Muonic Helium HFS Measurements at J-PARC

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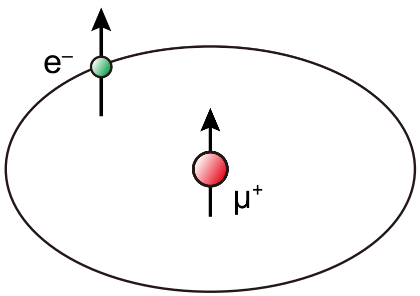
On behalf of the

MuSEUM Collaboration

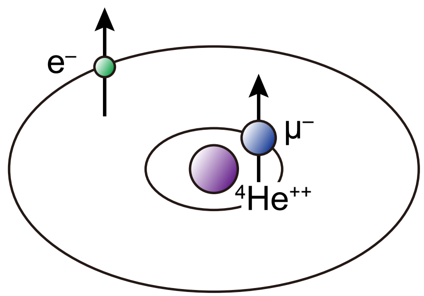
(**Mu**onium **S**pectroscopy **E**xperiment **U**sing **M**icrowave)

The 9th International Symposium on Symmetries in Subatomic Physics (SSP2025)
Nara Kasugano International Forum (IRAKA), Nara, Japan, September 23-28, 2025

Muonic Helium Atom

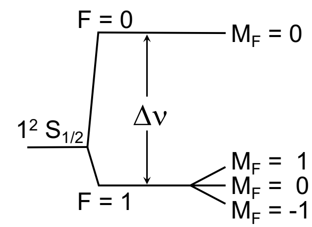


Muonium



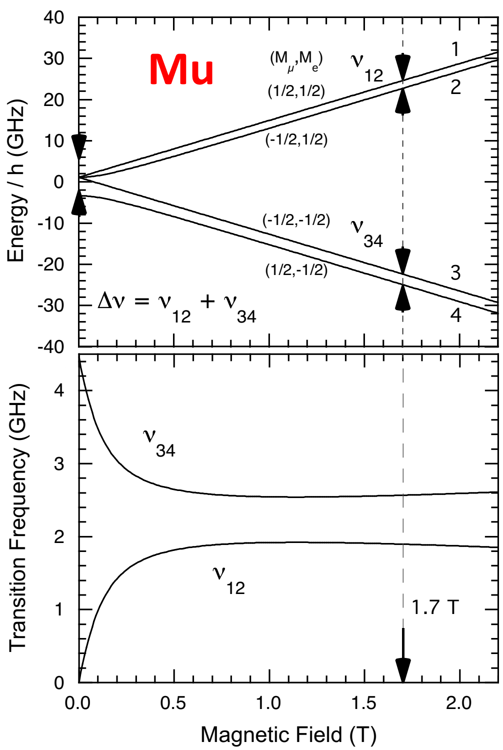
Muonic Helium

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

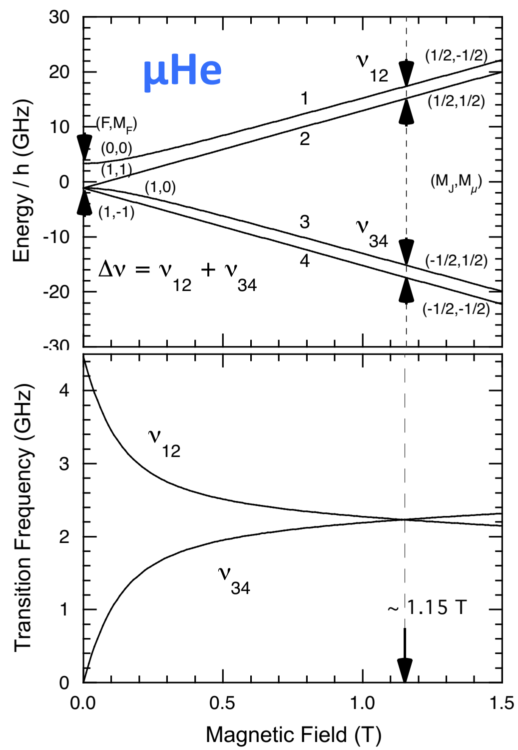


Ground-state muonic helium HFS structure and low-field Zeeman splitting

$\Delta\nu$(Mu) = 4463.302765(53) MHz



$\Delta\nu$(μHe) = 4464.980(20) MHz



Breit-Rabi energy level diagrams

Sensitive tool to …

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

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

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

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

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

Muon Precision Measurement @ 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

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

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

BNL(μ^-)

FNAL(μ^+)

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

POSITIVE MUON

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

m_{μ^+}

MuMass@PSI

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

Muon $g-2$

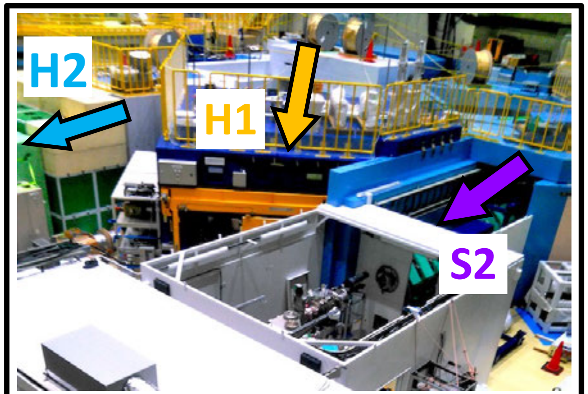
New physics beyond SM

m_{μ^+}

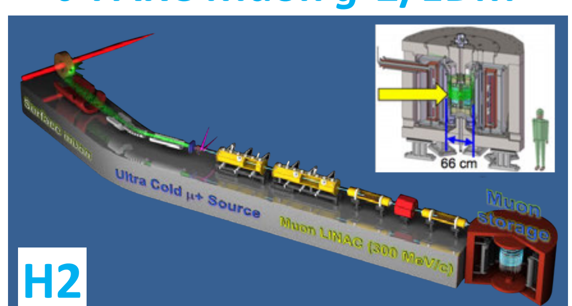
Muonium $1s-2s$

Muon mass m_{μ^+}

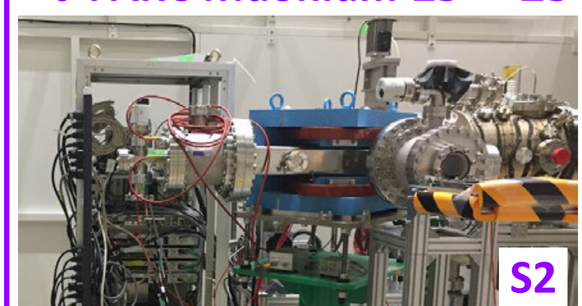
J-PARC MLF



J-PARC Muon *g*-2/EDM



J-PARC Muonium $1s-2s$



Previous μHe HFS Experiments ('80s)

Zero Field (SIN)

pressure: 20 atm

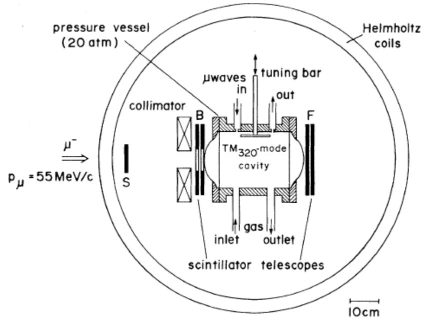
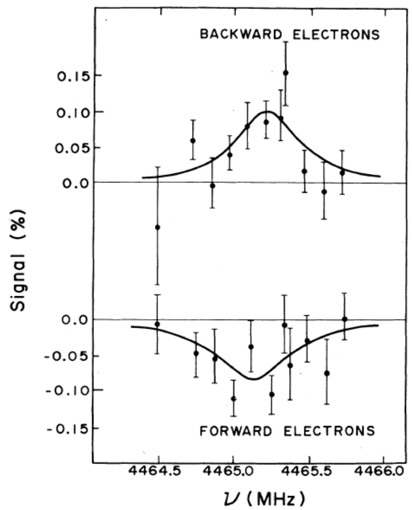
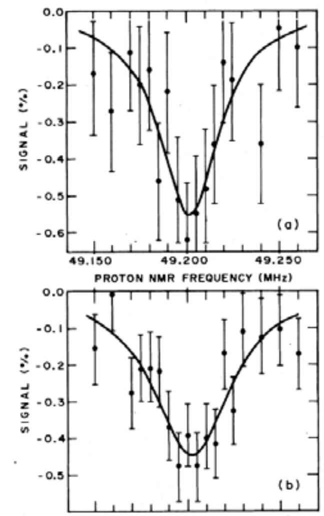


FIG. 2. Schematic view of the apparatus. The Helmholtz coils are used for muon-spin rotation. A cylindrical high-permeability metal shield (diameter 50 cm, length 100 cm) was installed (not shown in the figure) during the microwave magnetic-resonance experiment to reduce the stray magnetic fields.



High Field (LAMPF)



pressure: 5 & 15 atm

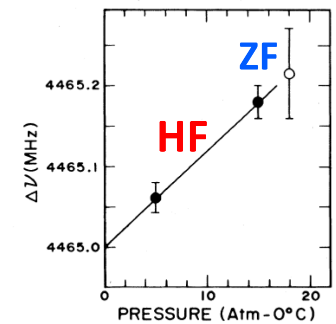


FIG. 2. Δν as a function of He+Xe(1.5%) gas pressure. Closed circles show the results of this experiment; the open circle is the result of Ref. 3. The straight line shows the linear extrapolation used to extract Δν(0).

	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 will soon come out:
- **MuSEUM** at J-PARC
- **Mu-MASS** at PSI [6]
- **Muonium 1S-2S spectroscopy** at J-PARC

- The direct experimental value of the "**negative muon mass**" is only determined to **3.1 ppm** from muonic X-ray studies using bent-crystal spectrometer [7]. μ_{μ^-} obtained within the same accuracy.
  - ➢ The ratio μ_{μ^+}/μ_{μ^-} gives a **CPT invariance 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 existing BNL muon g–2 experiment [9].

[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

More precise measurement of the negative muon magnetic moment highly desirable !

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

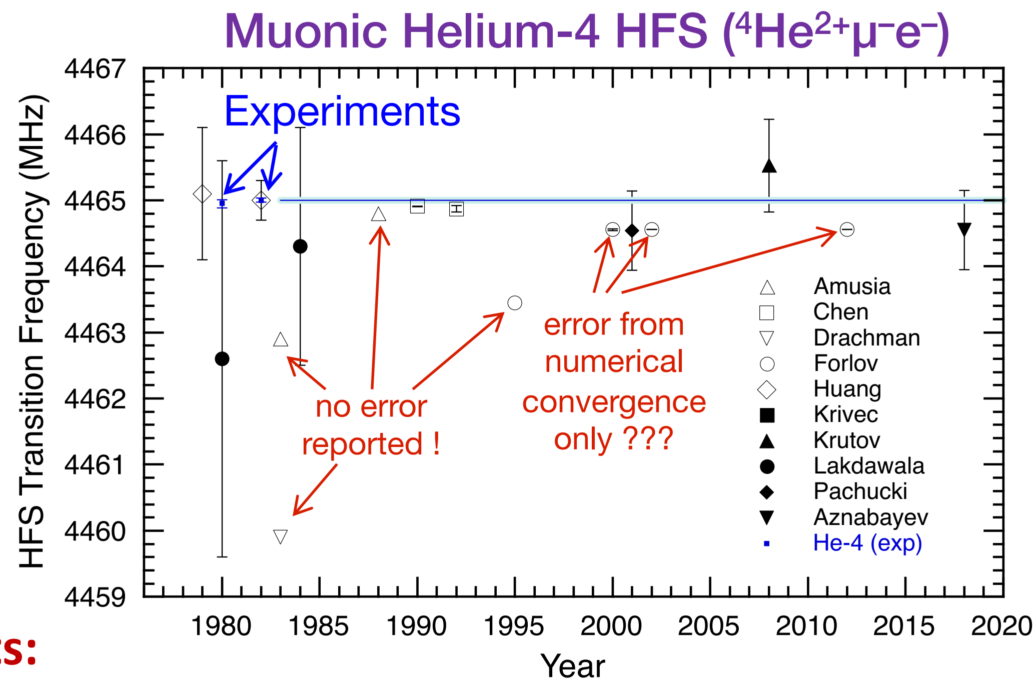
- Ground state HFS of muonic helium is very similar to muonium.
- In reality, however, muonic helium is complicated because three-body interaction has to be considered, thus limiting the theoretical approach.

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

Muonic Atom Spectroscopy Theory Initiative

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Muonic Atom Spectroscopy Theory Initiative

URL: https://asti.uni-mainz.de/

from **PUZZLE** ASTI *to* **PRECISION**

Inspired by the success of the Muon g-2 Theory Initiative we are launching the Muonic Atom Spectroscopy Theory Initiative (μASTI).

The initiative aims to support the experimental effort on the spectroscopy of light muonic atoms by improving the Standard Model theory predictions for the Lamb shift and hyperfine splitting in muonic hydrogen, deuterium, and helium, in order to match the anticipated accuracy of future measurements. An initial focus will be on the ground state hyperfine splitting in muonic hydrogen.

Next summer (**28.07.-01.08.2025**) we will have a workshop on **"New perspectives in the charge radii determination of light nuclei"** at the **ECT* centre** (European centre for theoretical studies in nuclear physics and related areas) in Trento.

All workshops are hybrid events.

Steering Committee

Aldo Antognini

Carl Carlson

Franziska Hagelstein

Paul Indelicato

Krzysztof Pachucki

Vladimir Pascalutsa

Aim to improve the Standard Model theory predictions for the Lamb shift and hyperfine splitting in muonic hydrogen, deuterium, and muonic helium ion.

Note: the HFS in the three-body muonic ^{4}He atom is not covered at present.

Why so difficult compared to Mu?

Muonic helium atom residual polarization

- Depolarization during muon cascade process: **100% $\rightarrow$ 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 **$(^4\mathrm{He}\mu^-)^+$** ion $\rightarrow$ 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

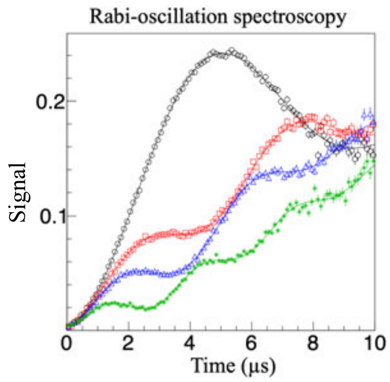
New μHe HFS at J-PARC MUSE

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

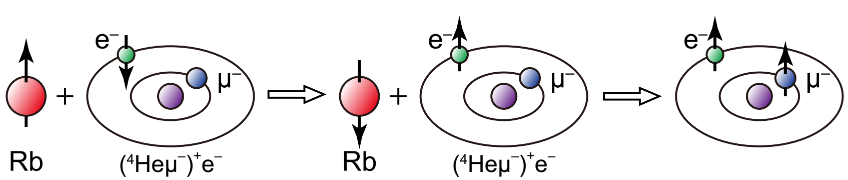
Three key components for improvement:

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

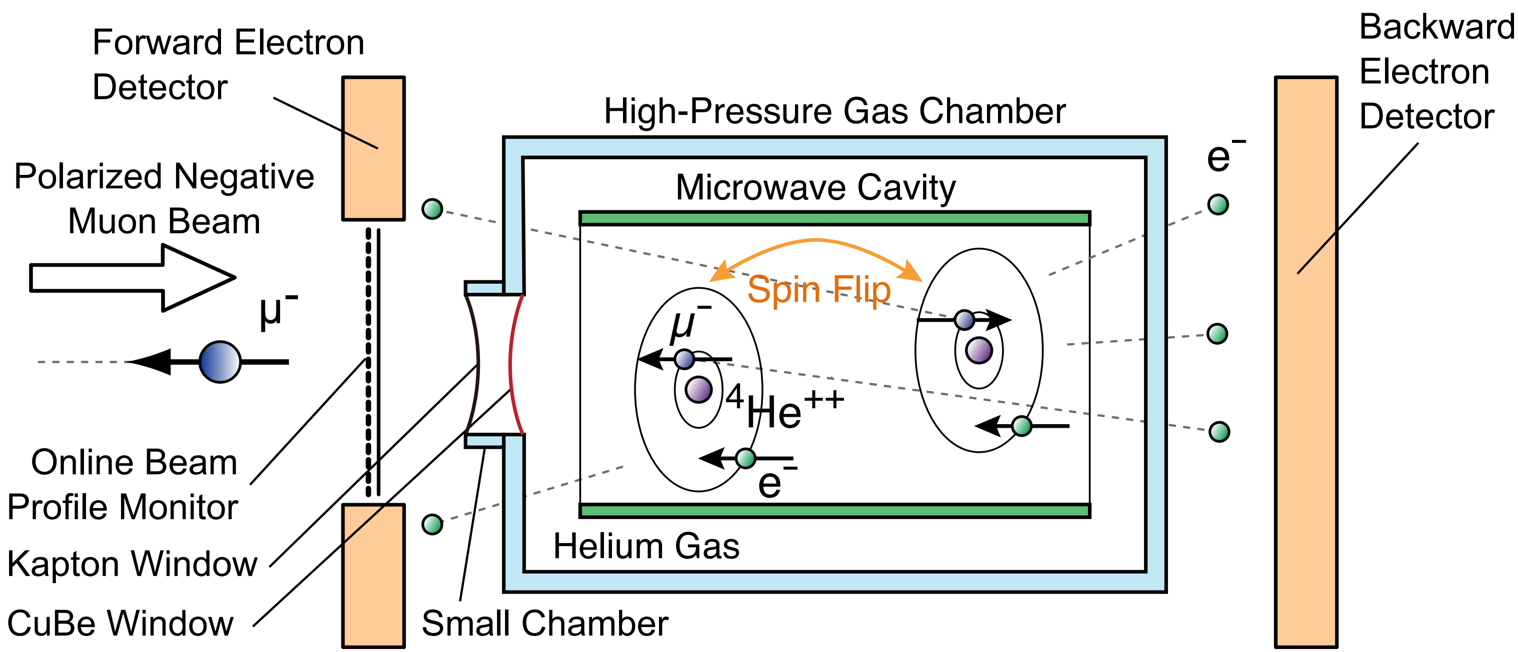
2) Applying **Rabi-oscillation spectroscopy technique** to HFS measurements.



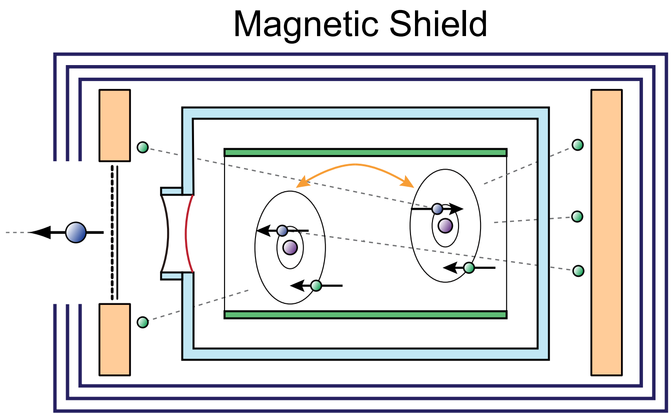
3) Producing **highly-polarized muonic helium atoms** to improve the μ⁻ residual polarization in helium by Spin Exchange Optical Pumping (SEOP).



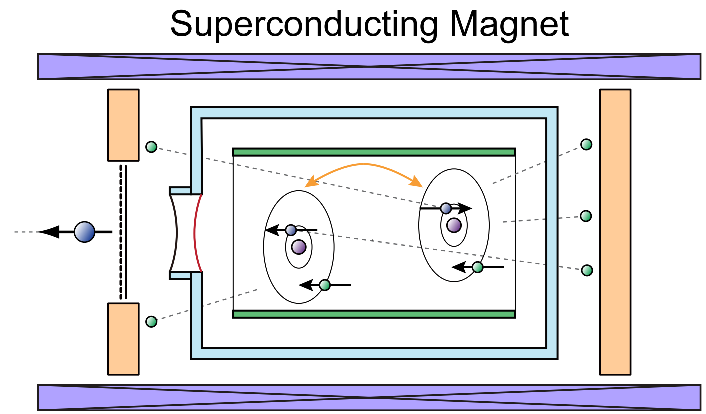
Experimental Arrangement



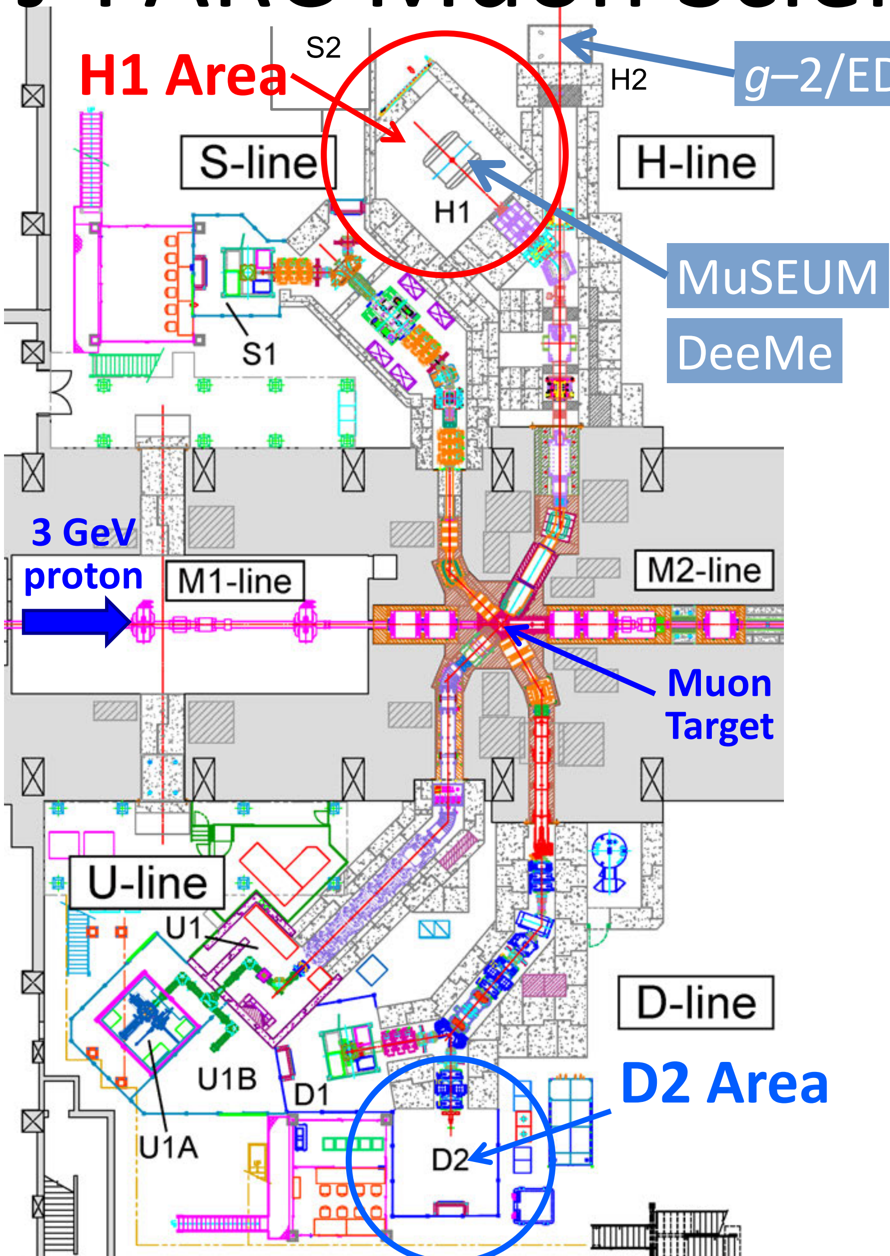
Zero-Field Measurements



High-Field Measurements



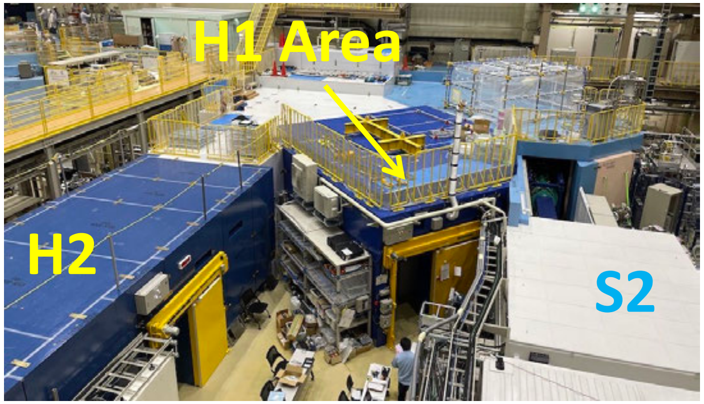
J-PARC Muon Science Facility (MUSE)



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:

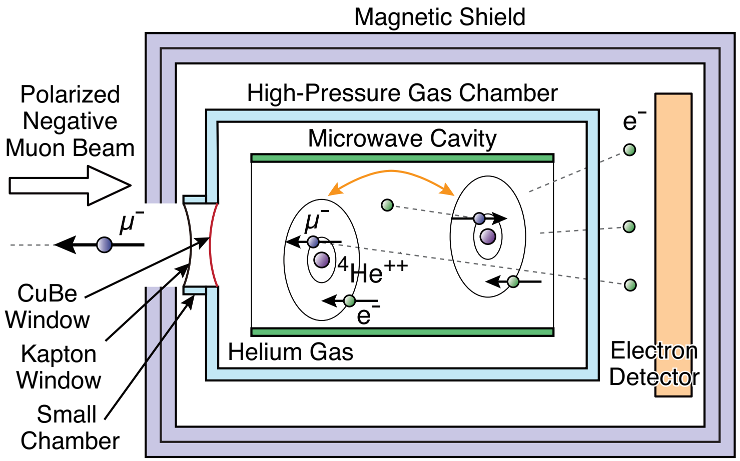
- MuSEUM experiment has similar systematical errors.
- Present estimation: ~ 2 ppb for $\Delta\nu$ and ~ 20 ppb for μ_{μ^-}/μ_p.

D-line: (zero field)

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

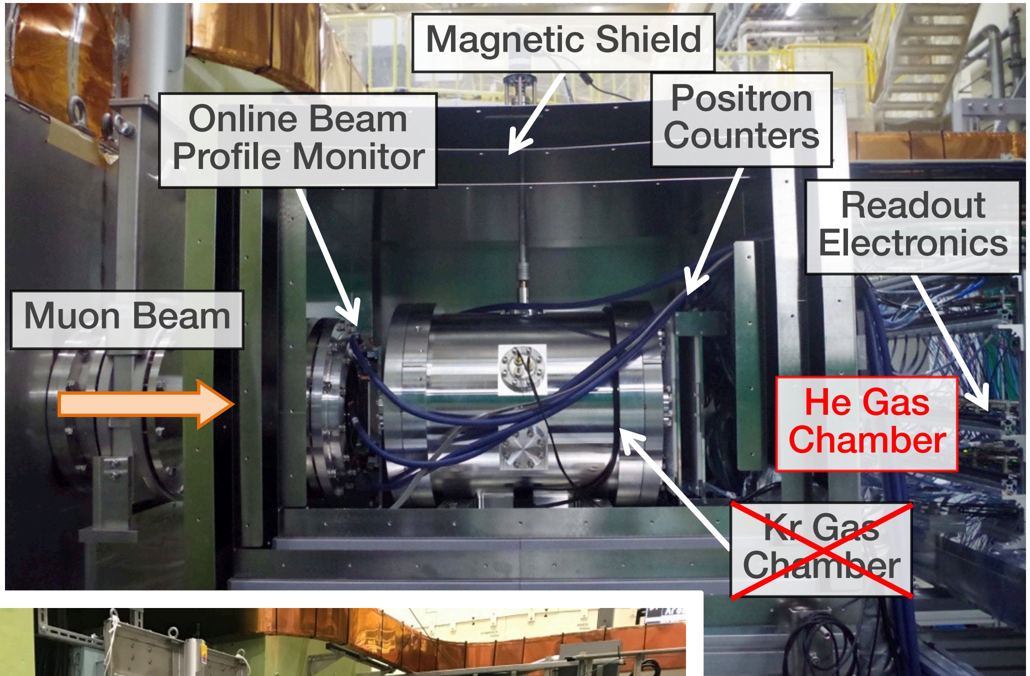
General User Program

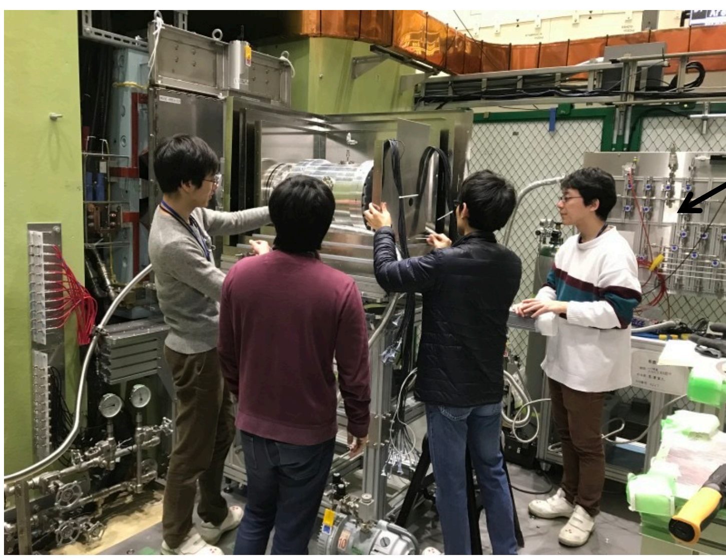
Muonic Helium HFS Measurement at Zero-Field



μHe HFS Measurements at Zero-Field

Experimental Setup



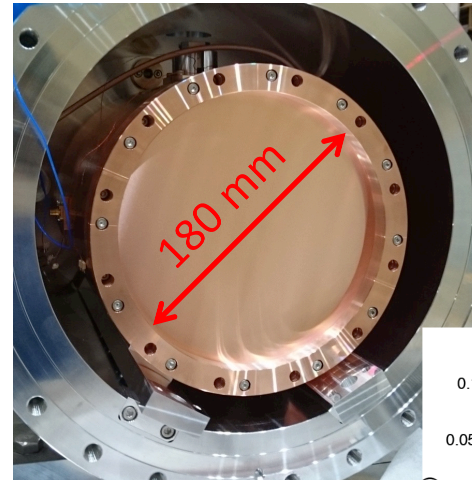


[2019B0318]

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

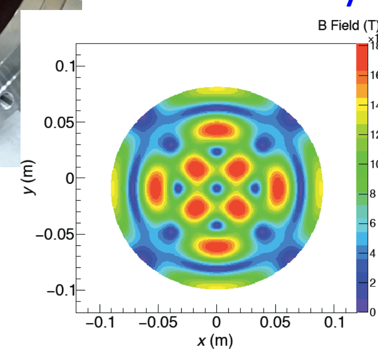
Q-Value:

20,000 (calc.)

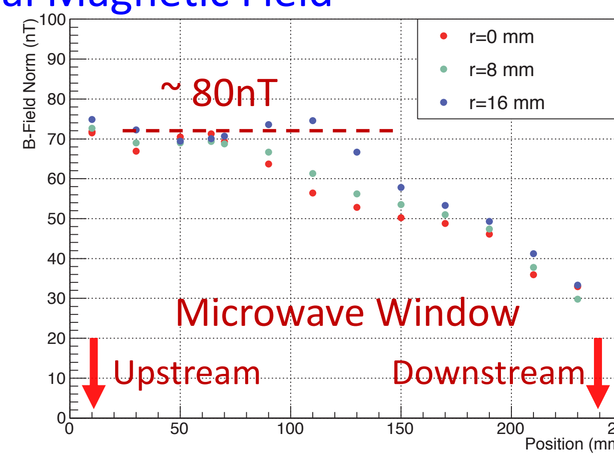
~~$\Delta\nu$ = 4.463 GHz~~

$\Delta\nu$ = 4.465 GHz

MW Intensity

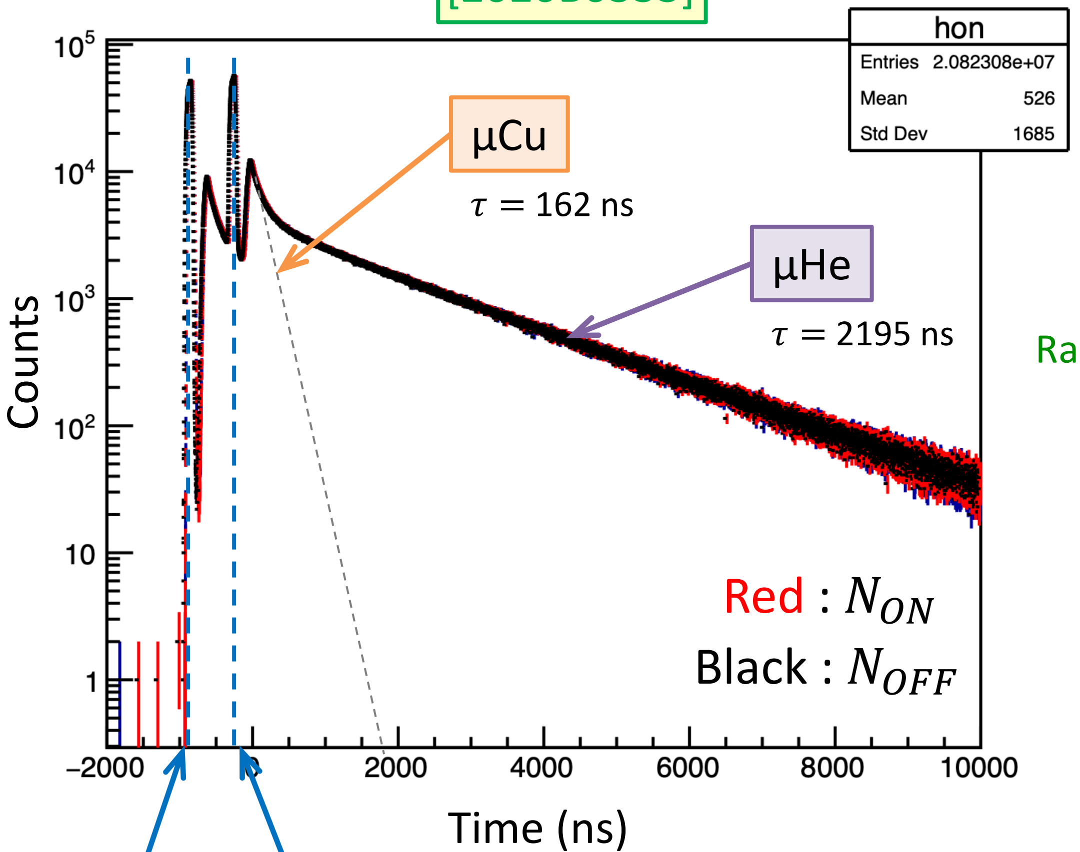


Residual Magnetic Field



Decay Electron Time Spectra

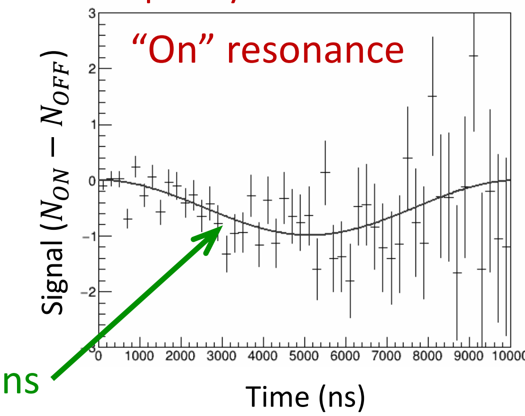
[2020B0333]



1st Muon Peak (-600 ns)

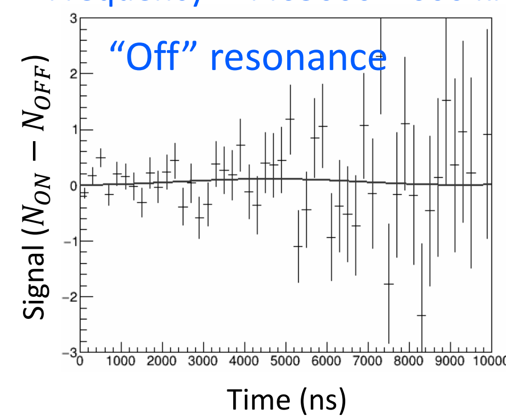
2nd Muon Peak (0 ns)

Frequency = 4465000 + 0 kHz



Rabi Oscillations

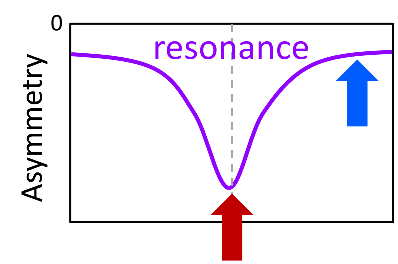
Frequency = 4465000 + 600 kHz



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

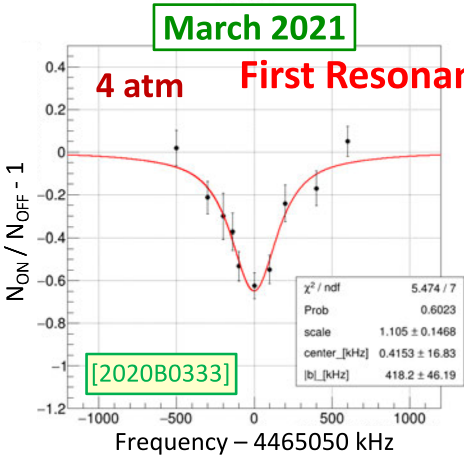
N_{ON} : Number of e⁻ with microwave

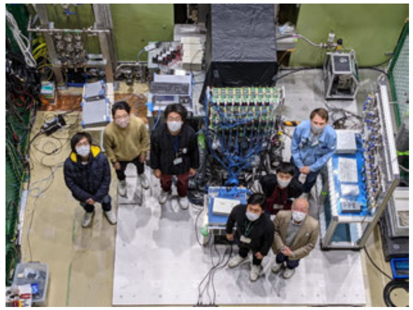
N_{OFF} : Number of e⁻ without microwave

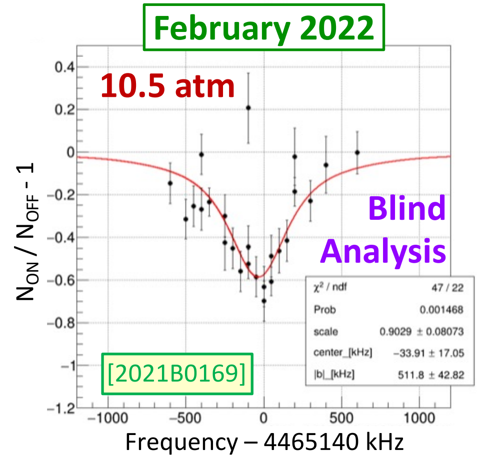


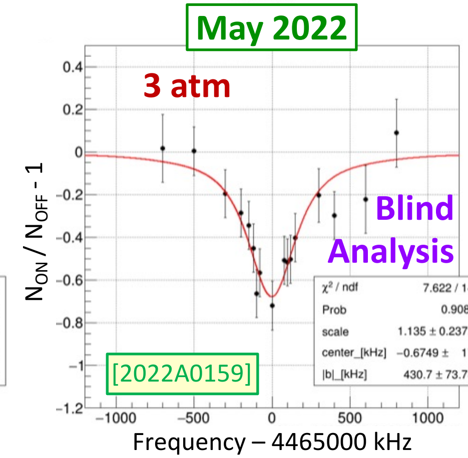
μHe HFS Resonance Curve

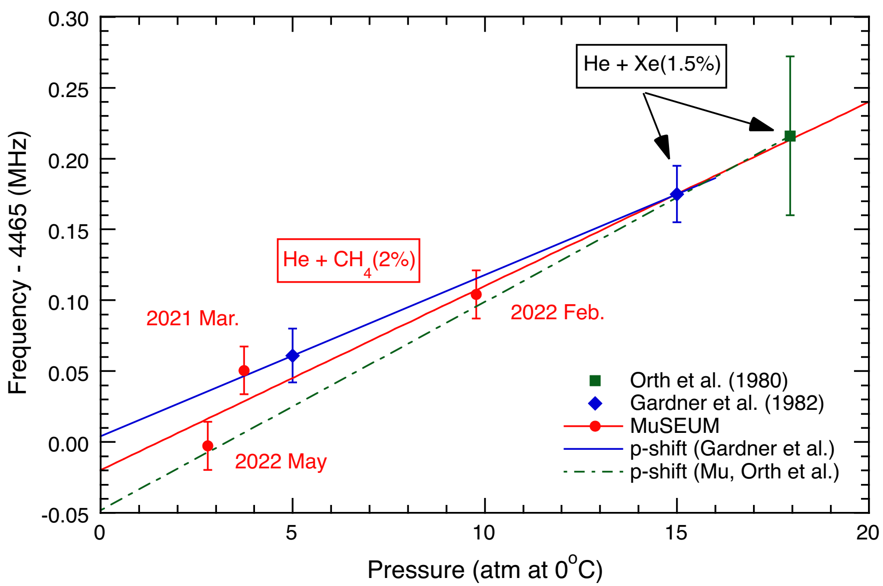
First Resonance Observed











Time cut: electron data from 1.6 μs after second μ^- pulse !

ZF: H. Orth et al., PRL **45** (1980) 1483

HF: C. J. Gardner et al., PRL **48** (1982) 1168

After 40 years
New World Record!

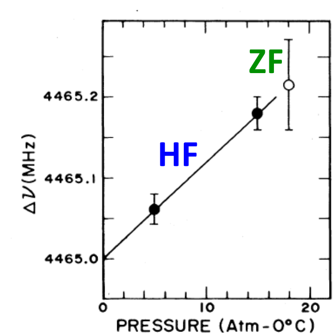


FIG. 2. Δν as a function of He+Xe(1.5%) gas pressure. Closed circles show the results of this experiment; the open circle is the result of Ref. 3. The straight line shows the linear extrapolation used to extract Δν(0).

Δν = 4464.95(6) MHz (Orth et al.) [13 ppm] zero field (ZF)

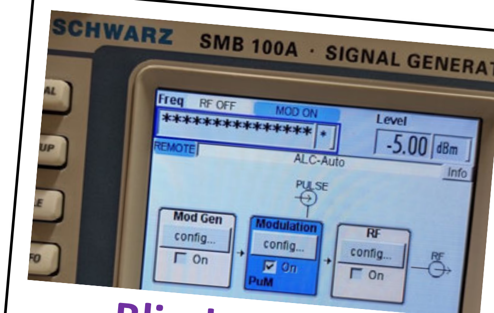
Δν = 4465.004(29) MHz (Gardner et al.) [6.5 ppm] high field (HF)

Δν = 4464.980(20) MHz (MuSEUM) [4.5ppm] zero field

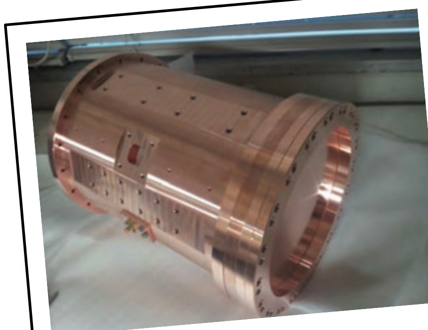
P. Strasser et al., Phys. Rev. Lett. **131** (2023) 253003

Development for High-Field Experiment

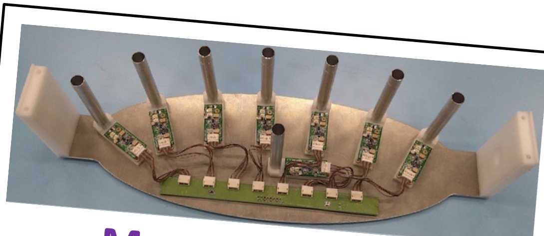
MRI Magnet



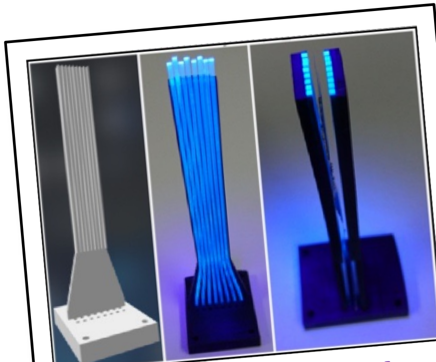
Blind Analysis



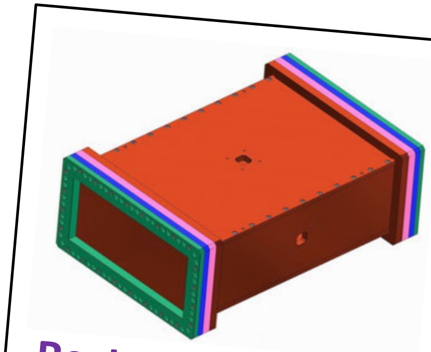
HF Cavity



Magnetic Probes



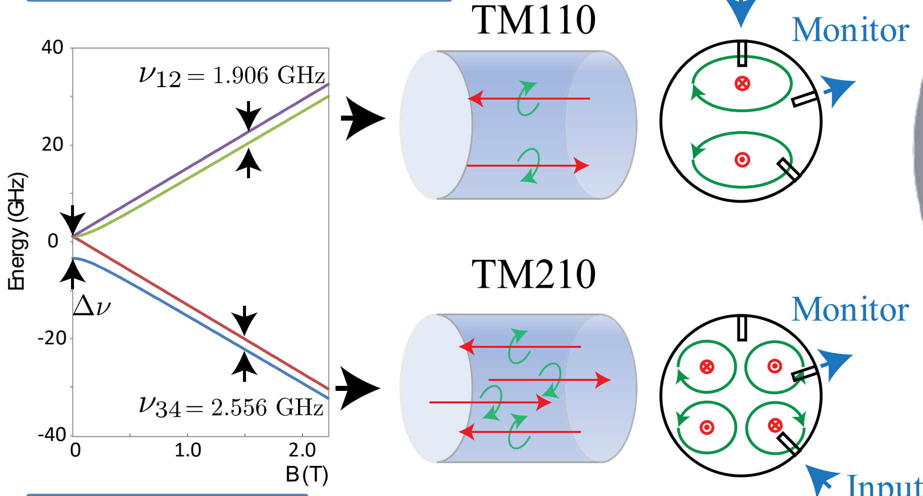
Upstream Detector



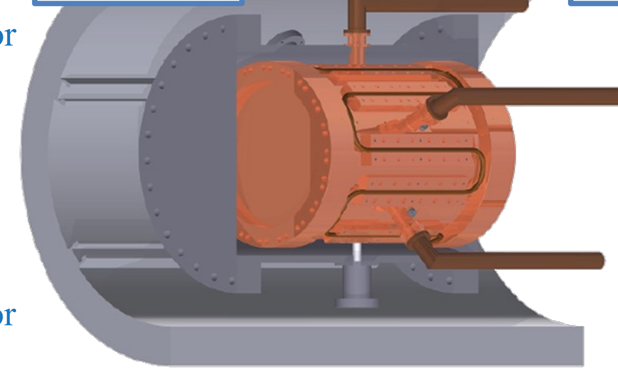
Rectangular Cavity

High-Field Microwave Cavity (Mu&μHe)

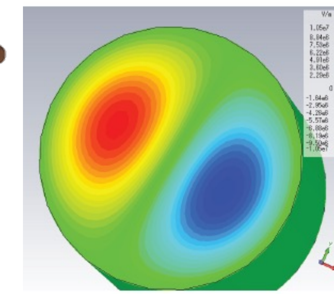
Cylindrical Cavity



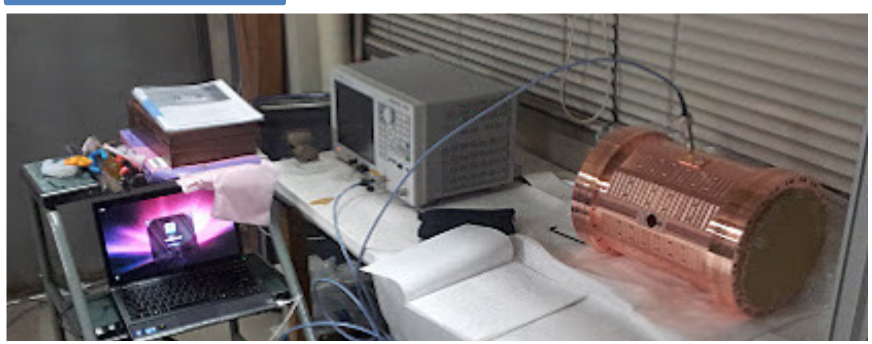
3D CAD



MWS Simulation

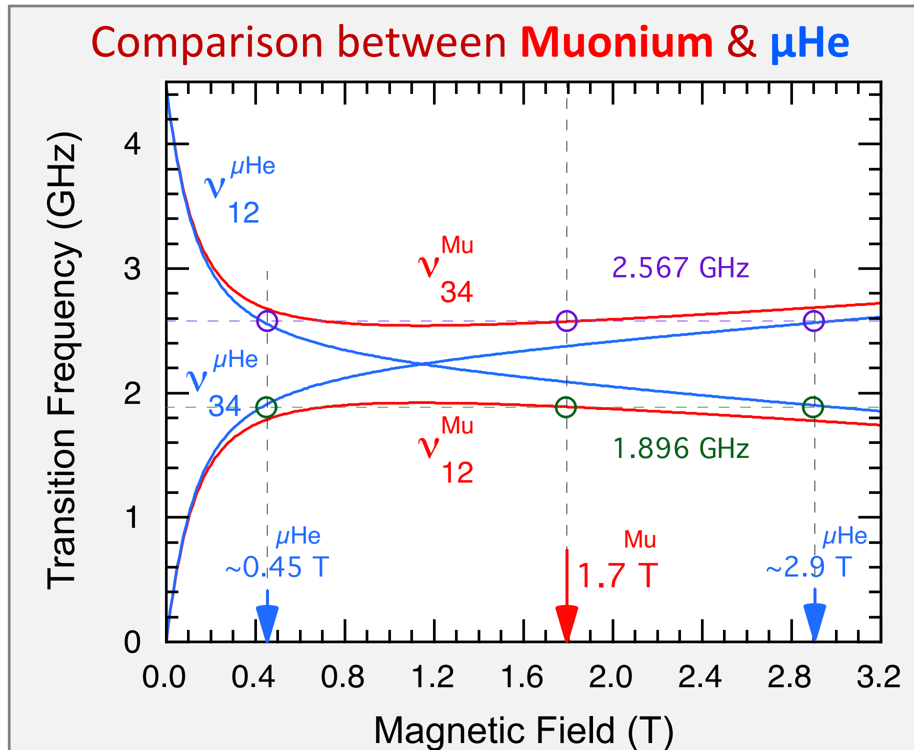


Cavity Test

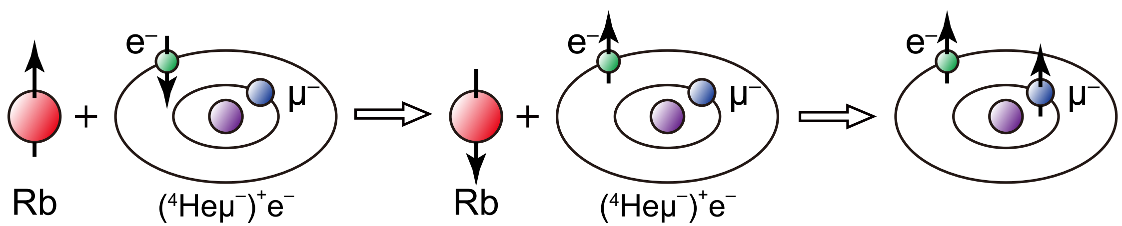


Q Value

Modes	Q (measured)	Q (simulation)
TM110	1.13 x 10⁴	2.97 x 10⁴
TM210	8.05 x 10³	2.89 x 10⁴



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)

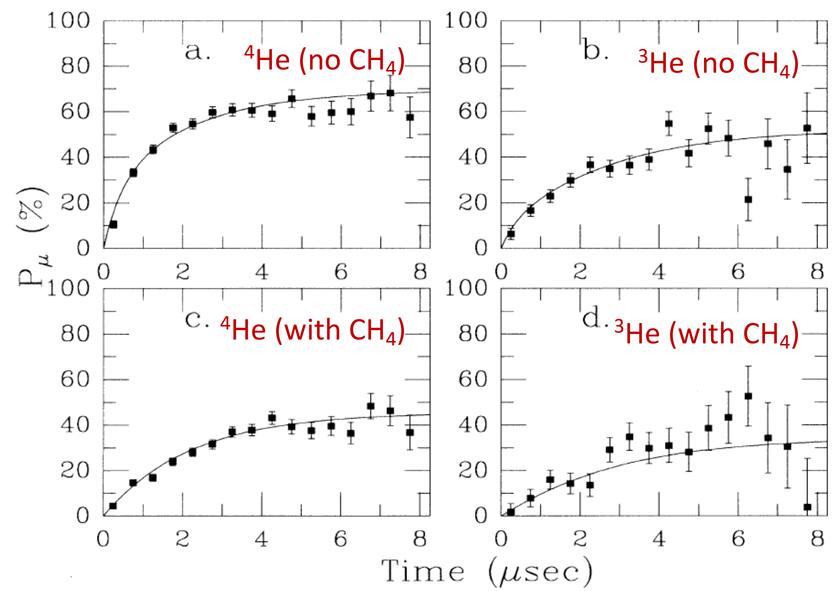
Glass cell target: (T ≈ 200°C)

- 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^4He: 6% → 44%

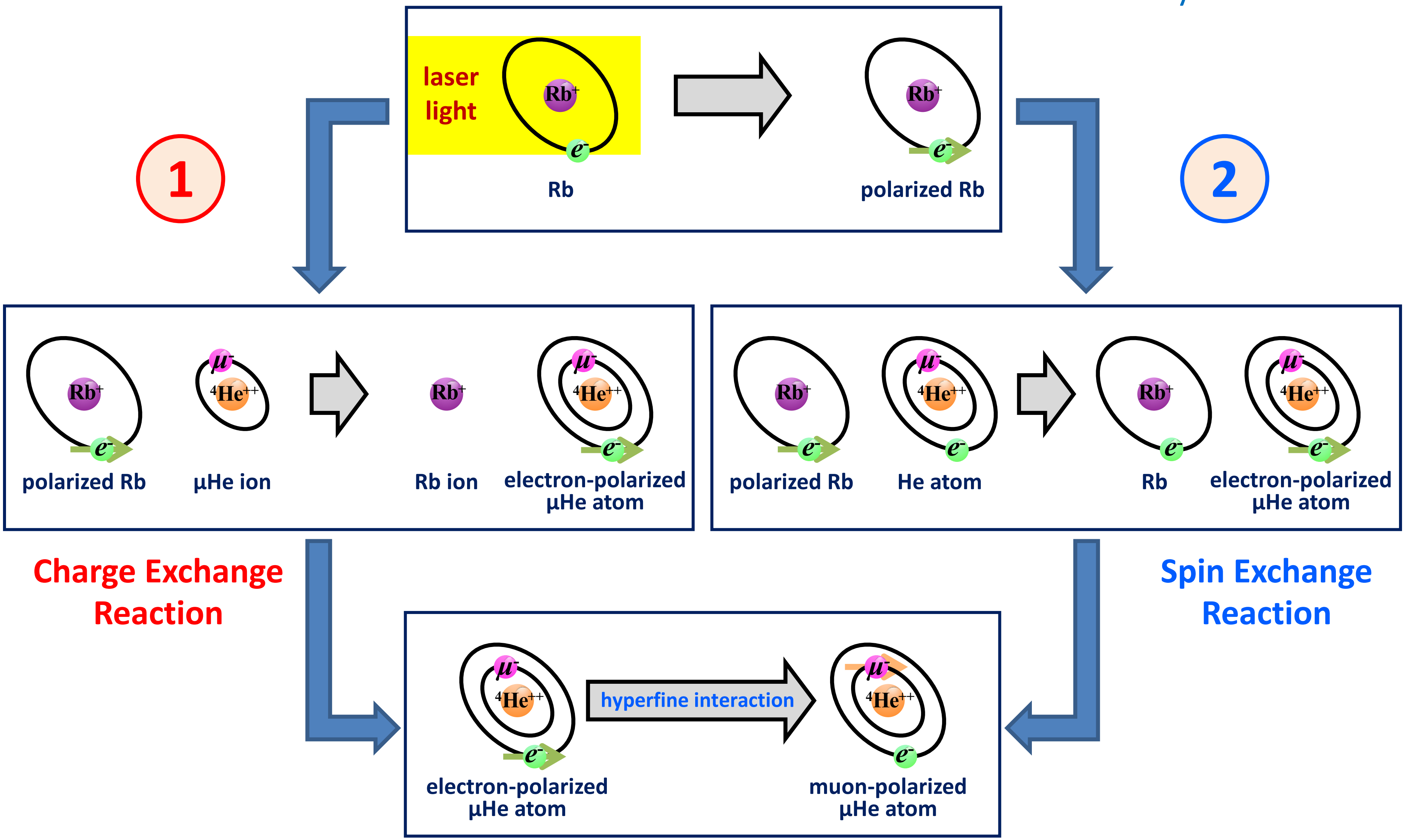
Improvement by a factor 7 achieved !

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



Polarization of Muonic He Atom

by S. Fukumura



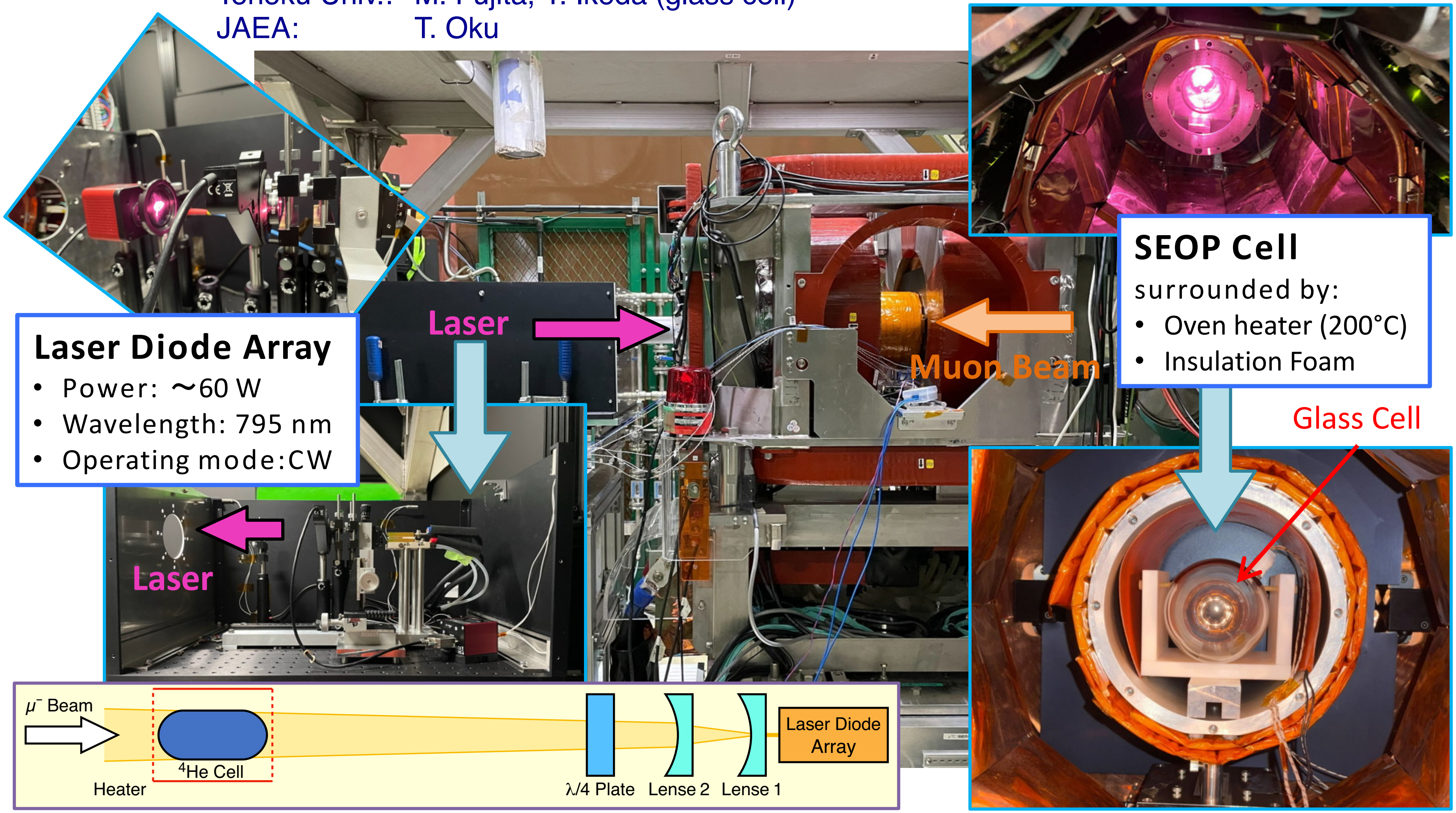
μHe SEOP Objectives

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



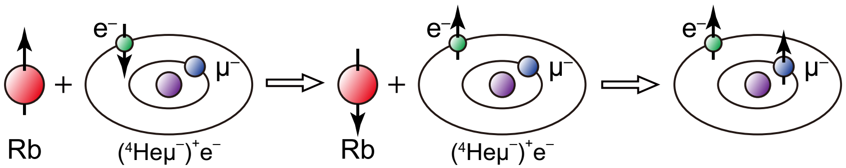
Laser Diode Array
- Power: ～60 W
- Wavelength: 795 nm
- Operating mode:CW

SEOP Cell
surrounded by:
- Oven heater (200°C)
- Insulation Foam

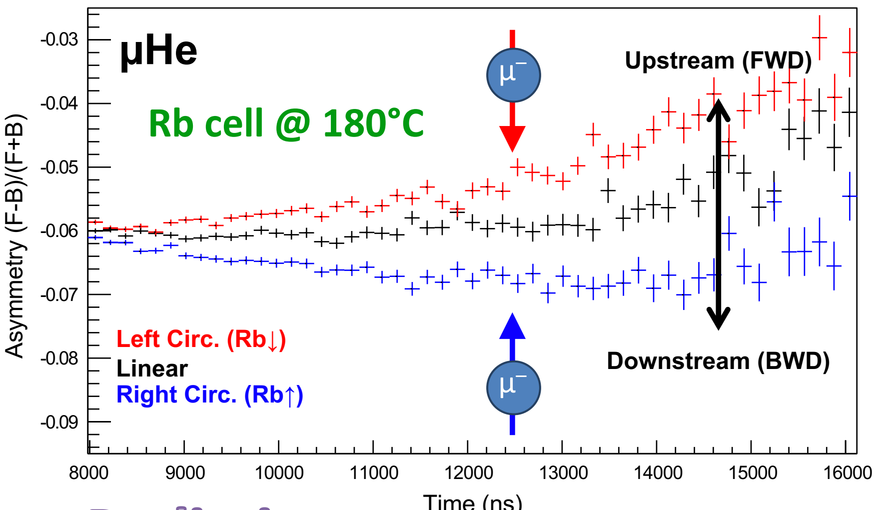
μHe SEOP Beamtime (Feb. 2023)

Muonic helium atom residual polarization

- Depolarization during muon cascade → **~5%** (muonium 50%)
- Re-polarization of muonic He atom by spin exchange optical pumping (SEOP)

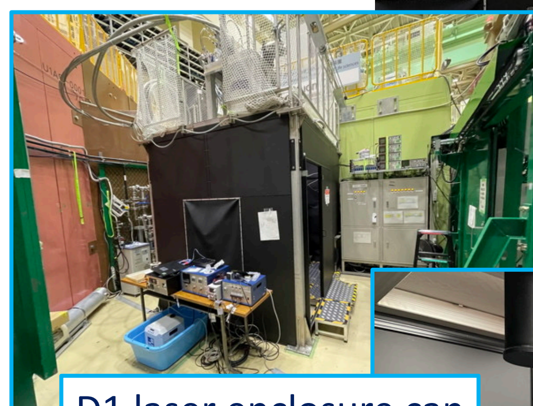


S. Fukumura
T. Okudaira
(Nagoya Univ.)



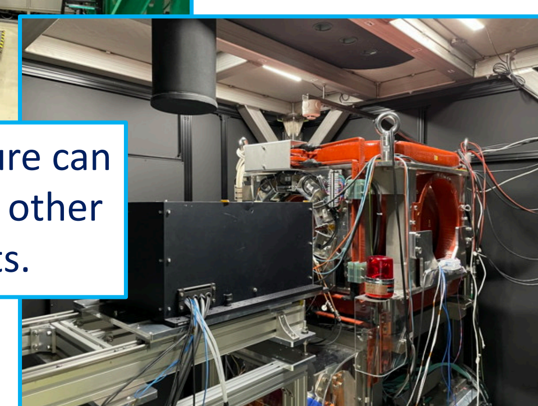
Very Preliminary

- ➢ **First laser experiment at area D1**
- ➢ **First successful μHe SEOP Results!**

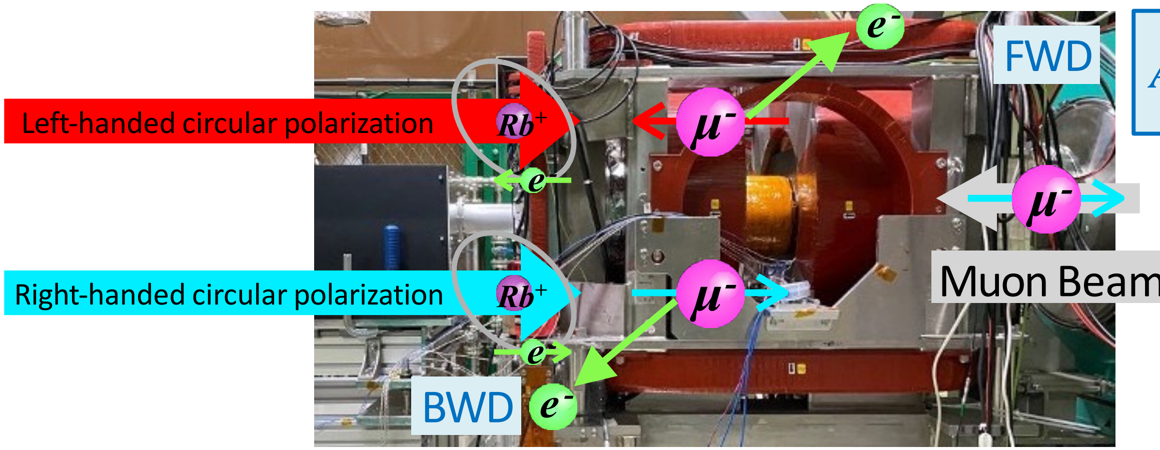


&

D1 laser enclosure can also be used by other experiments.



Glass Cell Development



$$A(t) = \frac{F(t) - B(t)}{F(t) + B(t)}$$

P3
Latest developments
Please see poster
by Takashi Ino
(today from 16:30)

Glass Cells:

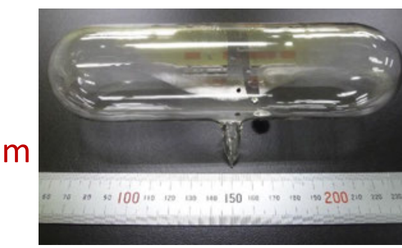
- Blown at the Glass Workshop of Tohoku University
- Filled and tested by Takashi Ino (KEK)

Old Pyrex Cell

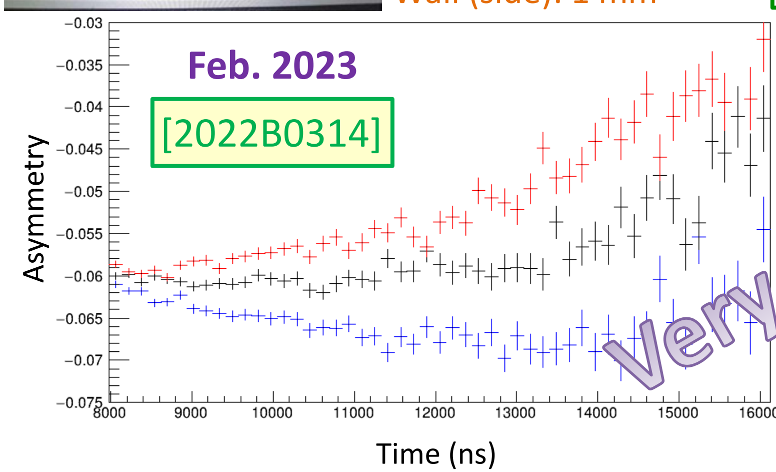
Size: Ø75 mm x 150 mm
Wall (front): 1 mm
Wall (side): 1 mm

Rb cell: 180°C

New GE-180 Cell



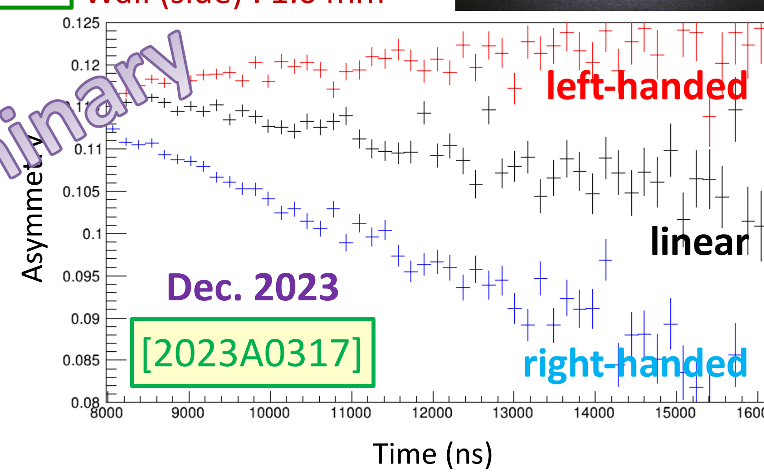
Size: Ø50 mm x 180 mm
Wall (front) : 0.5 mm
Wall (side) : 1.0 mm



Upstream (FWD)

Downstream (BWD)

Very Preliminary

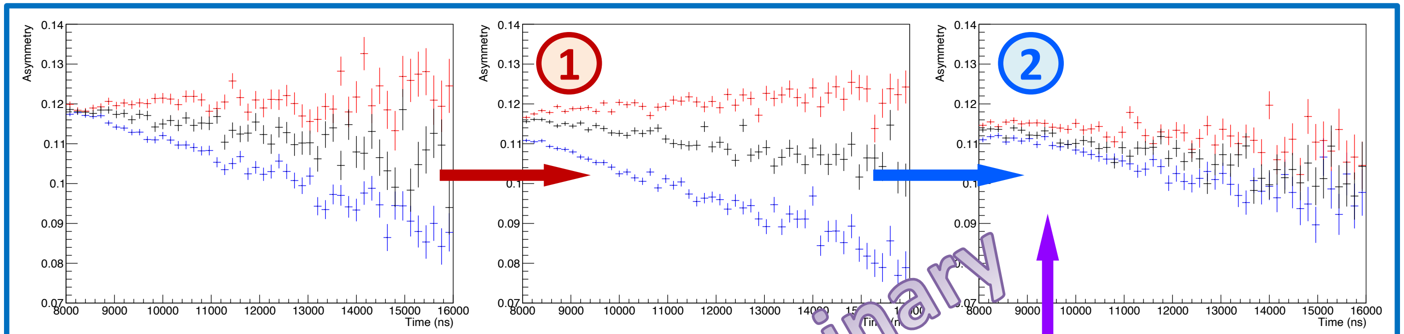


μHe SEOP vs. Hybrid-SEOP

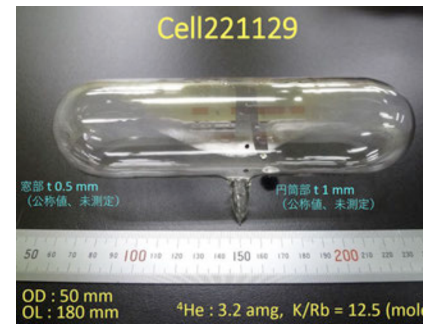
160 °C | 180 °C | 200 °C | 240°C

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

Rb Pure Cell

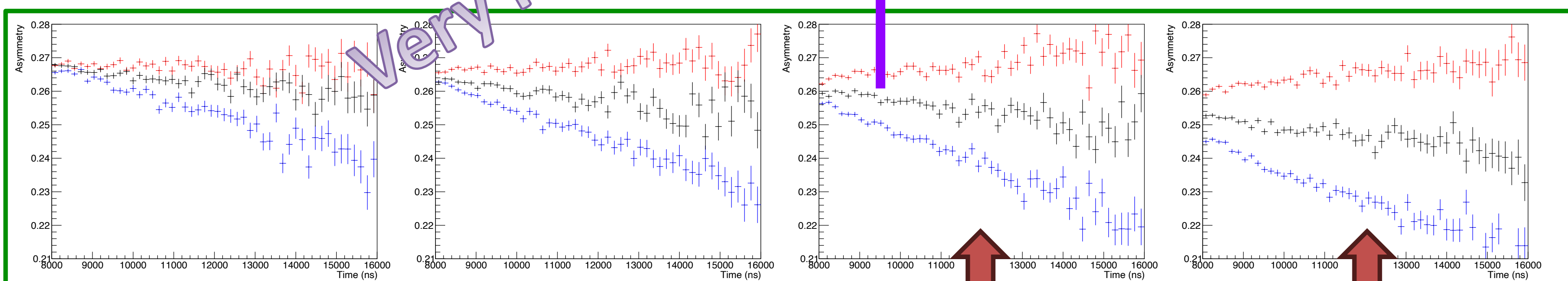


Hybrid Cell
[K]/[Rb] = 12.5 (mole)



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)

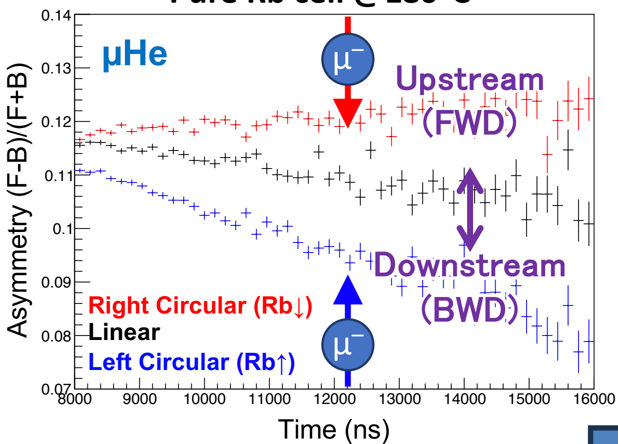
Comparison: Pure & Hybrid Cell

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

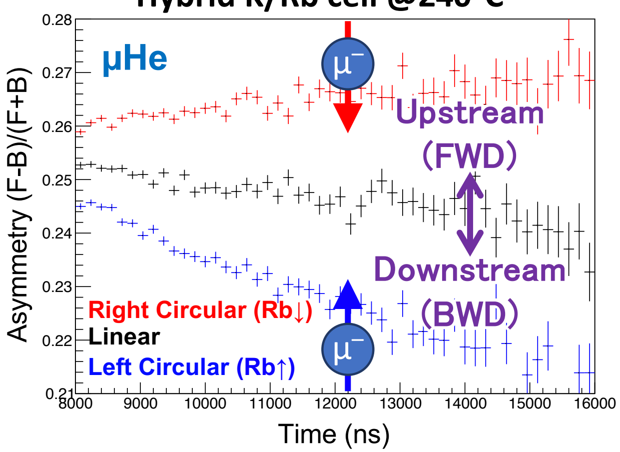
$$A_0 P_{SEOP}(t) = \frac{R(t) - L(t)}{(N_{He}^{R} + N_{He}^{L})\exp(-\lambda_{He} t)}$$

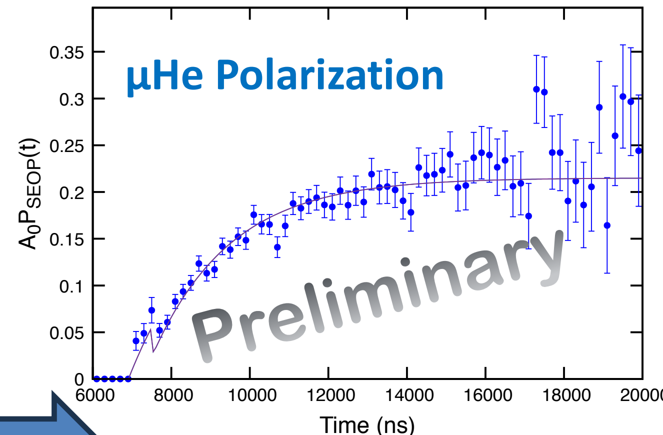
Muons stopped in He

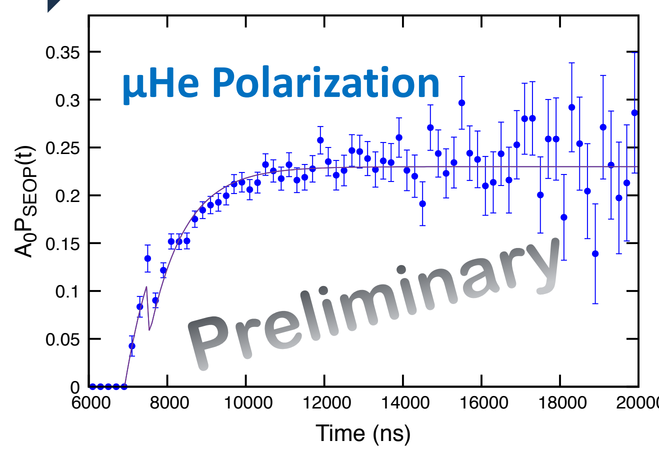
Pure Rb cell @180°C



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

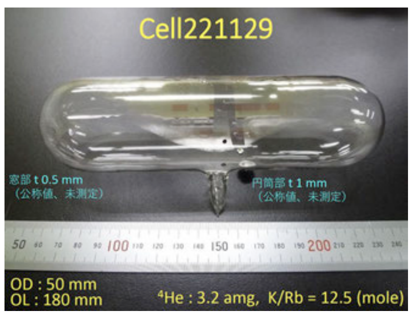
Analysis in progress

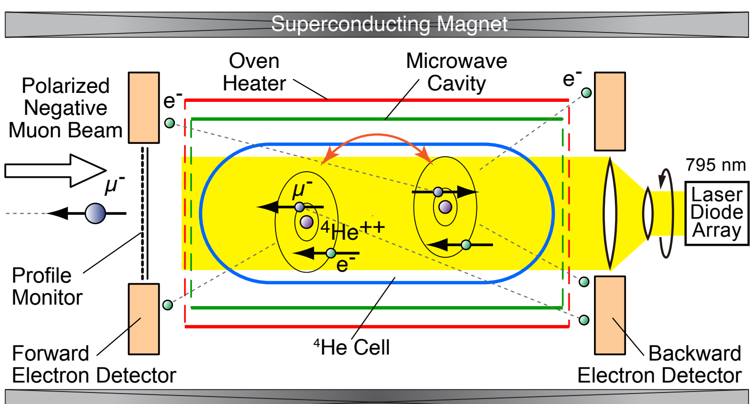
- High polarizing rate with high polarization efficiency achieved with “Hybrid” at 240°C

From Glass to Metal Cell

Advantages:

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





Apparatus for SEOP μHe-HFS experiment

Laser polarized muonic ^{3}He and spin dependent μ^- capture

P.A. Souder[a,*], P.L. Bogorad[b], E.J. Brash[c], G.D. Cates[b], W.J. Cummings[e], A. Gorelov[c], M.D. Hasinoff[d], O. Hausser[c,e], K. Hicks[f], R. Holmes[a], J.C. Huang[d], K.S. Kumar[b], B. Larson[g], W. Lorenzon[g], J. McCracken[a], P. Michaux[e], H. Middleton[b], E. Saettler[d], D. Siegel[b], D. Tupa[h], X. Wang[a], A. Young[b]

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[b] Princeton University, Princeton, NJ 08544, USA
[c] Simon Fraser University, Burnaby, BC, Canada V5A 1S6
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[e] TRIUMF, Vancouver, BC, Canada V6T 2A3
[f] Ohio University, Athens, OH 45701, USA
[g] University of Pennsylvania, Philadelphia, PA, USA
[h] Los Alamos National Lab, Los Alamos, NM 08754, USA

Abstract

We have developed an apparatus that can polarize muonic ^{3}He and detect the triton from the reaction $\mu^- + {}^3He \to \nu + {}^3H$. With this apparatus, we have measured the vector analyzing power of the reaction. This technique promises to provide a good test of QCD.

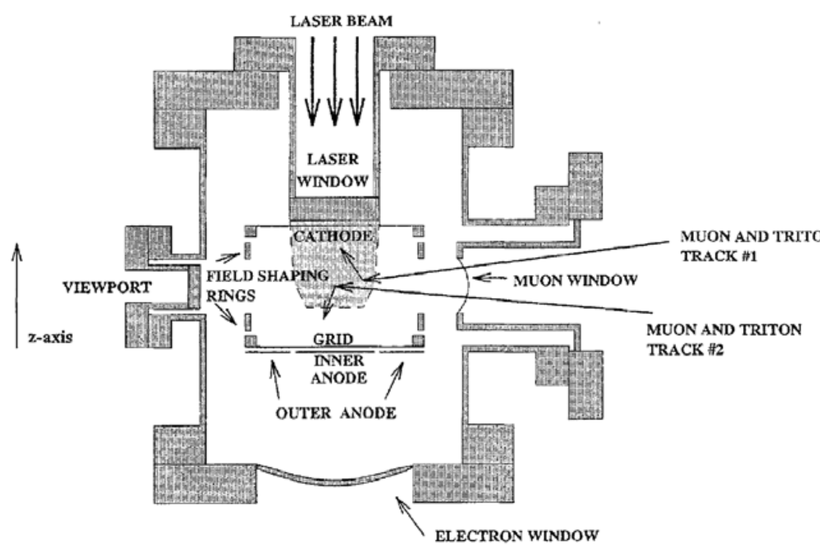

Fig. 1. Diagram of the polarized target/drift chamber.

P.A. Souder et al., Nucl. Instum. Meth. A **402** (1998) 311

Summary

- We are now performing precise measurements of the **ground-state hyperfine splitting of muonic helium atoms** at J-PARC MUSE
- New **zero-field measurements** using MuSEUM setup at **D2 area**
  - After 40 years, new **world's highest precision** of **4.5 ppm**
  - Zero-pressure value determined using only our data for He + 2% CH_4
- The **high-field experiment** planned at **H1 area** after muonium measurements
- Formation of **highly-polarized μHe atoms** by **SEOP** under development
- Beyond new frontiers …

"Muon Penning Trap at J-PARC"
Poster by
Takayuki Yamazaki

P10

(today from 16:30)

MuSEUM Collaboration

(Muonium Spectroscopy Experiment Using Microwave)

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