Challenges in Improving Measurements of the Hyperfine Structure of Muonic Helium Atoms

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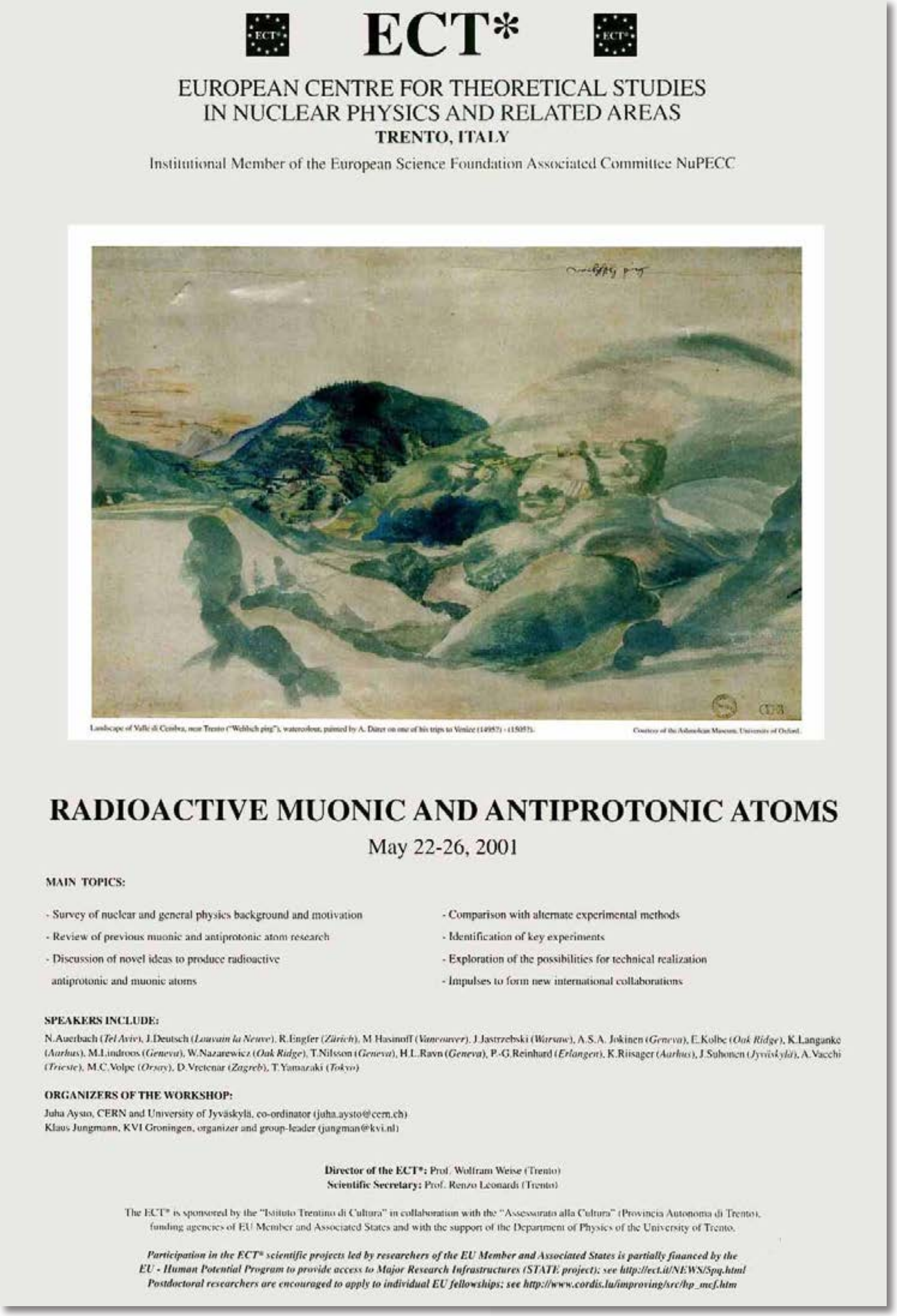
On behalf of the MuSEUM Collaboration

KAMPAI Workshop - Kaonic, Antiprotonic, Muonic, Pionic and "onia" exotic Atoms: Interchanging knowledge and recent results
ECT*, Trento, Italy, September 30 - October 4, 2024.

Old Memories

ECT*
RAMA Workshop
(2001)



ECT*

EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS
TRENTO, ITALY

Institutional Member of the European Science Foundation Associated Committee NuPECC

Landscape of Valle di Cembra, near Trento ("Welsch pirg"), watercolour, painted by A. Dürer on one of his trips to Venize (1495?) - (1505?).

Courtesy of the Ashmolean Museum, University of Oxford.

RADIOACTIVE MUONIC AND ANTIPROTONIC ATOMS

May 22-26, 2001

MAIN TOPICS:

- Survey of nuclear and general physics background and motivation
- Review of previous muonic and antiprotonic atom research
- Discussion of novel ideas to produce radioactive antiprotonic and muonic atoms
- Comparison with alternate experimental methods
- Identification of key experiments
- Exploration of the possibilities for technical realization
- Impulses to form new international collaborations

SPEAKERS INCLUDE:

N.Auerbach (*Tel Aviv*), J.Deutsch (*Louvain la Neuve*), R.Engfer (*Zürich*), M.Hasinoff (*Vancouver*), J.Jastrzebski (*Warsaw*), A.S.A. Jokinen (*Geneva*), E.Kolbe (*Oak Ridge*), K.Langanke (*Aarhus*), M.Lindroos (*Geneva*), W.Nazarewicz (*Oak Ridge*), T.Nilsson (*Geneva*), H.L.Ravn (*Geneva*), P.-G.Reinhard (*Erlangen*), K.Riisager (*Aarhus*), J.Suhonen (*Jyväskylä*), A.Vacchi (*Trieste*), M.C.Volpe (*Orsay*), D.Vretenar (*Zagreb*), T.Yamazaki (*Tokyo*)

ORGANIZERS OF THE WORKSHOP:

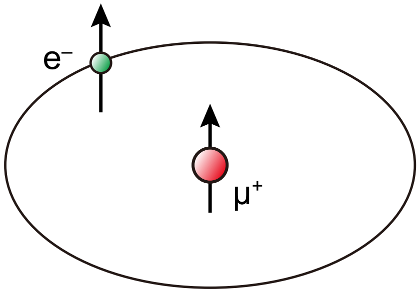
Juha Aysto, CERN and University of Jyväskylä, co-ordinator (juha.aysto@cern.ch)
Klaus Jungmann, KVI Groningen, organizer and group-leader (jungman@kvi.nl)

Director of the ECT*: Prof. Wolfram Weise (Trento)
Scientific Secretary: Prof. Renzo Leonardi (Trento)

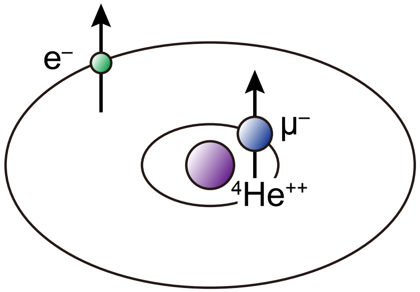
The ECT* is sponsored by the "Istituto Trentino di Cultura" in collaboration with the "Assessorato alla Cultura" (Provincia Autonoma di Trento), funding agencies of EU Member and Associated States and with the support of the Department of Physics of the University of Trento.

Participation in the ECT* scientific projects led by researchers of the EU Member and Associated States is partially financed by the EU - Human Potential Program to provide access to Major Research Infrastructures (STATE project): see http://ect.it/NEWS/5pq.html
Postdoctoral researchers are encouraged to apply to individual EU fellowships: see http://www.cordis.lu/improving/src/hp_mcf.htm

Muonic Helium Atom



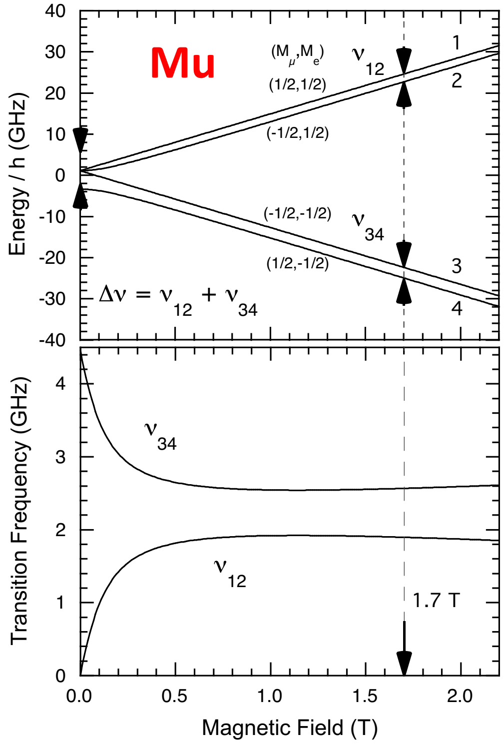
Muonium



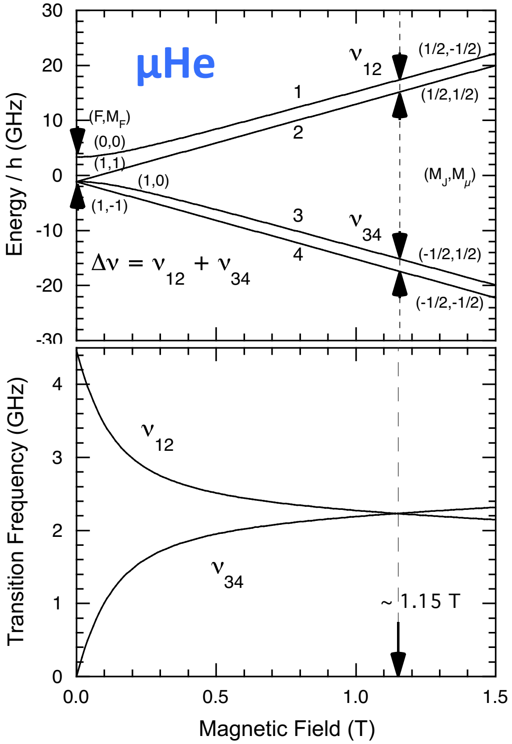
Muonic Helium

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

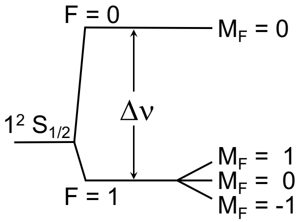
$\Delta\nu$(Mu) = 4463.302765(53) MHz



$\Delta\nu$(μHe) = 4465.004(29) MHz



Breit-Rabi energy level diagrams



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

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**

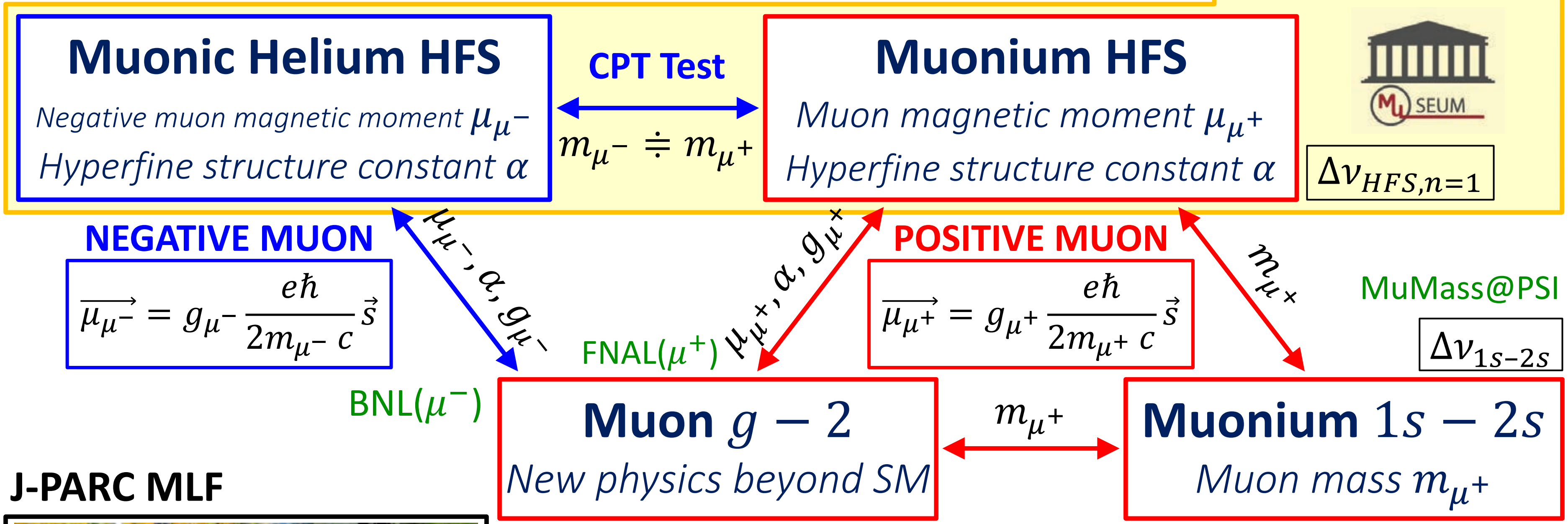
$$\boxed{\nu_{34} - \nu_{12} \approx \frac{\mu_{\mu^-}}{\mu_p}}$$

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

Muon Precision Measurement @ J-PARC MLF

MuSEUM

Diagram borrowed from Klaus Jungmann



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

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

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 $g-2$

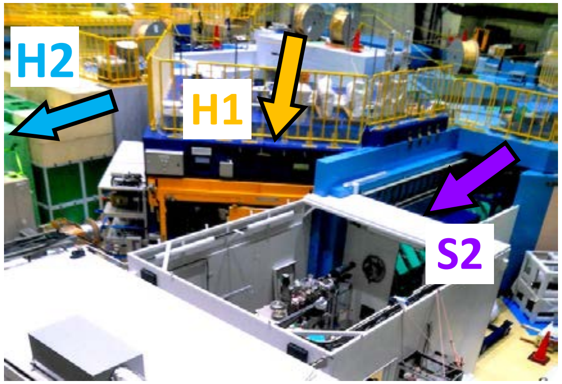
New physics beyond SM

m_{μ^+}

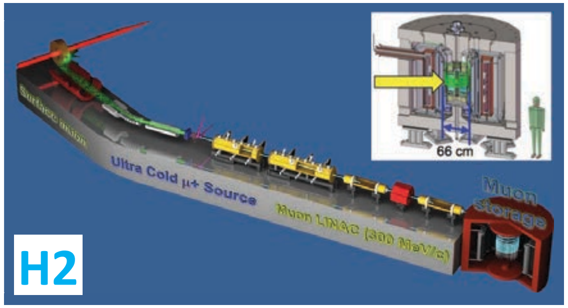
Muonium $1s-2s$

Muon mass m_{μ^+}

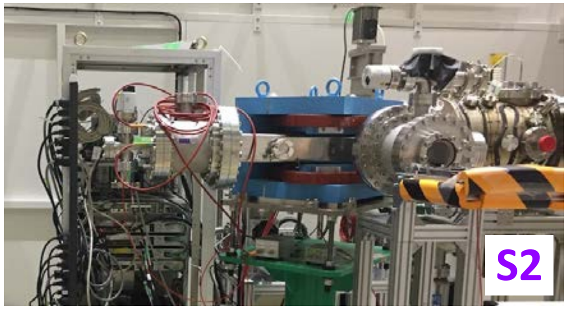
J-PARC MLF



J-PARC Muon *g*-2/EDM



J-PARC Muonium $1s-2s$



Previous μHe HFS Experiments

Zero Field (SIN)

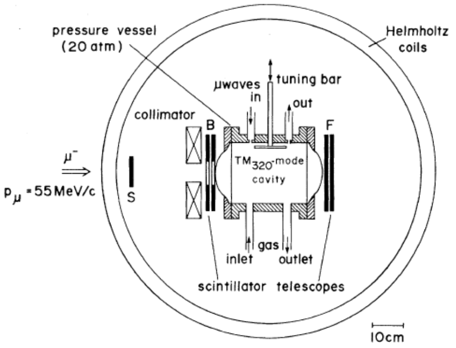


FIG. 2. Schematic view of the apparatus. The Helmholtz coils are used for muon-spin rotation. A cylindrical high-permeability metal shield (diameter 50 cm, length 100 cm) was installed (not shown in the figure) during the microwave magnetic-resonance experiment to reduce the stray magnetic fields.

$\Delta\nu$ = 4464.95(6) MHz
[13 ppm]

pressure: 20 atm

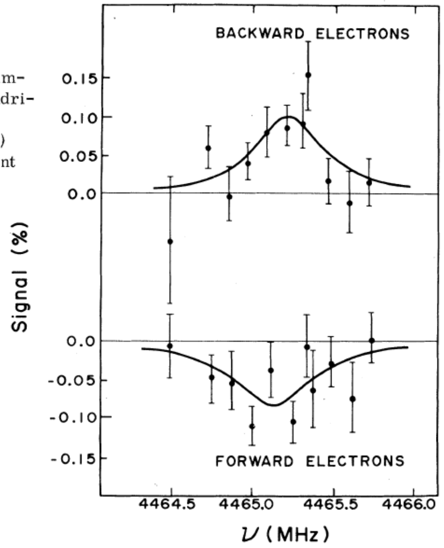


FIG. 3. Resonance curves for the $\Delta F=\pm1$, $\Delta M_F=\pm1$ hfs transitions in $({}^4\mathrm{He}^{++}\mu^-e^-)^0$, simultaneously observed in the backward (upper graph) and forward (lower graph) electron telescopes as a function of the microwave resonance frequency.

High Field (LAMPF)

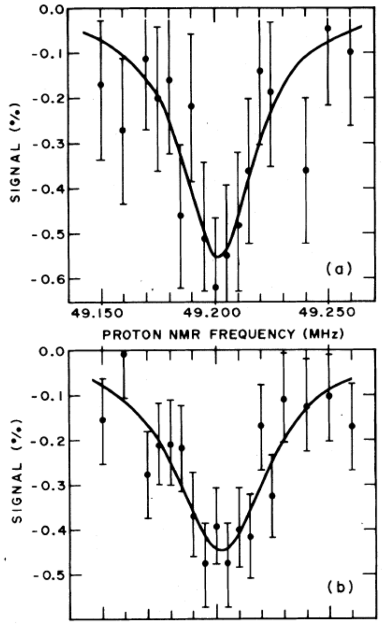


FIG. 1. Typical resonance curves for the ν_{12} transition obtained with the forward telescope at (a) 15 atm and (b) 5 atm. The data for these curves were obtained in (a) 24 h and (b) 100 h. For each curve obtained with the forward telescope there is a corresponding curve for the backward telescope.

pressure: 5 & 15 atm

$\Delta\nu$ = 4465.004(29) MHz
[6.5 ppm]

μ_{μ^-}/μ_p = 3.18328(15)
[47 ppm]

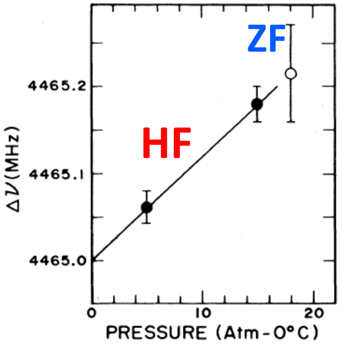


FIG. 2. $\Delta\nu$ as a function of He + Xe(1.5%) gas pressure. Closed circles show the results of this experiment; the open circle is the result of Ref. 3. The straight line shows the linear extrapolation used to extract $\Delta\nu(0)$.

ZF: H. Orth, et al., Phys. Rev. Lett. **45** (1980) 1483
HF: C. J. Gardner, et al., Phys. Rev. Lett. **48** (1982) 1168

Previous Measurements (1980s)

Previous measurements were performed in early 1980s at PSI (Paul Scherrer Institute) and LAMPF (Los Alamos Meson Physics Facility) with experimental uncertainties mostly dominated by statistical errors.

	Condition	**Δν**	**μ_{μ^-}/μ_p**
^{4}He	weak field [1]	4464.95(6) MHz (13 ppm)	
	high field [2]	4465.004(29) MHz (6.5 ppm)	3.18328(15) (47 ppm)
^{3}He	weak 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 Electrodynamics*, 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 !

$\Delta\nu_{\mathrm{HFS}}$: 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.

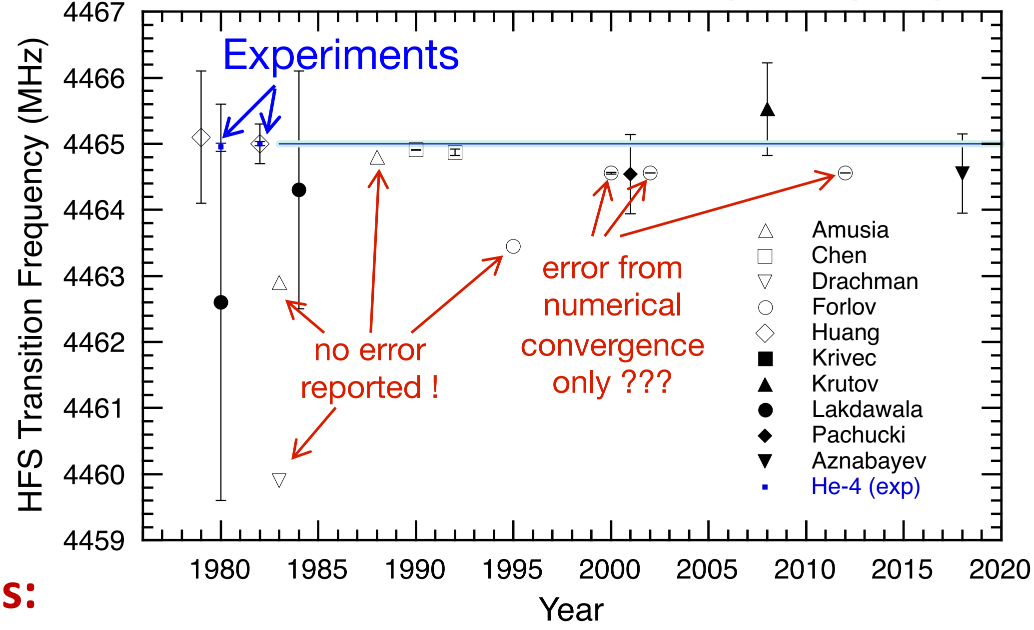
Calculations performed since the 1970s based on perturbation theory (PT), variational approach (VA), and Born-Oppenheimer (BO) theory.

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

Muonic Helium-4 HFS ($^4\mathrm{He}^{2+}\mu^-e^-$)



Experiments

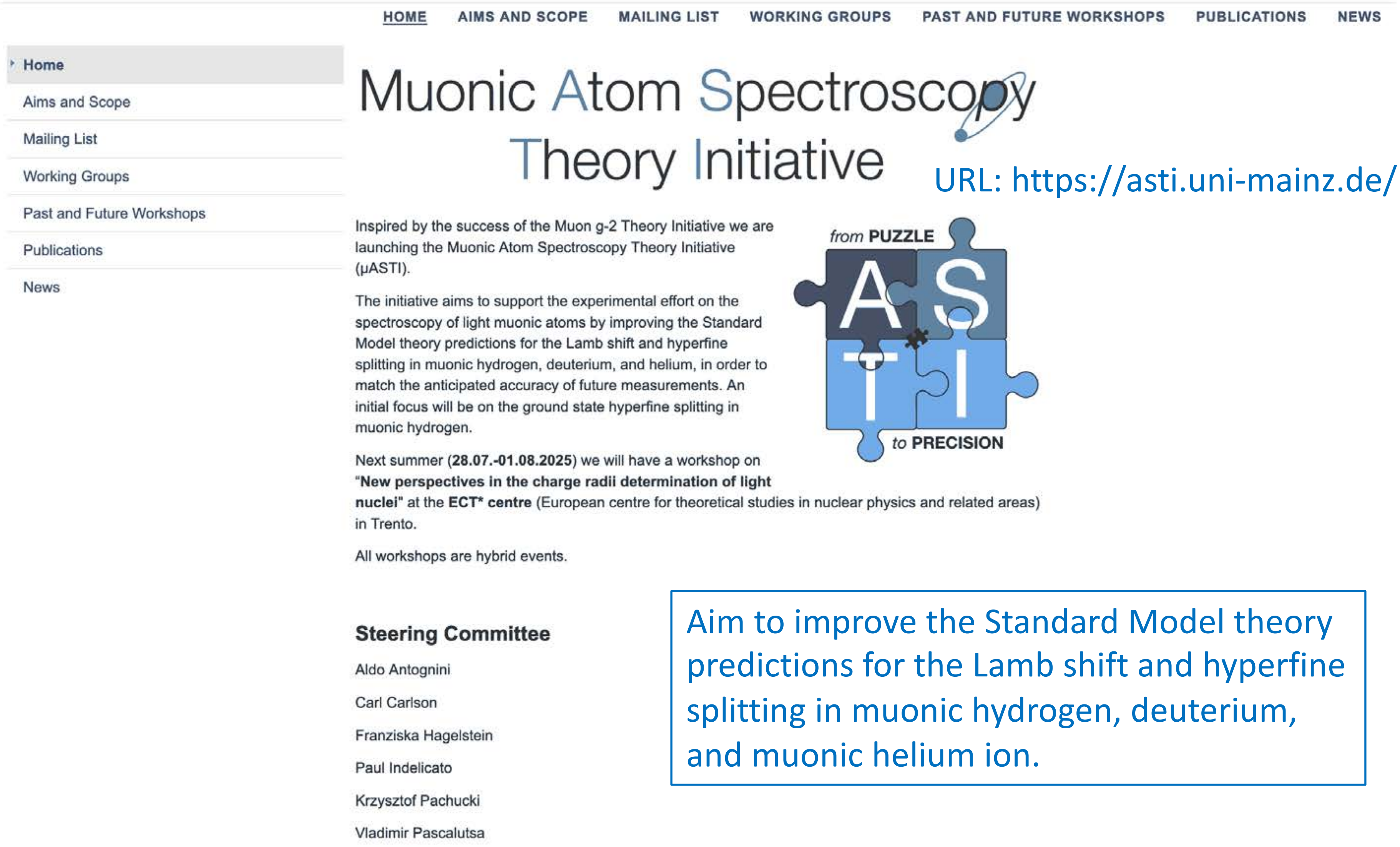
no error reported !

error from numerical convergence only ???

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



Muonic Atom Spectroscopy Theory Initiative

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

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

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% → 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 → 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

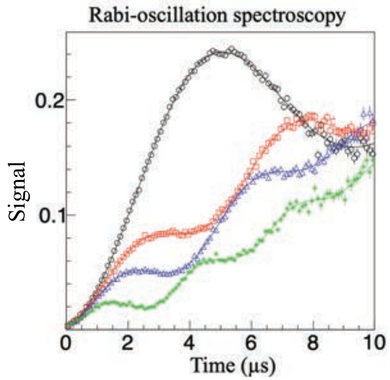
New μHe HFS at J-PARC MUSE

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

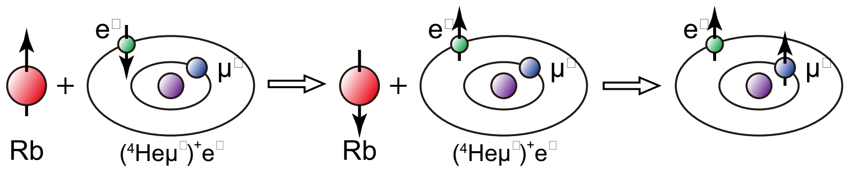
Three key components for improvement:

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

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

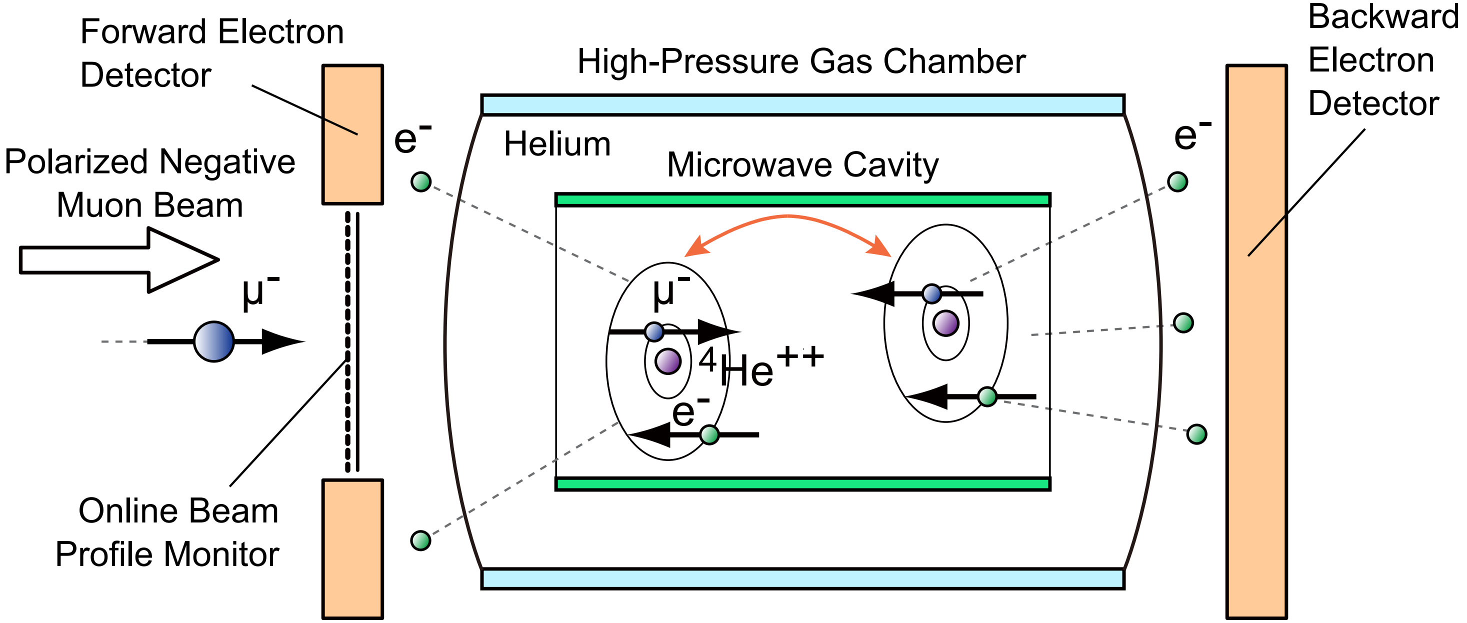


3) Producing **highly-polarized muonic helium atoms** to improve the μ^- residual polarization in helium by Spin Exchange Optical Pumping (SEOP).



Experimental Arrangement

Experiment apparatus



Forward Electron Detector

High-Pressure Gas Chamber

Backward Electron Detector

Polarized Negative Muon Beam

μ^-

e^-

Helium

Microwave Cavity

μ^-

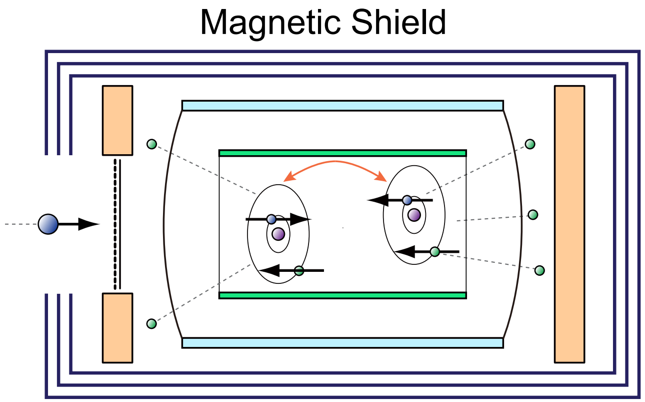
$^4He^{++}$

e^-

e^-

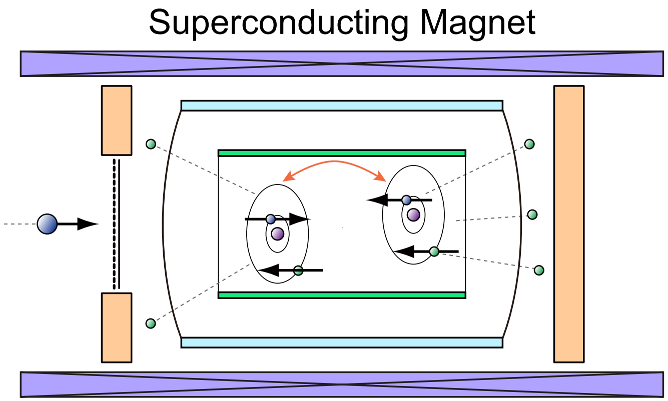
Online Beam Profile Monitor

Zero-field measurement



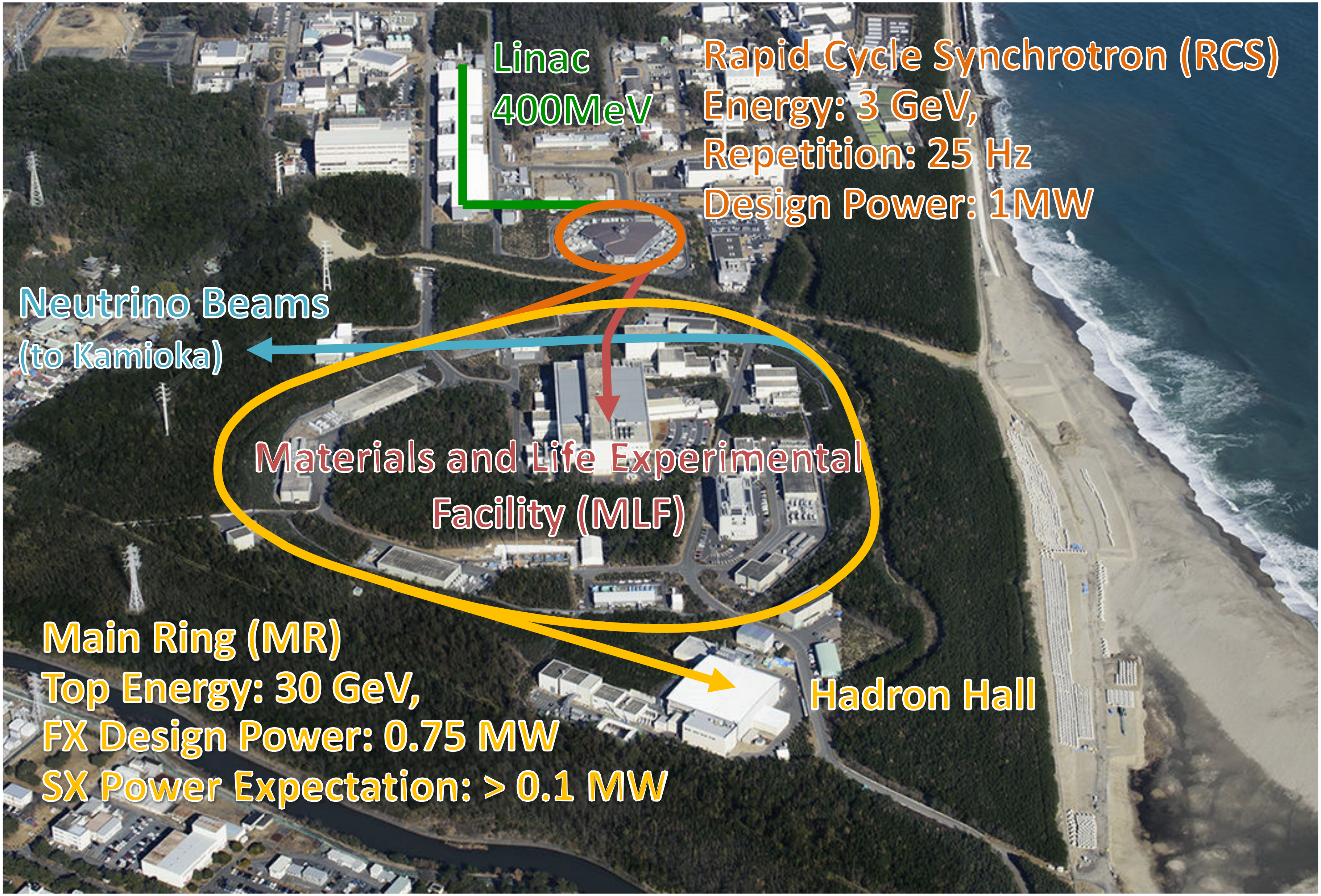
Magnetic Shield

High-field measurement



Superconducting Magnet

J-PARC Facility (KEK/JAEA）



Linac
400MeV

Rapid Cycle Synchrotron (RCS)
Energy: 3 GeV,
Repetition: 25 Hz
Design Power: 1MW

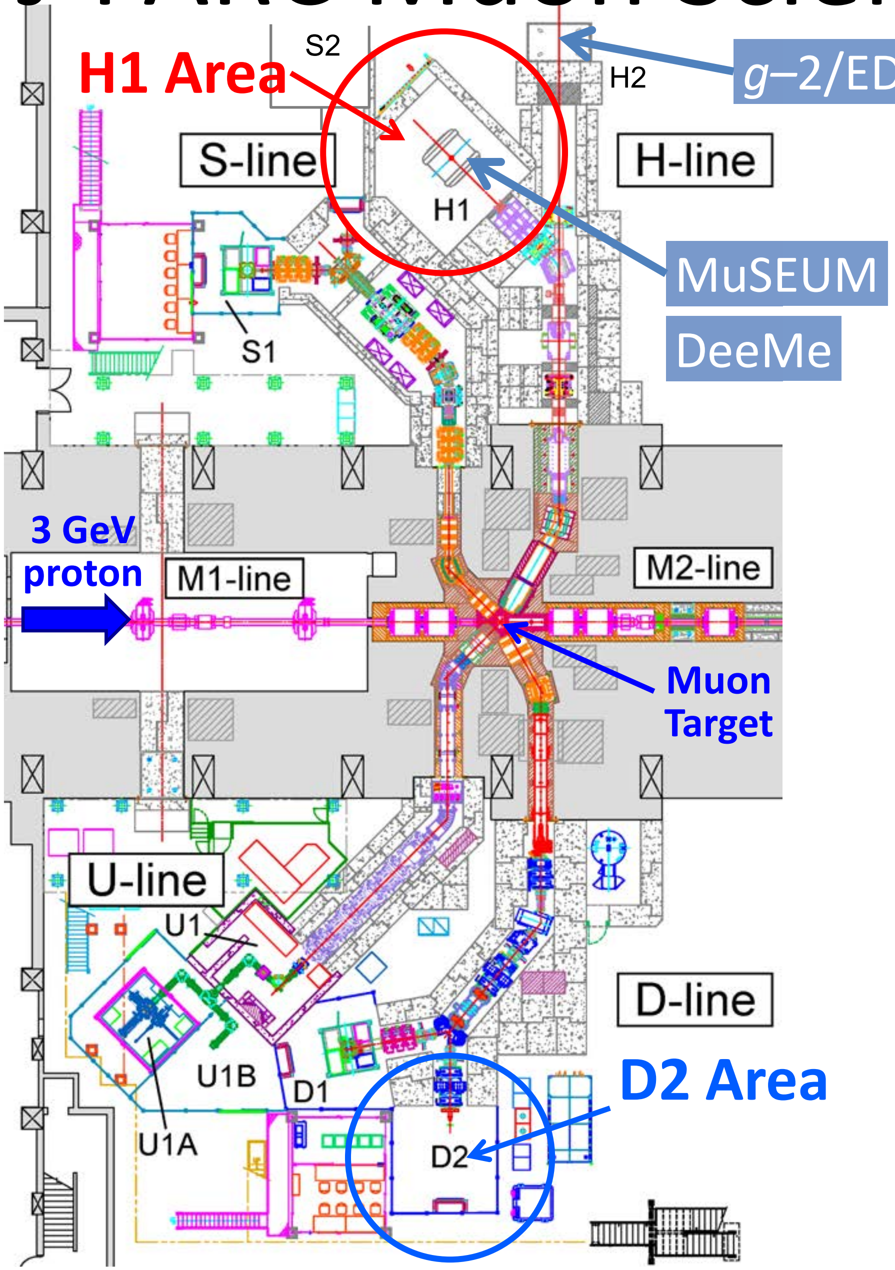
Neutrino Beams
(to Kamioka)

Materials and Life Experimental Facility (MLF)

Main Ring (MR)
Top Energy: 30 GeV,
FX Design Power: 0.75 MW
SX Power Expectation: > 0.1 MW

Hadron Hall

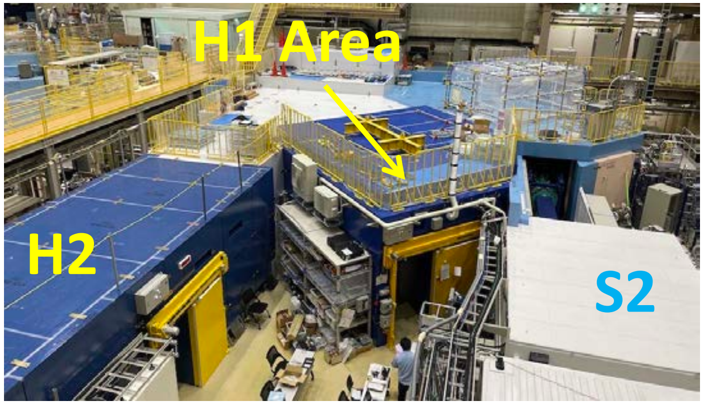
J-PARC Muon Science Facility (MUSE)



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.

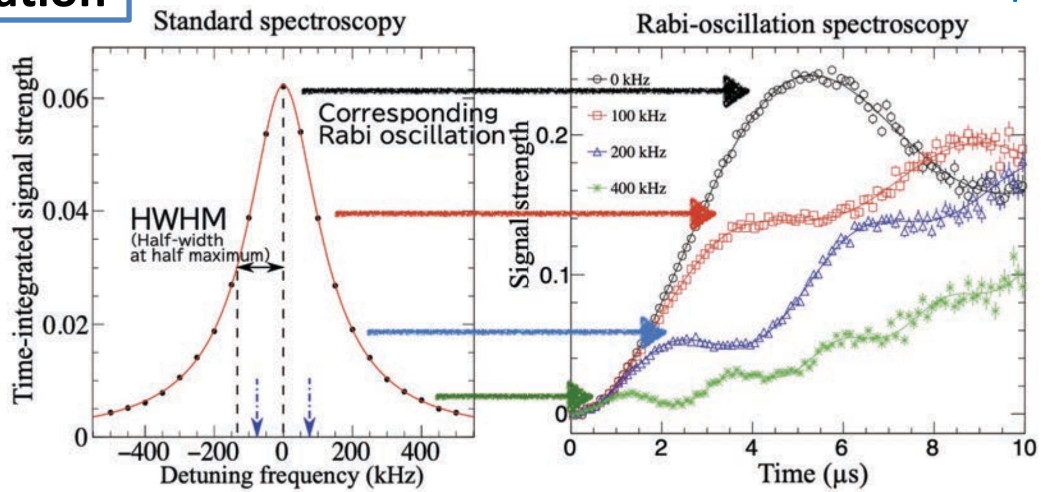
D-Line: Decay muon (μ^+ & μ^-)
Slow (50 keV) – fast (50 MeV) beam, general purpose.

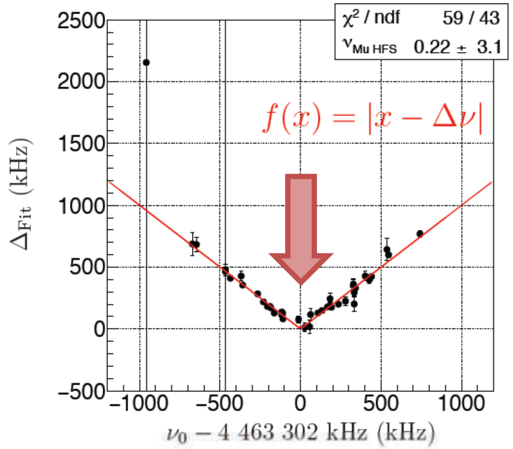
U-Line: Ultra-slow muon (μ^+)
Ultra-slow (0.1 – 30 keV) beam for near-surface condensed matter physics, chemistry, etc.

Rabi-Oscillation Spectroscopy Method

Simulation

Developed by Shoichiro Nishimura (KEK)

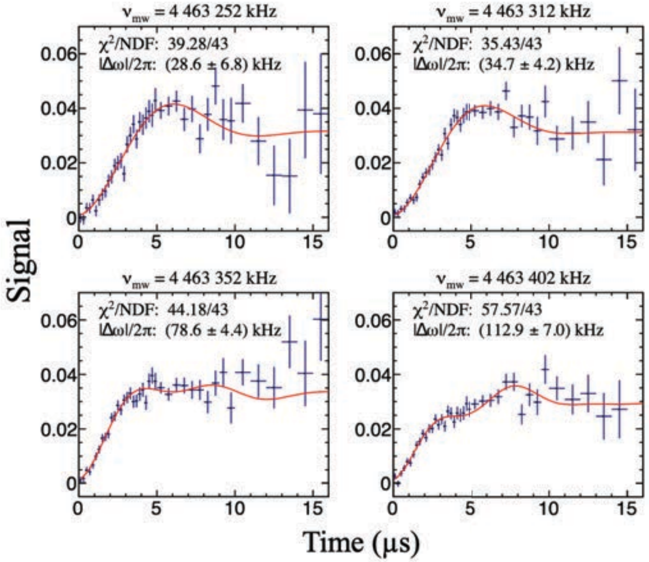




$\Delta\nu_{\mathrm{HFS}}(0) =$ 4 463 301.61(71) (160 ppb)

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

Experiment (2017 June)



Advantages:

- Each detuning frequency data fitted individually
- Can determine $\Delta\nu_{\mathrm{HFS}}$ 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

Expected Improvements

Previous experiments: ($\Delta\nu$: 6.5 ppm, μ_{μ^-}/μ_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:

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

Statistical Improvement	$\Delta\nu$	μ_{μ^-}/μ_p
10^4 statistics (×100)	100 ppb	1000 ppb
Rabi Spectroscopy (×3)	40 ppb	400 ppb
Highly-Polarized μ^-He (×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 $\mu_{\mu}-/\mu_p$.

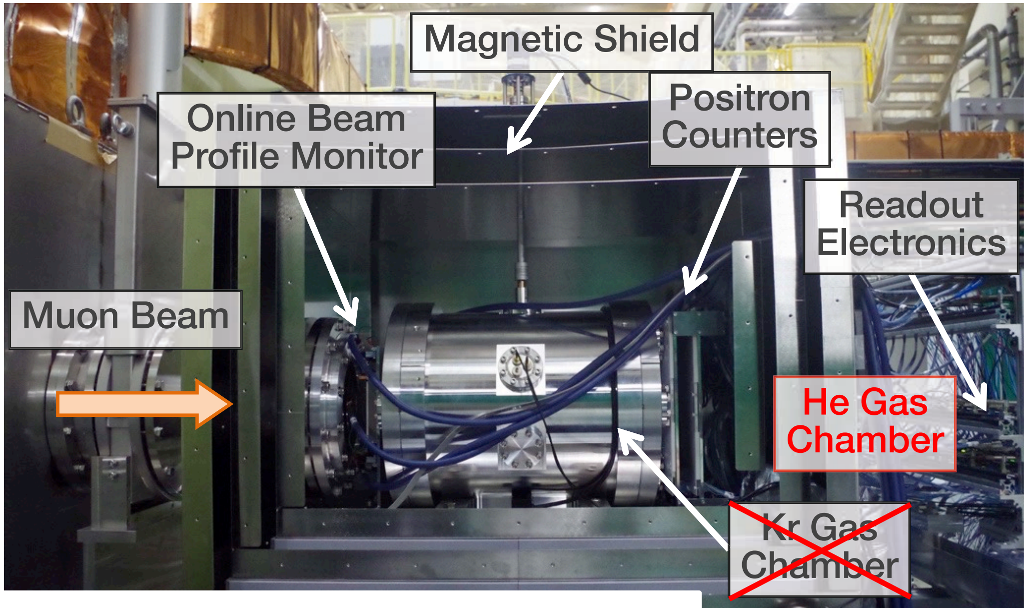
D-line: (zero field)

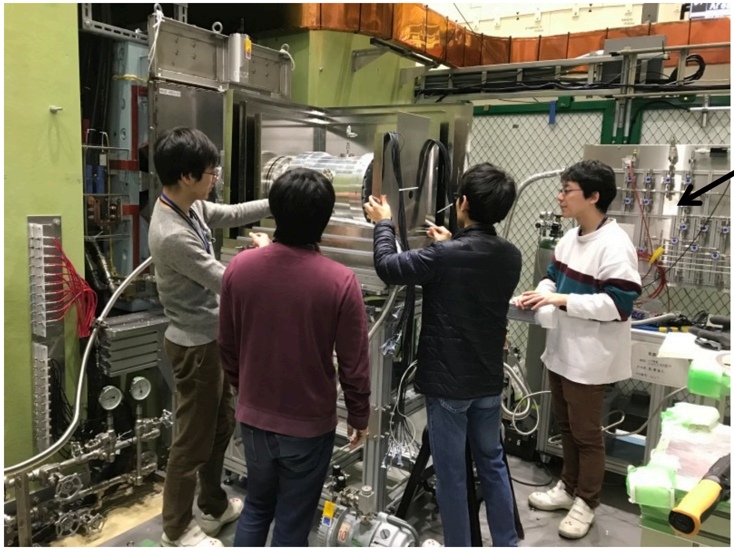
→ 10^2–10^3 times more statistics (depending on beamtime allocation)

Muonic Helium HFS Measurement at Zero-Field

μHe HFS Measurements at Zero-Field

Experimental Setup



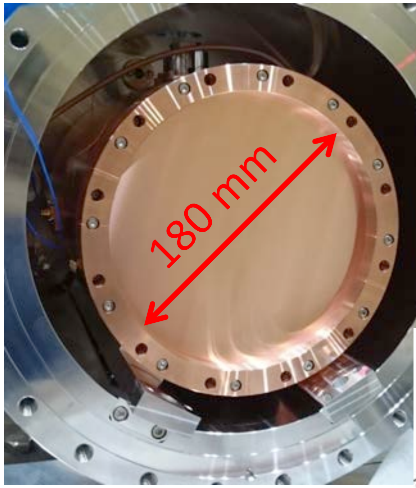


[2019B0318]

Preparation of MuSEUM apparatus in D2 area

(students from
Nagoya University and
the University of Tokyo)

Microwave Cavity (zero field)

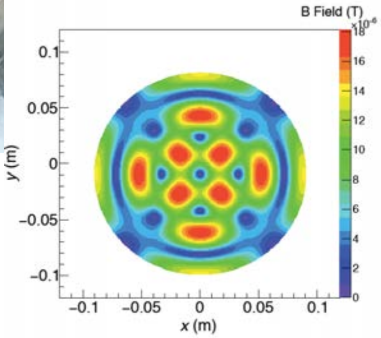


TM220 mode
Larger cavity
More muon stop
Q-Value:
20,000 (calc.)

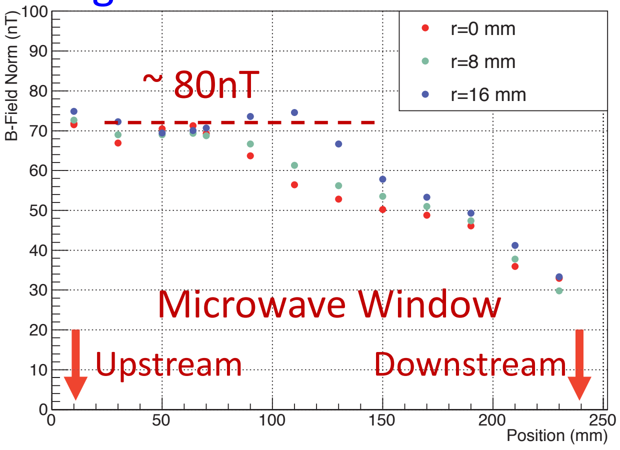
~~Δν = 4.463 GHz~~

Δν = 4.465 GHz

MW Intensity

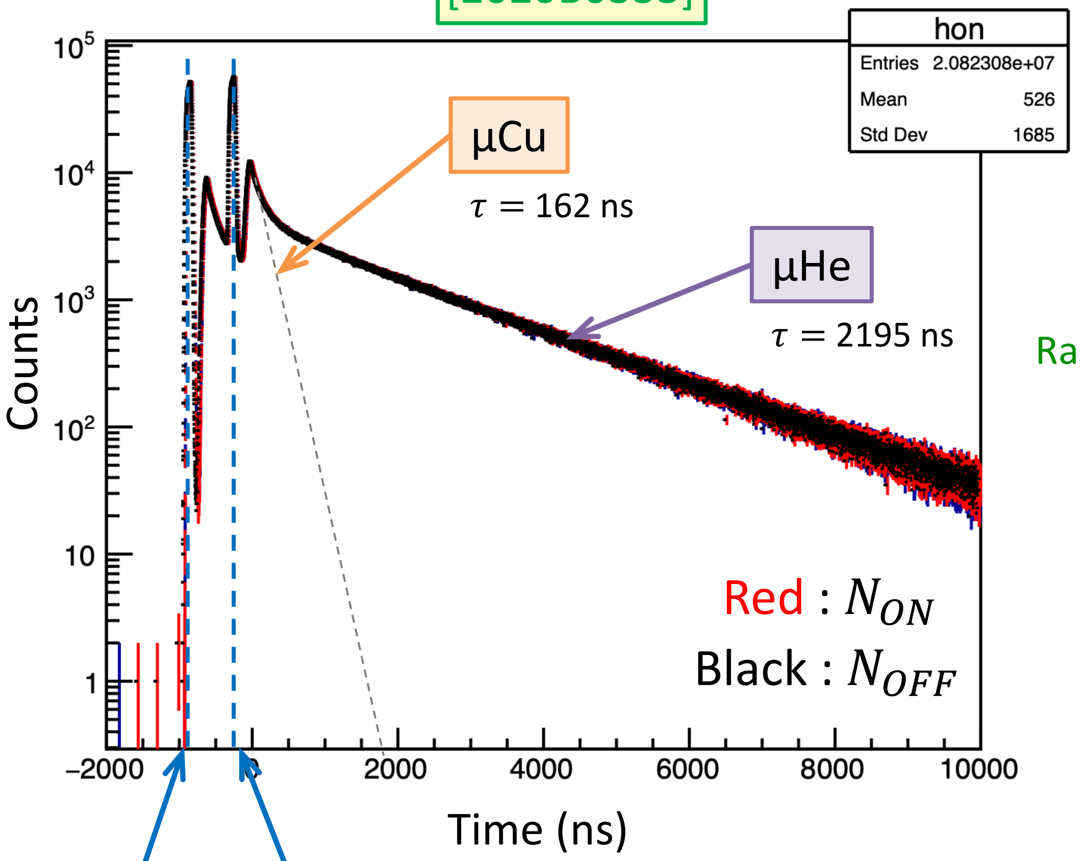


Residual Magnetic Field



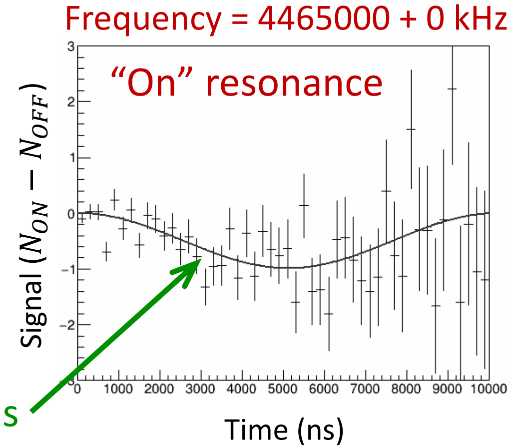
Decay Electron Time Spectra

[2020B0333]

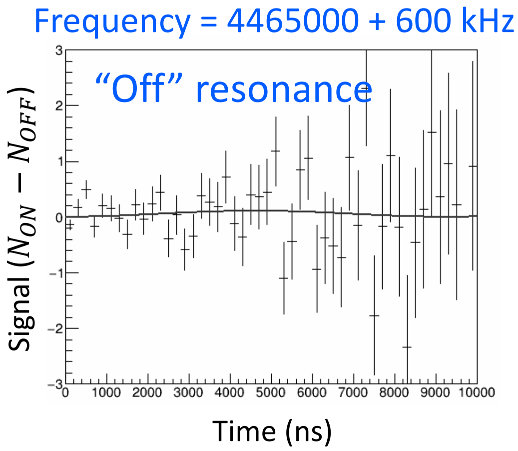


1st Muon Peak (-600 ns)

2nd Muon Peak (0 ns)



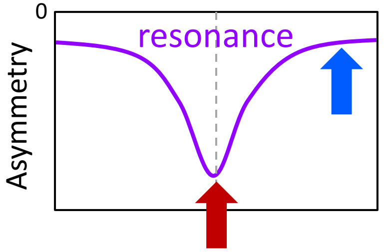
Rabi Oscillations



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

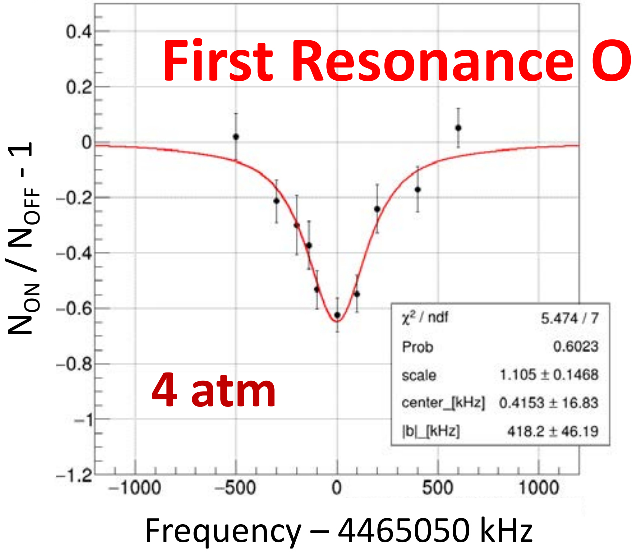
N_{ON} : Number of e⁻ with microwave

N_{OFF} : Number of e⁻ without microwave



μHe HFS Resonance Curve

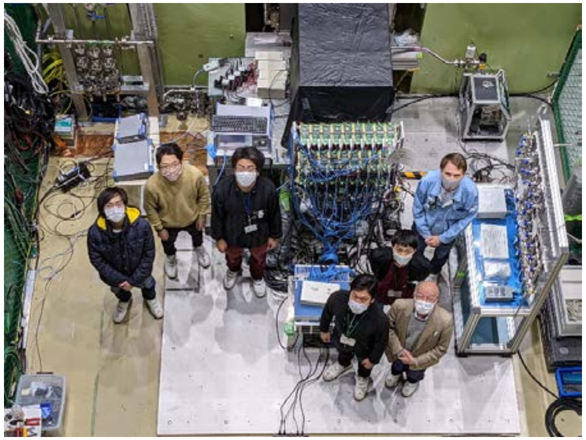
March 11–17, 2021 Beamtime



First Resonance Observed

4 atm

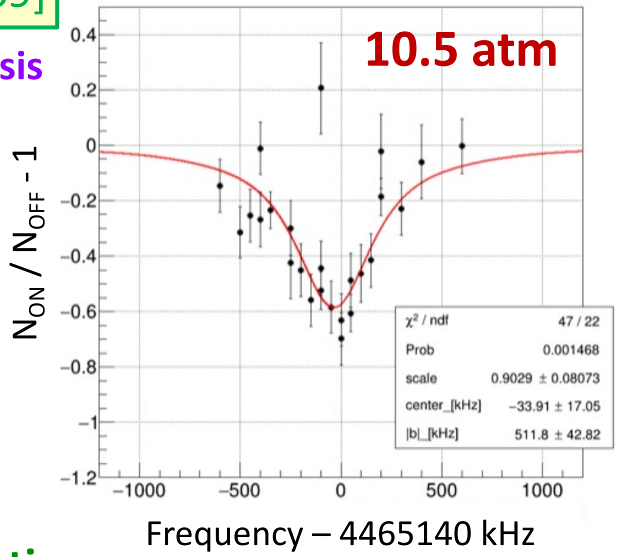
[2020B0333]



[2021B0169]

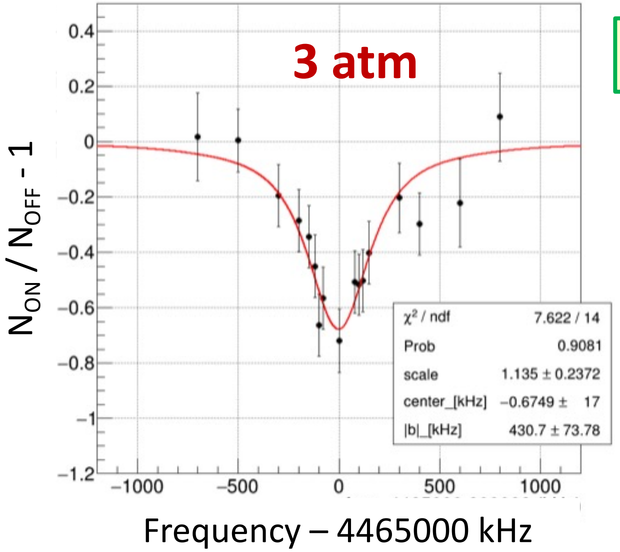
Blind Analysis

February 2022 Beamtime



10.5 atm

May 2022 Beamtime



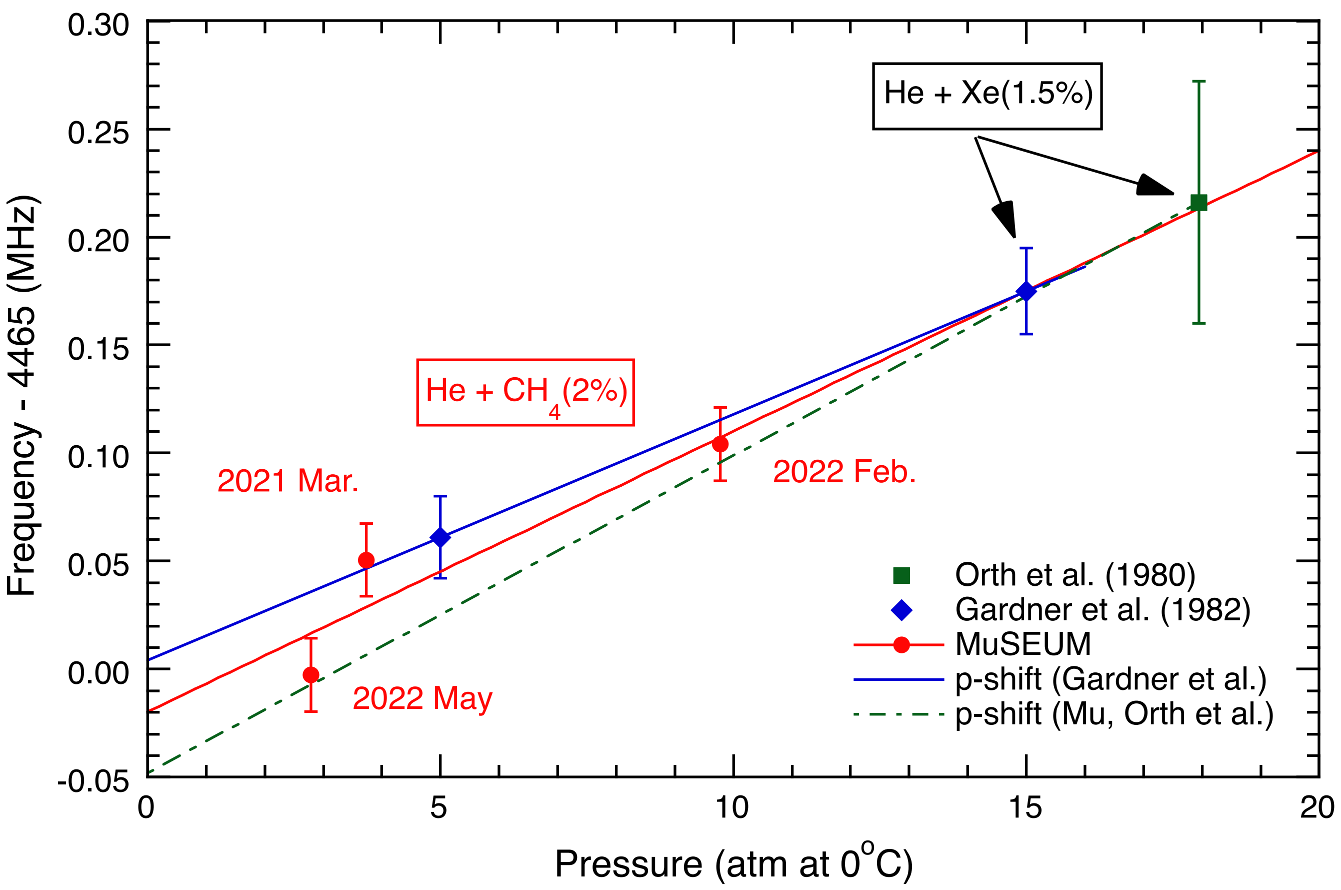
3 atm

[2022A0159]

Blind Analysis

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

Extrapolation to Zero Pressure



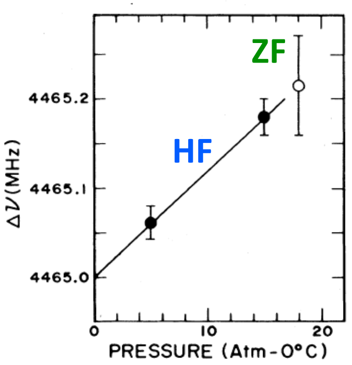


FIG. 2. $\Delta\nu$ as a function of He+Xe(1.5%) gas pressure. Closed circles show the results of this experiment; the open circle is the result of Ref. 3. The straight line shows the linear extrapolation used to extract $\Delta\nu(0)$.

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

$\Delta\nu$ = 4464.95(6) MHz (Orth et al.) [13 ppm] zero field (ZF)

$\Delta\nu$ = 4465.004(29) MHz (Gardner et al.) [6.5 ppm] high field (HF)

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

- **NEW World's highest precision after 40 years!**

ZF: H. Orth et al., PRL 45 (1980) 1483
HF: C. J. Gardner et al., PRL48 (1982) 1168

Systematic Uncertainty (Zero Field)

Systematics for muonic helium HFS measurements

- Most of the systematics common with muonium HFS measurements

Contributions	D-line (2022)	Prospects
Pressure gauge precision	5 Hz	5 Hz
Gas temperature fluctuation	45 Hz	3 Hz
CH_4 concentration	**< 3 Hz/atm**	< 1 Hz/atm
Quadratic pressure shift	**< 780 Hz**	*need measurements*
Microwave power drift	37 Hz	< 1 Hz
Muon beam intensity	1 Hz	< 1 Hz
Muon beam profile	10 Hz	1 Hz
Static magnetic field	0 Hz	0 Hz
Detector pileup (event loss)	**1 Hz**	< 1 Hz
Time accuracy of detector	1 Hz	1 Hz
Total	**783 Hz (175 ppb)**	**–**

Quadratic Pressure Shift

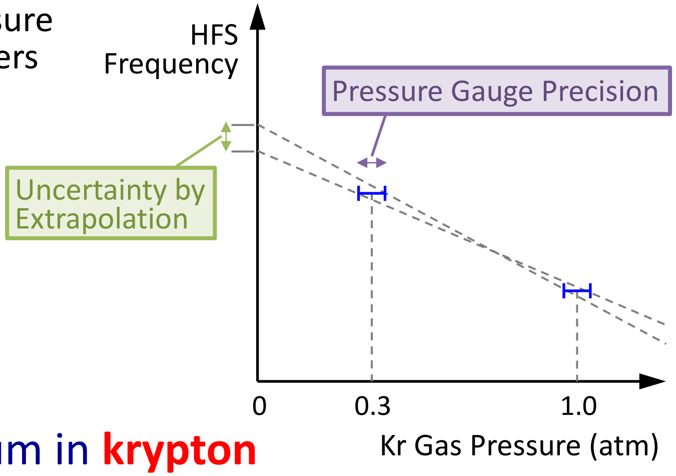
Pressure dependence on the HFS transition frequency

- Pressure shift due to collision between muonium and target gas atom

$$\boxed{\Delta\nu(P) = \Delta\nu(0) + AP + BP^2}$$

P: gas pressure
A,B: parameters

1) **Measurement at various gas pressures**
2) **Quadratic extrapolation to 0 atm**
3) **Determination of HFS in vacuum**



Quadratic coefficient for helium: Unknown

- Use the **most precise measurement of B** for muonium in **krypton**
- Justified since B becomes smaller with the atomic number of the noble gas and appears isotope-independent

$b_{Kr} = 9.7(2.0) \times 10^{-15}/\mathrm{Torr}^2$ (0°C) D. E. Casperson *et al.*, Phys. Lett. **59B** (1975) 397
$\rightarrow B_{Kr} = b_{Kr}\Delta\nu(0) = 0.0250(52)\ \mathrm{kHz/atm}^2$

- **Corresponding systematic errors:**

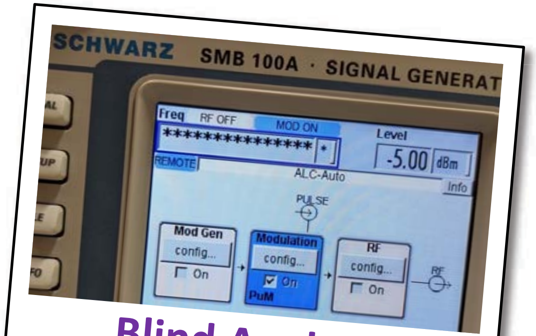
(upper limit)

$$\boldsymbol{\delta\Delta\nu(0)} = \Delta\nu(0, B = 0) - \Delta\nu(0, B \neq 0) = \mathbf{776\ Hz}$$

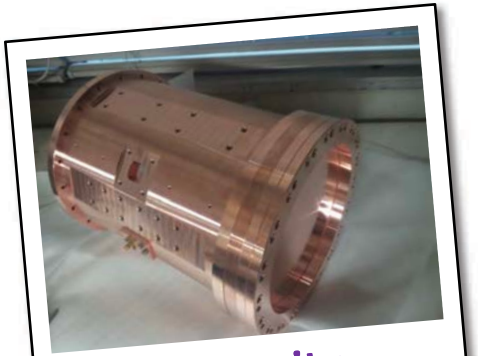
Need more measurements at higher pressure to determine B

Development for High-Field Experiment

MRI Magnet

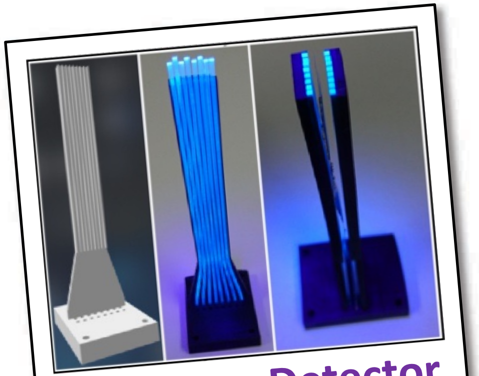


Blind Analysis

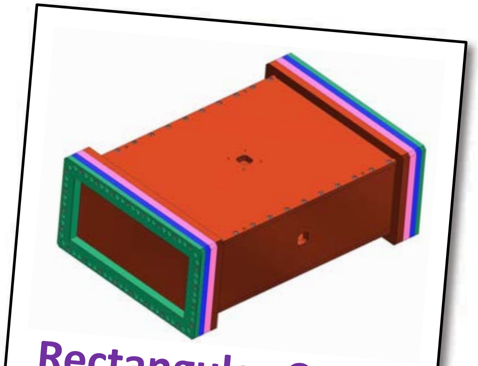


HF Cavity

Magnetic Probes



Upstream Detector

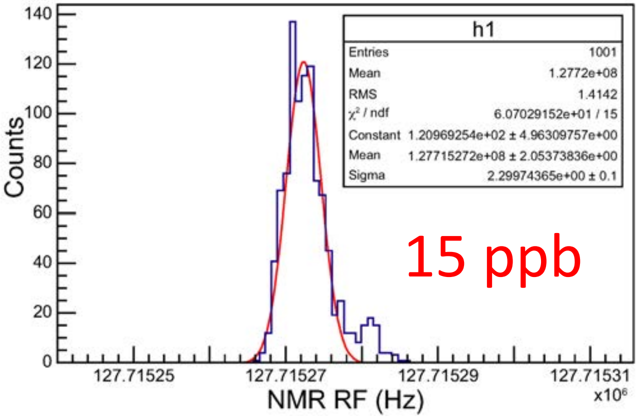


Rectangular Cavity

MRI Magnet for High-Field Experiment

Second-hand 2.9 T MRI magnet

CW-NMR Field Monitoring System

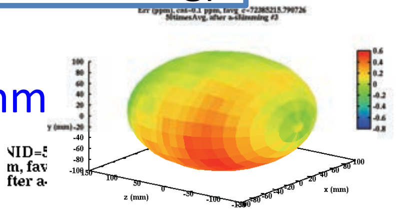


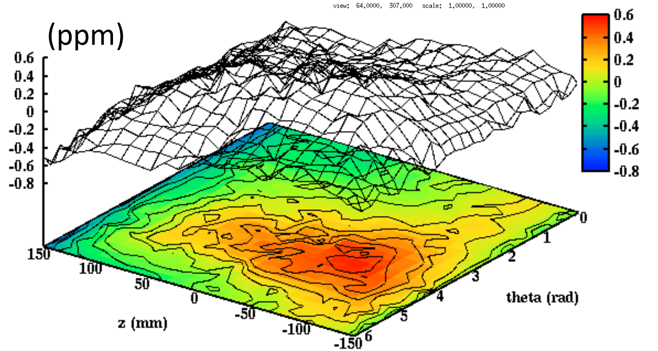
15 ppb

Field Homogeneity (after shimming)

Spheroid :
ø=200 mm, z=300 mm

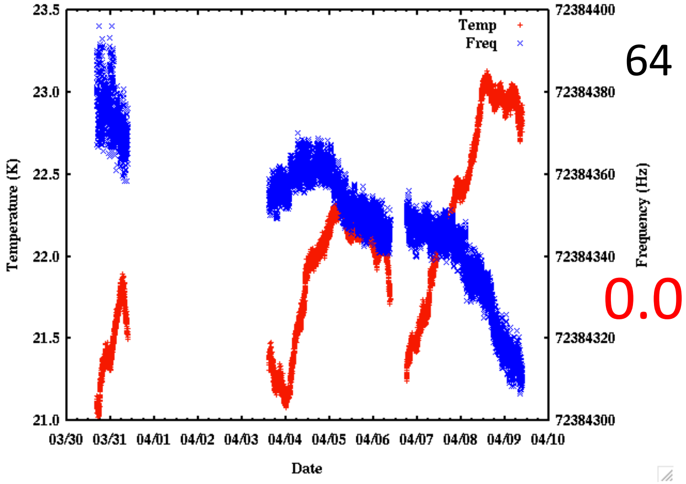
0.2 ppm (p-p)





these data: 1.4 ppm (p-p)

Long Term Stability



64 Hz / 9.7 days

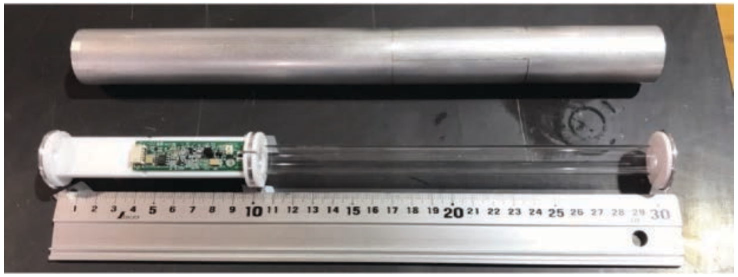
0.003 ppm /h

Magnetic Field Probes

Three types of probes are being developed

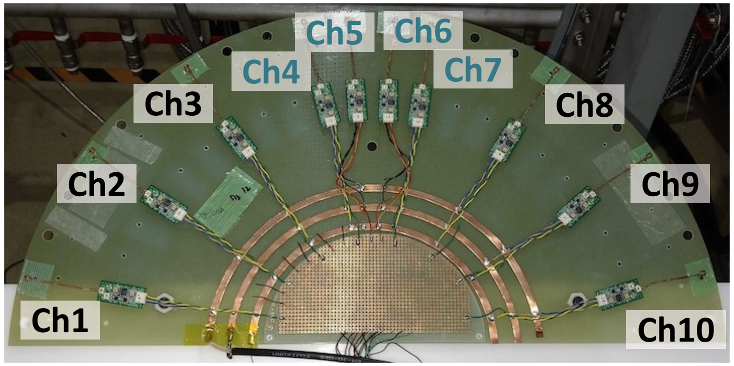
Standard Probe

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



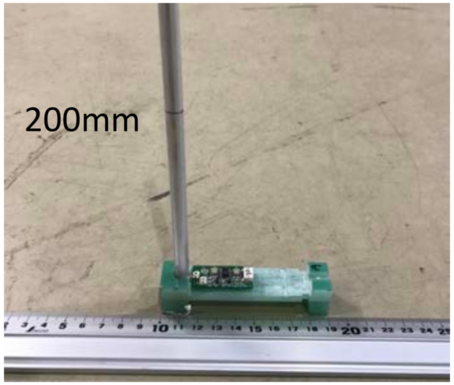
Field Camera

- 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

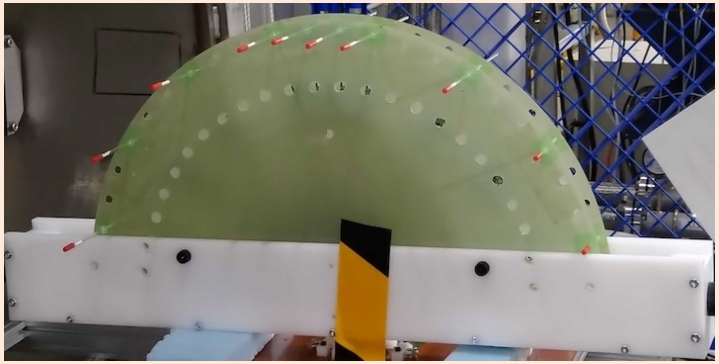


Field Camera

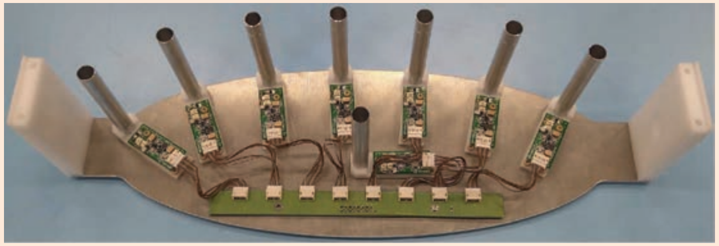
Scanning a sphere with a radius of 25 cm

Developed by Hiroki Tada (Nagoya Univ.)

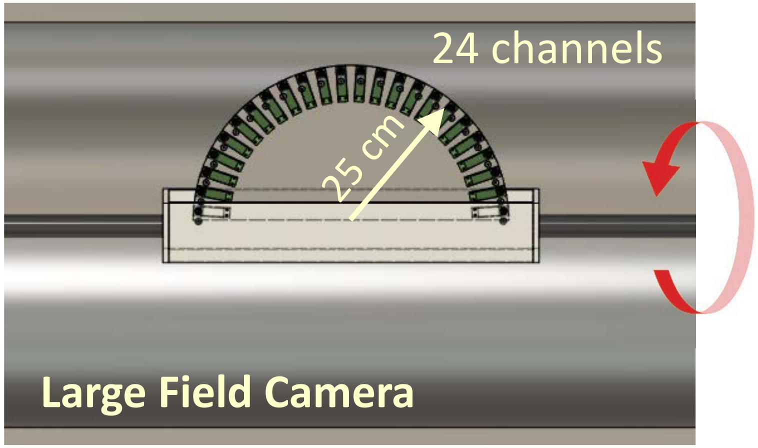
- 24-channel half-circle multi-channel system
- Scanning time: 3 hours (single probe) → 20 minutes (multi-channel system)

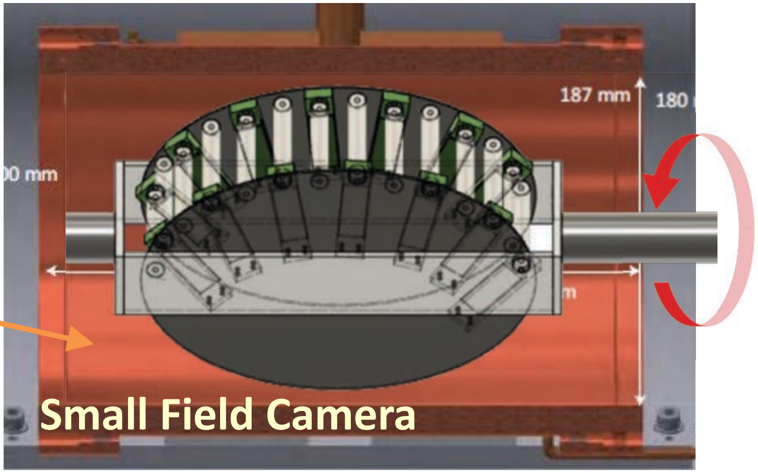


10-channel Prototype



Support Structure





Microwave Cavity

Blind Analysis for MuSEUM

Hidden answer method

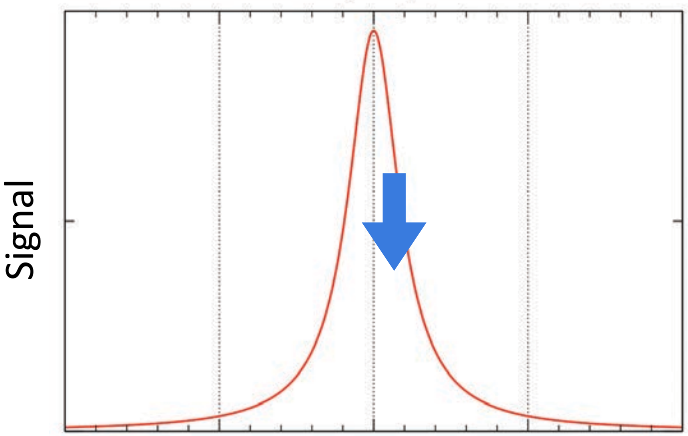
Value to be blinded: injected microwave frequency

- Microwave frequency input by user: $\boldsymbol{\nu_{set}}$
- Blinded offset: $\boldsymbol{\delta}$
- True microwave frequency: $\boldsymbol{\nu_{mw}}$

$$\boxed{\nu_{\mathrm{mw}} = \nu_{\mathrm{set}} + \boldsymbol{\delta}}$$

- δ constant for all $\boldsymbol{\nu_{set}}$ to draw a resonance curve
- If $|\boldsymbol{\delta}| < 8$kHz
    - ○ blind value sufficient for the target precision
    - ○ rate of change in stored microwave energy < 0.07%

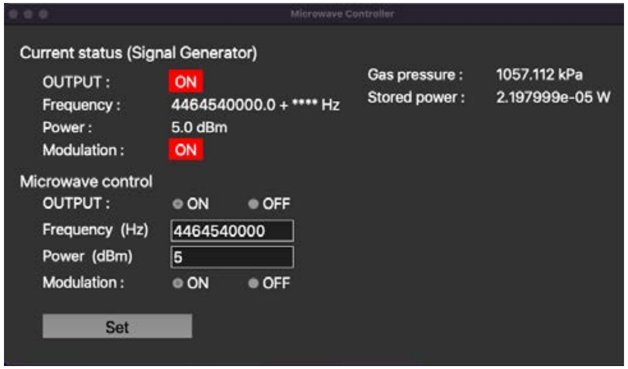
Before opening the blind



$\boldsymbol{\nu_{mw}}$ – 4,463,302 kHz – $\boldsymbol{\delta}$

= $\boldsymbol{\nu_{set}}$ – 4,463,302 kHz

Implemented in Python3



Current status (Signal Generator)

OUTPUT : ON

Frequency : 4464540000.0 + **** Hz

Power : 5.0 dBm

Modulation : ON

Gas pressure : 1057.112 kPa

Stored power : 2.197999e-05 W

Microwave control

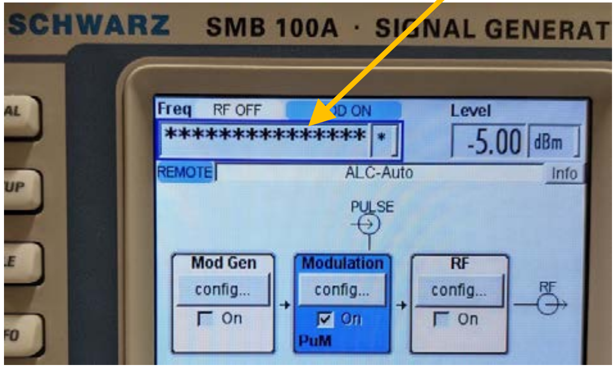
OUTPUT : ○ ON ○ OFF

Frequency (Hz) 4464540000

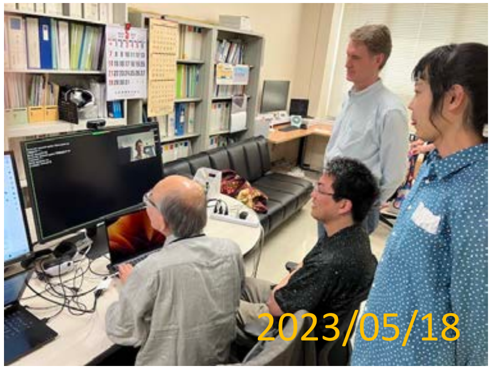
Power (dBm) 5

Modulation : ○ ON ○ OFF

True frequency hidden



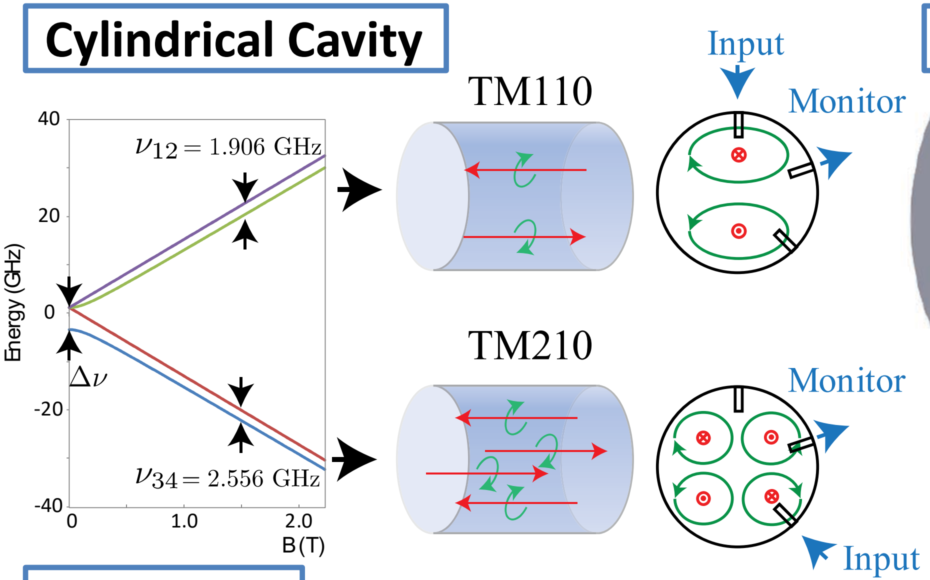
Blind Test (for μHe HFS)


2023/05/18

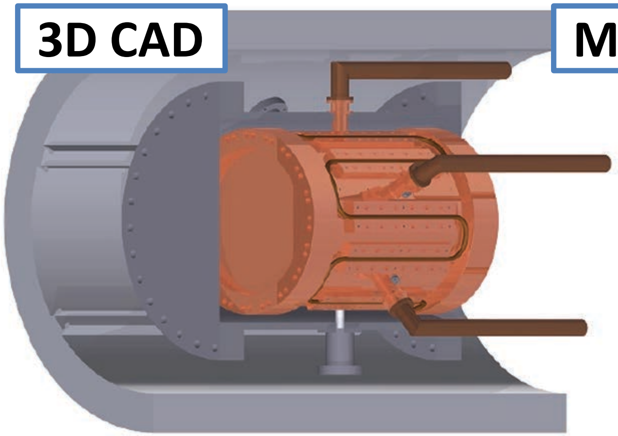
Password protected, safety/protection features to prevent mis-operation
Microwave power and gas pressure are also monitored and recorded

High-Field Microwave Cavity (Mu&μHe)

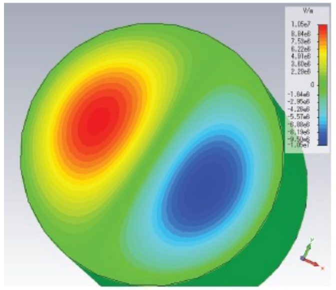
Cylindrical Cavity



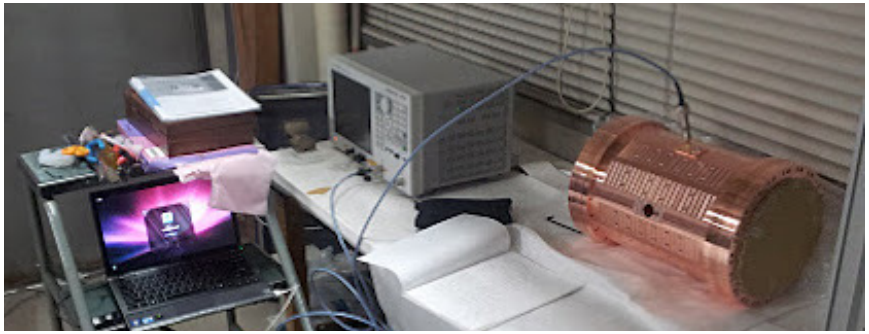
3D CAD



MWS Simulation

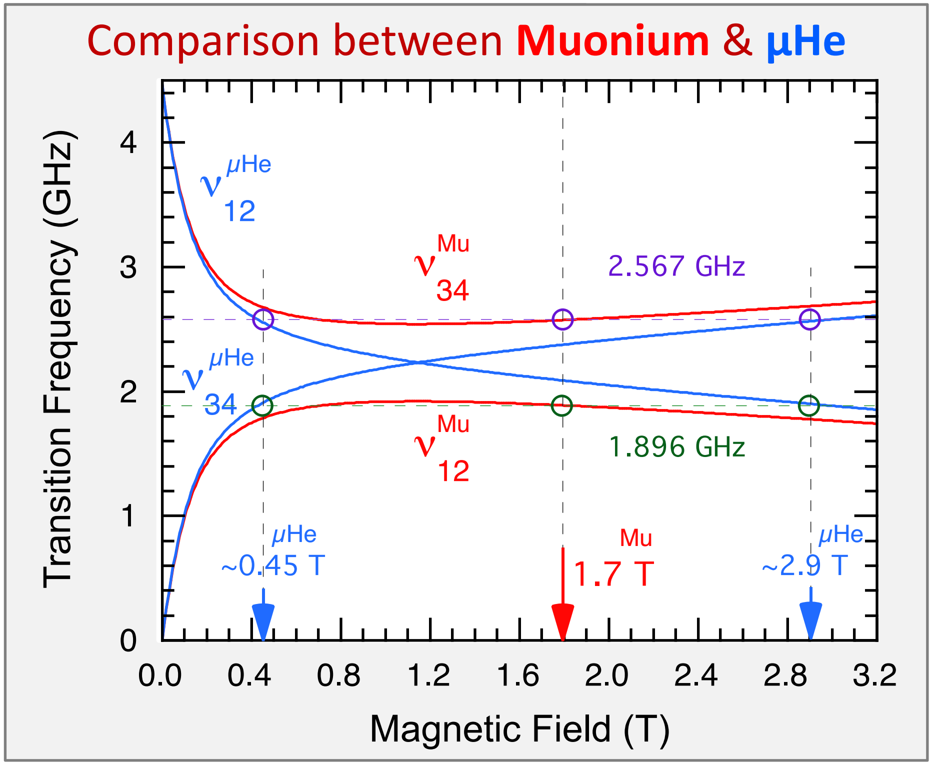


Cavity Test



Q Value

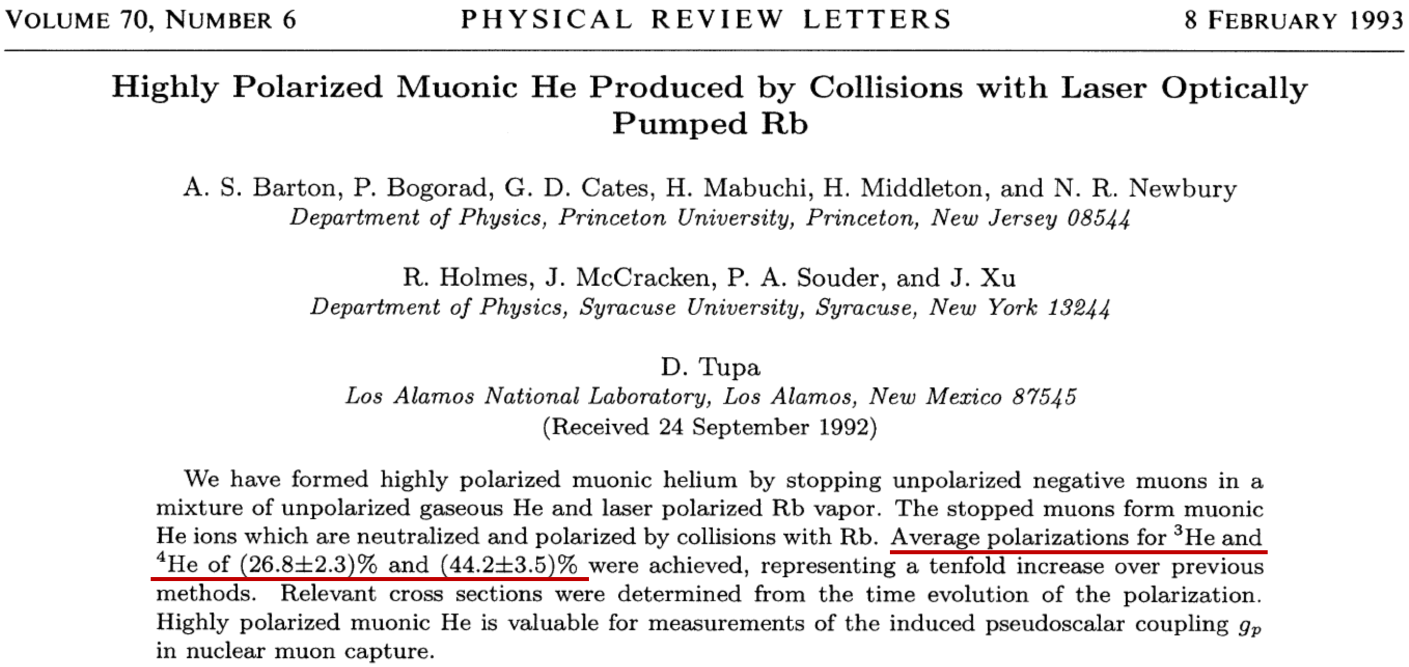
Modes	Q (measured)	Q (simulation)
TM110	1.13 x 10^4	2.97 x 10^4
TM210	8.05 x 10^3	2.89 x 10^4



Highly-Polarized Muonic He Atom

Highly-Polarized Muonic He Atom

Production of highly-polarized muonic helium 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.

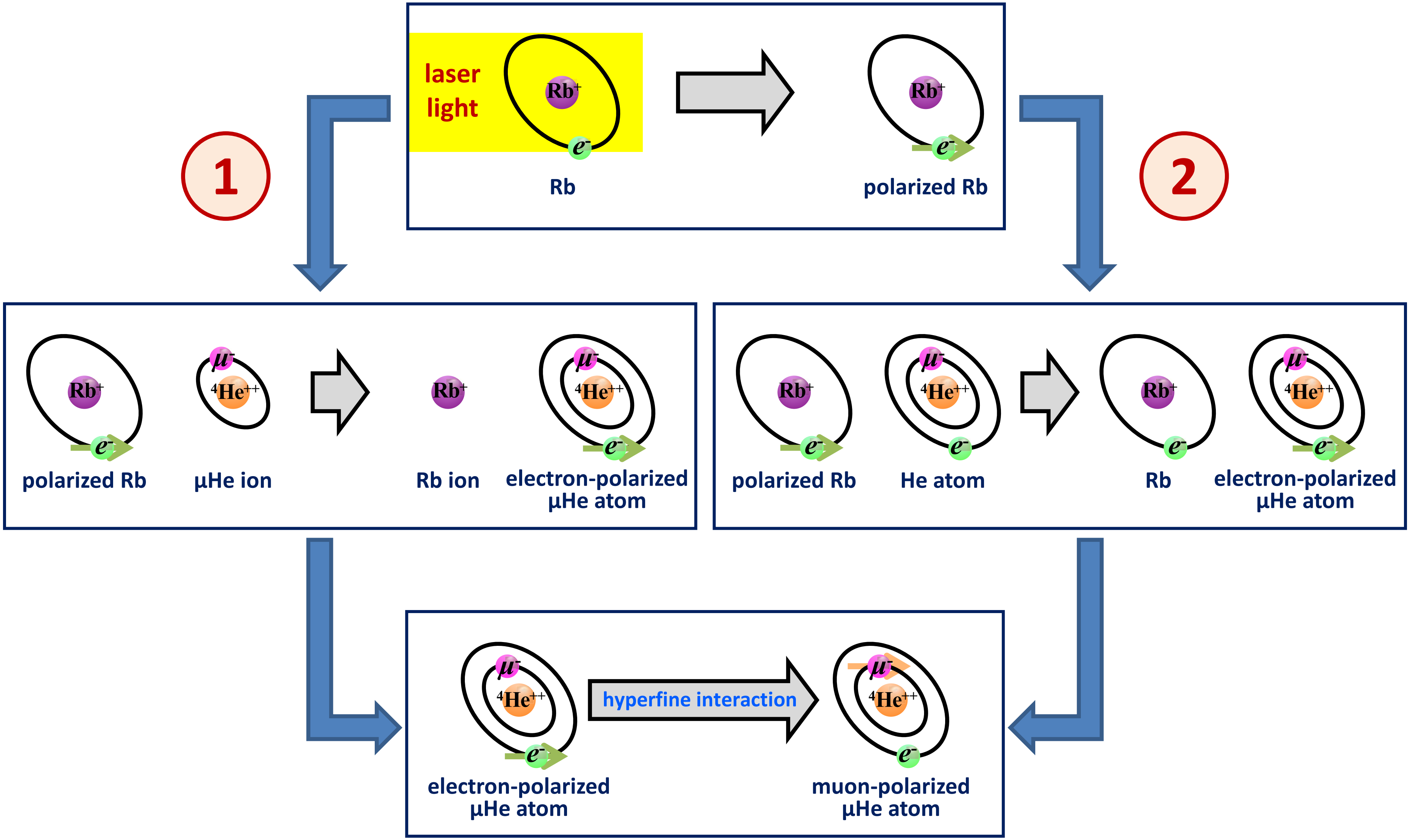
A. S. Barton et al., Phys. Rev. Lett. **70**, 758 (1993)

for μ^{4}He: 6% → 44%

Improvement by a factor 7 achieved !

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

Polarization of Muonic He Atom



laser light

Rb

polarized Rb

polarized Rb

μHe ion

Rb ion

electron-polarized μHe atom

polarized Rb

He atom

Rb

electron-polarized μHe atom

electron-polarized μHe atom

hyperfine interaction

muon-polarized μHe atom

Muon Polarization in Muonic He

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

$$A(t) = \frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}}$$

Rb polarization reversed every 2 min.

$$P_\mu(t) = \frac{A(t)}{f(t)a_e}$$

$f(t)$: fraction from He, a_e: analyzing power

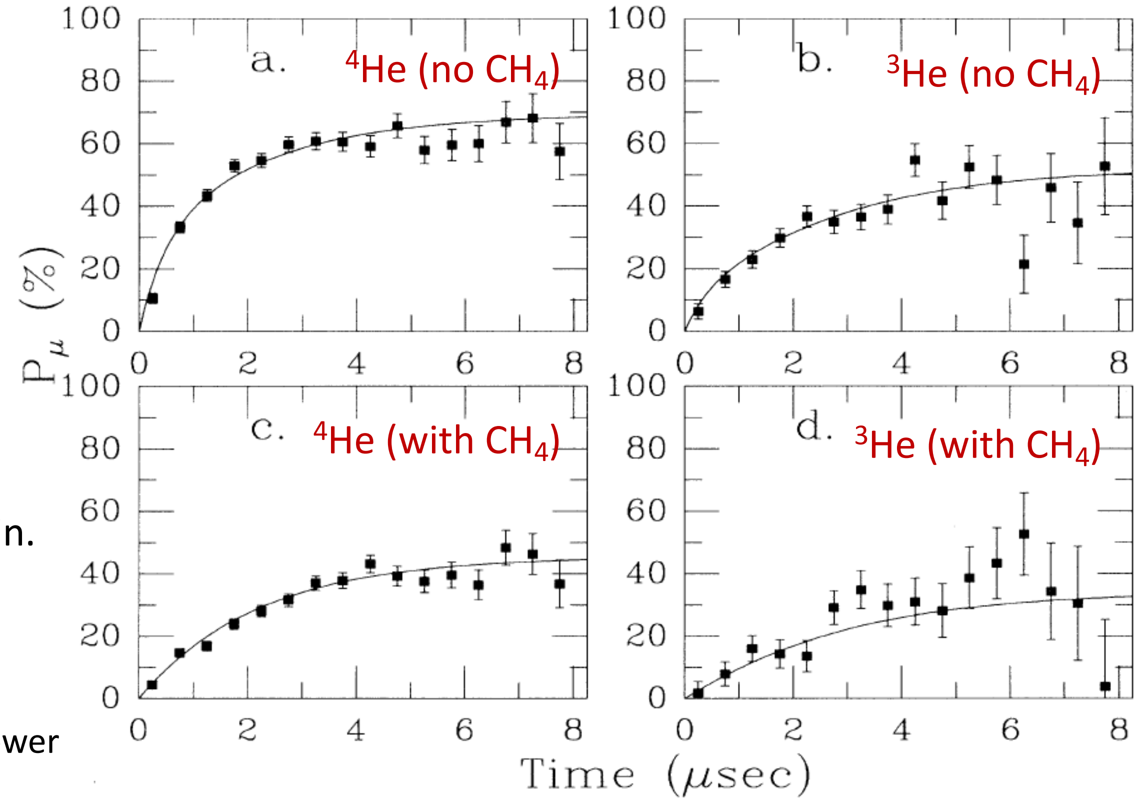


FIG. 1. Muon polarization as a function of time in muonic He. The four graphs correspond to four target cells: (a) ^{4}He without CH_4, (b) ^{3}He without CH_4, (c) ^{4}He with CH_4, and (d) ^{3}He with CH_4. The solid lines are given by (6) for (a) and (b), and by (5) for (c) and (d), where the numerical values of the parameters resulted from a global fit to all of the data (including the muonium data of Fig. 2).

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

(1) $Rb\uparrow + He(\mu^-He)^+ \rightarrow Rb^+ + He + (\mu^-He)^+\, e^-\uparrow$

(2) $Rb\uparrow + (\mu^-He)^+ e^-\downarrow \rightarrow Rb\downarrow + (\mu^-He)^+\, e^-\uparrow$

(3) $CH_4 + (\mu^-He)^+ \rightarrow CH_4^+ + (\mu^-He)^+\, e^-$

- without CH_4: reactions (1) + (2)
- with CH_4: reactions (3) and (2) only

μHe SEOP Objectives

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

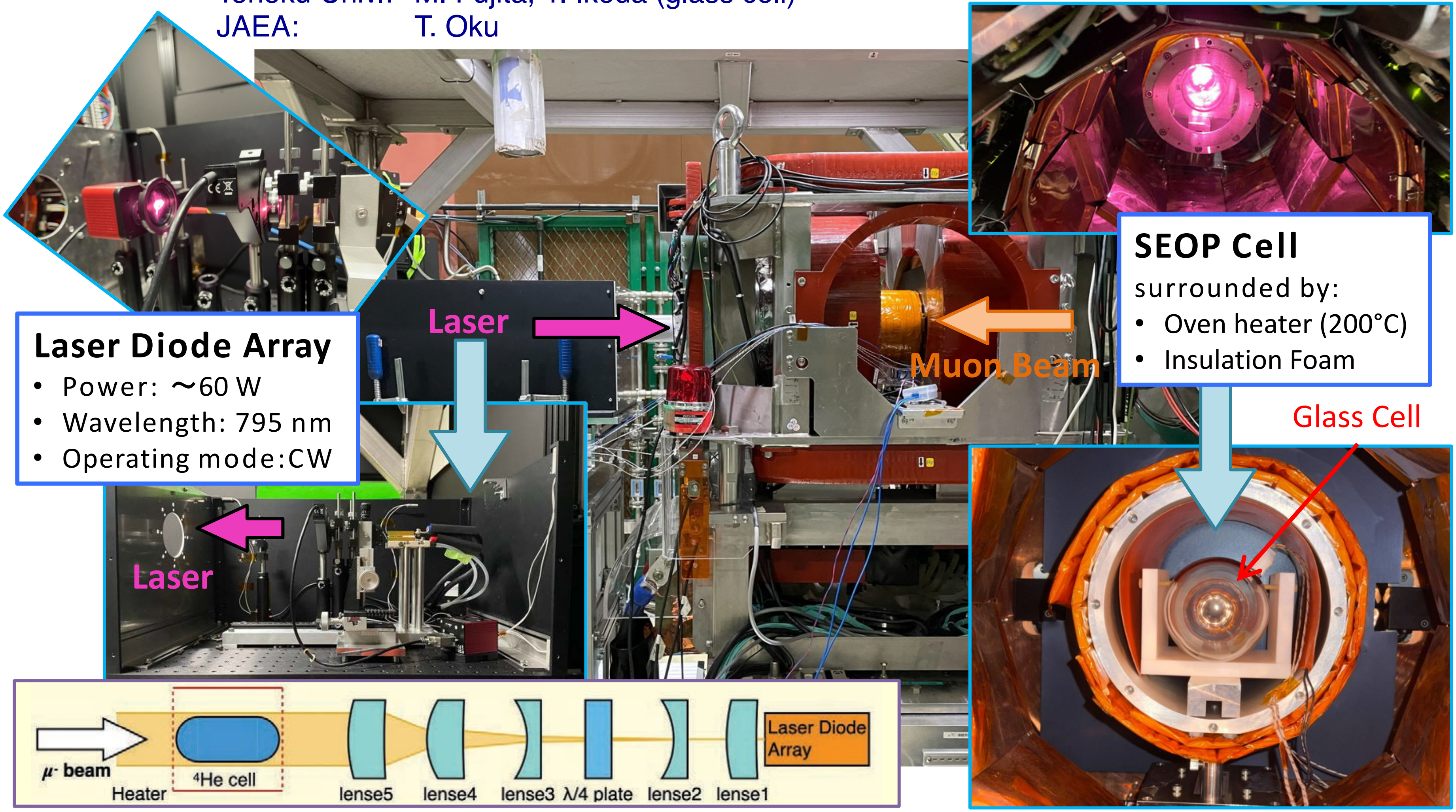
2) Further improvements expected with a **hybrid-SEOP technique**
   - Use **K/Rb** to enhance the spin-exchange efficiency
   - Rb is used as a spin-transfer agent to K, to prevent depolarization of Rb due to Rb-Rb collision.
   - K-He transfers the angular momentum with much greater efficiency than 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



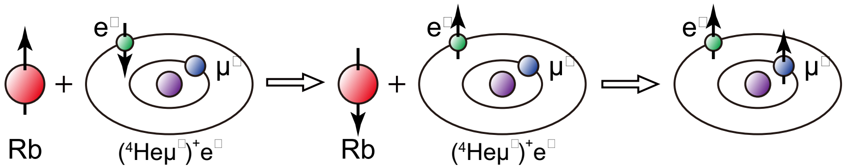
Laser Diode Array
- Power: ～60 W
- Wavelength: 795 nm
- Operating mode:CW

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

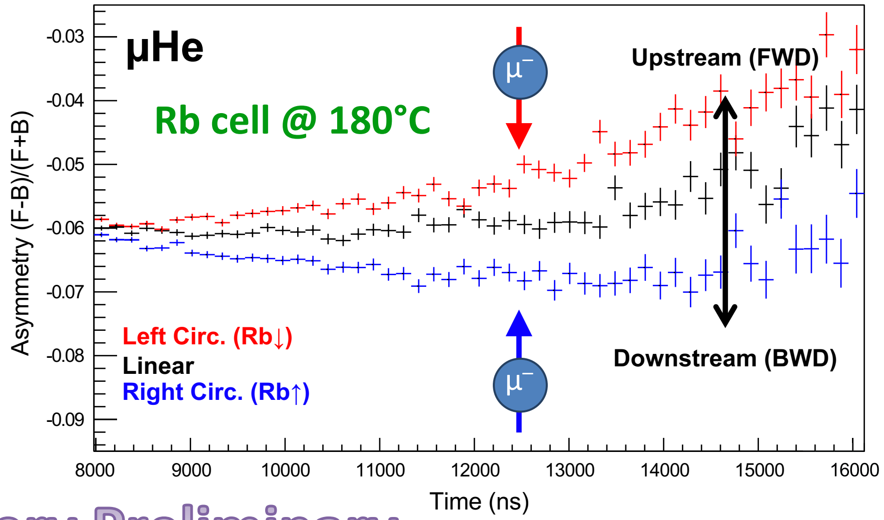
μHe SEOP Beamtime (Feb. 2023)

Muonic helium atom residual polarization

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



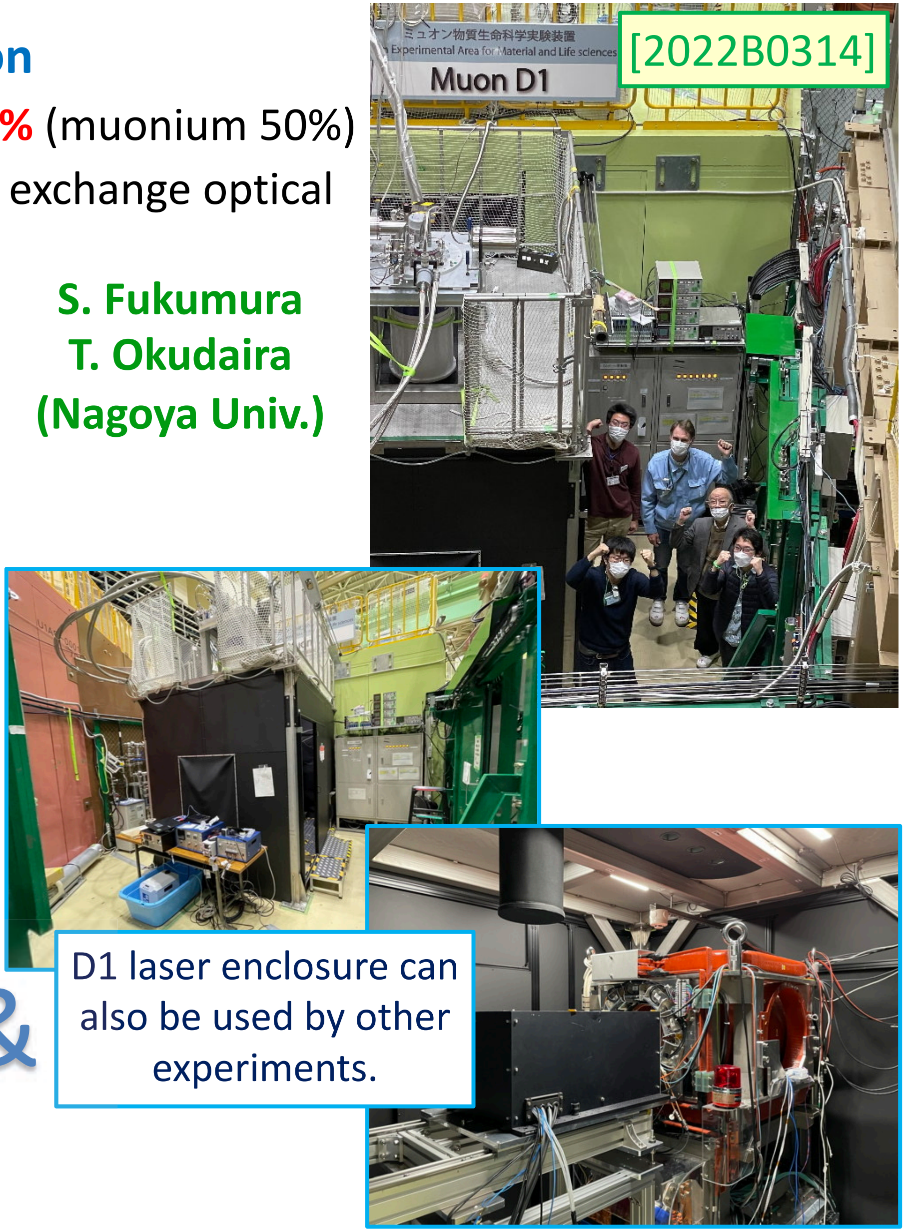
S. Fukumura
T. Okudaira
(Nagoya Univ.)



Very Preliminary

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

&



D1 laser enclosure can also be used by other experiments.

μHe SEOP Beamtime (Dec. 2023)

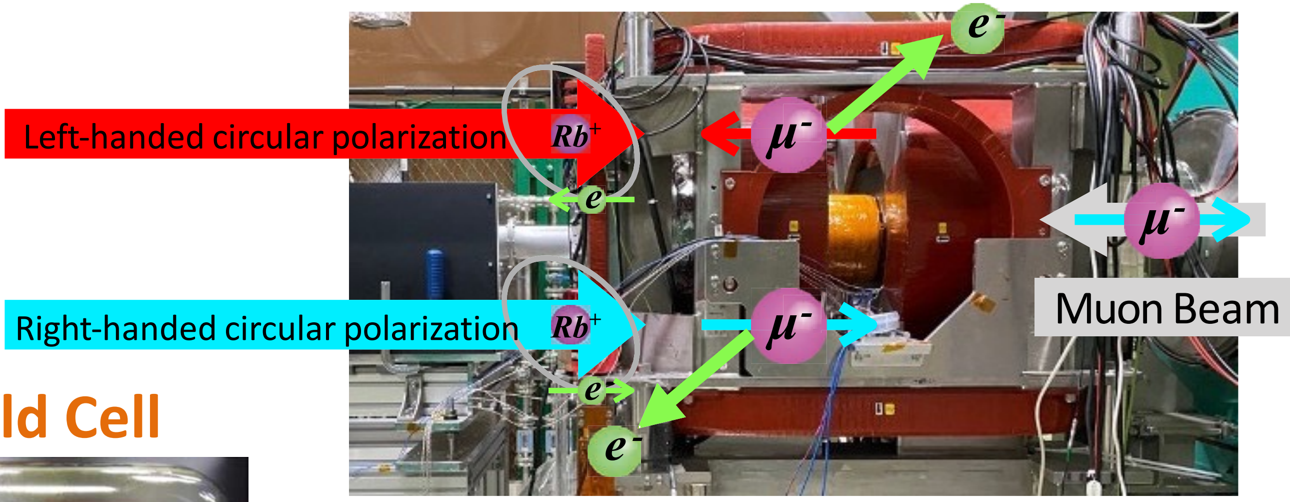
Nagoya U.

NIIGATA UNIVERSITY

JAEA

µHe SEOP Beamtime (Dec. 2023)

by S. Fukumura

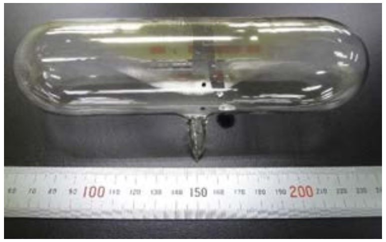


Old Cell

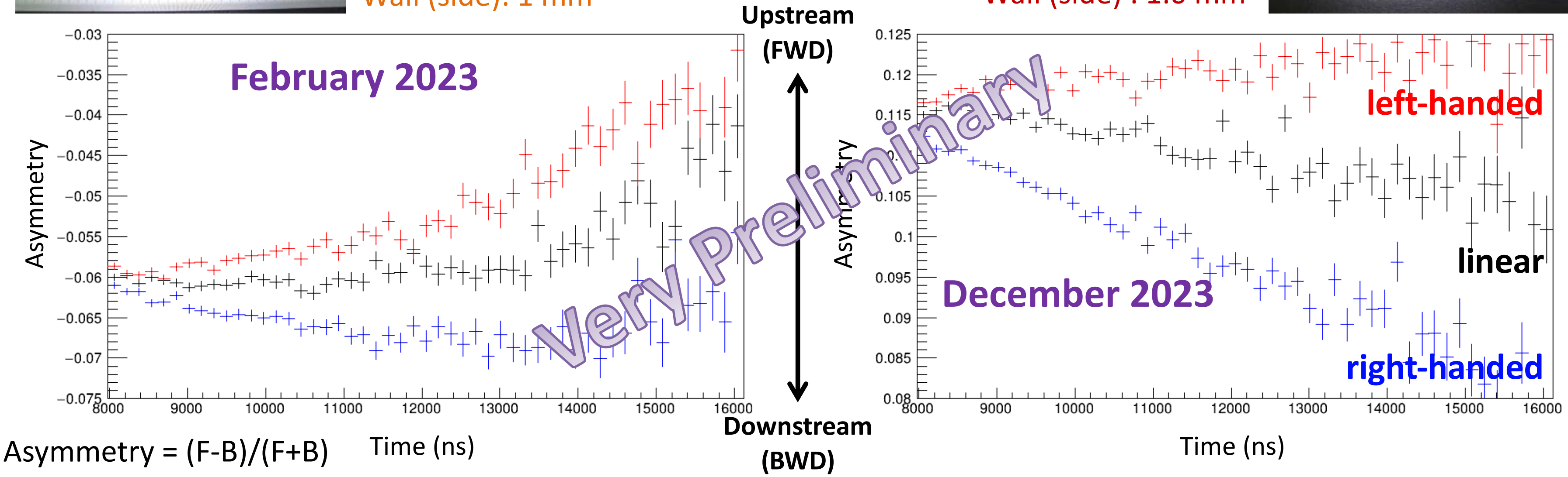
OD : 75 mm
OL : 150 mm
Wall (front): 1 mm
Wall (side): 1 mm

Rb cell: 180°C

New Cell



OD : 50 mm
OL : 180 mm
Wall (front) : 0.5 mm
Wall (side) : 1.0 mm



Asymmetry = (F-B)/(F+B)

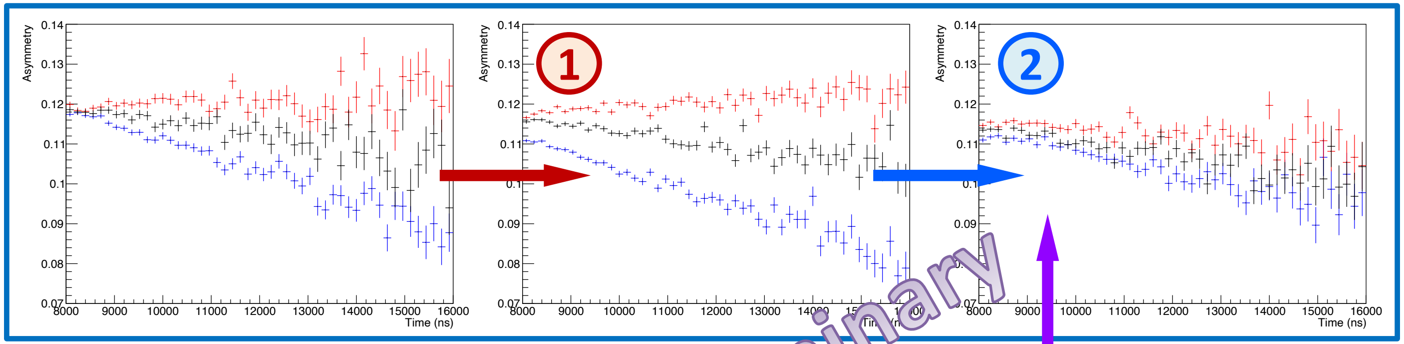
μHe SEOP vs. Hybrid-SEOP

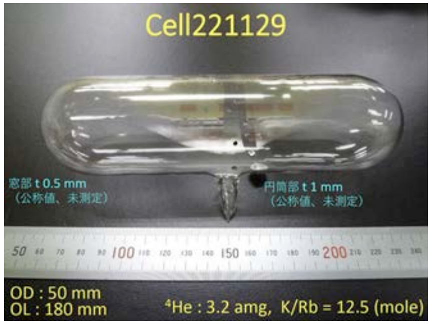
160 °C 180 °C 200 °C 240°C

Rb Pure Cell

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

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

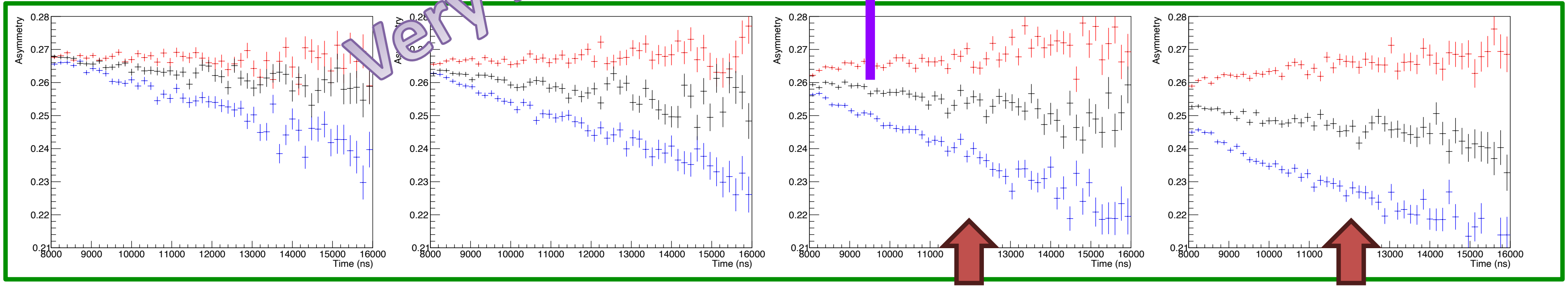




Decrease in polarization efficiency due to spin relaxation

Very Preliminary

Hybrid K/Rb Cell

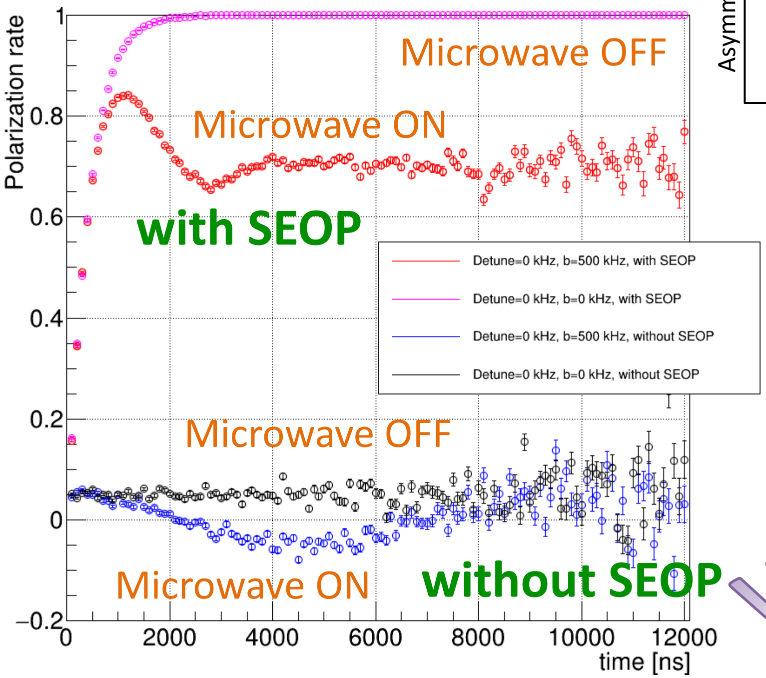


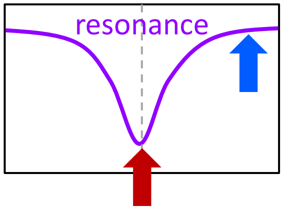
Increased polarization efficiency at higher temperatures due to K-μHe spin exchange

(on-line analysis only)

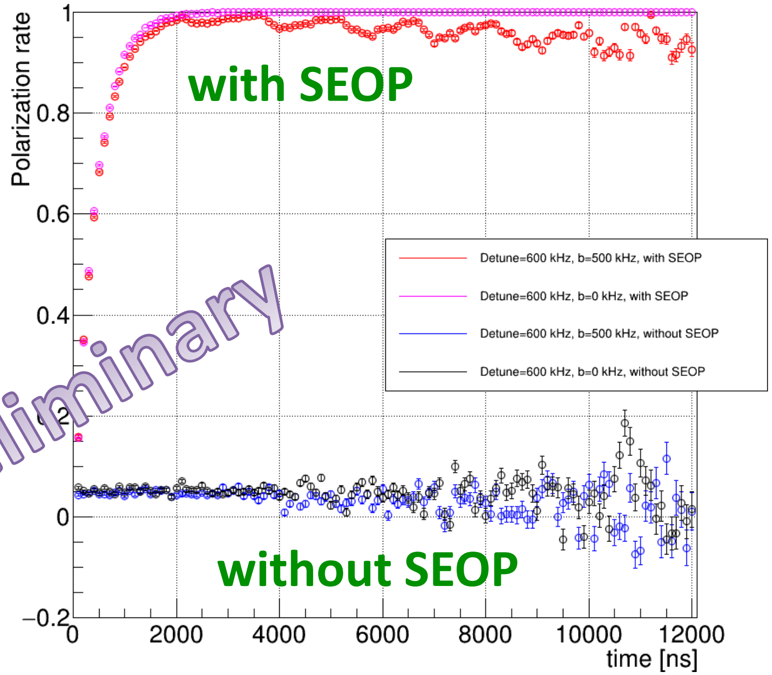
Simulation Studies

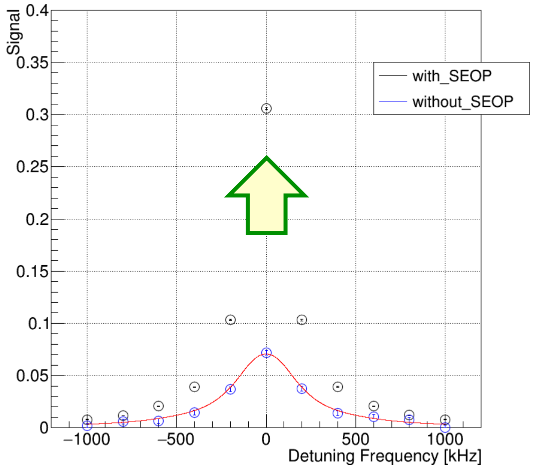
“On” resonance (0 kHz)





“Off” resonance (600 kHz)





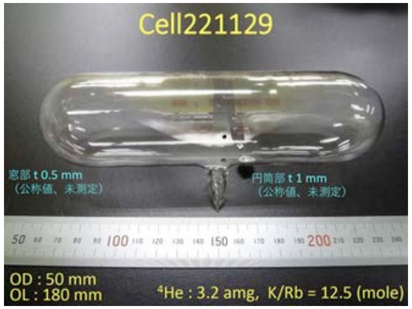
- **SEOP** can increase the resonance signal.
- But increase limited due to the competition between **SEOP** and **microwave**.
- We need to use a **pulsed laser** to polarize Rb before muon injection.

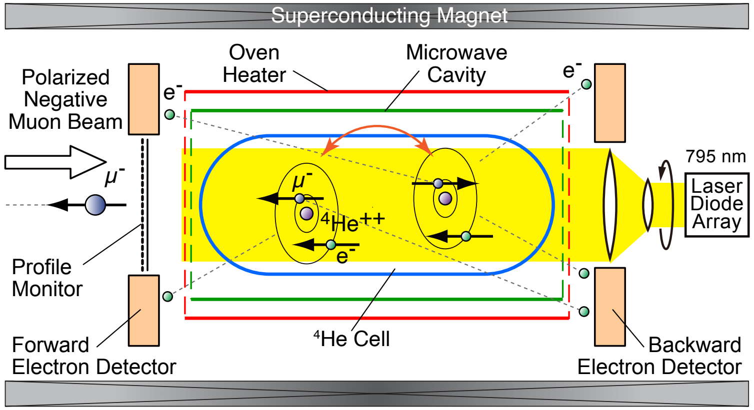
Simulation by S. Fukumura

From Glass to Metal Cell

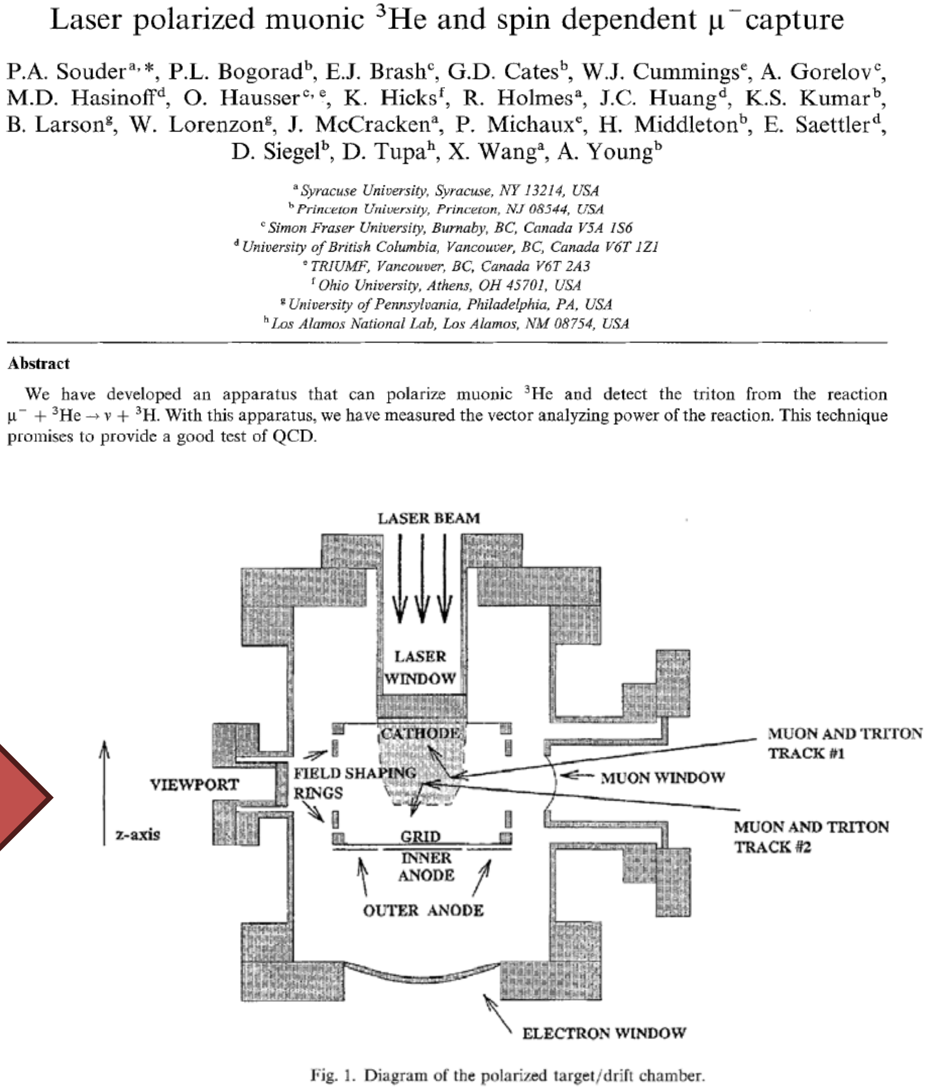
Advantages:

- 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

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Abstract

We have developed an apparatus that can polarize muonic ^{3}He and detect the triton from the reaction $\mu^- + {}^3\mathrm{He} \rightarrow \nu + {}^3\mathrm{H}$. 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 HFS splittings of muonic helium atoms at J-PARC MUSE
- New **μHe HFS measurements at zero field** using MuSEUM setup at **D2 area**
- Zero-Field experiment successful! **World's highest precision: 4.5 ppm**
  - Zero-pressure value determined using only our data for He + 2% CH_4
  - Need more measurements at higher pressure to determine **quadratic pressure shift coefficient** in helium
- Formation of **highly-polarized μHe atoms** by **SEOP** under development
- The **high-field experiment** is planned at **H1 area** after muonium
- This project is supported by a Kakenhi grant No. 21H04481 (FY2021–2023)
  "High-precision measurement of the negative muon mass by muonic helium atom hyperfine structure spectroscopy"

MuSEUM Collaboration

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

KEK

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S. Fukumura, R. Azuma

On behalf of the extended MuSEUM Collaboration

Open Questions, Remarks, …

Remarks:

- In general, polarized muonic atoms are not needed in element analysis, muon catalyzed fusion, etc.
- On the other hand, μ^-SR requires polarized muonic atoms

Questions:

- Are there other ways to repolarize μHe helium?
- Can we prevent muons from being depolarized during the cascade?
- Can the SEOP technique be applied to other exotic atoms like antiprotonic atoms?

FIN