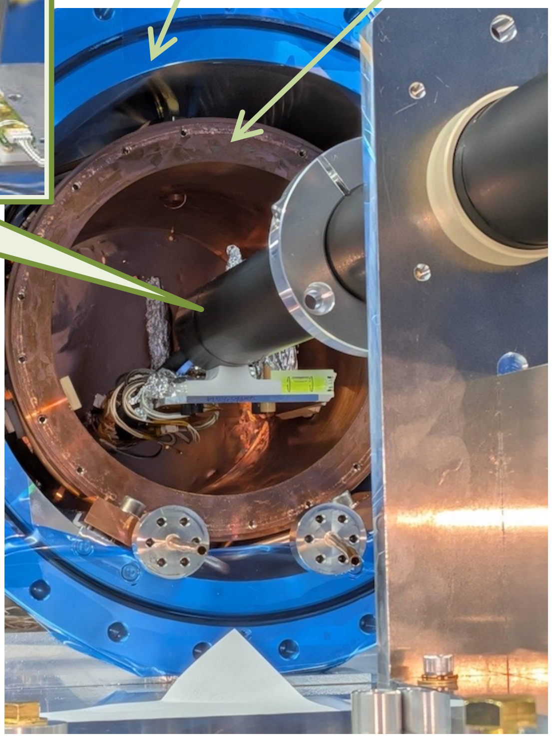
Field measurements and adjustment with all components in place

Developed by Yu Goto (Nagoya Univ.)

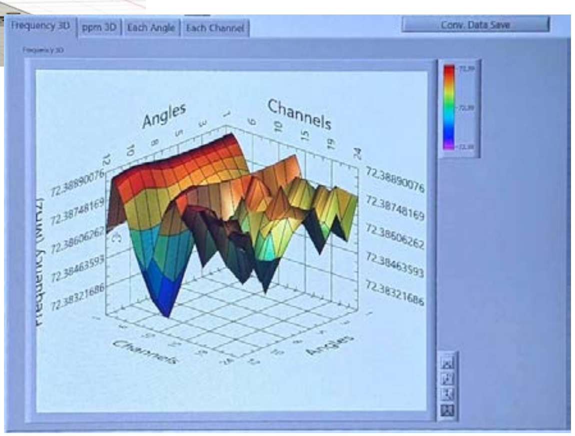




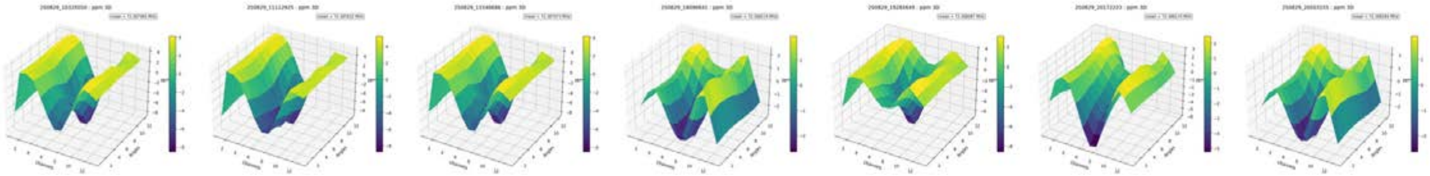
13 NMR Probes
x
12 angles



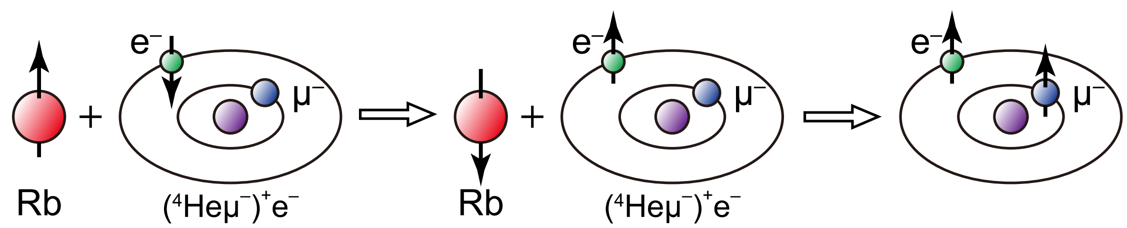
Raw field data:



Preliminary measurements:

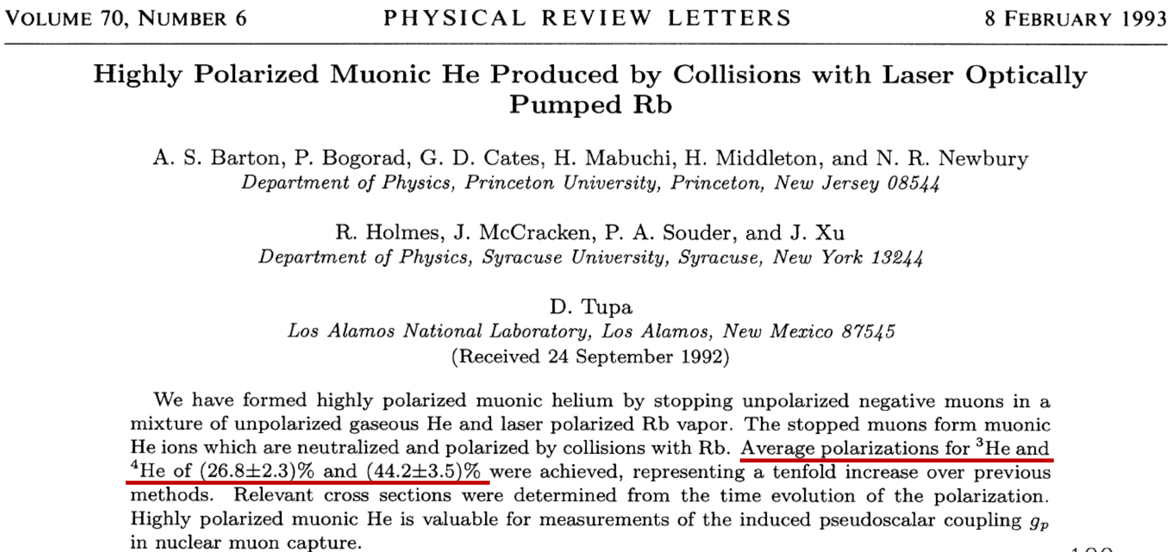


Highly-Polarized Muonic Helium Atom



Highly-Polarized Muonic He Atom

by Spin Exchange Optical Pumping (SEOP)


VOLUME 70, NUMBER 6 PHYSICAL REVIEW LETTERS 8 FEBRUARY 1993

Highly Polarized Muonic He Produced by Collisions with Laser Optically Pumped Rb

A. S. Barton, P. Bogorad, G. D. Cates, H. Mabuchi, H. Middleton, and N. R. Newbury
Department of Physics, Princeton University, Princeton, New Jersey 08544

R. Holmes, J. McCracken, P. A. Souder, and J. Xu
Department of Physics, Syracuse University, Syracuse, New York 13244

D. Tupa
Los Alamos National Laboratory, Los Alamos, New Mexico 87545
(Received 24 September 1992)

We have formed highly polarized muonic helium by stopping unpolarized negative muons in a mixture of unpolarized gaseous He and laser polarized Rb vapor. The stopped muons form muonic He ions which are neutralized and polarized by collisions with Rb. Average polarizations for ^{3}He and ^{4}He of (26.8±2.3)% and (44.2±3.5)% were achieved, representing a tenfold increase over previous methods. Relevant cross sections were determined from the time evolution of the polarization. Highly polarized muonic He is valuable for measurements of the induced pseudoscalar coupling g_P in nuclear muon capture.

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

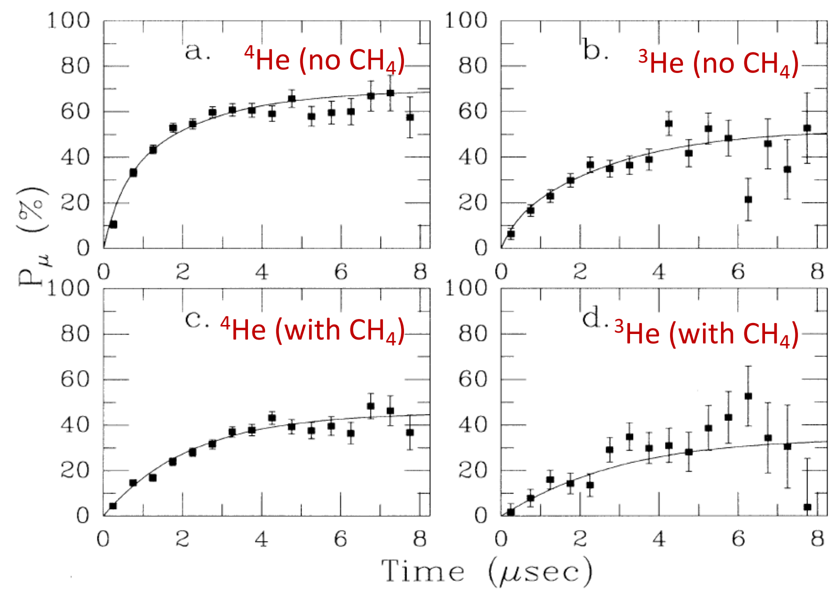
Glass cell target: (T ≈ 200°C)

- Sphere: ~Ø2.5 cm x 100 μm^t
- He: 8 atm
- Rb: 4.4 x 10^{14} atoms/cm^3
- N_2 : 75 Torr
- CH_4 : up to 250 Torr

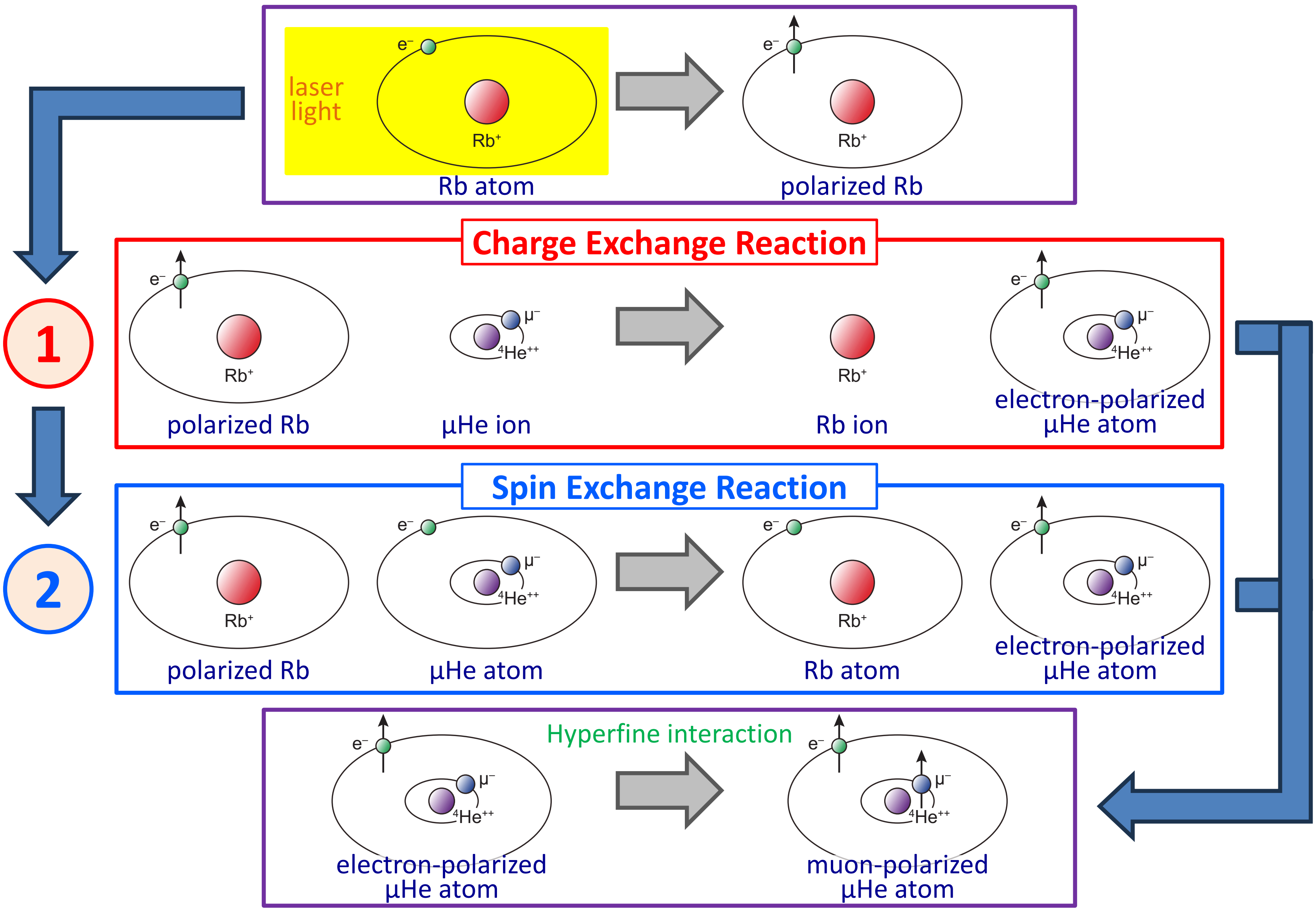
for μ^{4}He: 6% → 44%

Improvement by a factor 7 achieved !

Maximum theoretical polarization:
^{4}He = 100%, ^{3}He = 75%



Repolarization of Muonic He Atom



μHe SEOP Objectives

1) Demonstrate re-polarization of μHe atoms at using the **SEOP technique**
    - Test experiment at D1 area under development

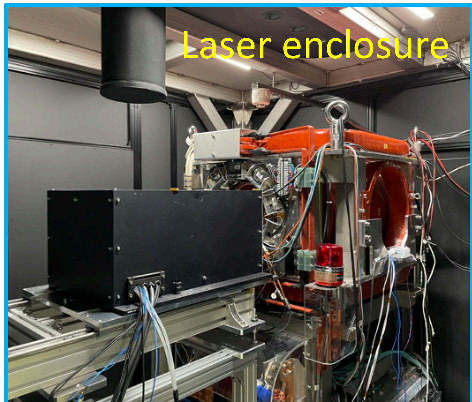
2) Further improvements expected with a **hybrid-SEOP technique**
    - Use **K/Rb** to enhance the spin-exchange efficiency
    - Rb is used as a spin-transfer agent to K, to prevent depolarization of Rb due to Rb-Rb collision.
    - K-He transfers the angular momentum with much greater efficiency than directly Rb-He (nearly 10 times greater than with pure Rb pumping).
    - Can achieve **high polarizing rate** with **high polarization**, which is very important for HFS measurements

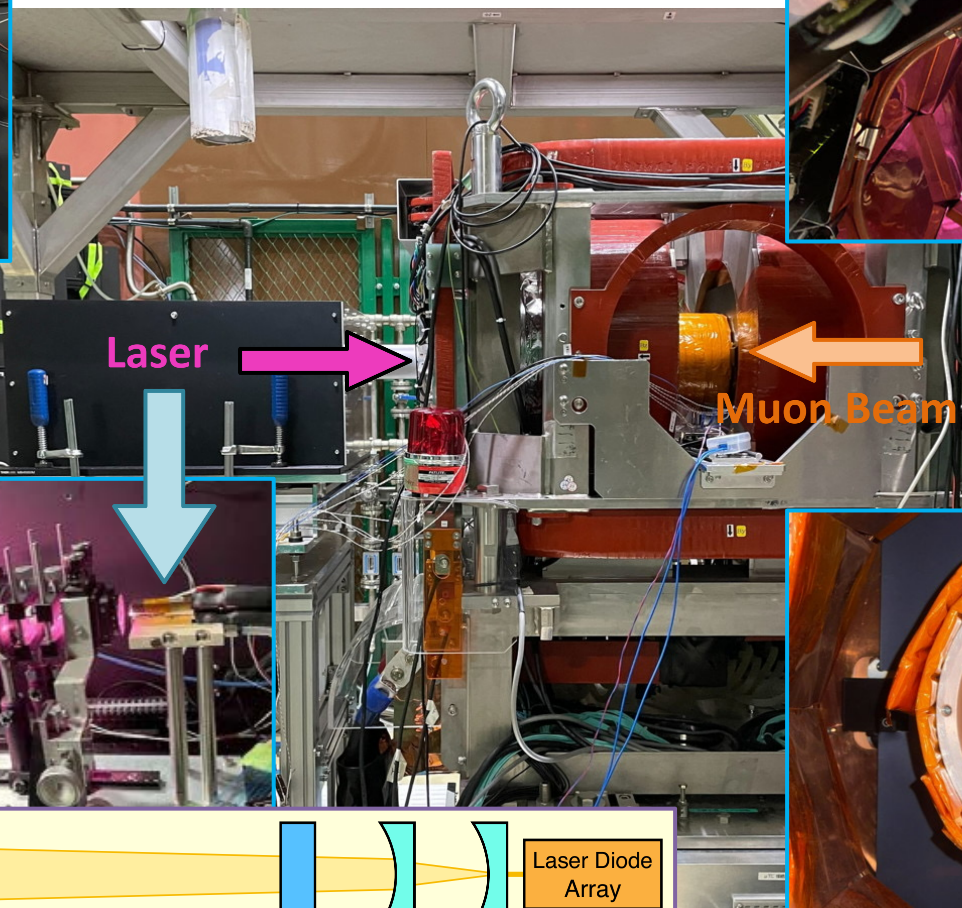
3) Demonstrate that the **SEOP technique** can be applied to **muonic helium HFS** measurements
    - Simulation (in progress)
    - Test experiment

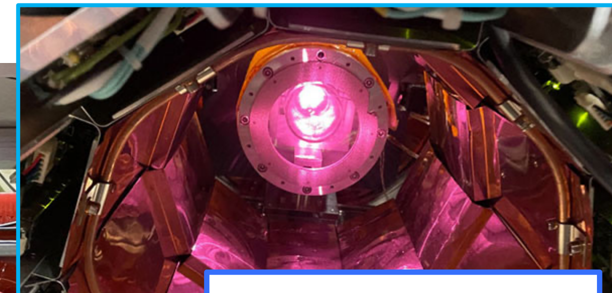
SEOP Experimental Setup for μHe

New MuSEUM-SEOP collaboration: MUON + NEUTRON Kakenhi(A): FY2021-2023

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



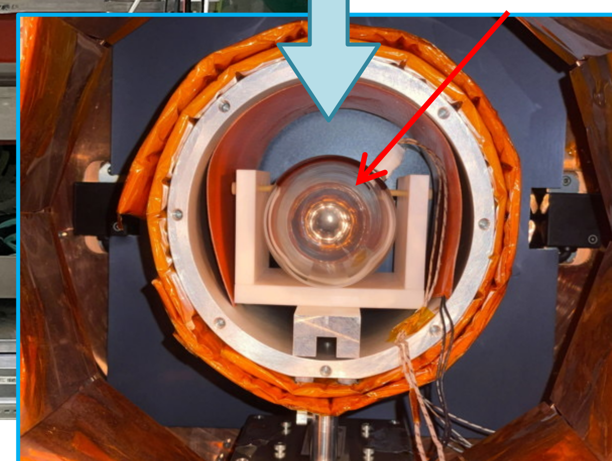




SEOP Cell

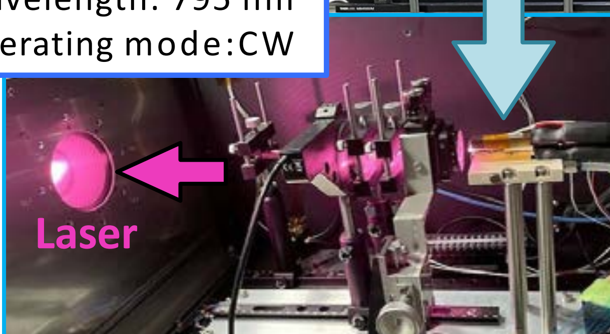
surrounded by:

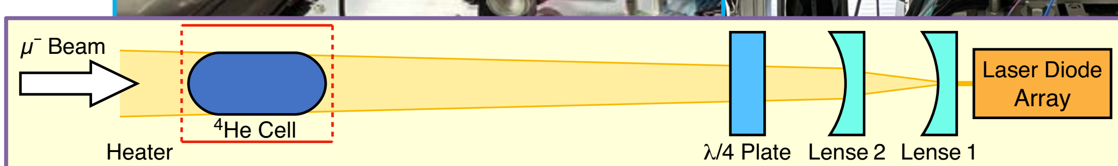
- Oven heater (200°C)
- Insulation Foam



Laser Diode Array

- Power: ~80 W
- Wavelength: 795 nm
- Operating mode:CW





Muonic Helium Repolarization

Muonic helium atom residual polarization

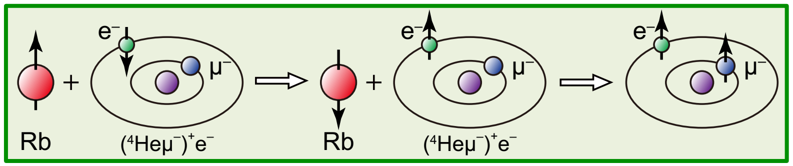
- Depolarization during muon cascade: 100% → **~5%** (muonium 50%)

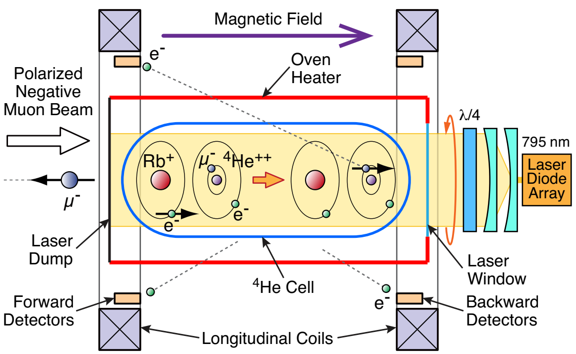
Repolarization of muonic He atom by spin-exchange optical pumping

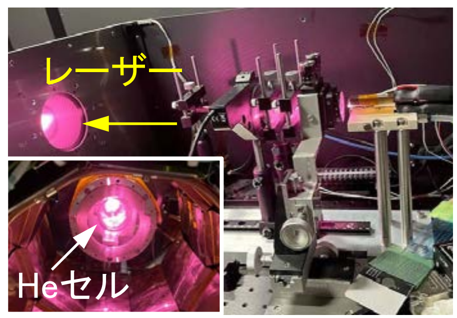
(SEOP)

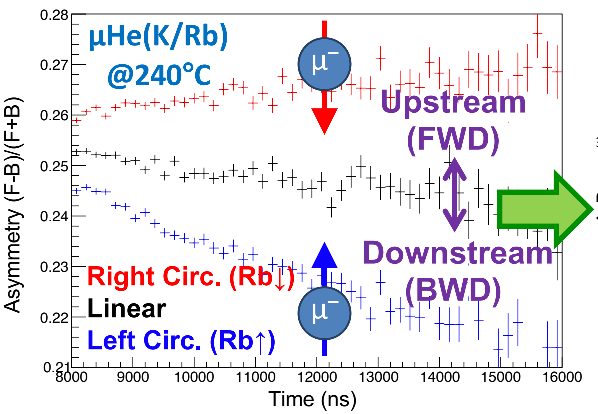
- Muonic He atoms repolarize when they collide with polarized K/Rb vapor

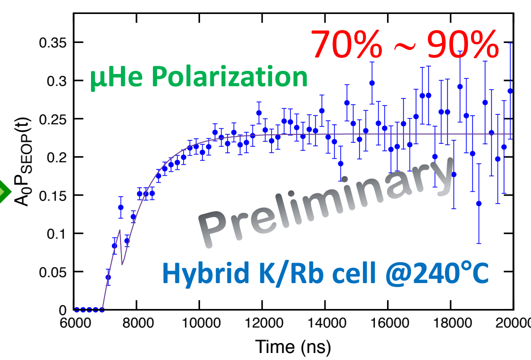
He Glass Cell







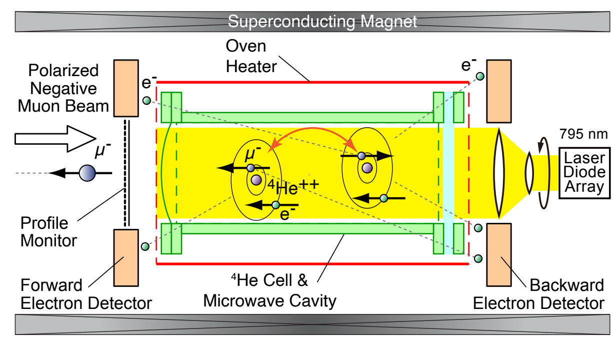




Analysis in progress

From Glass to Metal Cell

- Less background from high-Z nuclei, shorter lifetime, …
- The **metal cell** is the **microwave cavity**
- Higher pressure can be achieved
- Reusable



Combining metal cell and cavity

Metal cells already used for the SEOP experiment
P.A. Souder, Nucl. Instum. Meth. A **402** (1998) 311

Summary

- We are now performing new precise measurements of the **ground-state hyperfine splitting** of **muonic helium atoms** at J-PARC
- New **zero-field measurements** using MuSEUM setup at **D2 area**
  - After 40 years, new **highest precision** of **4.5 ppm** achieved
- The **high-field experiment** planned at **H1 area** after muonium measurements
  - The same cavity as with muonium can be used at a 2.9 T field
  - Bare field homogeneity of 0.2 ppm (p-p) achieved
  - Adjustment with all components in progress
- Formation of **highly-polarized μHe atoms** by **SEOP** under development
  - Higher polarizing rate achieved using **Hybrid K/Rb SEOP**
- …

MuSEUM Collaboration

(**Mu**onium **S**pectroscopy **E**xperiment **U**sing **M**icrowave)

KEK

M. Abe, M. Hiraishi, T. Ino, S. Kanda, S. Nishimura, H. Okabe,
K. Sasaki, K. Shimomura, P. Strasser

Nagoya University

K. Asai, M. Fushihara, Y. Goto, S. Kawamura, M. Kitaguchi,
T. Okudaira, M. Okuizumi, H. M. Shimizu, H. Tada

JAEA

T. Oku

University of Tokyo

H. A. Torii

Michigan State Univ.

R. Iwai

Tohoku University

H. Okabe

Ibaraki University

M. Hiraishi

NIIGATA UNIVERSITY

S. Fukumura,
R. Azuma, K. Yamura

On behalf of the extended MuSEUM Collaboration

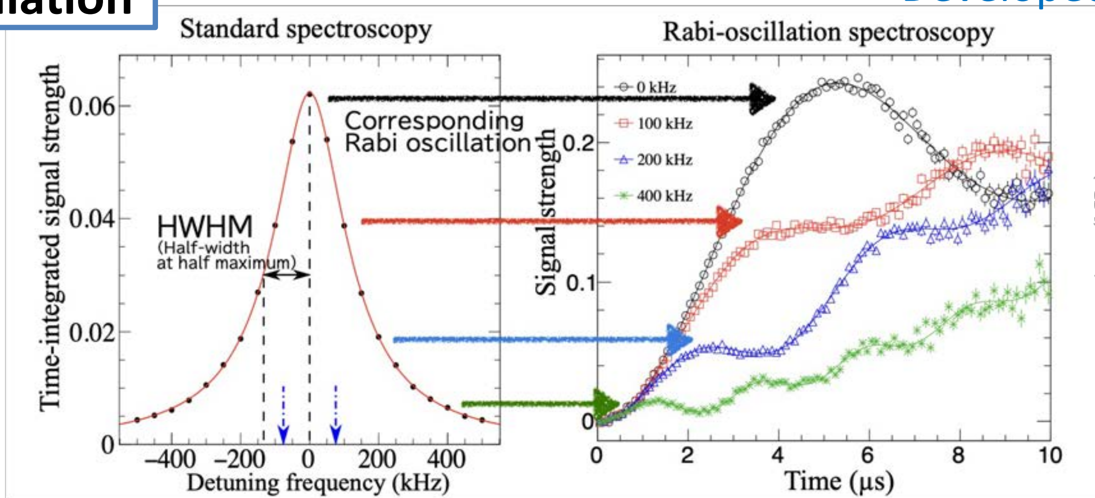
FIN

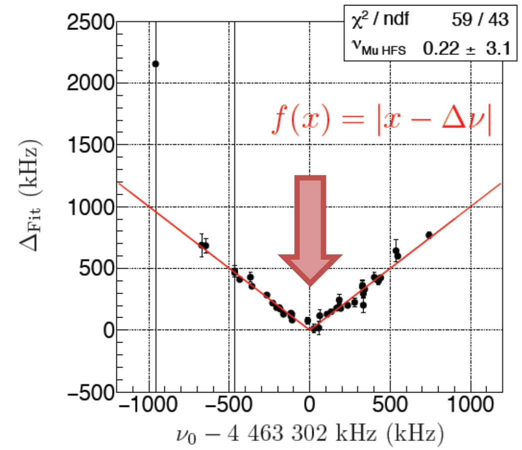
EXTRA SLIDES

Rabi-Oscillation Spectroscopy Method

Simulation

Developed by Shoichiro Nishimura (KEK)

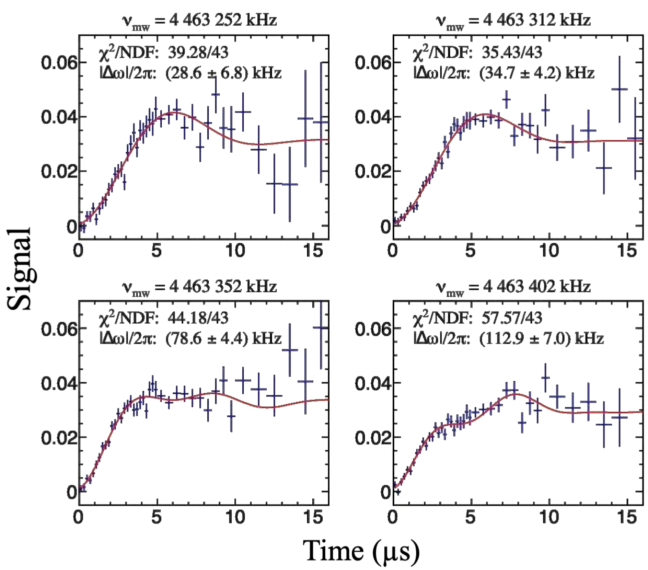




$\Delta\nu_{HFS}(0) =$ 4 463 301.61(71) (160 ppb)

S. Nishimura *et al.*, Phys. Rev. A **104** (2021) L020801

Experiment (2017 June)



Advantages:

- Each detuning frequency data fitted individually
- Can determine $\Delta\nu_{HFS}$ with only one frequency data
- **Can improve statistical uncertainty by 3.2 times** compared to the conventional method
- Can **reduce systematics** due to **microwave power** variation (free fitting parameter)
- Need fast detector and high-statistics data

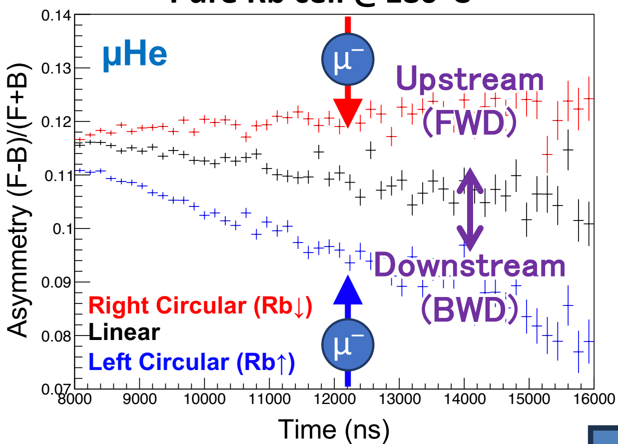
Comparison: Pure & Hybrid Cell

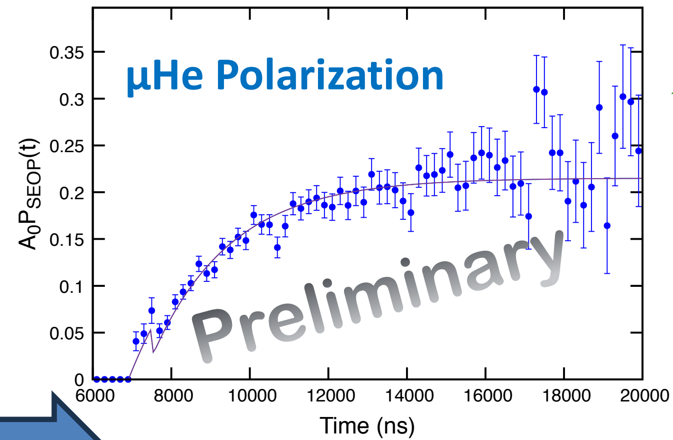
Asymmetry: $A(t) = \dfrac{F(t) - B(t)}{F(t) + B(t)}$

$$A_0 P_{SEOP}(t) = \frac{R(t) - L(t)}{(N^R_{He} + N^L_{He})\exp(-\lambda_{He} t)}$$

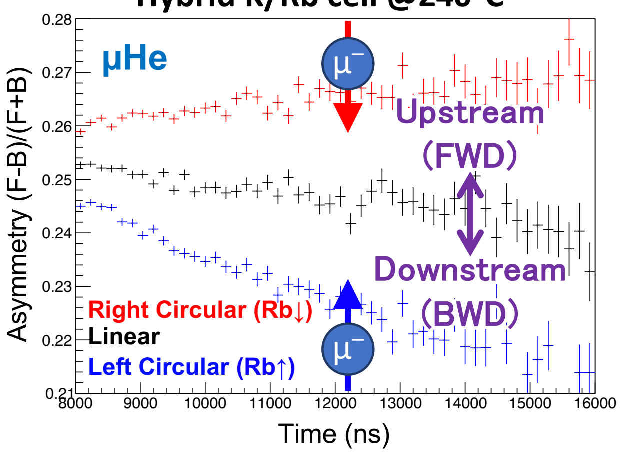
Muons stopped in He

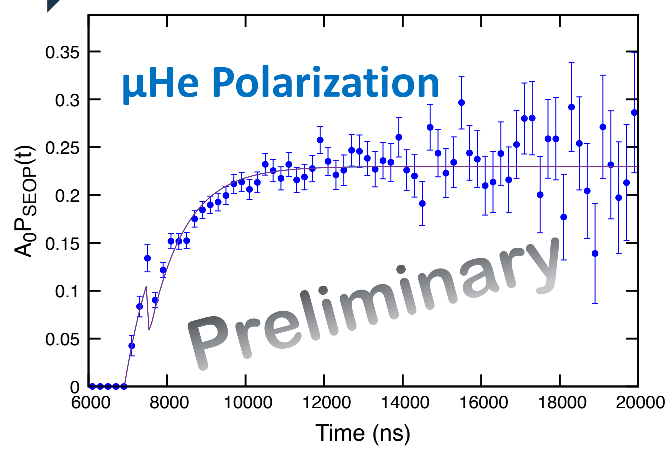
Pure Rb cell @180°C





Hybrid K/Rb cell @240°C





A_0 : Experimental asymmetry

- A_0 = 1/3 (theory)
- A_0 = 0.25 (exp. thin target)

	P_{SEOP}
Lower Limit (A_0 = 1/3)	≈ 70%
Upper Limit (A_0 = 0.25)	≈ 90%

- Geant4 simulations needed to determine A_0

Analysis in progress

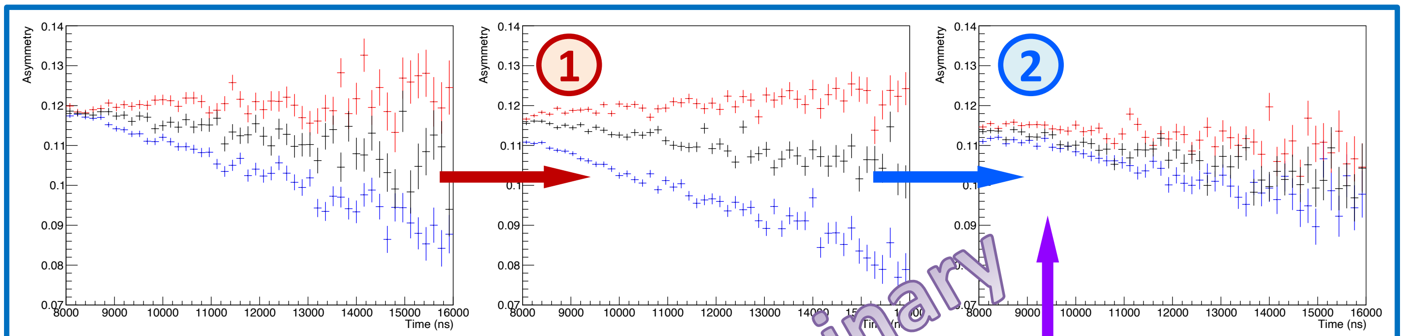
- High polarizing rate with high polarization efficiency achieved with "Hybrid" at 240°C

μHe SEOP vs. Hybrid-SEOP

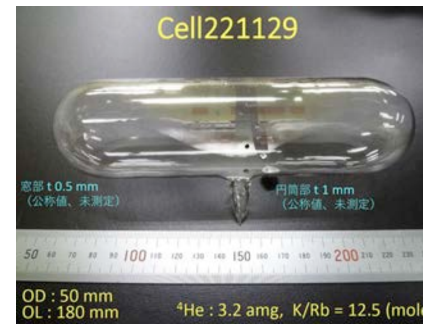
160 °C | 180 °C | 200 °C | 240°C

Rb Pure Cell

1. Polarization increases with Rb mobility
2. Polarization decreases due to Rb-Rb collisions



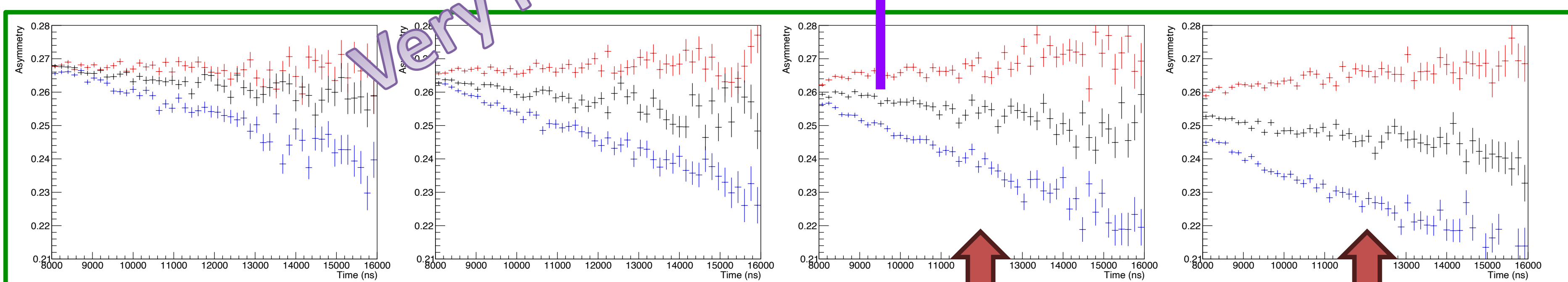
Hybrid Cell
[K]/[Rb] = 12.5 (mole)



Very Preliminary

Decrease in polarization efficiency due to spin relaxation

Hybrid K/Rb Cell



Increased polarization efficiency at higher temperatures due to K-μHe spin exchange

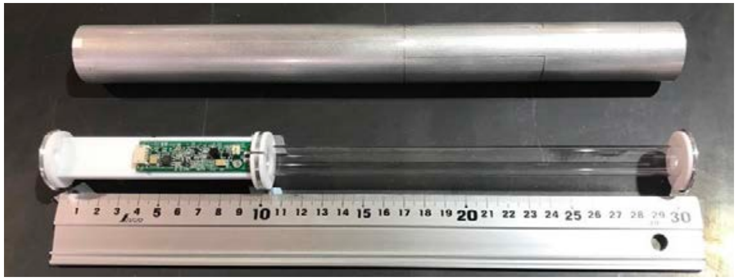
(on-line analysis only)

Magnetic Field Probes

Three types of probes are being developed

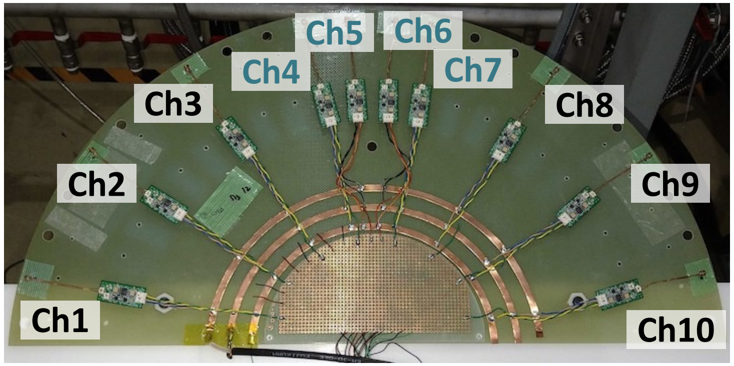
Standard Probe

- CW-NMR field monitoring system
- Precision of **15 ppb** has been achieved



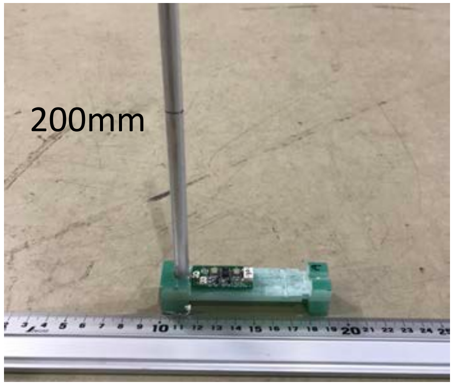
Field Camera

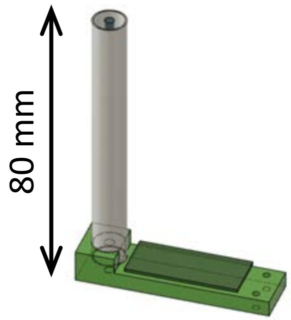
- 24-channels rotating NMR probe to map magnetic fields
- Used for shimming
- 10-channel prototype has been developed



Fixed Probe

- Compact probe to monitor magnetic field stability during experiment

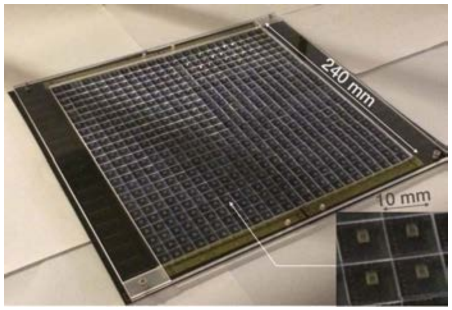


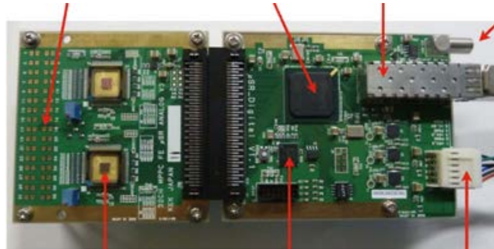


Counter Development

Positron Counter (1)

Segmented Scintillation Detector





Plastic scintillator + MPPC(SiPM) + Kaliope readout circuit

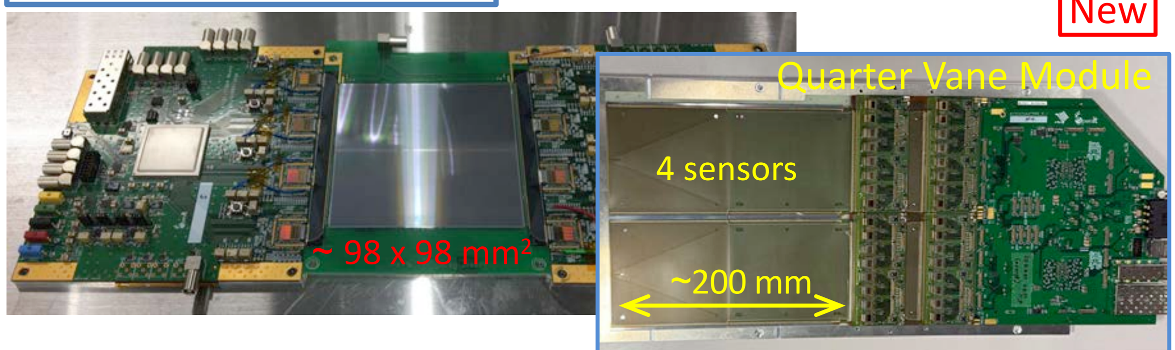
- Unit cell: 10 mm × 10 mm × 3 mm^t
- Area: 240 mm × 240 mm
- 24x24 segments x 2 layers = 1152 ch

- High-rate capability
- Pileup loss at 3 MHz/ch ~ 2%

Positron Counter (2)

Silicon Strip Detector

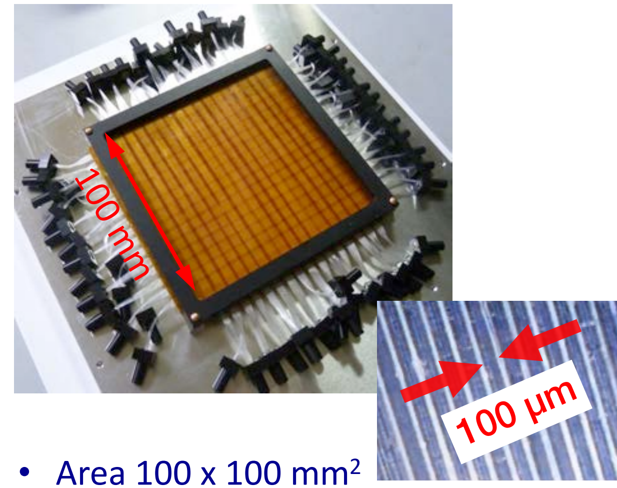
New



- Readout chips (SliT128A, 128 ch/chip)
- Developed for **J-PARC g−2/EDM experiment**
- Highly-segmented
- High-rate capability (S/N ~ 21)

- Strip pitch: 0.19 mm
- Strip length: 48.575 mm
- No. of strips: 512 x 2 blocks
- Thickness: 0.32 mm

Muon Beam Profile Monitor



- Area 100 x 100 mm^2
- 100-µm fiber hodoscope (16 ch x 2)
- 3 x 3mm^2 active area MPPC with 15-µm pixel pitch
- EASIROC readout