The MuSEUM experiment at J-PARC

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On behalf of the MuSEUM Collaboration

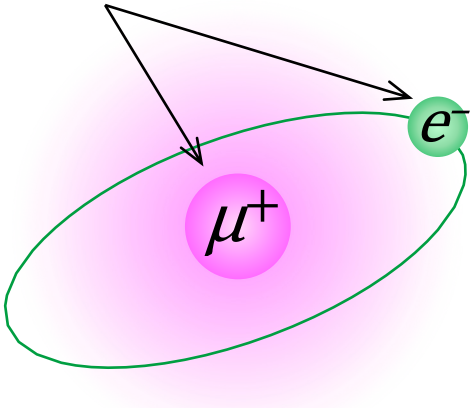
Topical Workshop on Precision Determinations of the Fine-structure Constant (ALPHA2025)
MITP - Mainz Institute for Theoretical Physics, Johannes Gutenberg University Mainz, Germany, October 27–31, 2025

Muonium

Muonium: bound state of μ^+ and e^-

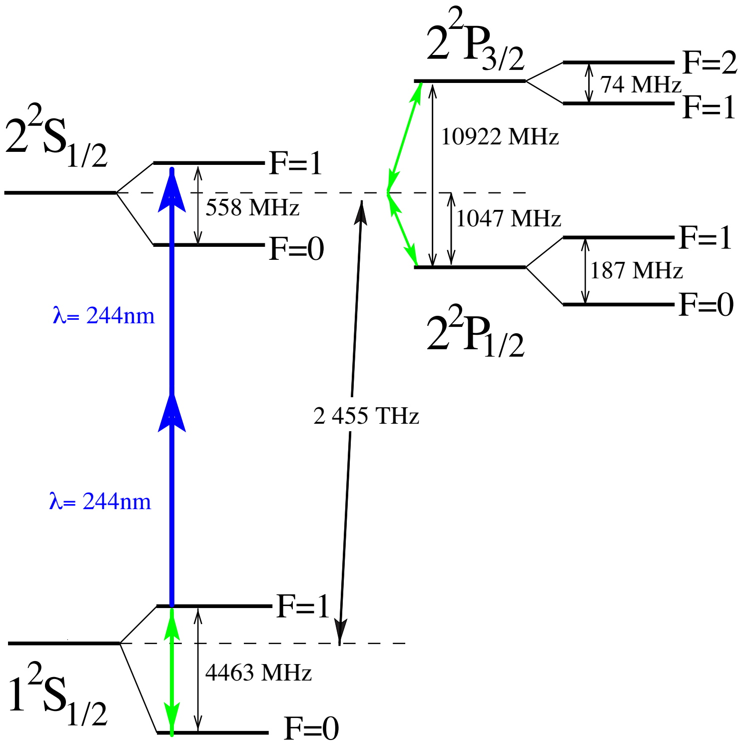
Lifetime: 2.2 μs

Leptons (= point particles)



- Hydrogen-like atom: simplest bound-system
- Precise theoretical calculation of energy levels possible → QED development

Muonium Energy Level Diagram



Klauss Jungmann, LNP 570, pp. 81–102 (2001)

- Compare precise experiments with theoretical calculations
  - **Precision test of the Standard Model**
- If discrepancy found between theory & experiment
  - Could be an evidence of **New Physics Beyond the Standard Model**

Muonium

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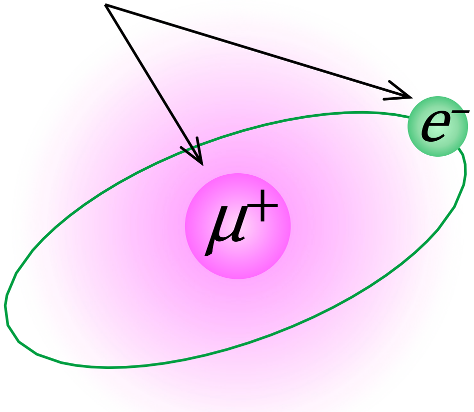

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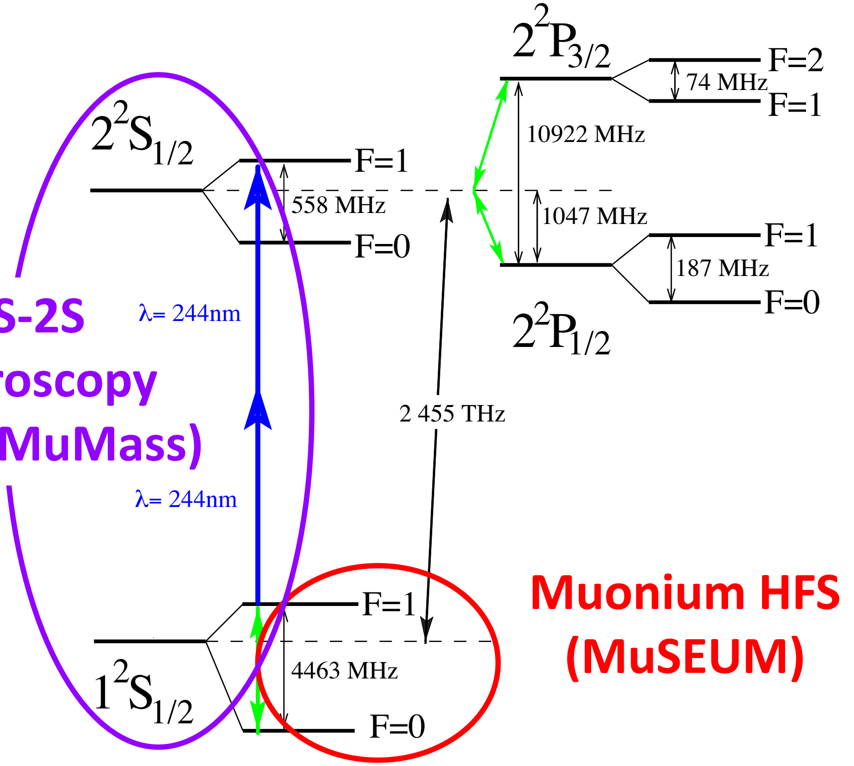
Muonium Energy Level Diagram



Muonium 1S-2S Laser Spectroscopy (AMuLET & MuMass)

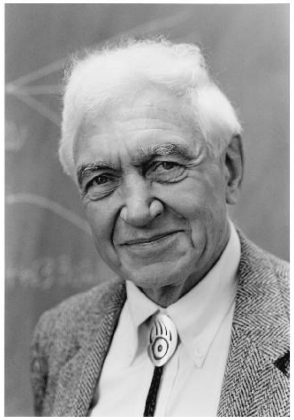
Muonium HFS (MuSEUM)

Klauss Jungmann, LNP 570, pp. 81–102, (2001)

- Compare precise experiments with theoretical calculations
  - **Precision test of the Standard Model**
- If discrepancy found between theory & experiment
  - Could be an evidence of **New Physics Beyond the Standard Model**

Slide from Klaus Jungmann

Past of Muonium (Ground State Hyperfine Structure)

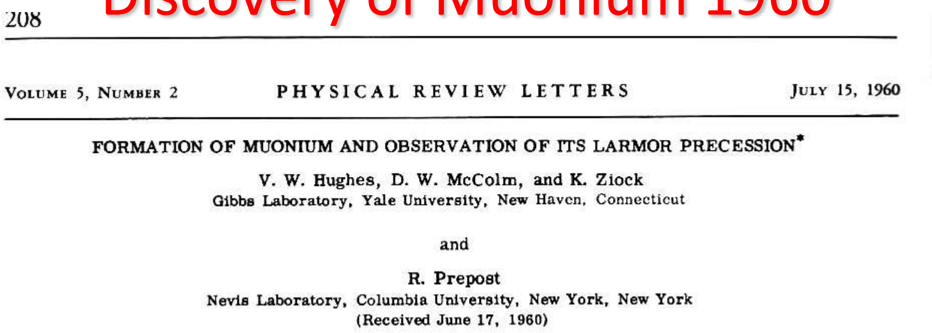


Vernon W. Hughes

There was stimulating competition

Valentine Telegdi

Discovery of Muonium 1960



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VOLUME 5, NUMBER 2 PHYSICAL REVIEW LETTERS JULY 15, 1960

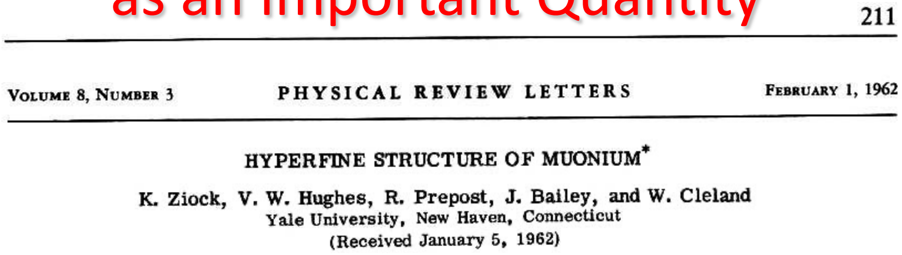
FORMATION OF MUONIUM AND OBSERVATION OF ITS LARMOR PRECESSION*

V. W. Hughes, D. W. McColm, and K. Ziock
Gibbs Laboratory, Yale University, New Haven, Connecticut

and

R. Prepost
Nevis Laboratory, Columbia University, New York, New York
(Received June 17, 1960)

Hyperfine Structure addressed as an Important Quantity



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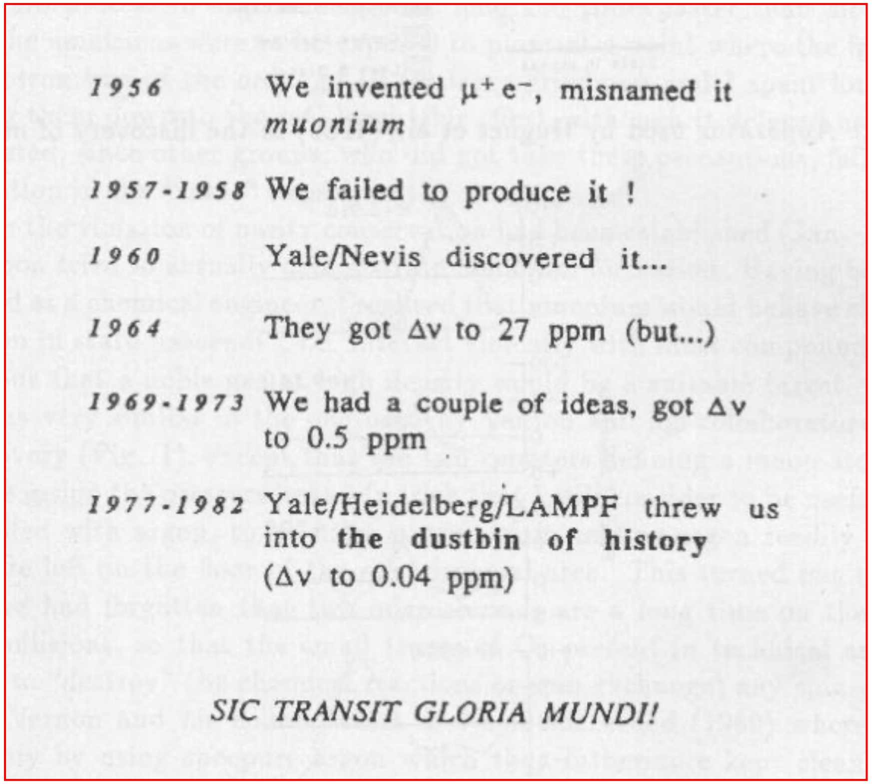
VOLUME 8, NUMBER 3 PHYSICAL REVIEW LETTERS FEBRUARY 1, 1962

HYPERFINE STRUCTURE OF MUONIUM*

K. Ziock, V. W. Hughes, R. Prepost, J. Bailey, and W. Cleland
Yale University, New Haven, Connecticut
(Received January 5, 1962)



1956	We invented $\mu^+ e^-$, misnamed it *muonium*
1957-1958	We failed to produce it !
1960	Yale/Nevis discovered it...
1964	They got $\Delta\nu$ to 27 ppm (but...)
1969-1973	We had a couple of ideas, got $\Delta\nu$ to 0.5 ppm
1977-1982	Yale/Heidelberg/LAMPF threw us into **the dustbin of history** ($\Delta\nu$ to 0.04 ppm)

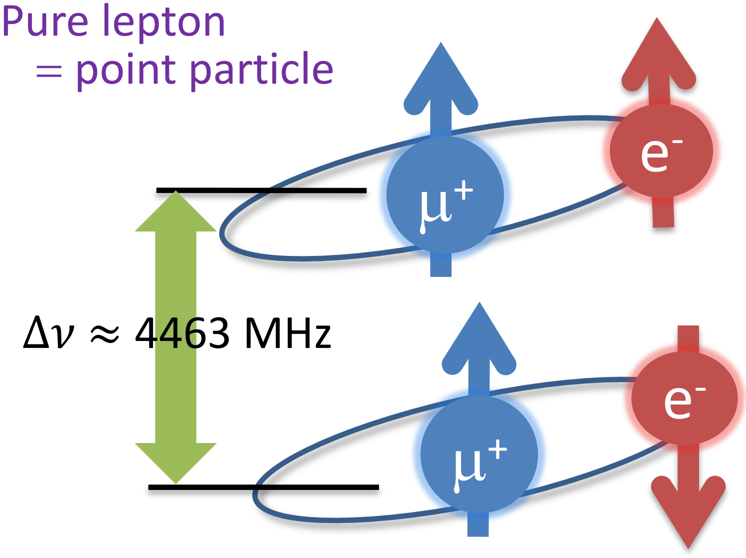
SIC TRANSIT GLORIA MUNDI!

From: V. Telegdi, in: “A Festschrift for Vernon W. Hughes”, 1990

Muonium Hyperfine Structure

Muonium: bound state of μ^+ and e^-

Pure lepton
= point particle



Δν : Muonium Hyperfine Structure

ZF: 4 463 302.2(14) kHz (310 ppb)
HF: 4 463 302.765(51)(17) kHz (12 ppb)

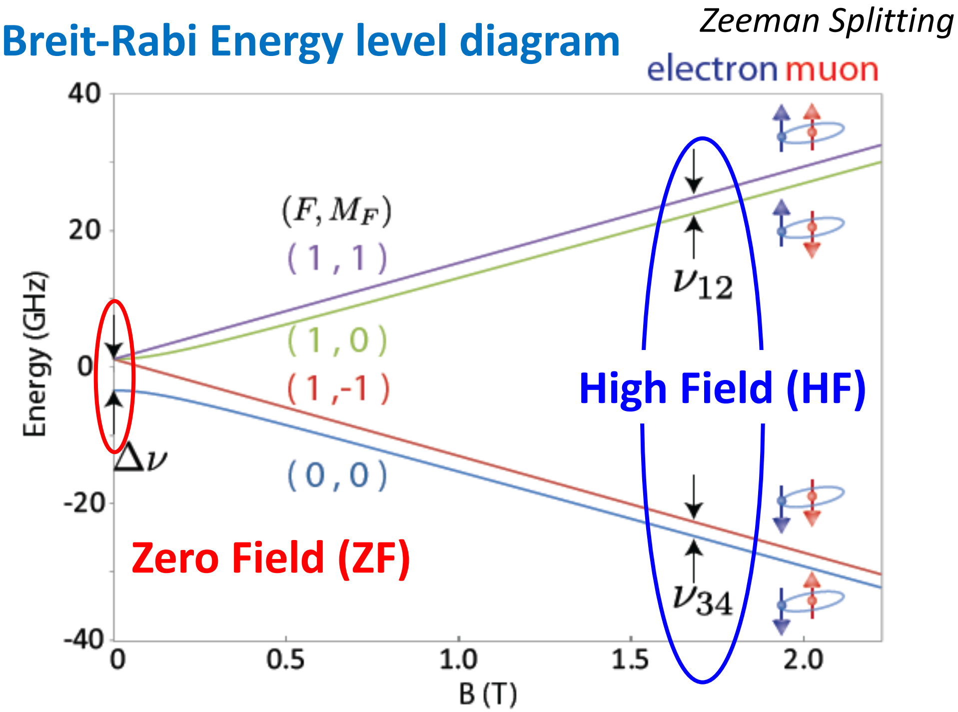
Exp. dominated by statistical uncertainty!

MuSEUM goal: ~ 2ppb

ZF: D. E. Casperson *et al.*, Phys. Lett. B **59**, 397 (1975)
HF: W. Liu *et al.*, Phys. Rev. Lett. **82**, 711 (1999)

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

Breit-Rabi Energy level diagram



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

$$\frac{\mu_\mu}{\mu_p} = \frac{4\nu_{12}\nu_{34} + r'_e \nu_p (\nu_{34} - \nu_{12})}{2\nu_p \left(r'_e \nu_p + (\nu_{34} - \nu_{12})\right)} \frac{g_\mu}{g'_\mu}$$

with $r'_e = g_J \mu_B^e / \mu_p$ and $h\nu_p = 2\mu_p H$

Most Precise Test of Bound-State QED

Experiment:

LAMPF Experiment (1999)

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

ν_{HFS}(exp) 4463.302 765 (53) MHz [12 ppb]

μ_μ/μ_p = 3.18334524(37) [120ppb]

m_μ/m_e = 206.768277(24) [120ppb]

Theory:

M. I. Eides Phys. Lett. B **795**, 113 (2019)

ν_{HFS}(theory) 4463.302 868 (515) MHz [120 ppb]

ν_{HFS}(QED) 4463.302 720 (511) (70) (1) MHz

(m_μ/m_e) (QED) (α)

ν_{HFS}(weak) -65 Hz

ν_{HFS}(had. v.p.) 237.7(1.5) Hz

ν_{HFS}(had. h.o.) 5 (2) Hz

m_μ uncertainty

120 ppb (exp)

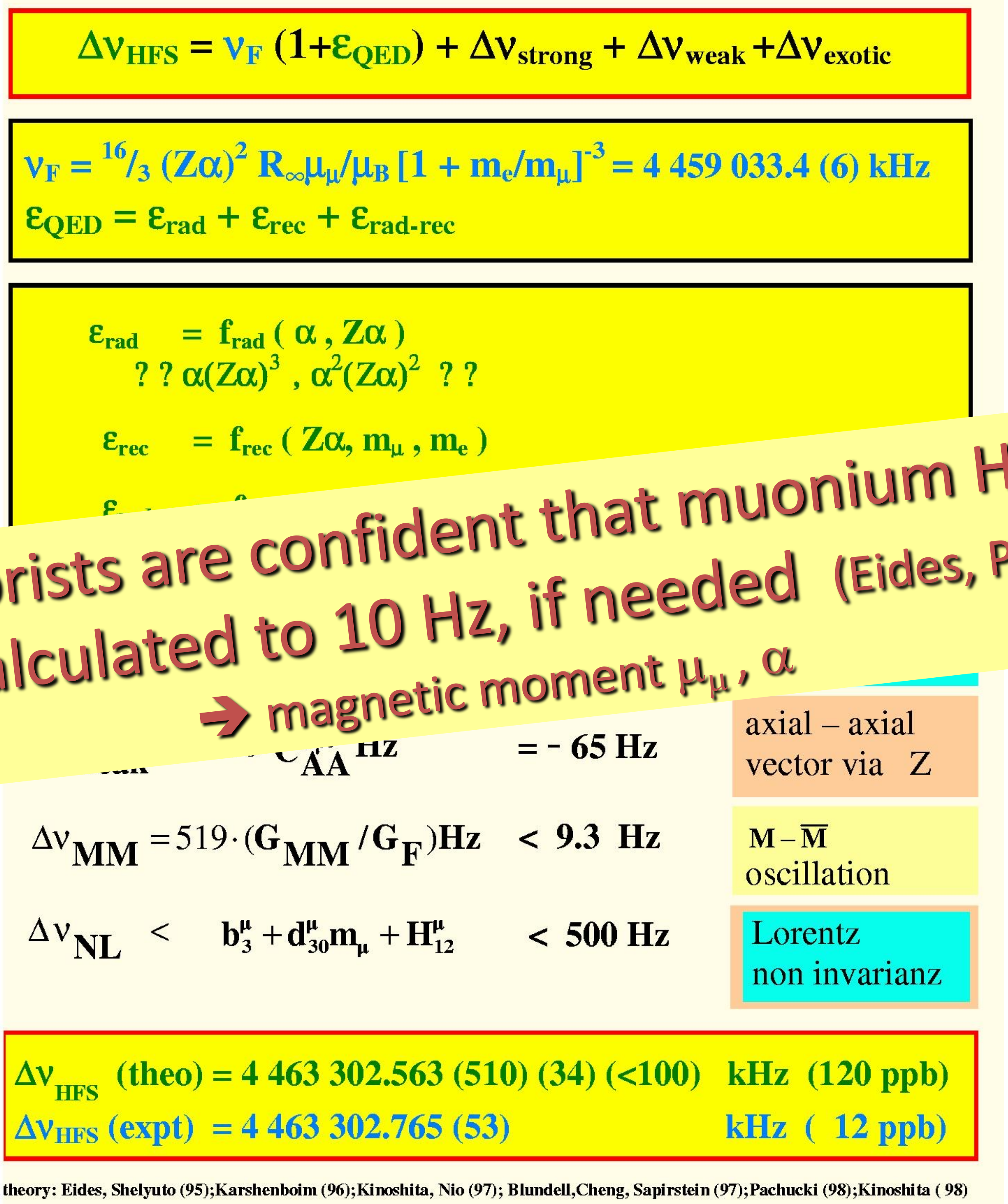
CODATA 2022

22 ppb (theo+exp)

$$\nu(\text{Fermi}) = \frac{16}{3}\alpha^2 c R_\infty \boxed{\frac{m_e}{m_\mu}\left(1+\frac{m_e}{m_\mu}\right)^{-3}}$$

QED calculations: Effort for 10 Hz accuracy in progress (by Eides *et al.*)

Slide from
Klaus Jungmann
(~2005)



$$\Delta\nu_{HFS} = \nu_F\,(1+\varepsilon_{QED}) + \Delta\nu_{strong} + \Delta\nu_{weak} + \Delta\nu_{exotic}$$

$$\nu_F = {}^{16}/_3\,(Z\alpha)^2\,R_\infty \mu_\mu/\mu_B\,[1 + m_e/m_\mu]^{-3} = 4\,459\,033.4\,(6)\text{ kHz}$$

$$\varepsilon_{QED} = \varepsilon_{rad} + \varepsilon_{rec} + \varepsilon_{rad\text{-}rec}$$

$\varepsilon_{rad} = f_{rad}\,(\alpha, Z\alpha)$

? ? $\alpha(Z\alpha)^3$, $\alpha^2(Z\alpha)^2$? ?

$\varepsilon_{rec} = f_{rec}\,(Z\alpha, m_\mu, m_e)$

C_{AA} Hz = - 65 Hz

axial – axial
vector via Z

$\Delta\nu_{MM} = 519 \cdot (G_{MM}/G_F)$ Hz < 9.3 Hz

$M - \overline{M}$
oscillation

$\Delta\nu_{NL} < b^\mu_3 + d^\mu_{30} m_\mu + H^\mu_{12}$ < 500 Hz

Lorentz
non invarianz

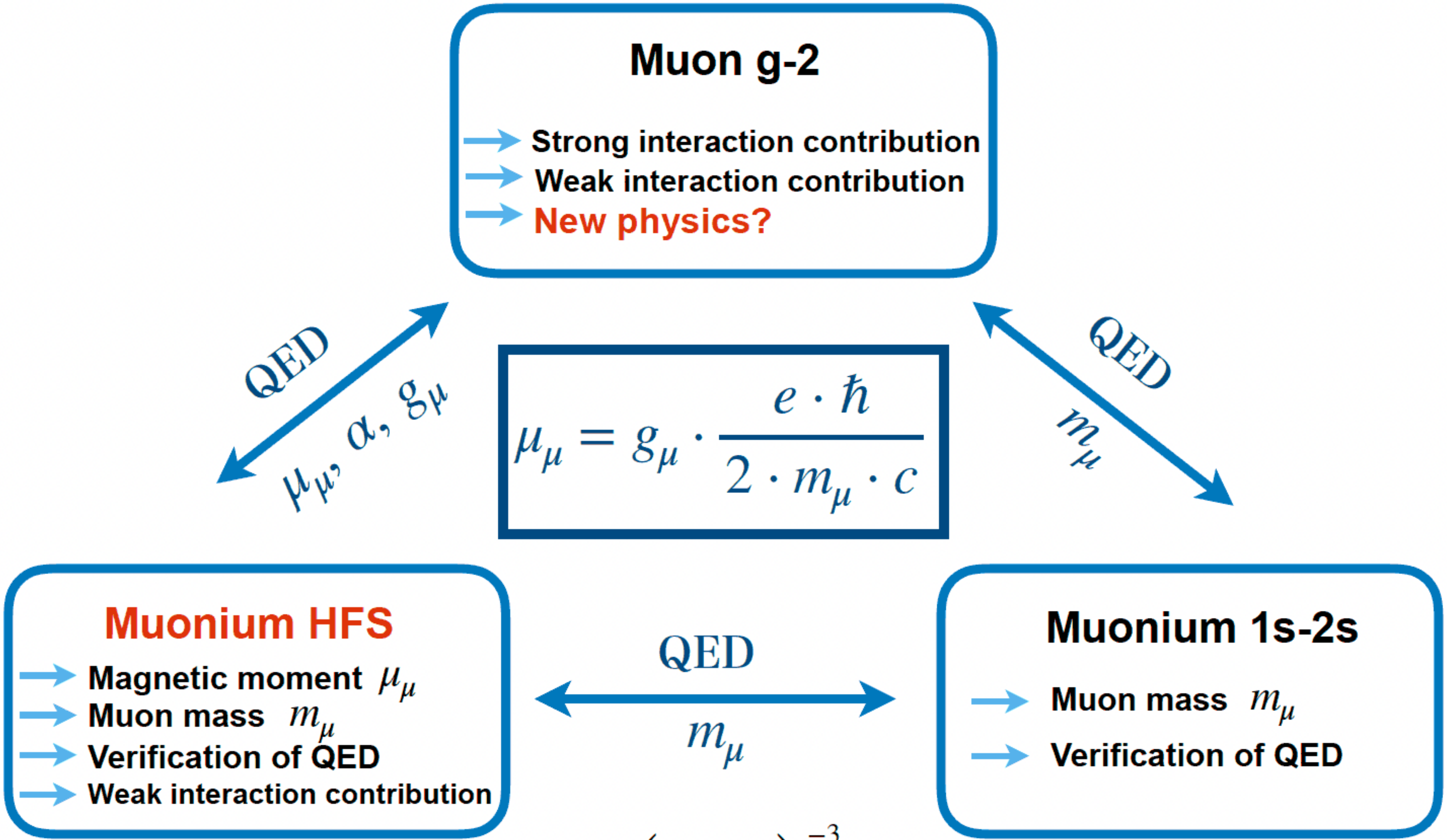
$\Delta\nu_{HFS}$ (theo) = 4 463 302.563 (510) (34) (<100) kHz (120 ppb)
$\Delta\nu_{HFS}$ (expt) = 4 463 302.765 (53) kHz (12 ppb)

theory: Eides, Shelyuto (95);Karshenboim (96);Kinoshita, Nio (97); Blundell,Cheng, Sapirstein (97);Pachucki (98);Kinoshita (98)

Theorists are confident that muonium HFS
Can be calculated to 10 Hz, if needed (Eides, Pachucki,…)
➔ magnetic moment μ_μ , α

Slide from Klaus Jungmann

Muon Precision Measurements



Muon g-2

- Strong interaction contribution
- Weak interaction contribution
- New physics?

QED μ_μ, α, g_μ

QED m_μ

$$\boxed{\mu_\mu = g_\mu \cdot \frac{e \cdot \hbar}{2 \cdot m_\mu \cdot c}}$$

Muonium HFS

- Magnetic moment μ_μ
- Muon mass m_μ
- Verification of QED
- Weak interaction contribution

QED m_μ

Muonium 1s-2s

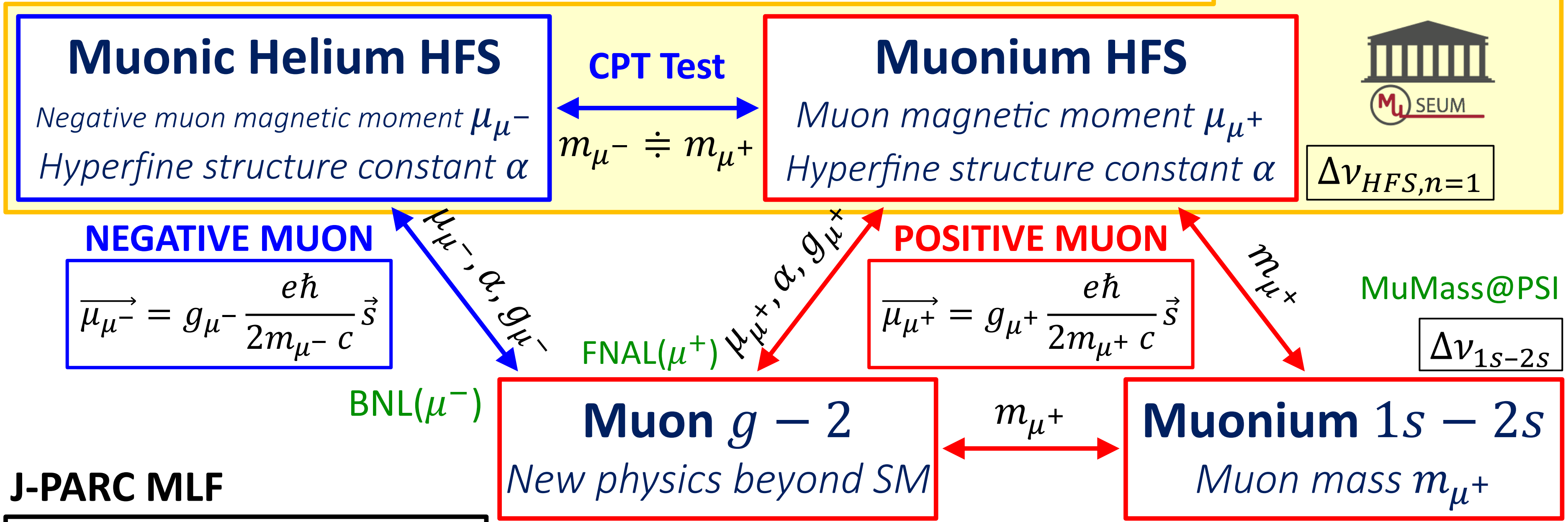
- Muon mass m_μ
- Verification of QED

$$\Delta\nu_{HFS}^{th} = \frac{16}{3} Z^4 \alpha^2 c R_\infty \frac{m_e}{m_\mu}\left(1 + \frac{m_e}{m_\mu}\right)^{-3} + \Delta\nu_{QED} + \underset{237\text{ Hz}}{\Delta\nu_{QCD}} + \underset{65\text{ Hz}}{\Delta\nu_{weak}}$$

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

MuSEUM

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

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 $g-2$

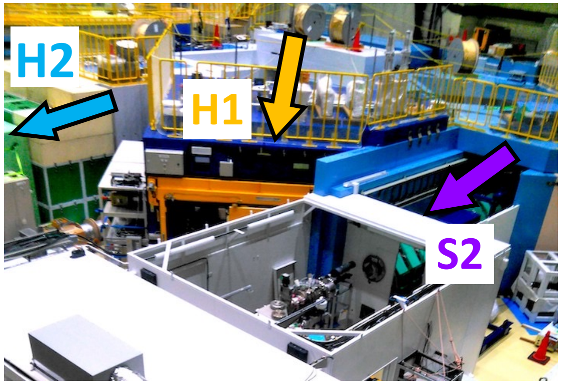
New physics beyond SM

m_{μ^+}

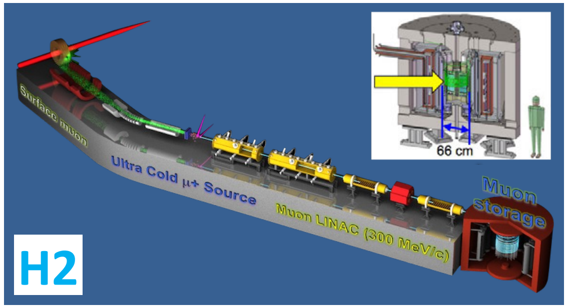
Muonium $1s-2s$

Muon mass m_{μ^+}

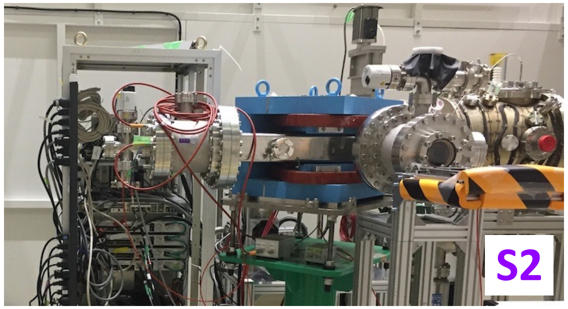
J-PARC MLF



J-PARC Muon *g*-2/EDM



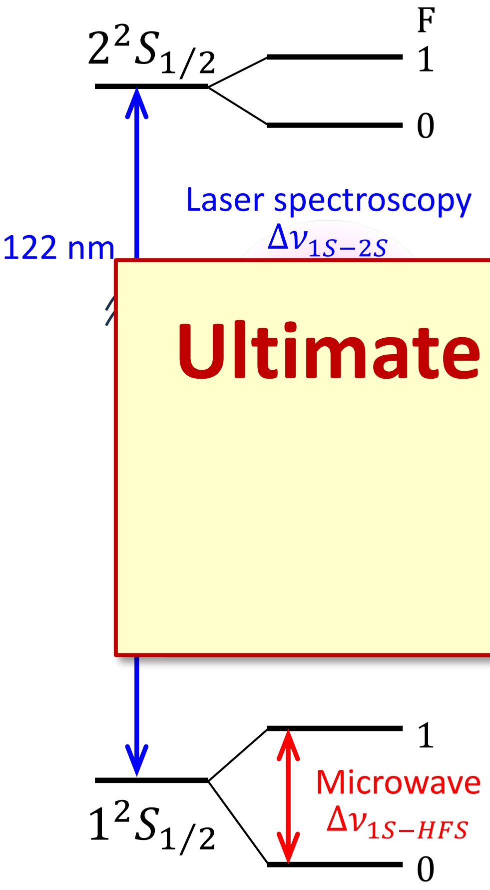
AMuLET (J-PARC)



1S-2S Current Precision and Goal

From S. Uetake (Okayama Univ.)

Muonium Energy Level



1S-2S Laser Spectroscopy

$$\Delta\nu_{1S-2S} \simeq \frac{3\alpha^2}{8h} m_e c^2 \left(1+\frac{m_e}{\underbrace{m_\mu}_{\text{mass}}}\right)^{-1}$$

$u[\Delta\nu_{1S-2S}]$:

Exp(RAL 1999): 9.8 MHz [4]
Theory: 1.4 MHz [5]
QED alone: 6 kHz [5]

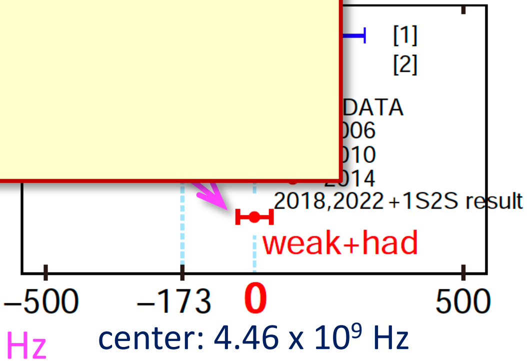
1S-2S Goal (a): 100 kHz
Reduce mass uncertainty
120 ppb ➡ 8 ppb

Ultimate Goal by AMuLET & MuMass

10 kHz precision

$\Delta m_\mu \approx 1\text{ppb}$

$$\left(1+\frac{m_e}{\underbrace{m_\mu}_{\text{mass}}}\right)^{-3}$$



Muon mass uncertainty:
511 Hz (120 ppb) [2]

center: 4.46 x 10^9 Hz

Electroweak contribution: -65 Hz
Hadronic vacuum polarization: +237.7 Hz

Electron mass uncertainty: $m_e \approx 0.3$ ppb

- Experiment (RAL 1999): 2 455 528 941.0(9.8) MHz [4]
- Bound-state QED predictions: 2 455 528 935.2(1.4) [5]
- QED calculations alone known down to 6 kHz (2.4 ppt) [5]

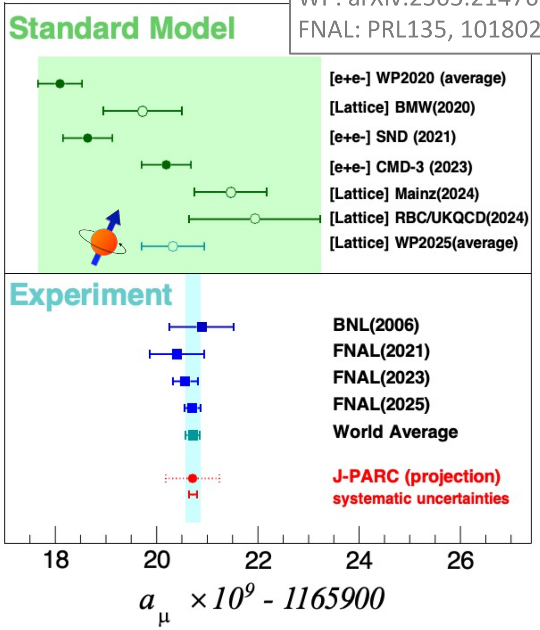
[1] F. G. Mariam et al., PRL **49**, 993 (1982)
[2] W. Liu *et al.*, PRL **82**, 711(1999)
[3] M. I. Eides, PLB **795**, 113 (2019)
[4] V. Meyer *et al.*, PRL **84**, 1136 (2000)
[5] I. Cortinovis *et al.*, EPJD **77**, 66 (2023)

Relation between Muon g–2 & MuHFS

Muon $g-2$ $$a_\mu = \frac{g-2}{2}$$

- 5σ discrepancy between theory and exp.
- Exp. precision value: 0.2 ppm (FNAL 2023)
- Exp. goal at J-PARC and FNAL: ~0.1 ppm
- Independent precise measurement of muon mass required !
  - ➢ Exp. value obtained using Muonium HFS result

WP: arXiv:2505.21476
FNAL: PRL135, 101802 (2025)



From M. Kimura's Talk at NuFACT2025

$$\boxed{a_\mu = \frac{R}{\lambda - R}} \qquad \boxed{R \equiv \frac{\omega_a}{\omega_p}} \qquad \boxed{\lambda \equiv \frac{\mu_\mu}{\mu_p}}$$

From g-2 storage ring

From Muonium HFS

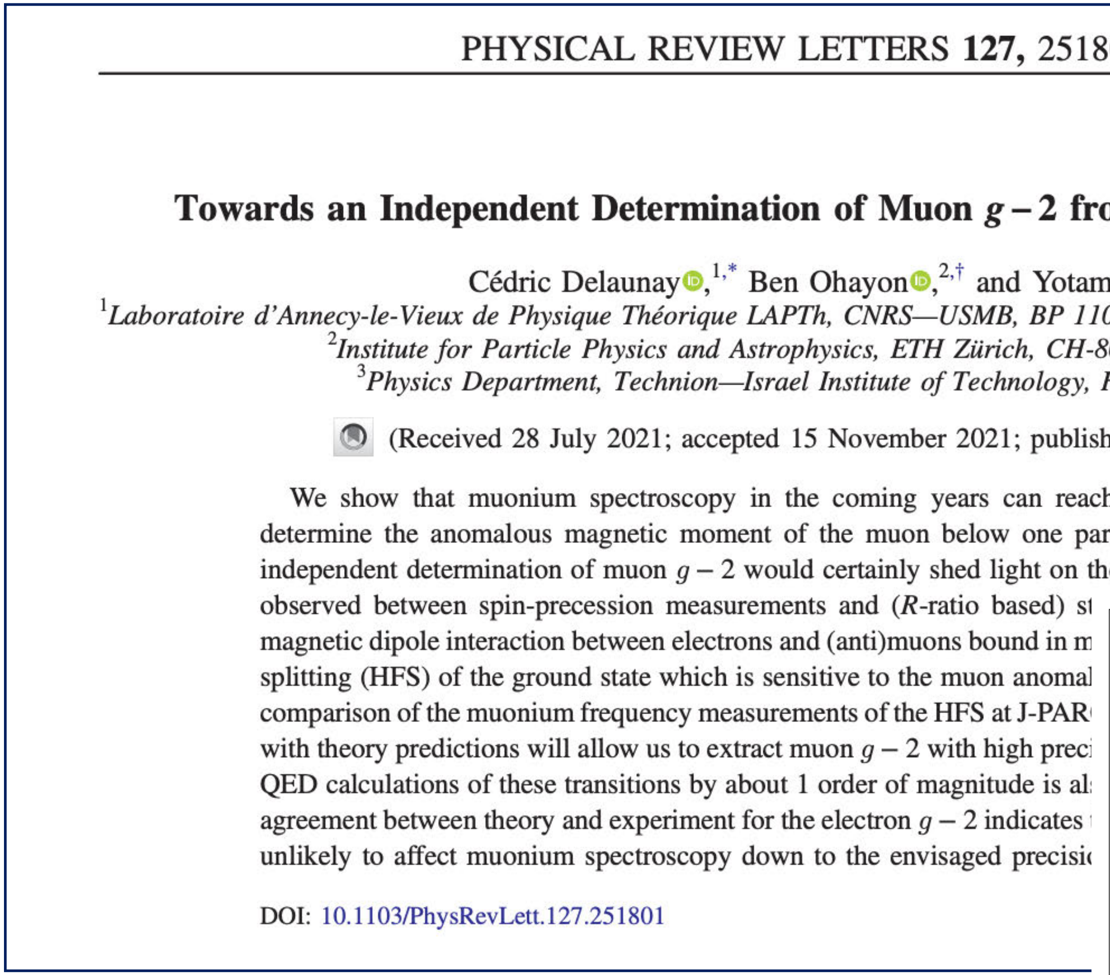
$$\frac{\omega_a}{\omega_L(\mu)} = \frac{a_\mu\left(\frac{eB}{mc}\right)}{g_\mu\left(\frac{eB}{2mc}\right)} = \frac{a_\mu}{\left(\frac{g_\mu}{2}\right)} = \underline{\frac{a_\mu}{1+a_\mu}}$$

$$= \frac{\omega_a}{\omega_L(p)}\frac{\omega_L(p)}{\omega_L(\mu)} = \frac{\omega_a}{\omega_p}\frac{\mu_p}{\mu_\mu} = \underline{\frac{R}{\lambda}}$$

μ_μ/μ_p accuracy from direct measurement: 120 ppb

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

MuHFS + Mu $1s - 2s$ = $g - 2$



PHYSICAL REVIEW LETTERS **127,** 251801 (2021)

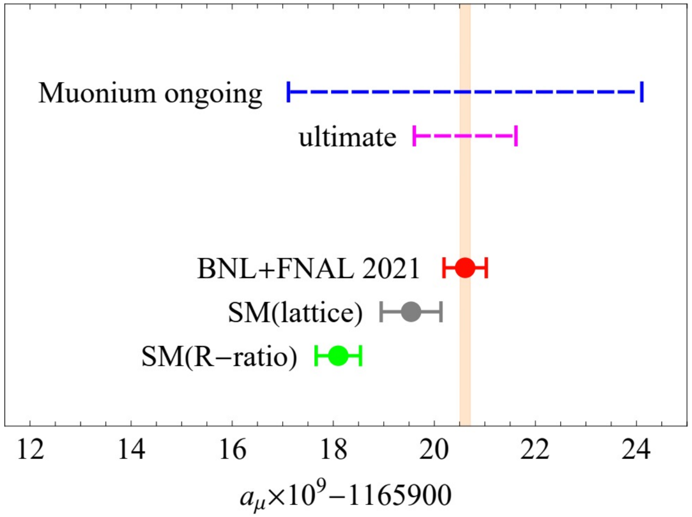
Towards an Independent Determination of Muon $g - 2$ from Muonium Spectroscopy

Cédric Delaunay,[1,*] Ben Ohayon,[2,†] and Yotam Soreq[3,‡]
[1] *Laboratoire d'Annecy-le-Vieux de Physique Théorique LAPTh, CNRS—USMB, BP 110 Annecy-le-Vieux, F-74941 Annecy, France*
[2] *Institute for Particle Physics and Astrophysics, ETH Zürich, CH-8093 Zürich, Switzerland*
[3] *Physics Department, Technion—Israel Institute of Technology, Haifa 3200003, Israel*

(Received 28 July 2021; accepted 15 November 2021; published 15 December 2021)

We show that muonium spectroscopy in the coming years can reach a precision high enough to determine the anomalous magnetic moment of the muon below one part per million (ppm). Such an independent determination of muon $g - 2$ would certainly shed light on the ~2 ppm difference currently observed between spin-precession measurements and (R-ratio based) st
magnetic dipole interaction between electrons and (anti)muons bound in m
splitting (HFS) of the ground state which is sensitive to the muon anomal
comparison of the muonium frequency measurements of the HFS at J-PAR
with theory predictions will allow us to extract muon $g - 2$ with high preci
QED calculations of these transitions by about 1 order of magnitude is al
agreement between theory and experiment for the electron $g - 2$ indicates
unlikely to affect muonium spectroscopy down to the envisaged precisi

DOI: 10.1103/PhysRevLett.127.251801



Test of CPT and Lorentz Invariance

CPT broken Theory ⇒ Lorentz symmetry is broken

O.W. Greenberg, Phys. Rev. Lett. **89**, 231602 (2002)
R. Blihm, V.A. Kosteleky, C.D. Lane, Phys. Rev. Lett. **84**, 1098 (2000)
V.W. Hughs *et al.*, Phys. Rev. Lett. **87**, 111804 (2002)

CPT violation search

Ex: Muon difference $g_{\mu+}/\ g_{\mu-} \approx 10^{-8}$

g_μ–2/Muonium HFS precise measurement

Lorentz symmetry-violating term in STE Lagrangian b
Corresponding Muonium HFS transition ν_{12} and ν_{34}
These values might change in sidereal time (23h56m)

$$\tilde{b}_3{}^{\mu}/_{\pi} = -\delta\Delta\nu_{12} = \delta\Delta\nu_{34}$$

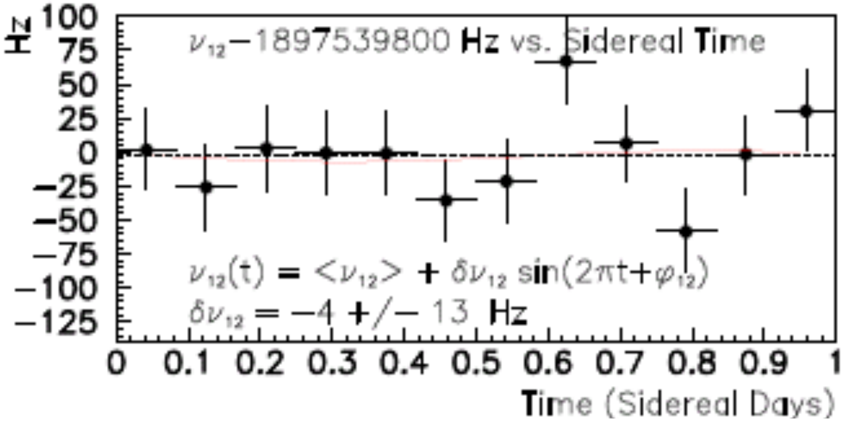


Figure of Merit of LAMPF Experiment

$$2\sqrt{\left(b^{\mu^+}x\right)^2 + \left(b^{\mu^+}y\right)^2}/m_\mu < 5\times10^{-22}$$

$m_\mu/M_P \sim 10^{-20}$

Plank scale sensitivity

V.A. Kostelecky, A.J. Vargas, Phys. Rev. D **92**, 056002 (2015)

Fundamental Constant Determination

Assuming the validity of the bound state QED theory

$$\Delta\nu_{HFS} = \frac{16}{3}\enclose{circle}{\alpha^2}\, c\, \enclose{circle}{R_\infty}\, \enclose{circle}{\frac{m_e}{m_\mu}}\left(1+\frac{m_e}{m_\mu}\right)^{-3} + \Delta\nu_{QED} + \Delta\nu_{QCD} + \Delta\nu_{weak}$$

The following values can be derived:

Constant	*Input parameters*	*Derived accuary*	
m_μ/m_e	α, R_∞, $\Delta\nu_{exp}$, *theory*	20 ppb	😊
R_∞	α, m_e/m_μ, $\Delta\nu_{exp}$, *theory*	125 ppb	☹
α	R_∞, m_e/m_μ, $\Delta\nu_{exp}$, *theory*	?	

rough estimation

Current relative uncertainty:

m_e: 3.1 x 10^{-10} (CODATA2022)
R_∞: 1.1 x 10^{-12} (CODATA2022)
α: 1.6 x 10^{-10} (CODATA2022)

$\Delta\nu_{exp}$: 1.2 x 10^{-8} (Liu 1999)
m_μ/m_e: 1.2 x 10^{-7} (Liu 1999)
theory: ≈ 70 Hz (≈ 1.6 x 10^{-8})

Determination of α from $\Delta\nu_{\mathrm{HFS}}$

$$\boxed{\Delta\nu_{HFS} = \frac{16}{3}\alpha^2 c R_\infty \frac{m_e}{m_\mu}\left(1+\frac{m_e}{m_\mu}\right)^{-3} + \Delta\nu_{QED} + \Delta\nu_{QCD} + \Delta\nu_{weak}}$$

- W. Liu, PhD Thesis, Yale University, 1997 (unpublished)

α^{-1} = 137.035 994 5 (82) (13) (26) [63 ppb]

errors from: m_μ $\Delta\nu_{\mathrm{exp}}$ theory

- K. Jungmann, Proc. Memorial Symposium in Honor of Vernon Willard Hughes (2004)

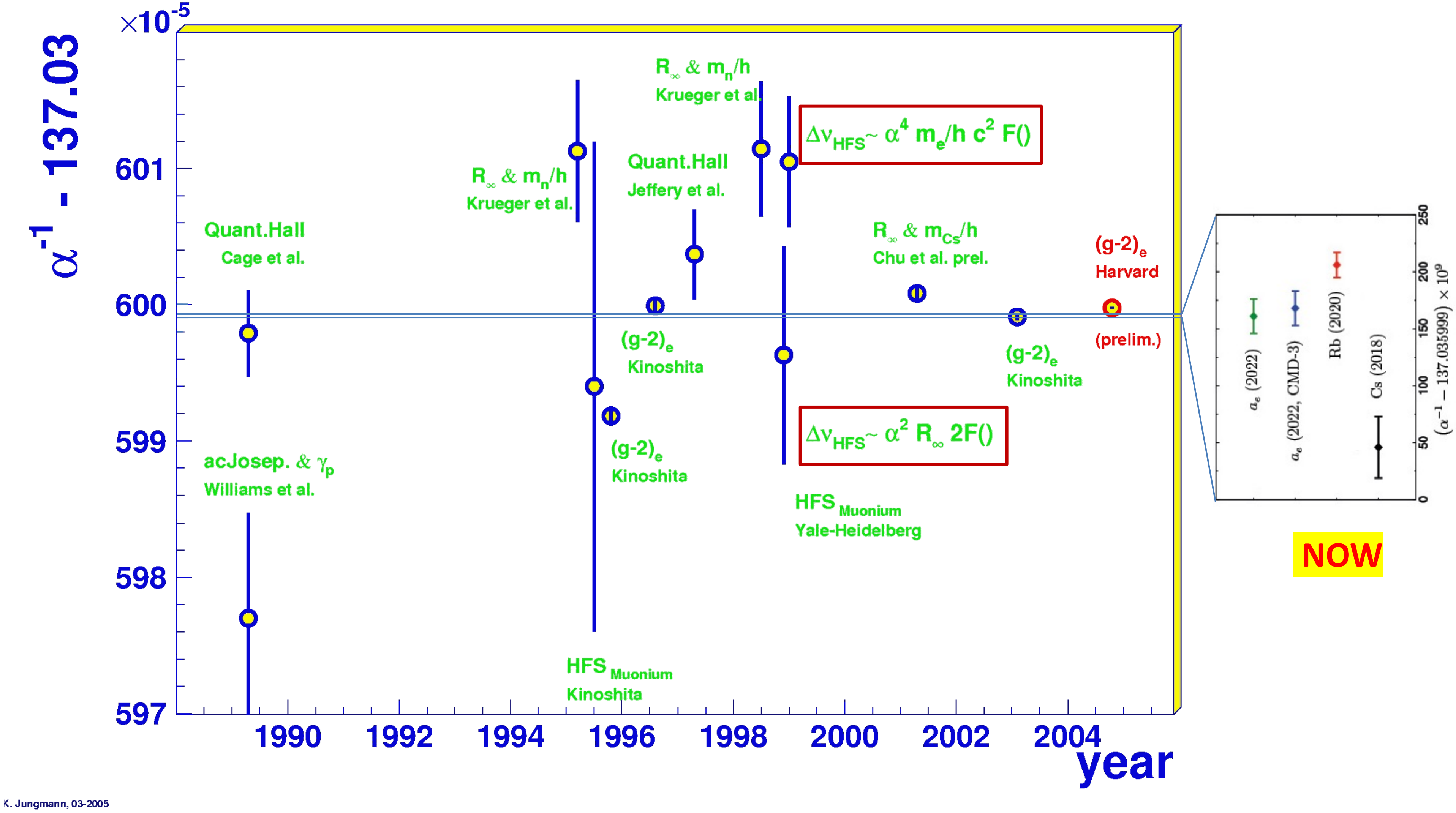
$\Delta\nu_{HFS} \simeq \alpha^2 R_\infty\ 2cF()$ $\Rightarrow$ α^{-1} = 137.035 996 3 (80) [59 ppb]

with $R_\infty = \alpha^2 \frac{m_e c}{2h}$

$\Delta\nu_{HFS} \simeq \alpha^4 m_e/h\ c^2 F(\,)$ $\Rightarrow$ α^{-1} = 137.036 004 7 (48) [35 ppb]

h/m_e: determined in measurements of the neutron de Broglie wavelength

Fine StructureConstant α



Slide from Klaus Jungmann (~2005)

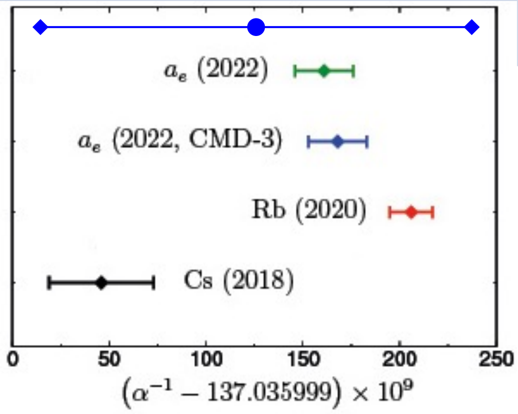
Future Prospects

$$\boxed{\Delta\nu_{HFS} = \frac{16}{3}\alpha^4 \frac{m_e c^2}{2h}\frac{m_e}{m_\mu}\left(1+\frac{m_e}{m_\mu}\right)^{-3} + \Delta\nu_{QED}+\Delta\nu_{QCD}+\Delta\nu_{weak}}$$

$$\Delta\nu_{HFS} \simeq \alpha^4\, m_e/h\ c^2 F(\,)$$

Expected improvement in accuracy:

	Current	***Expectation***	***Collaboration / Theorists***
m_μ	120 ppb	1 ppb	AMuLET & MuMass goal
$\Delta\nu_{exp}$	12 ppb	2 ppb	MuSEUM goal
Theory	70 Hz	10 Hz (2.2 ppb)	Eides, Pachucki, …
α^{-1}	32 ppb	**0.8 ppb**	



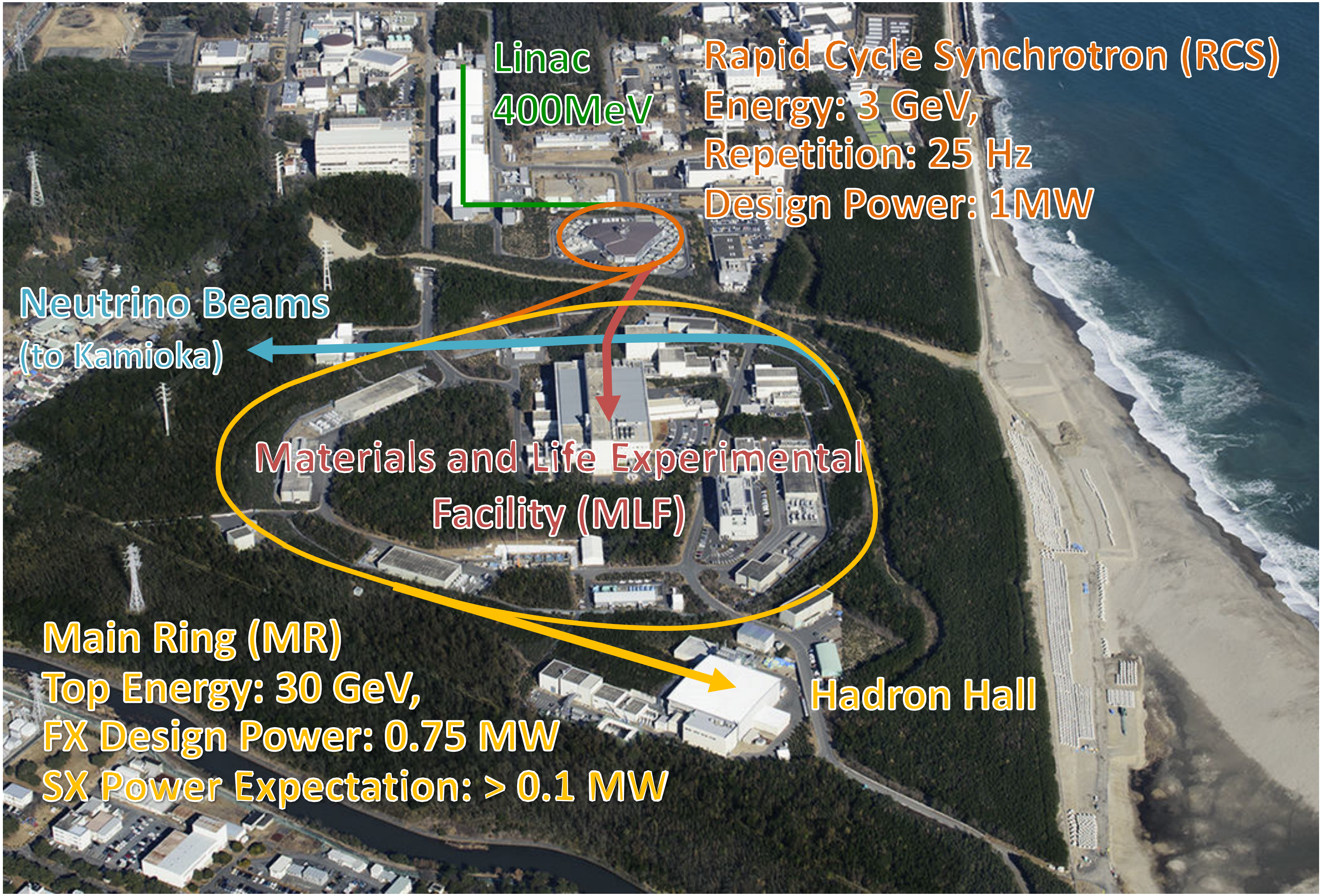
- **10 times larger than the current precision!**

Relative standard uncertainty for m_e: 0.31 ppb (CODATA2022)

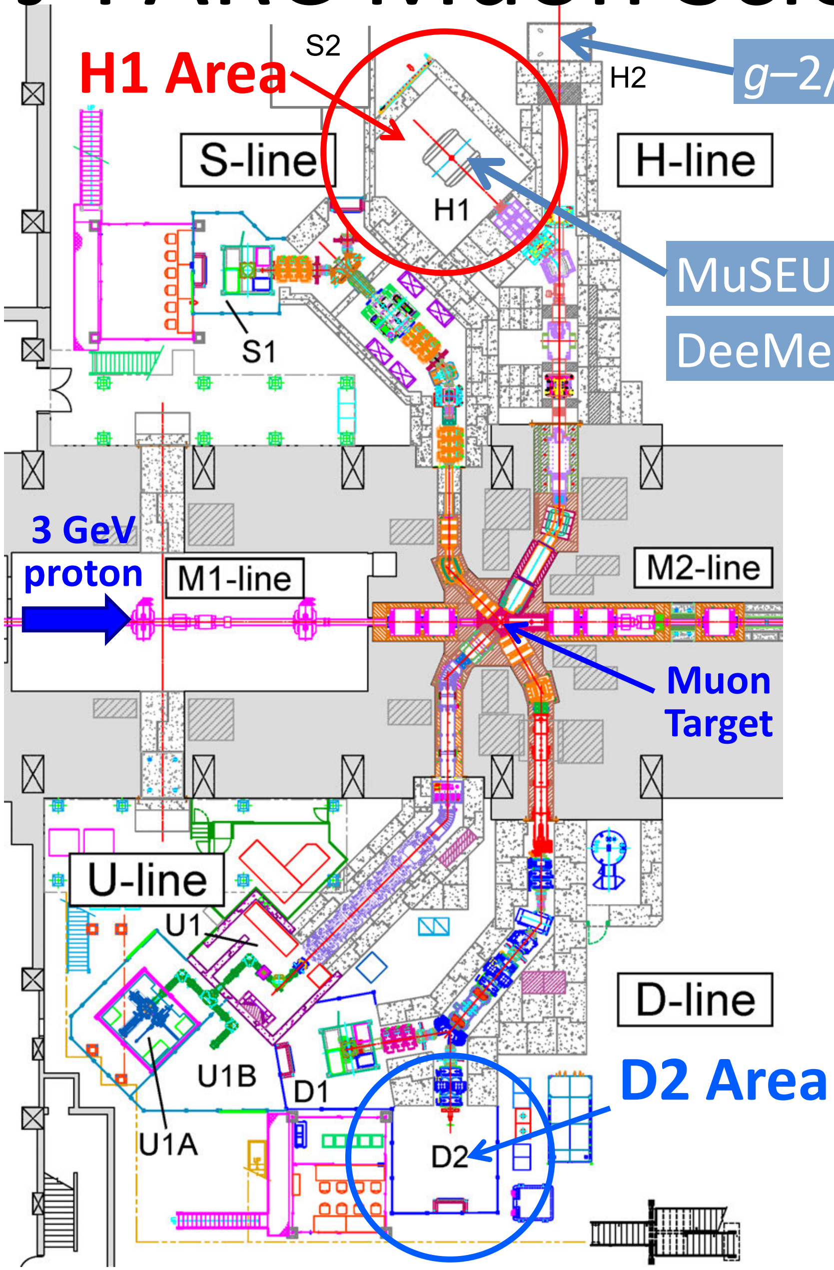
MuSEUM Collaboration

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

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.

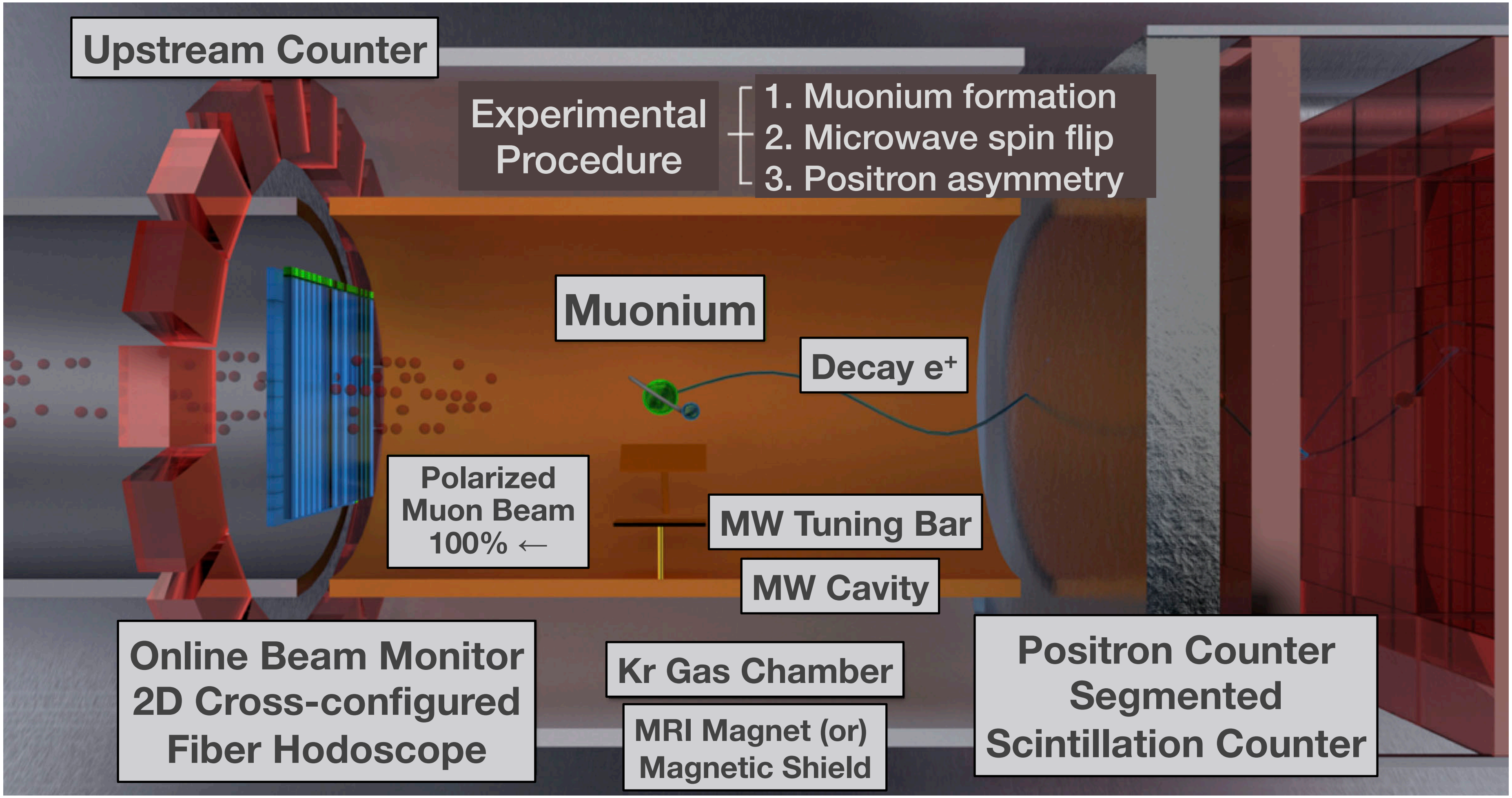
D-Line: Decay muon (μ^+ & μ^-)

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.

Muonium HFS Experiment Scheme



Upstream Counter

Experimental Procedure

1. Muonium formation
2. Microwave spin flip
3. Positron asymmetry

Muonium

Decay e⁺

Polarized Muon Beam 100% ←

MW Tuning Bar

MW Cavity

Online Beam Monitor
2D Cross-configured Fiber Hodoscope

Kr Gas Chamber

MRI Magnet (or) Magnetic Shield

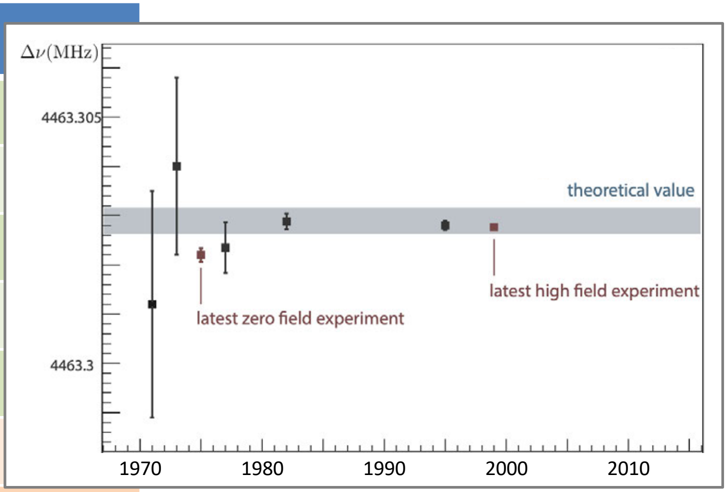
Positron Counter
Segmented Scintillation Counter

$$\boxed{\text{Signal} = \frac{N_{ON} - N_{OFF}}{N_{OFF}}}$$

N_{ON} : number of positrons when microwave ON
N_{OFF} : number of positrons when microwave OFF

Previous Experiments

Time	Group	Δν	ppm	B field (T)
1961	Yale-Nevis	5500^{+2900}_{-1500} MHz		0.01-0.58
1962	Yale-Nevis	4 461.3(2.0) MHz	450	1.1353
1964	Yale-Nevis	4 463.24(12) MHz	27	0.5
1966	Yale-Nevis	4 463.18(12) MHz	27	2.7 × 10^{-4}
1969	Yale-Nevis	4 463.26(4) MHz	9.0	3 × 10^{-4}
1969	Chicago	4 463.317(21) MHz	4.7	1.1353
1970	Chicago	4 463.302 2(89) MHz	2.0	1.1353
1971	Yales-Nevis	4 463.308(11) MHz	2.5	3 × 10^{-4} and 1 × 10^{-6}
1973	Chicago-SREL	4 463 304.4(2.3) kHz	0.5	0
1975	LAMPF	4 463 302.2(1.4) kHz	0.3	very weak
1977	LAMPF	4 463 302.35(52) kHz	0.12	1.36
1982	LAMPF	4 463 302.88(16) kHz	0.036	1.36
1999	LAMPF	4 463 302.765(53) kHz	0.012	1.7



- Precision improved greatly in the 1970s due to the improvement of muon facilities.
- Current world record is Liu (1999) at LAMPF.

→ **New high-intensity muon experiments are needed!**

MuSEUM Experiment Timeline

2011

- Muomium HFS proposal submitted
  K. Shimomura, AIP Conf. Proc. **1382**, 245 (2011)

2017

- Mu HFS resonance measured at **zero field** and Kr 1 atm

2018

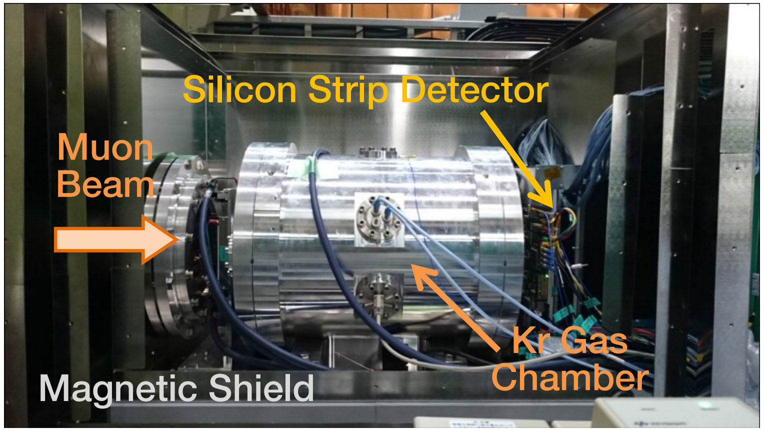
- Measurements at Kr 0.3, 0.4, 0.7 atm
- Lower pressure than previous experiments
- Development of **Rabi-oscillation spectroscopy**

2019

- Measurement with Kr-He mixture gas
- Upgrade with **silicon strip detector**

2022 ~

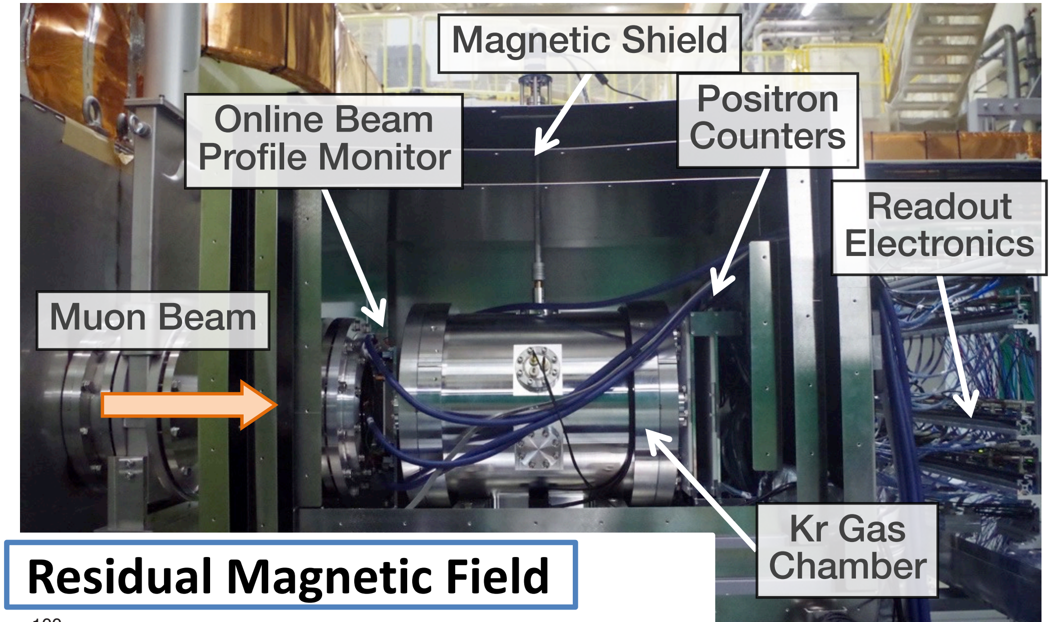
- H-line commissioning …
- Preparation for high-field measurements …



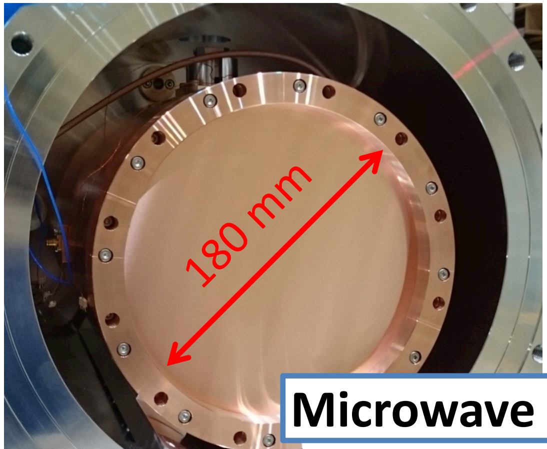
Zero-Field Experiment

MuSEUM Zero-Field Experiment

Experimental Setup

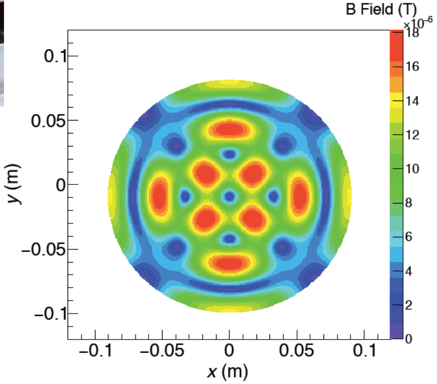


Microwave Cavity for Zero Field



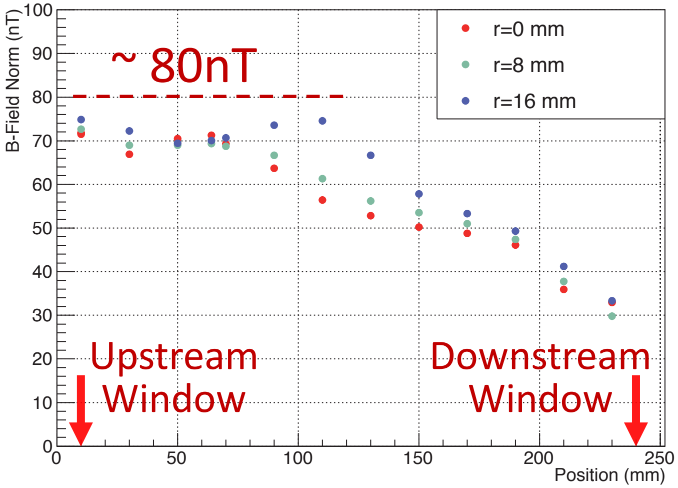
$\Delta\nu = 4.463$ GHz

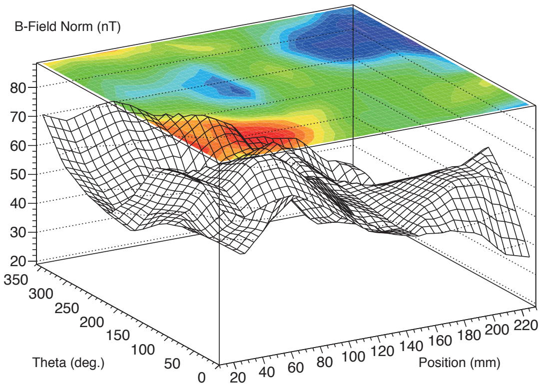
Microwave Intensity



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

Residual Magnetic Field

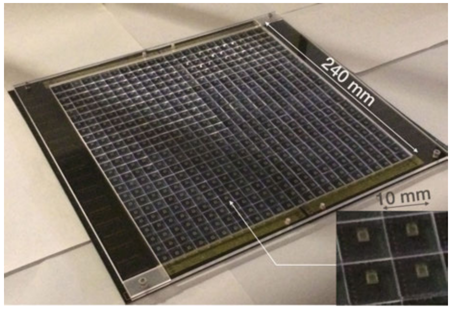


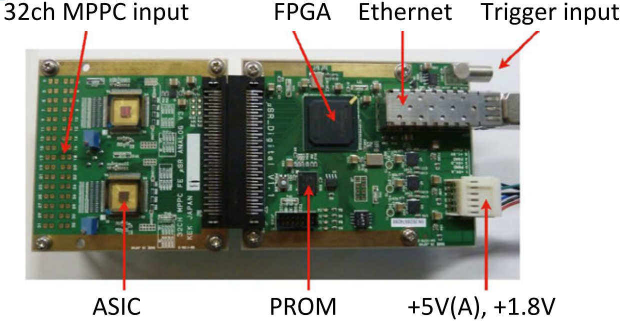


Counter Development

Positron Counter (1)

Segmented Scintillation Detector





Plastic scintillator + MPPC(SiPM) + Kaliope readout circuit

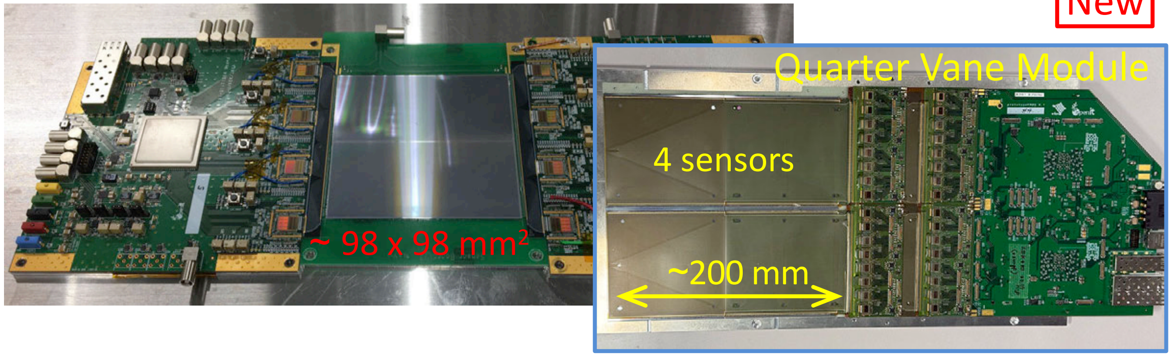
- Unit cell: 10 mm × 10 mm × 3 mm^t
- Area: 240 mm × 240 mm
- 24x24 segments x 2 layers = 1152 ch

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

Positron Counter (2)

Silicon Strip Detector

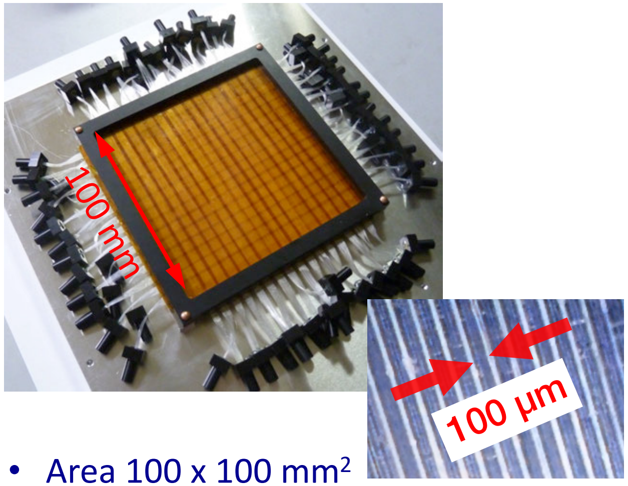
New



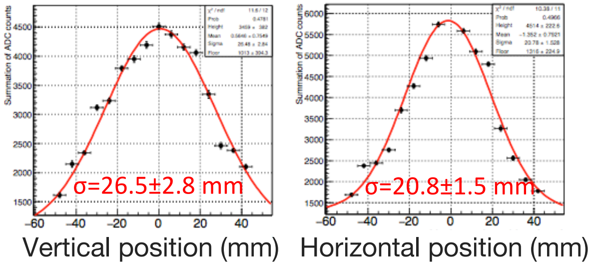
- Readout chips (SliT128A, 128 ch/chip)
- Developed for **J-PARC g–2/EDM experiment**
- Highly-segmented
- High-rate capability (S/N ~ 21)

- 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



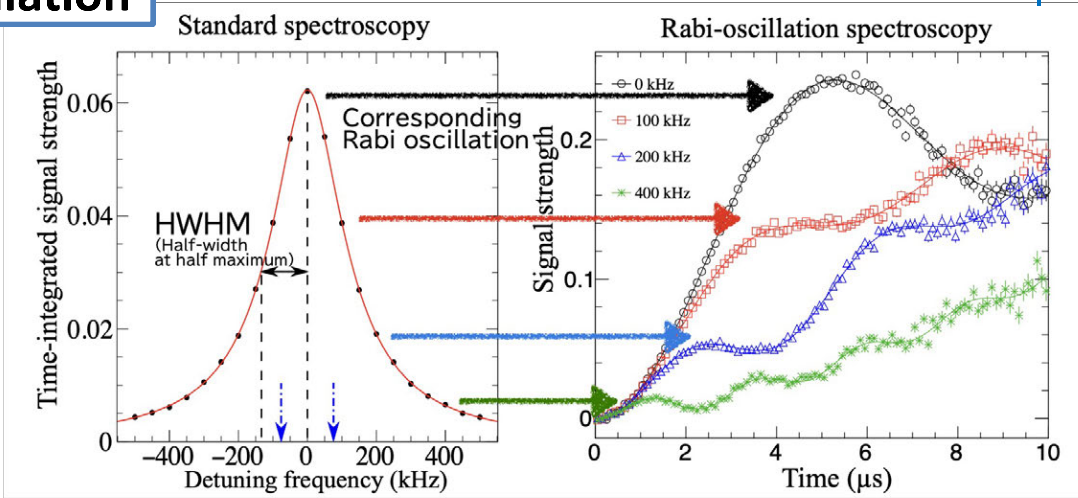
- Area 100 x 100 mm^2
- 100-μm fiber hodoscope (16 ch x 2)
- 3 x 3mm^2 active area MPPC with 15-μm pixel pitch
- EASIROC readout

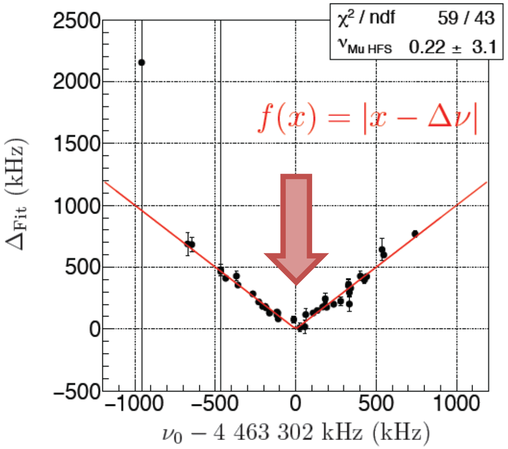


Rabi-Oscillation Spectroscopy Method

Simulation

Developed by Shoichiro Nishimura (KEK)

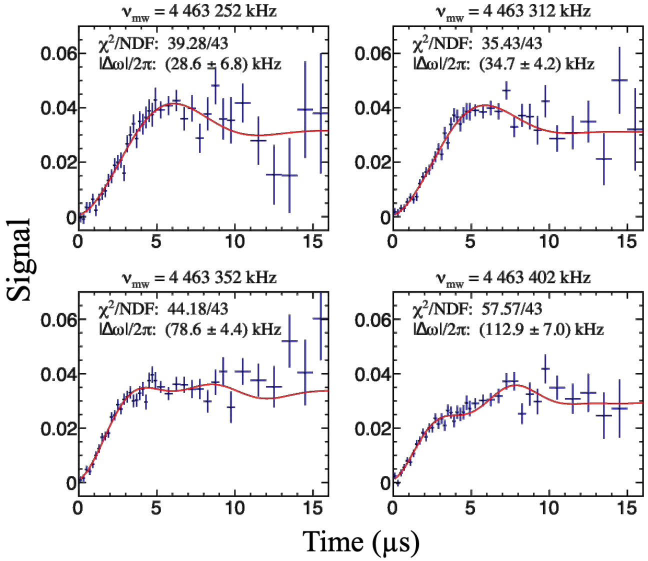




$\Delta\nu_{\mathrm{HFS}}(0) =$ 4 463 301.61(71) (160 ppb)

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

Experiment (2017 June)

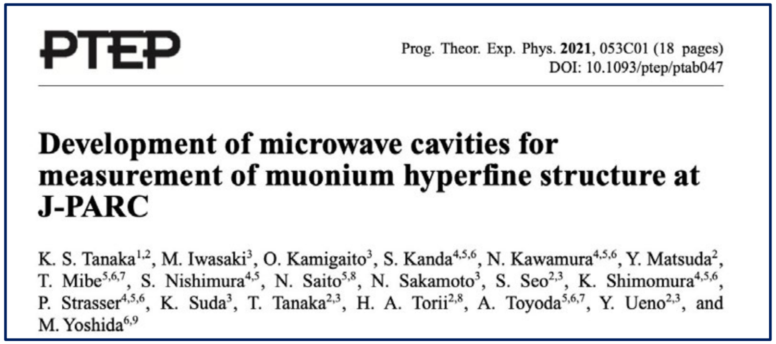


Advantages:

- 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

MuSEUM Recent Publications

❖ Zero-Field and High-Field Microwave Cavity

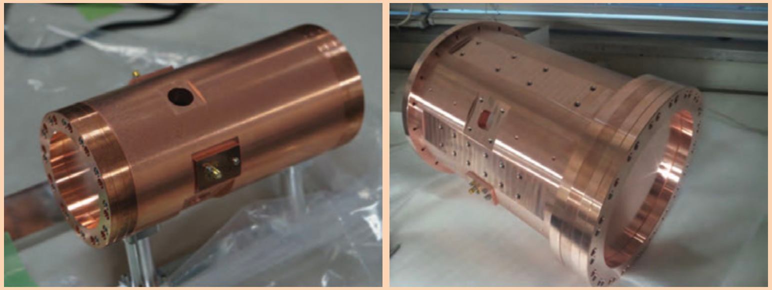


PTEP

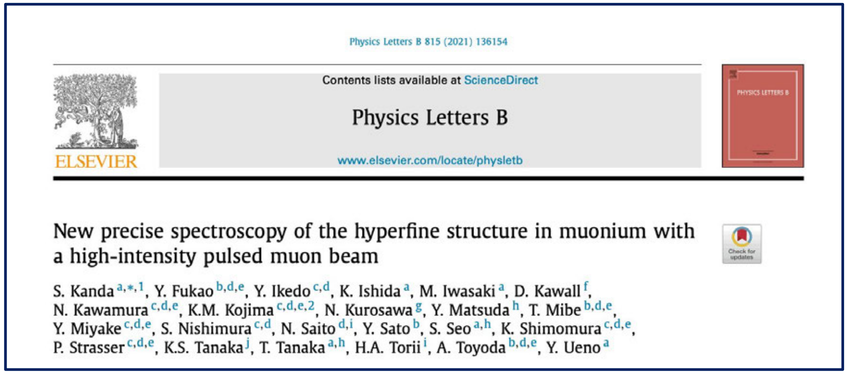
Prog. Theor. Exp. Phys. **2021**, 053C01 (18 pages)
DOI: 10.1093/ptep/ptab047

Development of microwave cavities for measurement of muonium hyperfine structure at J-PARC

K. S. Tanaka[1,2], M. Iwasaki[3], O. Kamigaito[3], S. Kanda[4,5,6], N. Kawamura[4,5,6], Y. Matsuda[2], T. Mibe[5,6,7], S. Nishimura[4,5], N. Saito[5,8], N. Sakamoto[3], S. Seo[2,3], K. Shimomura[4,5,6], P. Strasser[4,5,6], K. Suda[3], T. Tanaka[2,3], H. A. Torii[2,8], A. Toyoda[5,6,7], Y. Ueno[2,3], and M. Yoshida[6,9]



❖ Zero-Field Experimental Setup and First Result



Physics Letters B 815 (2021) 136154

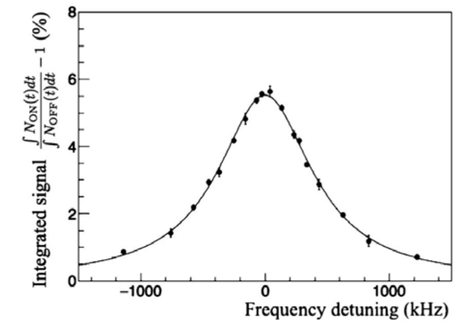
Contents lists available at ScienceDirect

Physics Letters B

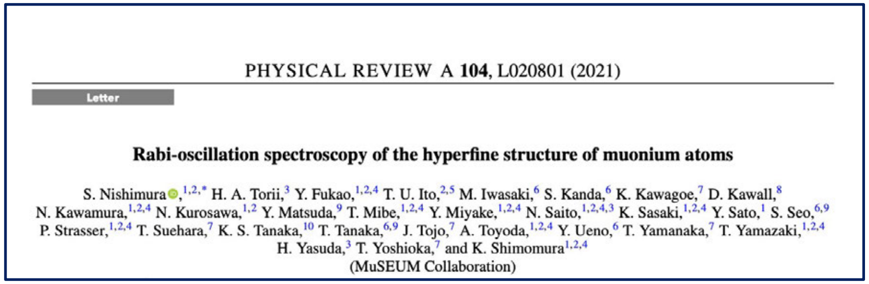
www.elsevier.com/locate/physletb

New precise spectroscopy of the hyperfine structure in muonium with a high-intensity pulsed muon beam

S. Kanda[a,*,1], Y. Fukao[b,d,e], Y. Ikedo[c,d], K. Ishida[a], M. Iwasaki[a], D. Kawall[f], N. Kawamura[c,d,e], K.M. Kojima[c,d,e,2], N. Kurosawa[g], Y. Matsuda[h], T. Mibe[b,d,e], Y. Miyake[c,d,e], S. Nishimura[c,d], N. Saito[d,i], Y. Sato[b], S. Seo[a,h], K. Shimomura[c,d,e], P. Strasser[c,d,e], K.S. Tanaka[j], T. Tanaka[a,h], H.A. Torii[i], A. Toyoda[b,d,e], Y. Ueno[a]



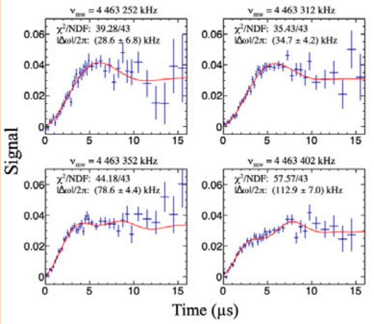
❖ Rabi-Oscillation Spectroscopy

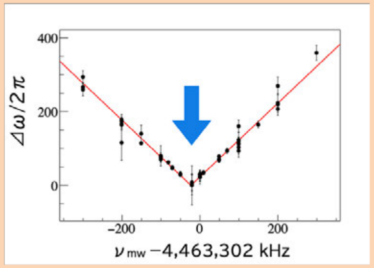


PHYSICAL REVIEW A **104**, L020801 (2021)

Rabi-oscillation spectroscopy of the hyperfine structure of muonium atoms

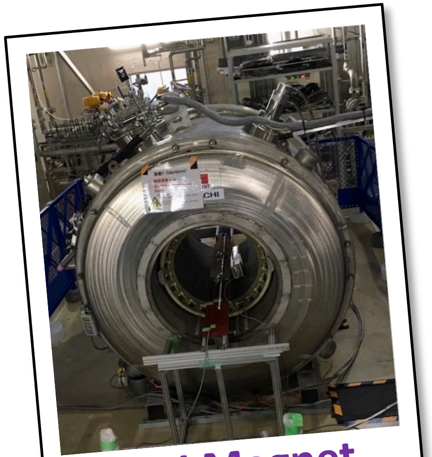
S. Nishimura,[1,2,*] H. A. Torii,[3] Y. Fukao,[1,2,4] T. U. Ito,[2,5] M. Iwasaki,[6] S. Kanda,[6] K. Kawagoe,[7] D. Kawall,[8] N. Kawamura,[1,2,4] N. Kurosawa,[1,2] Y. Matsuda,[9] T. Mibe,[1,2,4] Y. Miyake,[1,2,4] N. Saito,[1,2,4,3] K. Sasaki,[1,2,4] Y. Sato,[1] S. Seo,[6,9] P. Strasser,[1,2,4] T. Suehara,[7] K. S. Tanaka,[10] T. Tanaka,[6,9] J. Tojo,[7] A. Toyoda,[1,2,4] Y. Ueno,[6] T. Yamanaka,[7] T. Yamazaki,[1,2,4] H. Yasuda,[3] T. Yoshioka,[7] and K. Shimomura[1,2,4]
(MuSEUM Collaboration)



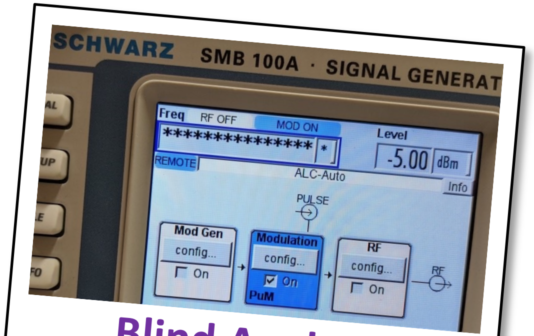


$\Delta\nu$ = 4,463,301.61(71) (160ppm)

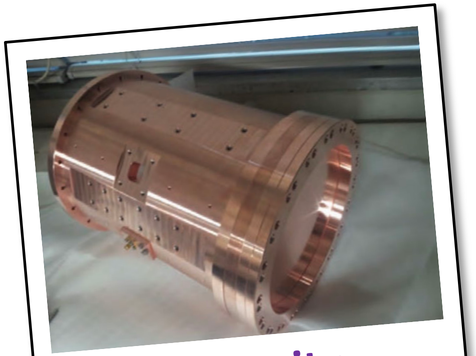
Development for High-Field Experiment



MRI Magnet

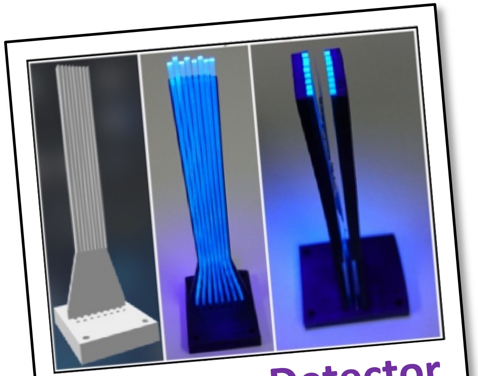


Blind Analysis

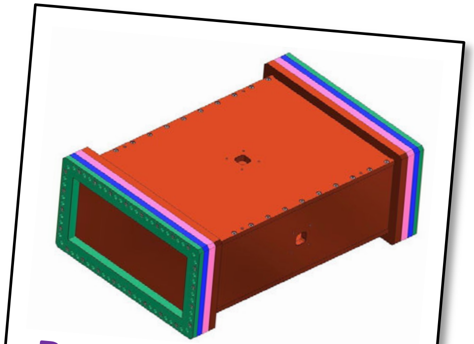


HF Cavity

Magnetic Probes



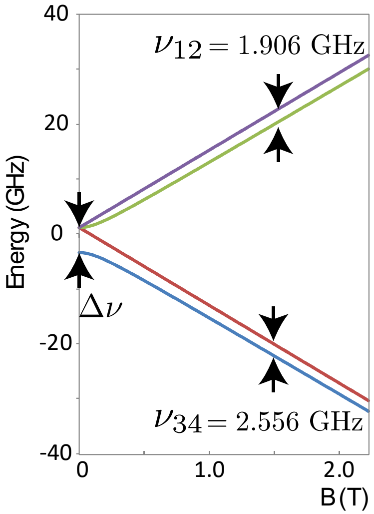
Upstream Detector

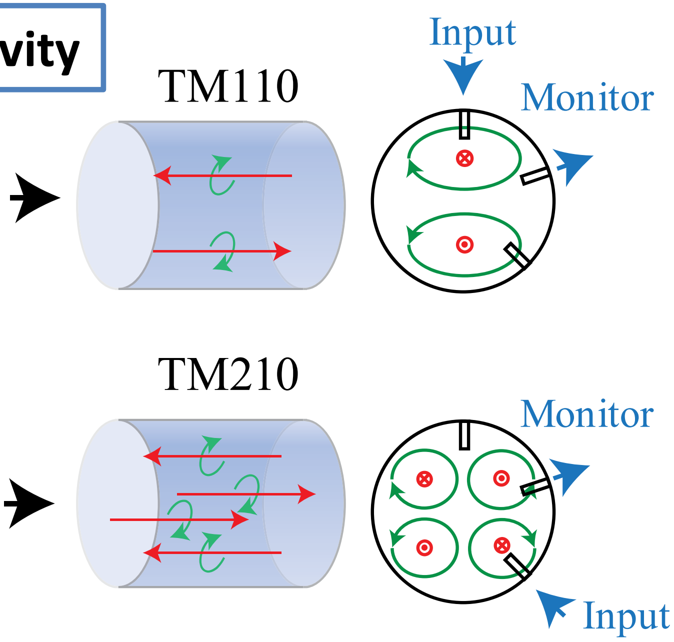


Rectangular Cavity

High-Field Microwave Cavity

Cylindrical Cavity

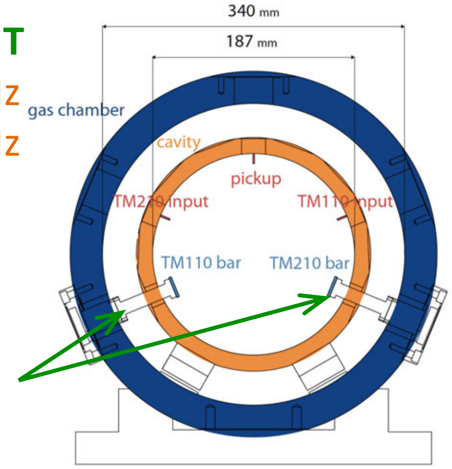




Frequencies at 1.7 T

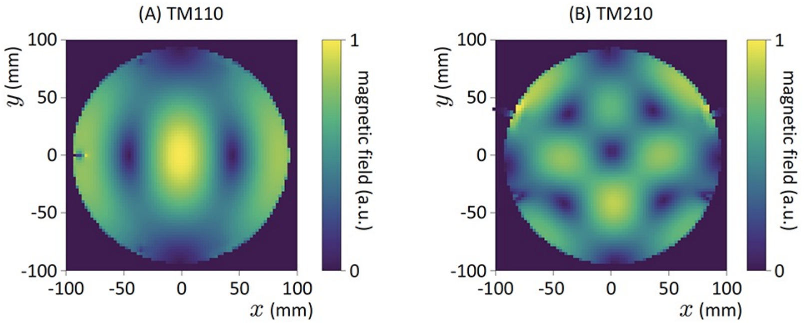
TM110 : 1.897 GHz

TM210 : 2.566 GHz

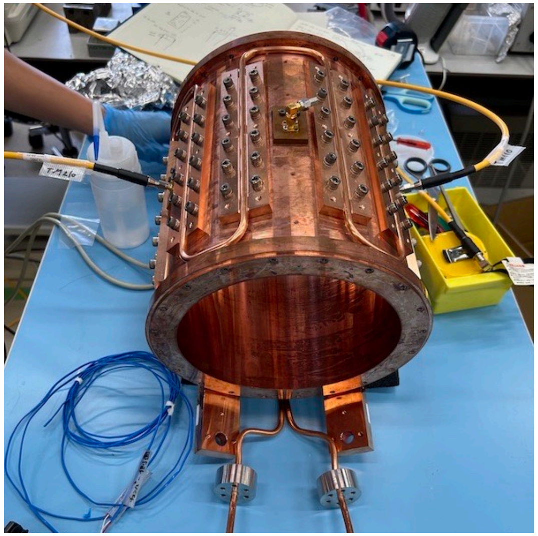


Two tuning bars

MWS Simulation



Cavity Test



Re-tuning
in progress !

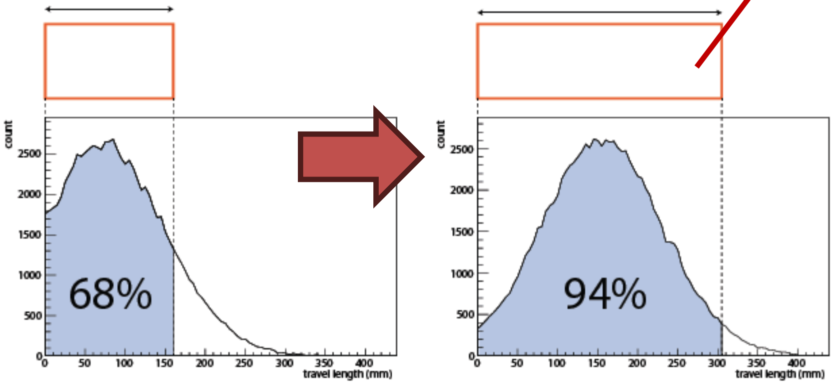
Q Value

Modes	Q (measured)	Q (simulation)
TM110	11,300	29,700
TM210	8,050	28,900

K. S. Tanaka *et al.*, PTEP **2021**, 053C01 (2021)

Improvement from LAMPF

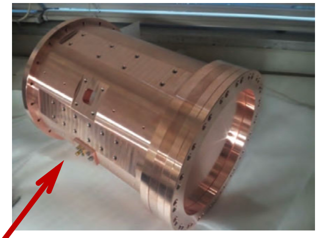
Cavity Length



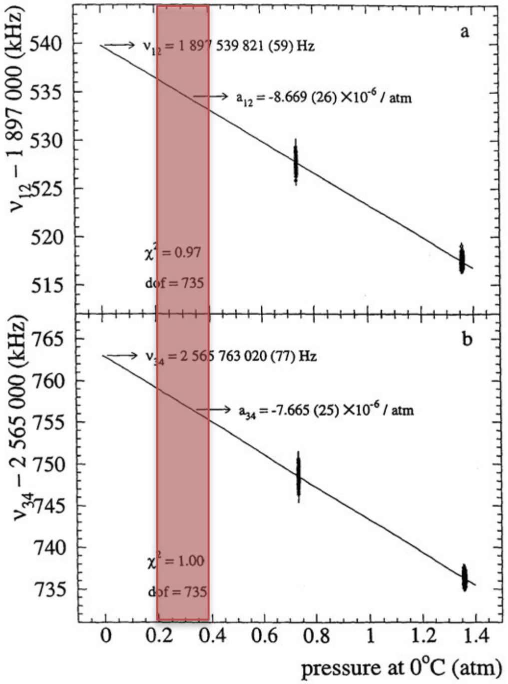
Muonium distribution at 0.3 atm Kr gas

159.73mm(LAMPF)

304mm(J-PARC)



MuSEUM Cavity



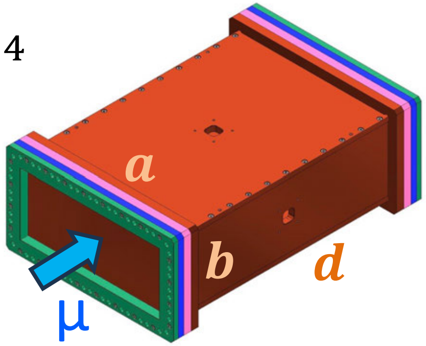
- Muonium transition frequency in gas varies with the gas pressure due to atomic collisions between Mu and Kr
- Previous experiment used fitting of 0.8 and 1.5 atm data only using old quadratic dependence parameter (LAMPF)
- Data at lower pressure needed to improve uncertainty

Rectangular Cavity for 2.9 T Measurement

Improve μ_μ/μ_p determination at higher field

Developed by Ryoto Iwai (KEK)
FRIB/MSU

- NMR probe has same accuracy at different magnetic field strengths
- Cylindrical cavity only works where $F_{TM110}/F_{TM210} \approx \nu_{12}/\nu_{34}$



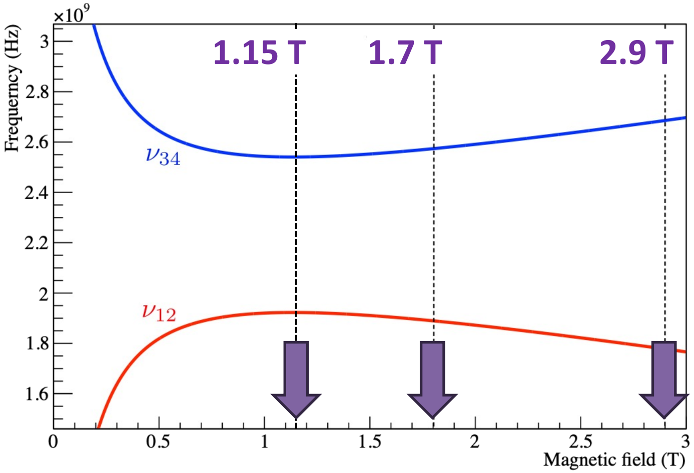
Frequencies ν_{12} = 1.778 GHz, ν_{34} = 2.686 GHz

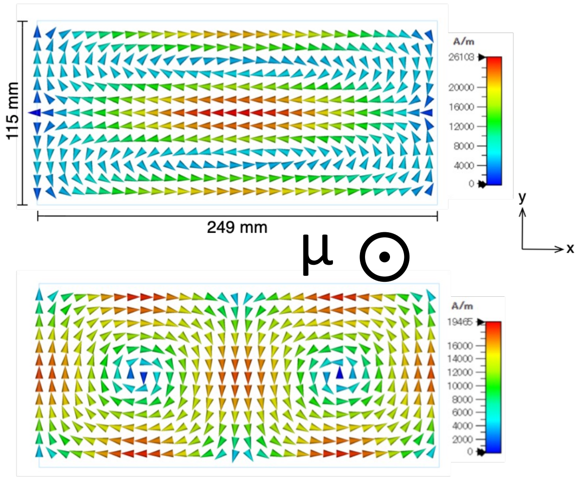
Cavity Size a = 249.19 mm, b = 114.54 mm

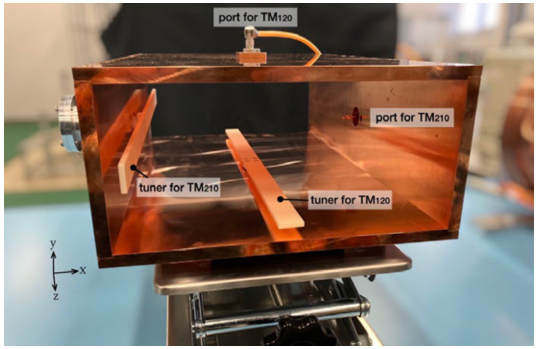
$$F_{mnl} = \frac{c}{2\sqrt{\mu_r \epsilon_r}} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{l}{d}\right)^2}$$

c: speed of light
μ_r, ϵ_r: relative permeability and permittivity
m, n, l: mode numbers
a, b, c: cavity dimensions

Cavity design is ongoing!
Prototype constructed and tested







R. Iwai *et al.*, Nucl. Intrum. Meth. A **1064**, 169434 (2024)

Blind Analysis for MuSEUM

Hidden answer method

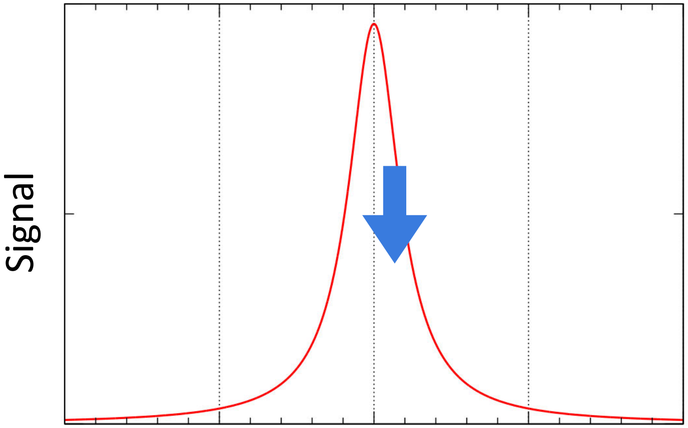
Value to be blinded: injected microwave frequency

- 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 $|\boldsymbol{\delta}| <$ 8kHz
  - ○ blind value sufficient for the target precision
  - ○ rate of change in stored microwave energy < 0.07%

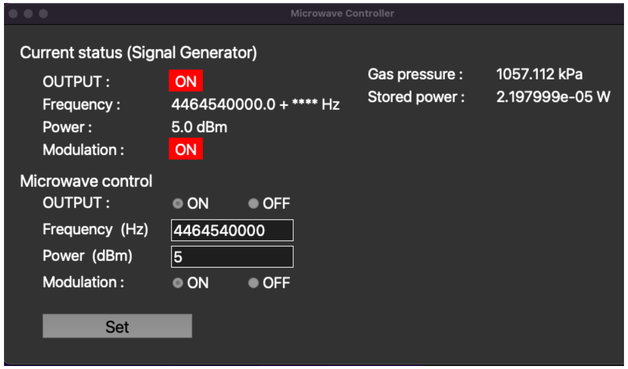
Before opening the blind



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

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

Implemented in Python3



Microwave Controller

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

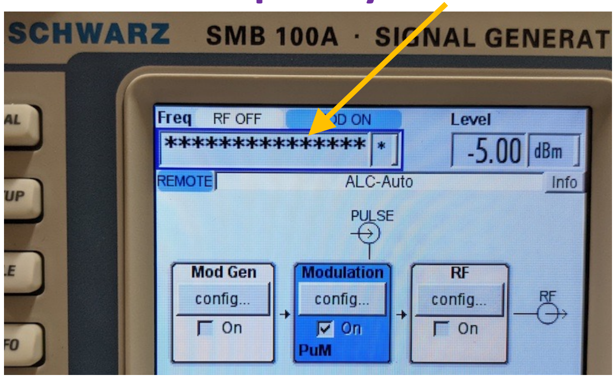
OUTPUT : ○ ON ○ OFF

Frequency (Hz) 4464540000

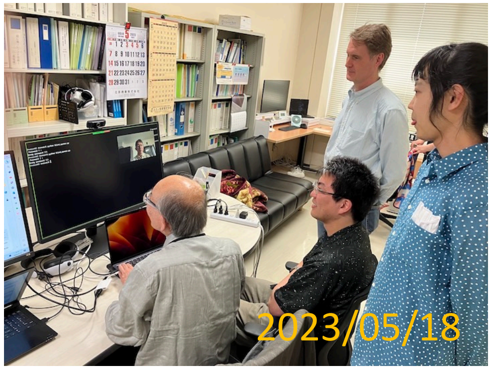
Power (dBm) 5

Modulation : ○ ON ○ OFF

True frequency hidden



Blind Test (for μHe HFS)



Password protected, safety/protection features to prevent mis-operation

Microwave power and gas pressure are also monitored and recorded

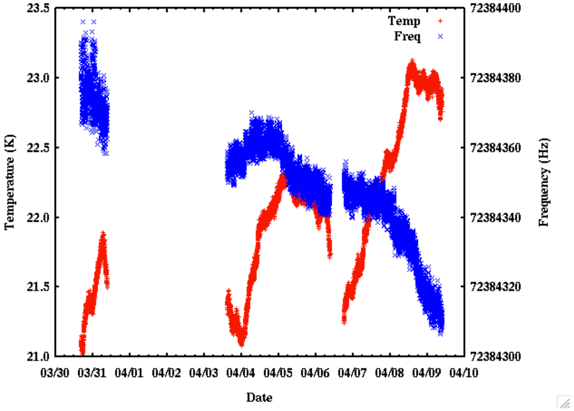
MRI Magnet for High-Field Experiment

Requirements for magnetic field

- 0.2 ppm (peak-to-peak) uniformity
- ±0.1 ppm stability during measurement

Second-hand 2.9 T MRI magnet

Long Term Stability

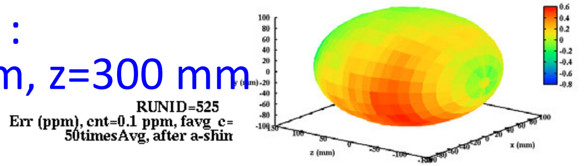


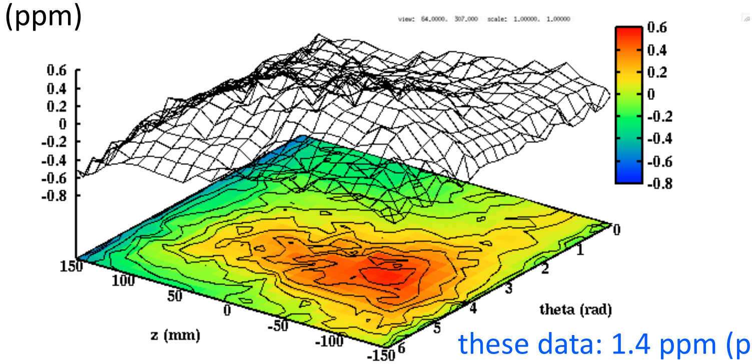
64 Hz / 9.7 days

0.003 ppm /h

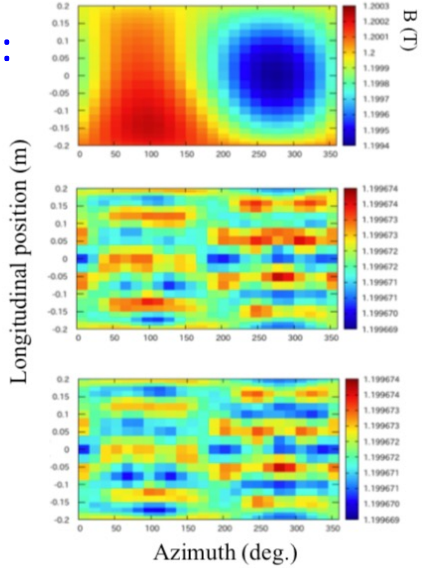
Field Homogeneity (after shimming)

Spheroid :
r=100 mm, z=300 mm





these data: 1.4 ppm (p-p)

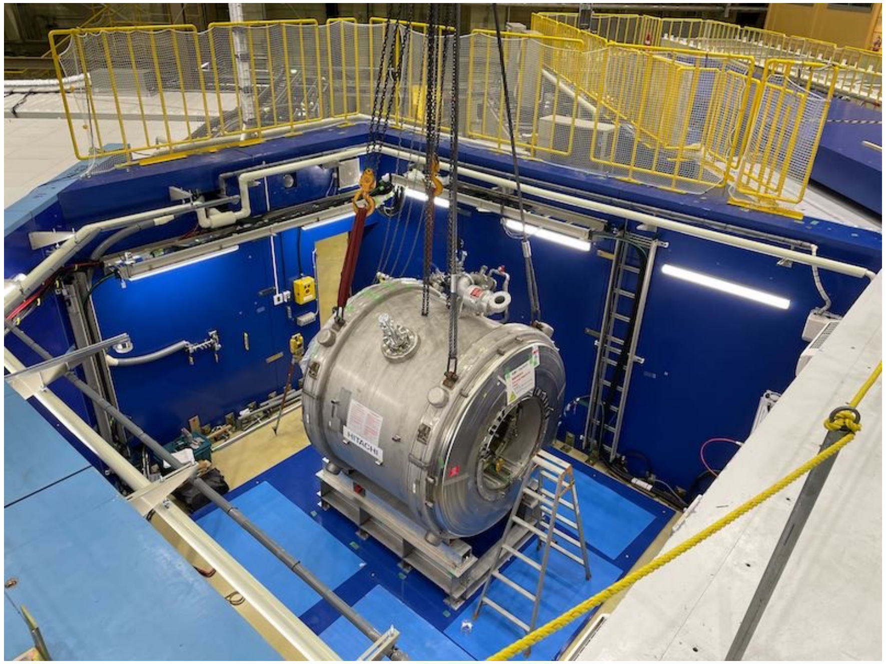
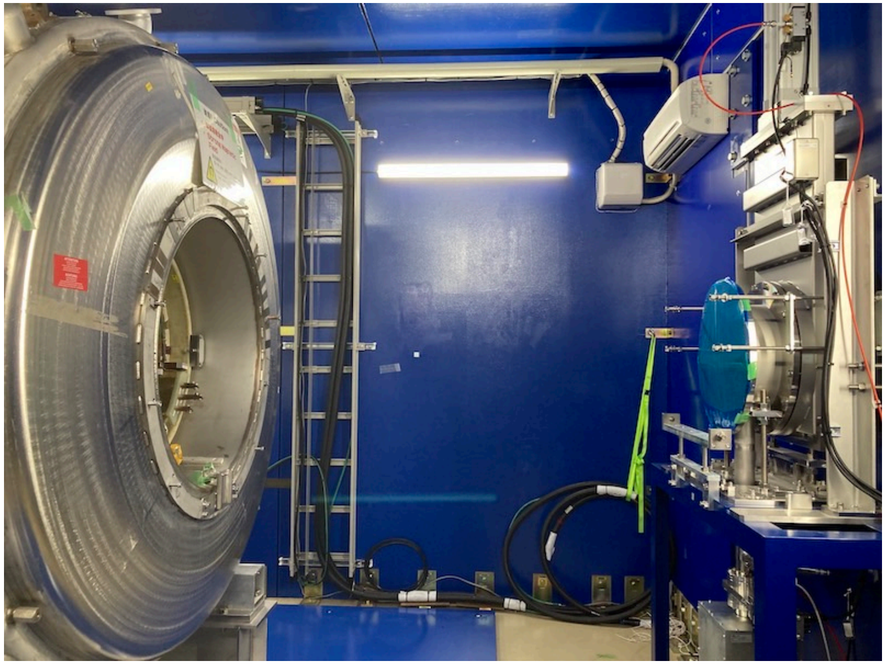


Iron shim plates:
341 ppm (p-p)

Nickel films:
0.27 ppm (p-p)
(achieved!)

Magnetic putty:
0.17 ppm (p-p)
(simulation)

MRI Magnet Installation in H1 Area

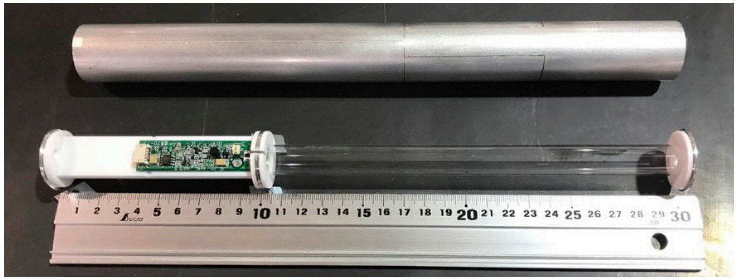
- Installation of the superconducting magnet in the H1 experimental area completed in November 2023
- Magnet successfully energized to the target field strength of 1.7 T
- Next magnetic field homogeneity through successive shimming

Magnetic Field Probes

Three types of probes are being developed

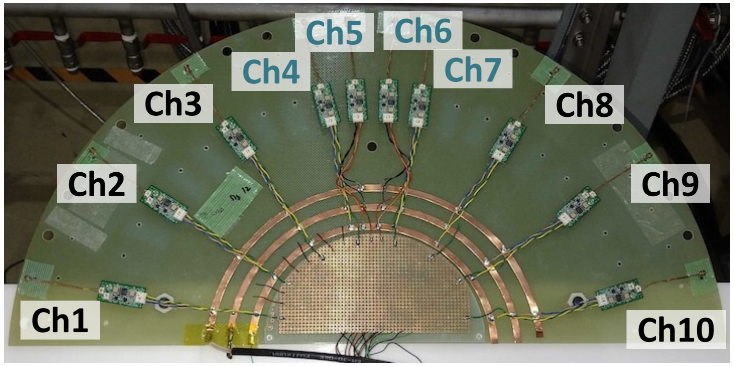
Standard Probe

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



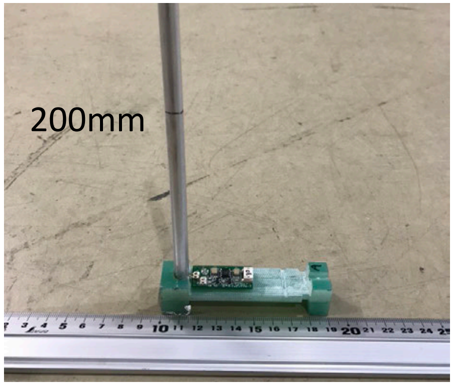
Field Camera

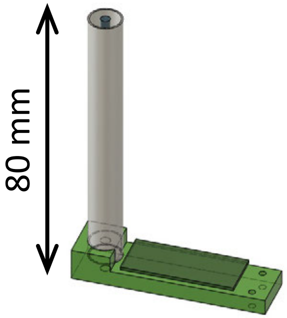
- 24-channels rotating NMR probe to map magnetic fields
- Used for shimming
- 10-channel prototype has been developed



Fixed Probe

- Compact probe to monitor magnetic field stability during experiment



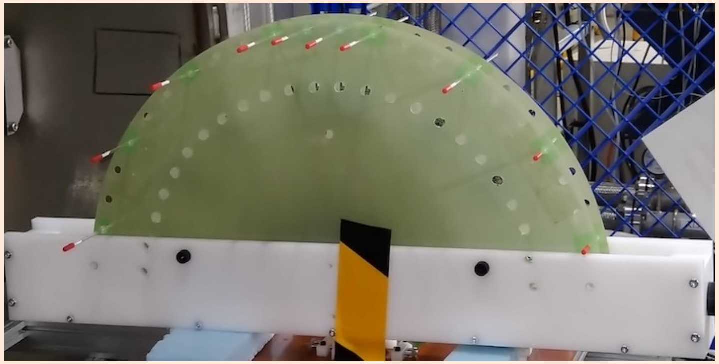


Field Camera

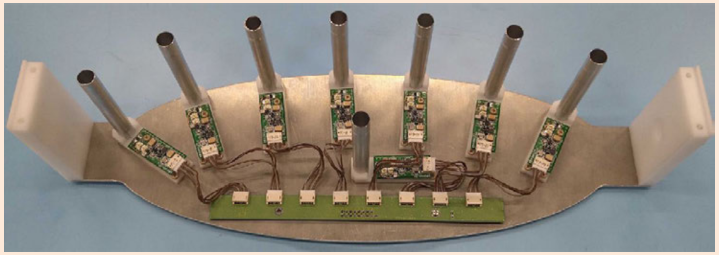
Scanning a sphere with a radius of 25 cm

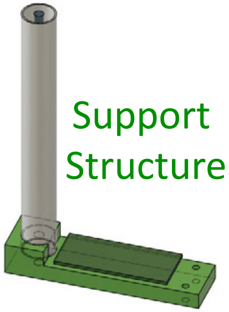
Developed by Hiroki Tada (Nagoya Univ.)

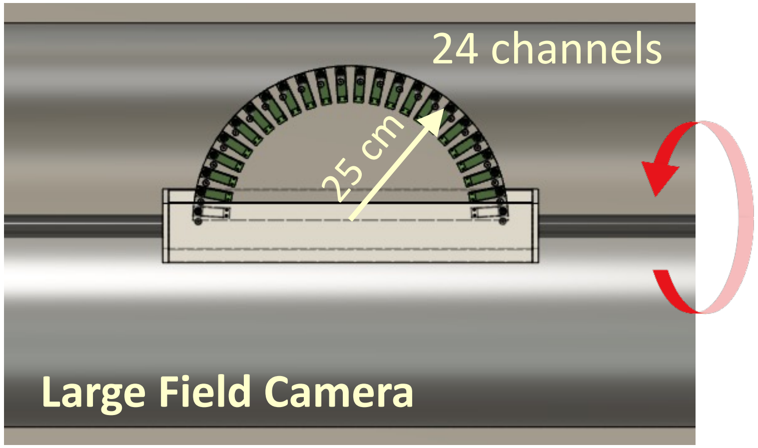
- 24-channel half-circle multi-channel system
- Scanning time: 3 hours (single probe) → 20 minutes (multi-channel system)

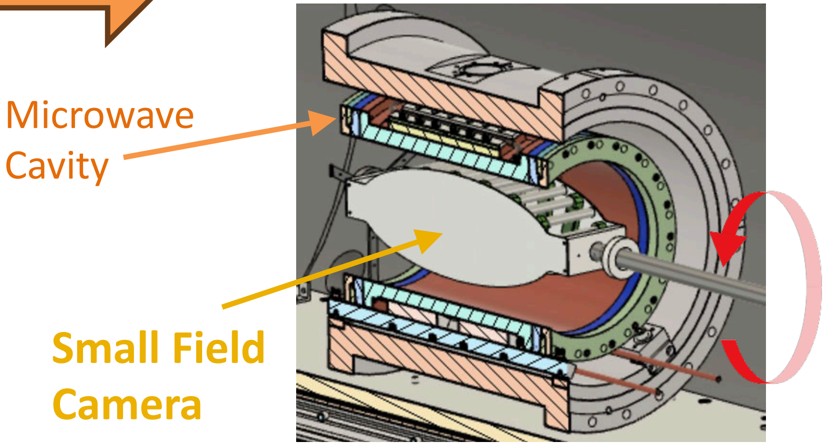


10-channel Prototype





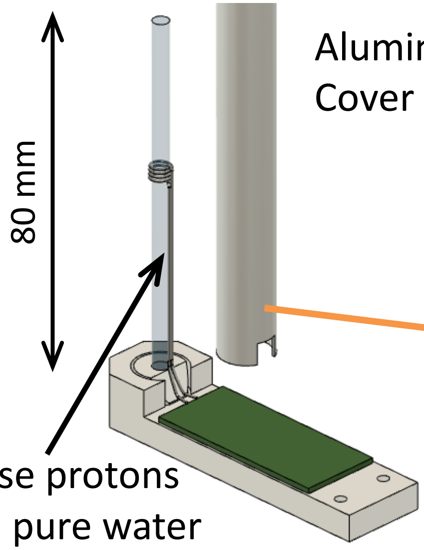




Magnetic Field Homogeneity Measurement

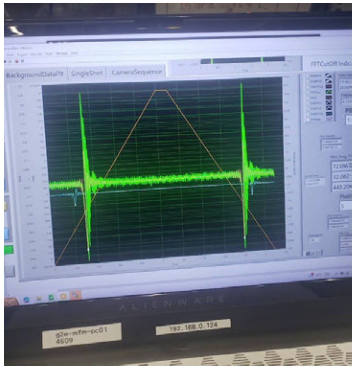
by Yu Goto (Nagoya Univ.)
Ken-ichi Sasaki (KEK)

Proton NMR



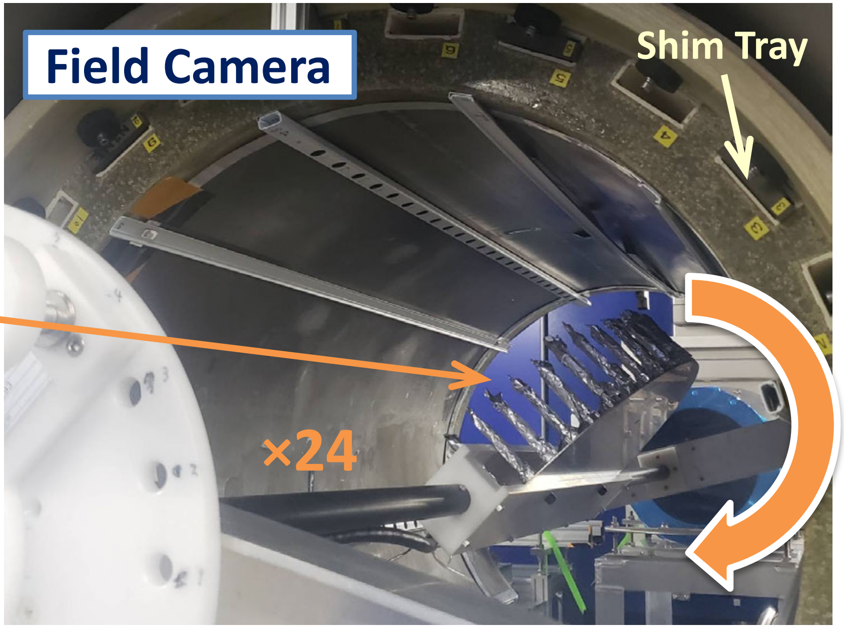
Aluminum Cover

Use protons in pure water



NMR Signal

Stability during measurement: ±0.1 ppm



Rotate the 24-channel magnetic field camera by 24 angles and create a 576-point magnetic field measurement map

By taking into account:

- Effect of the cylindrical shape of pure water
- Difference in resonance peaks between both paths of the modulation field
- Detuning of the LC resonant circuit
- Dependence on the probe direction

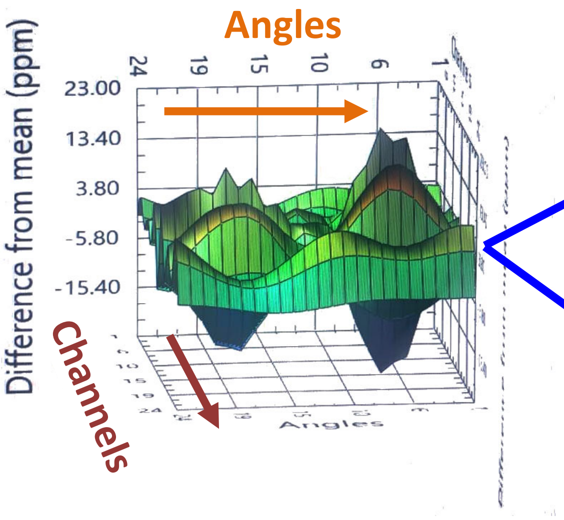
An absolute accuracy of 15 ppb can be achieved.

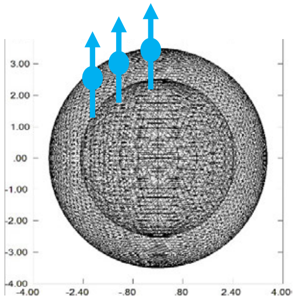
H. Tada, poster at FKK 2023
H. Tada *et al.*, IEEE Trans. Appl. Supercond. **32** (6), 9002205 (2022)

Field Mapping & Adjustment (1)

by Mitsushi Abe (KEK)

Raw field data





about 5000 points

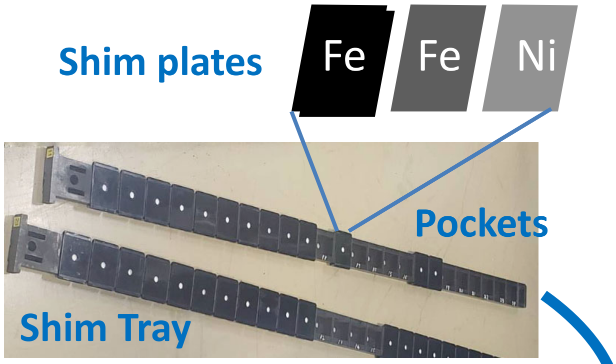
Magnetic Field Reconstruction Method

Field reconstruction from measurements by assuming magnetic moments on the outer spherical surface

Shimming

Calculate the number of shims required in each tray pocket

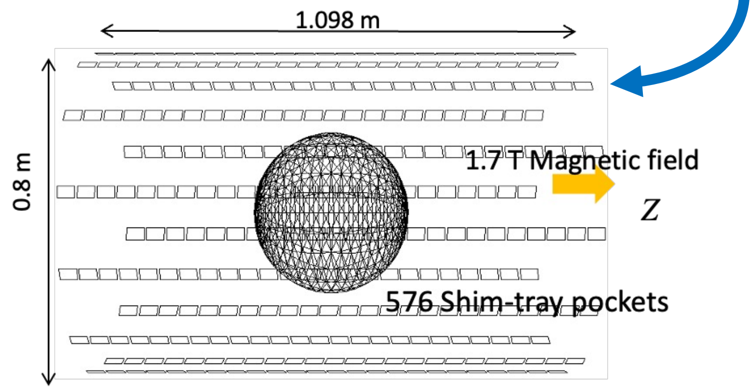
Shim plates



Truncated Singular Value Decomposition

Solving the inverse problem using a singular value decomposition method

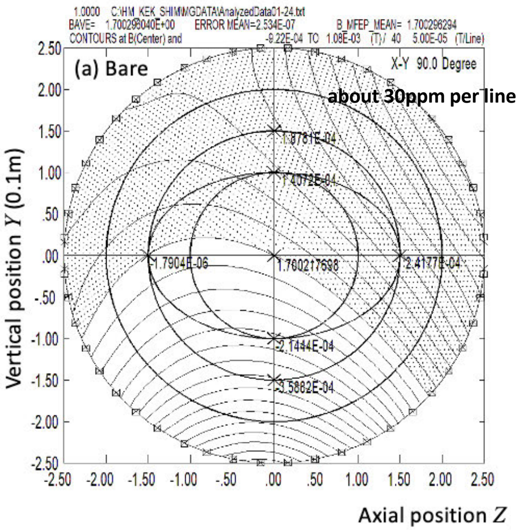
- Limiting the number of eigenvalues (modes) when solving the inverse matrix → Maximize the effect while minimizing the number of shim plates
- Increasing the total number of shimming iterations → Minimize the thermal effect of shim plates on the magnetic field



M. Abe *et al.*, IEEE Trans. on Appl. Supercond. **27** (7), 4400812 (2017)

Field Mapping & Adjustment (2)

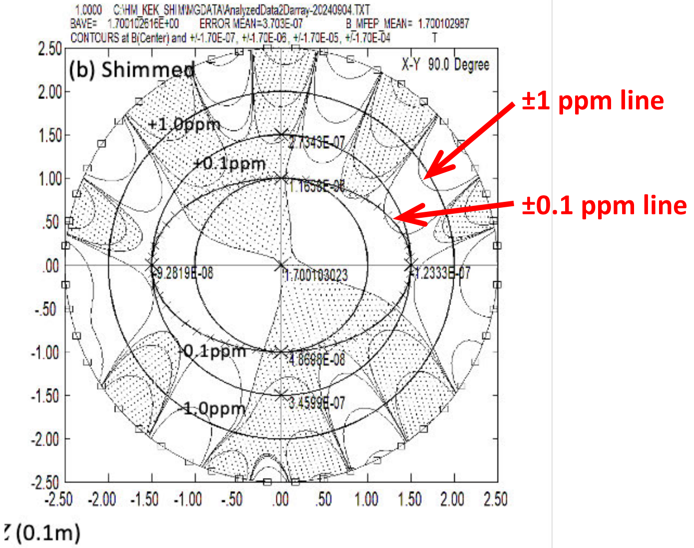
Bare Field



Field Homogeneity

After 2 coarse shimming and 3 fine shimming iterations

After Shimming



$$Homogeneity = \frac{B(maximum) - B(minimum)}{\mathrm{B}(average)} \times 10^{6}[\mathrm{ppm}]$$

Magnetic field	Fe Volume (cc)	Homogeneity (ppm) Ø20 x 30 cm DSS
Bare field	C1: 700.05	295.59
After C1	C2: 48.77	8.9182
After C2	F1: (29)	0.5281
Before F1	F1: 28.08	0.6854
After F1	F2: 1.020	0.5712
After F2	F3: 0.249 (Ni)	0.2506
After F3		0.2033

Coarse shimming:
Large-scale shimming with magnetic field ramp-up and ramp-down

Fine shimming:
Detailed shimming without ramping up or down the magnetic field

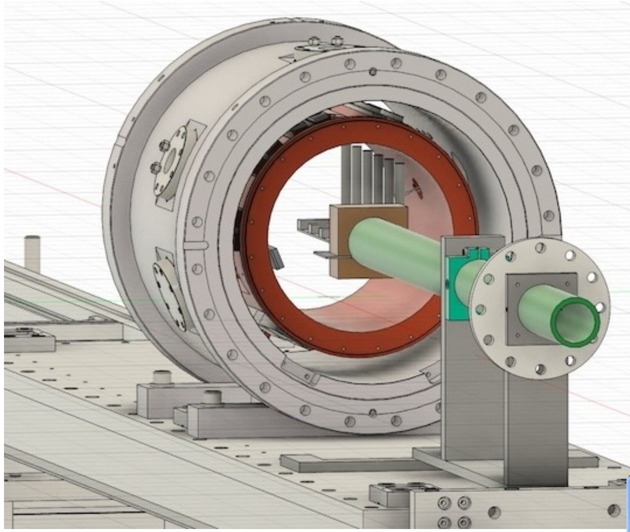
As a result of this shimming, a magnetic field homogeneity of **0.2ppm** was achieved.

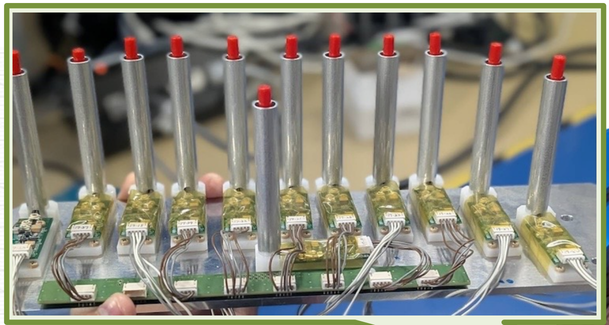
by Mitsushi Abe (KEK)

New Inner Field Camera

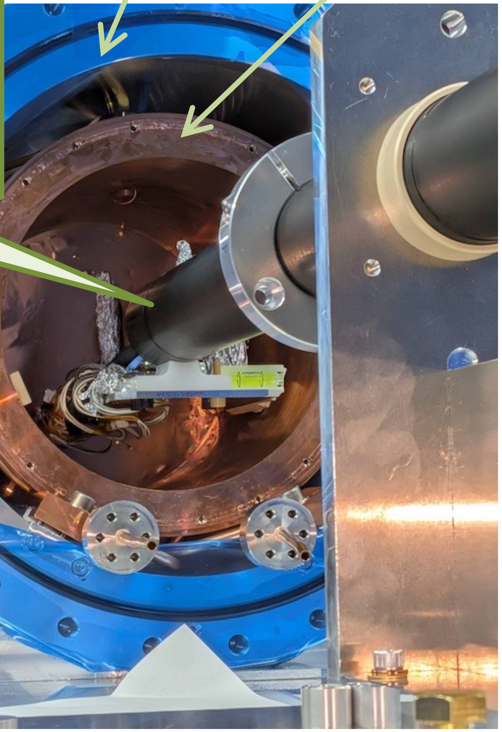
Field measurements and adjustment with all components in place

Developed by Yu Goto (Nagoya Univ.)

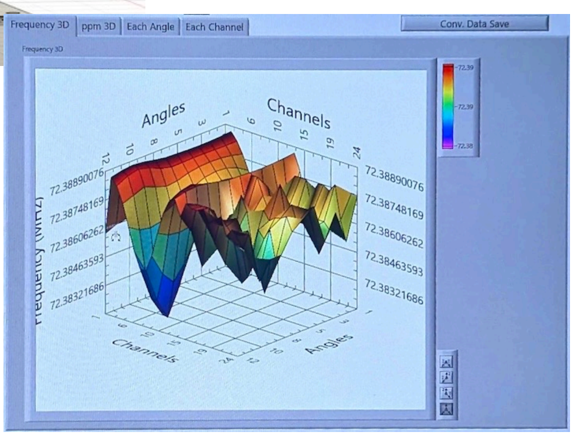




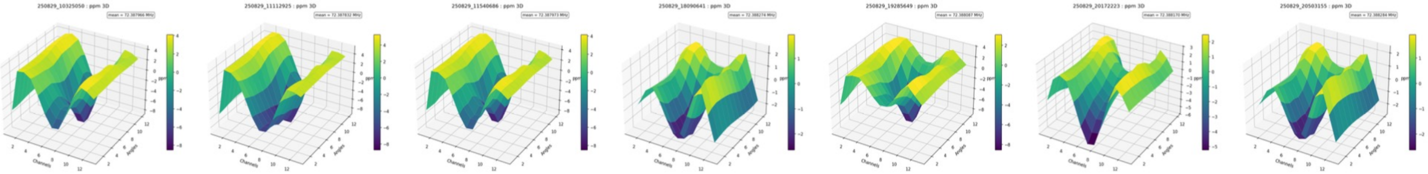
13 NMR Probes
x
12 angles



Raw field data:

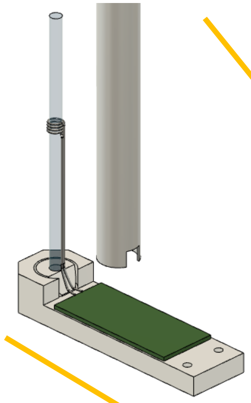


Preliminary measurements:



Experimental Preparation Status

Fixed Probe



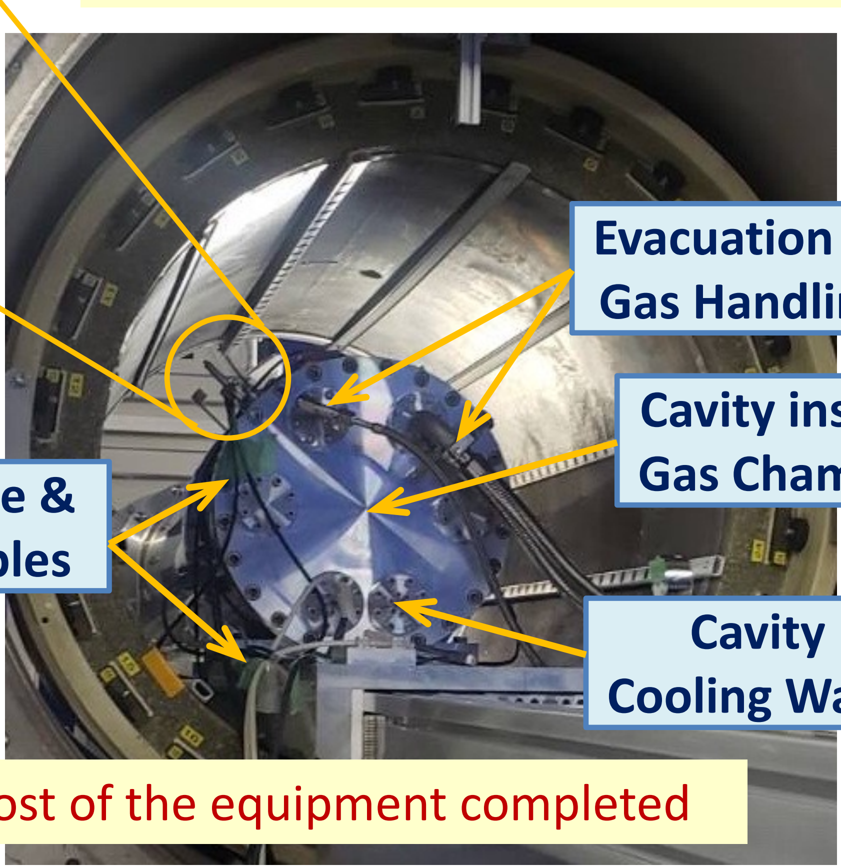
Magnetic Field Monitoring

by Yu Goto (Nagoya Univ.)

From past studies

- Temperature coefficient of magnetic field: 0.17 μT/K
- Field drift during long-term operation: ≈ 0.88 ppm/10 days

→ It was confirmed that precise magnetic field measurements can be performed during the experiment

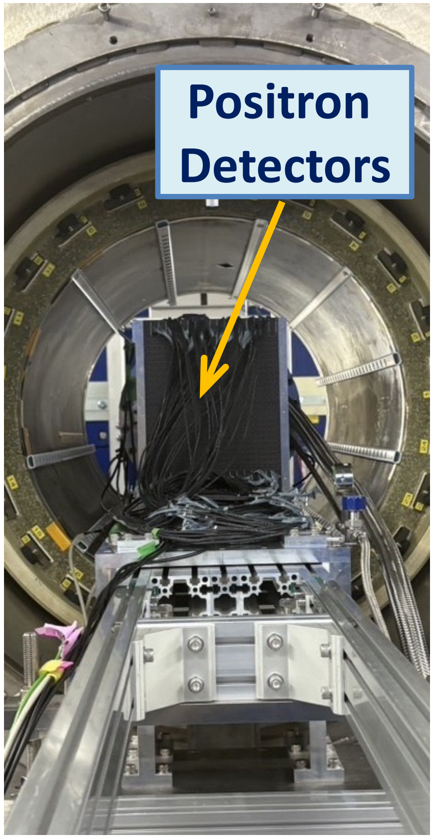


Evacuation & Gas Handling

Cavity inside Gas Chamber

Microwave & Piezo Cables

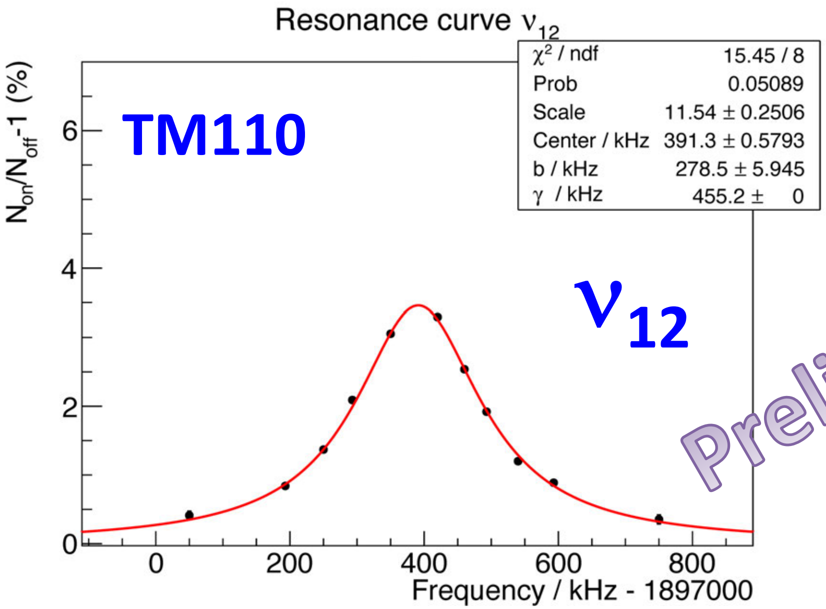
Cavity Cooling Water

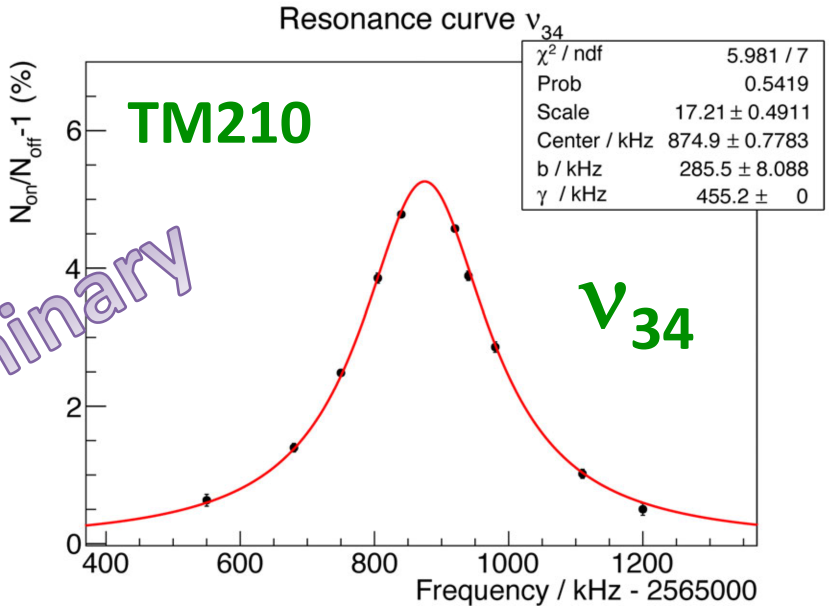


Positron Detectors

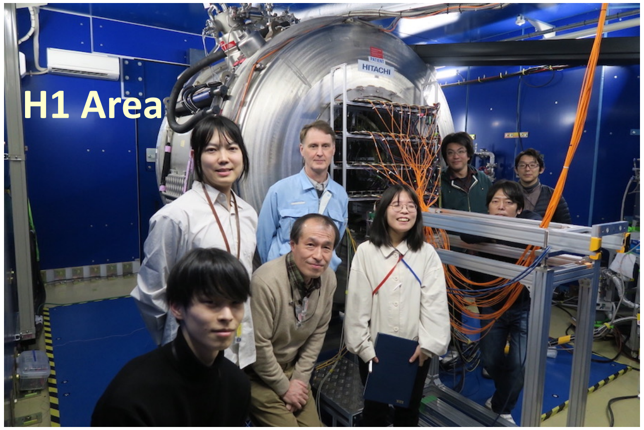
→ Installation of most of the equipment completed

First Muonium HFS at High Field



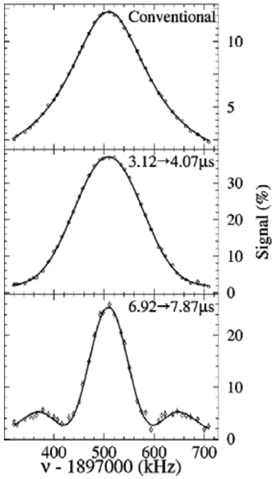


February 2025



- 2 days with **100 kW** proton beam
- Statistical error of $\Delta\nu$ is 1100 Hz
- To achieve an accuracy of 8 Hz (our goal):
  - 1 MW beam power (x$\sqrt{10}$)
  - Rabi-oscillation spectroscopy (x2~3)
  - 100 days (x$\sqrt{50}$)
  - S/N improvement (x3)

Liu (1999)



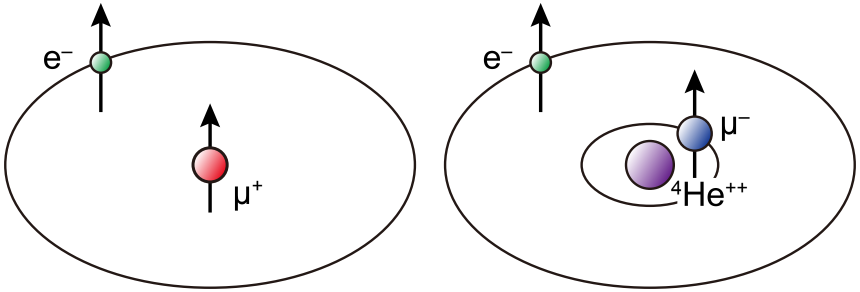
➢ Next μHe HFS at high field!

Preliminary Systematic Errors (High Field)*

Contributions	Accuracy	ν_{12} and ν_{34}	$\delta(\Delta\nu_{\mathrm{HFS}})$	$\delta(\mu_\mu/\mu_p)$
Magnetic Field	15 ppb		0.0 ppb	8 ppb
RF power	< 0.1 %	< 1 Hz	0.2 ppb	2 ppb
Kr gas temperature	0.2 deg.	< 2 Hz	0.4 ppb	4 ppb
Kr gas pressure	1 Pa	1 Hz	0.2 ppb	0 ppb
H impurity	< 50 ppm	1 Hz	0.5 ppb	0 ppb
Quadratic dependence		5 Hz	1.0 ppb	5 ppb
Muonium position (x,y)	1 mm	3 Hz	0.6 ppb	6 ppb
Muonium position (z)	1 mm	< 1 Hz	0.2 ppb	2 ppb
Beamline	10^{-4}	< 1 Hz	0.2 ppb	2 ppb
Detector pile-up	w/o absorber w/ absorber	2.8 Hz 0.3 Hz	0.5 ppb < 0.1 ppb	3 ppb < 1 ppb
Total			**~ 1.5 ppb**	**~ 13 ppb**

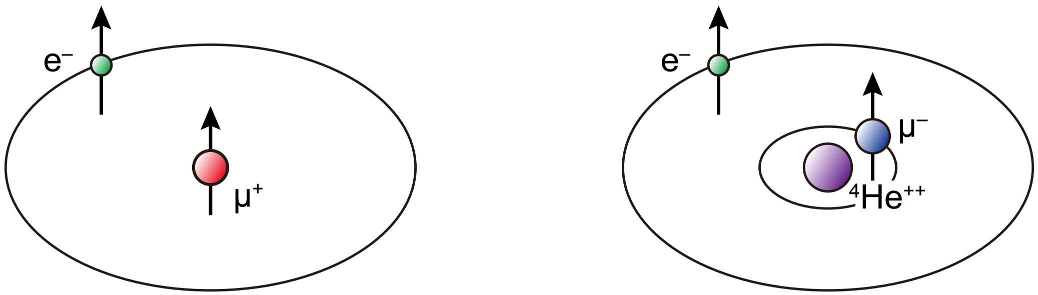
* Should be re-estimated by the latest progress and further MC simulation (old estimation)

Muonic Helium Atom Ground-State HFS



Muonium Muonic Helium

Muonic Helium Atom

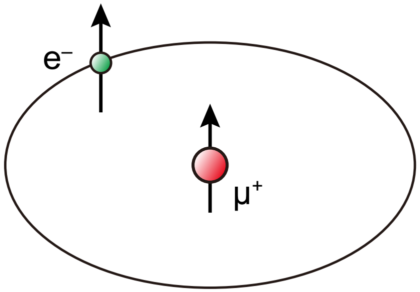


Muonium

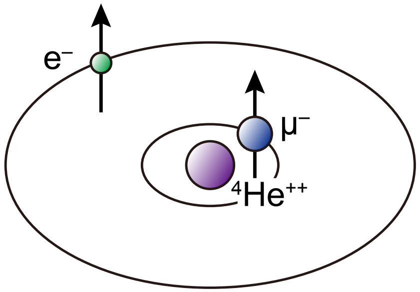
Muonic Helium

- System composed of a helium atom with one of its two electrons replaced by a **negative muon** (μ^-) (bound muon Bohr radius: $\mathbf{r_\mu \cong 1/400\ a_o}$).
- A hydrogen-like atom very similar to **muonium** (Mu).
- Ground state hyperfine structure (HFS) results from the interaction of the remaining **electron** and the **negative muon magnetic moment** (almost equal to that of muonium but inverted).
- Same technique as with muonium used to measure muonic helium HFS.
- Sensitive tool to test **3-body atomic system** and **bound-state QED** theories and determine fundamental constants of the **negative muon magnetic moment** and **mass** to test **CPT invariance** with **2nd generation lepton**.

Muonic Helium Atom

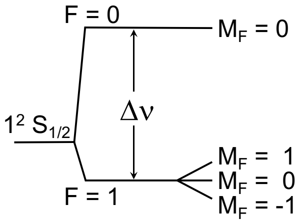


Muonium



Muonic Helium

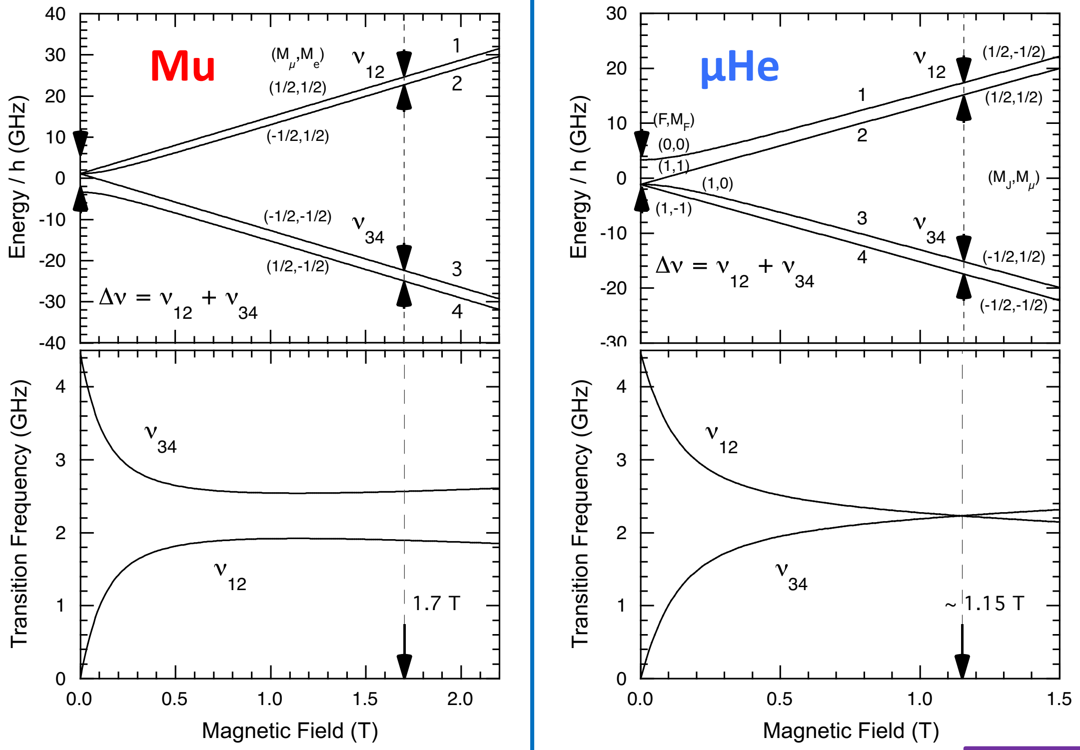
- Hydrogen-like atom similar to **muonium**
- Similar ground-state HFS but inverted
- Same technique to measure **μHe** HFS



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**

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

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

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

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

Previous μHe HFS Experiments ('80s)

Zero Field (SIN)

pressure: 20 atm

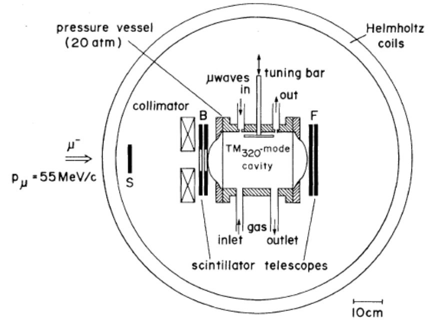
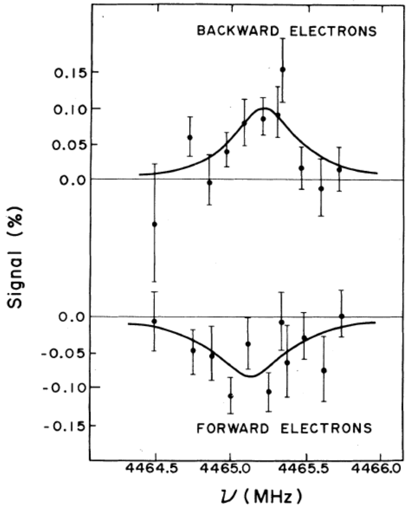
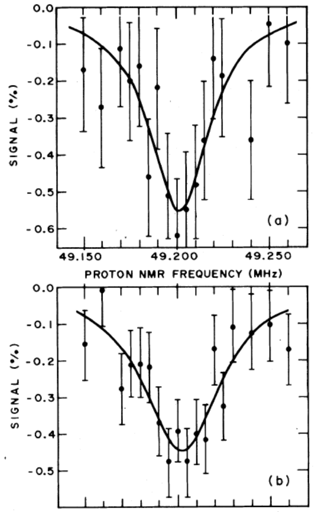


FIG. 2. Schematic view of the apparatus. The Helmholtz coils are used for muon-spin rotation. A cylindrical high-permeability metal shield (diameter 50 cm, length 100 cm) was installed (not shown in the figure) during the microwave magnetic-resonance experiment to reduce the stray magnetic fields.



High Field (LAMPF)



pressure: 5 & 15 atm

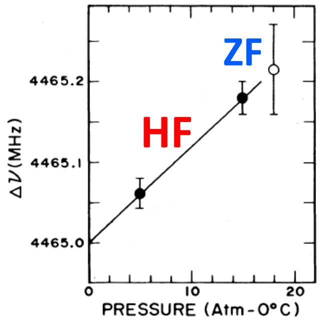


FIG. 2. Δν as a function of He+Xe(1.5%) gas pressure. Closed circles show the results of this experiment; the open circle is the result of Ref. 3. The straight line shows the linear extrapolation used to extract Δν(0).

	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 !

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

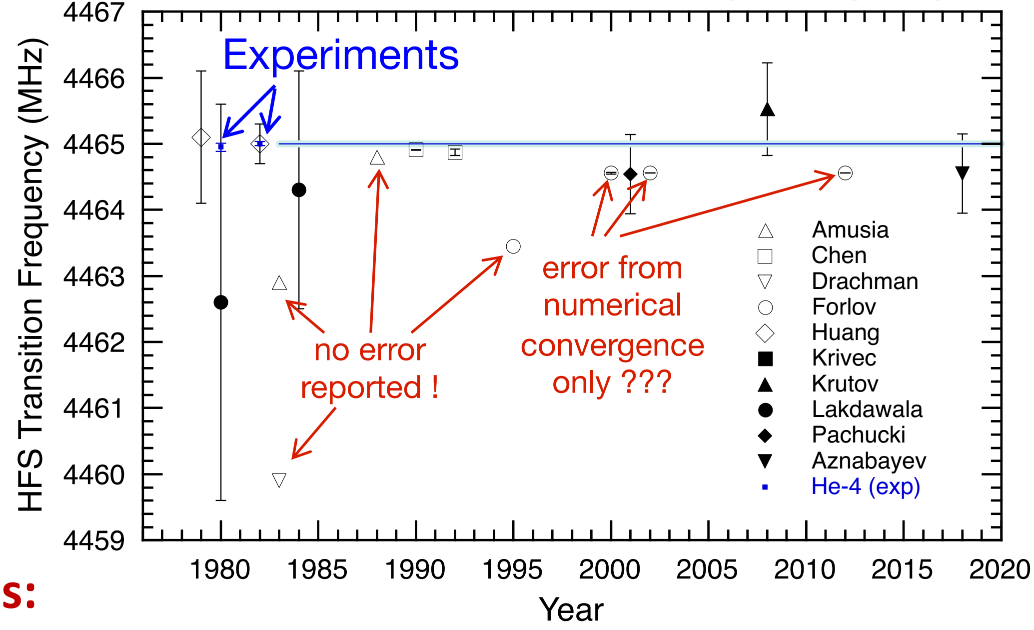
Calculations performed since the 1970s based on perturbation theory (PT), variational approach (VA), and Born-Oppenheimer (BO) theory.

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

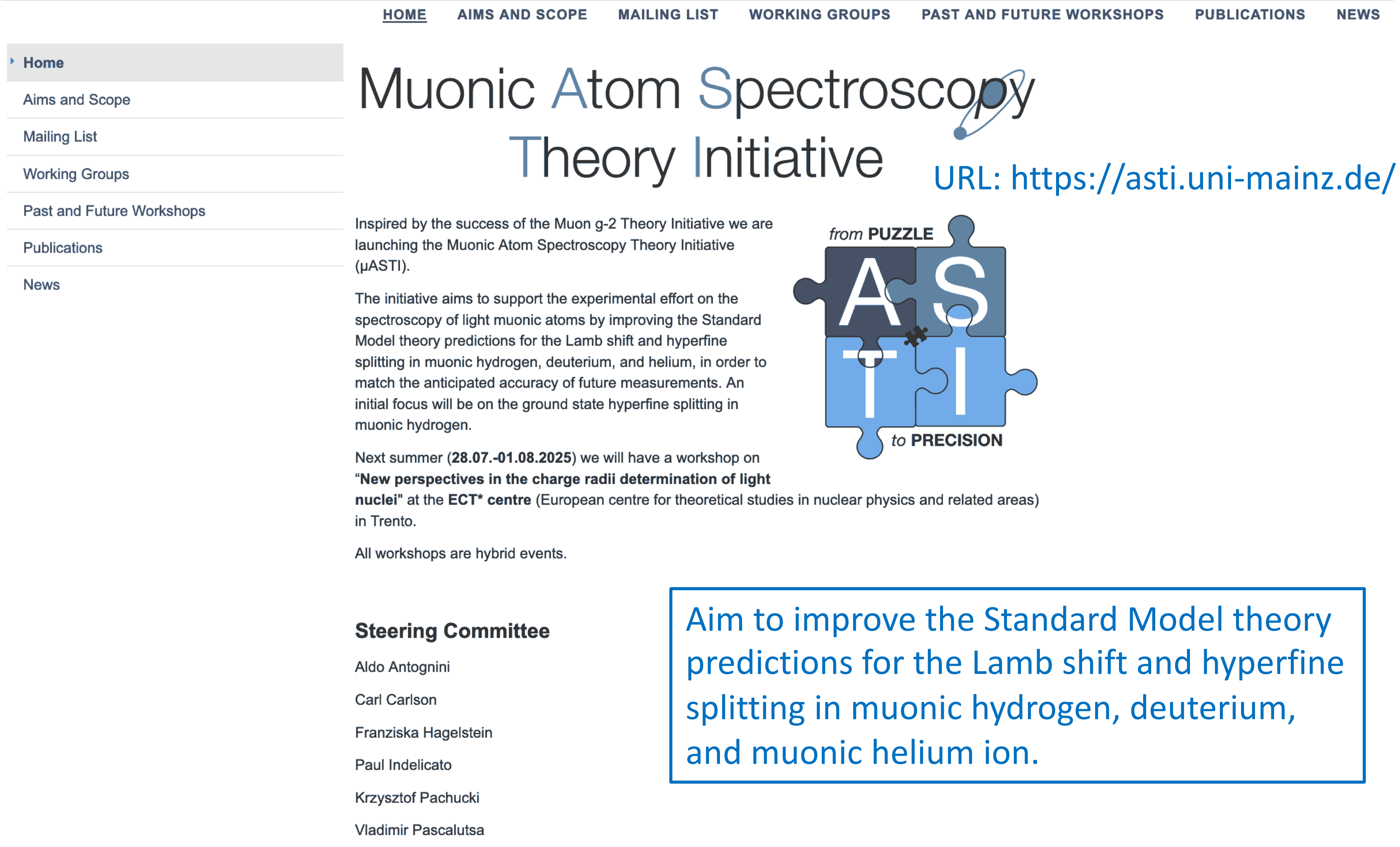
Muonic Helium-4 HFS ($^4He^{2+}\mu^-e^-$)



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

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

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% → 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

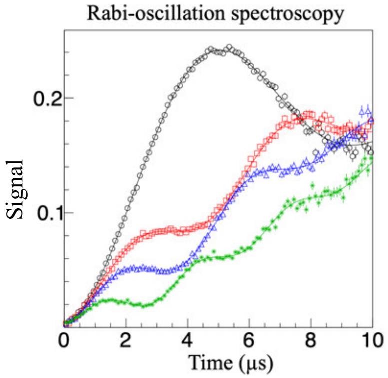
New µHe HFS at J-PARC MUSE

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

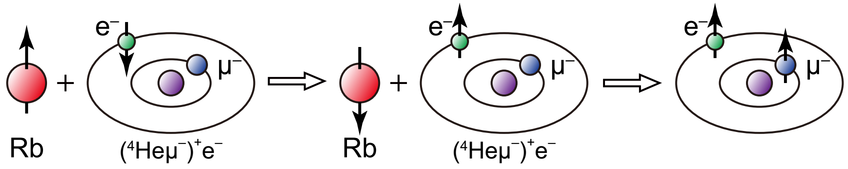
Three key components for improvement:

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

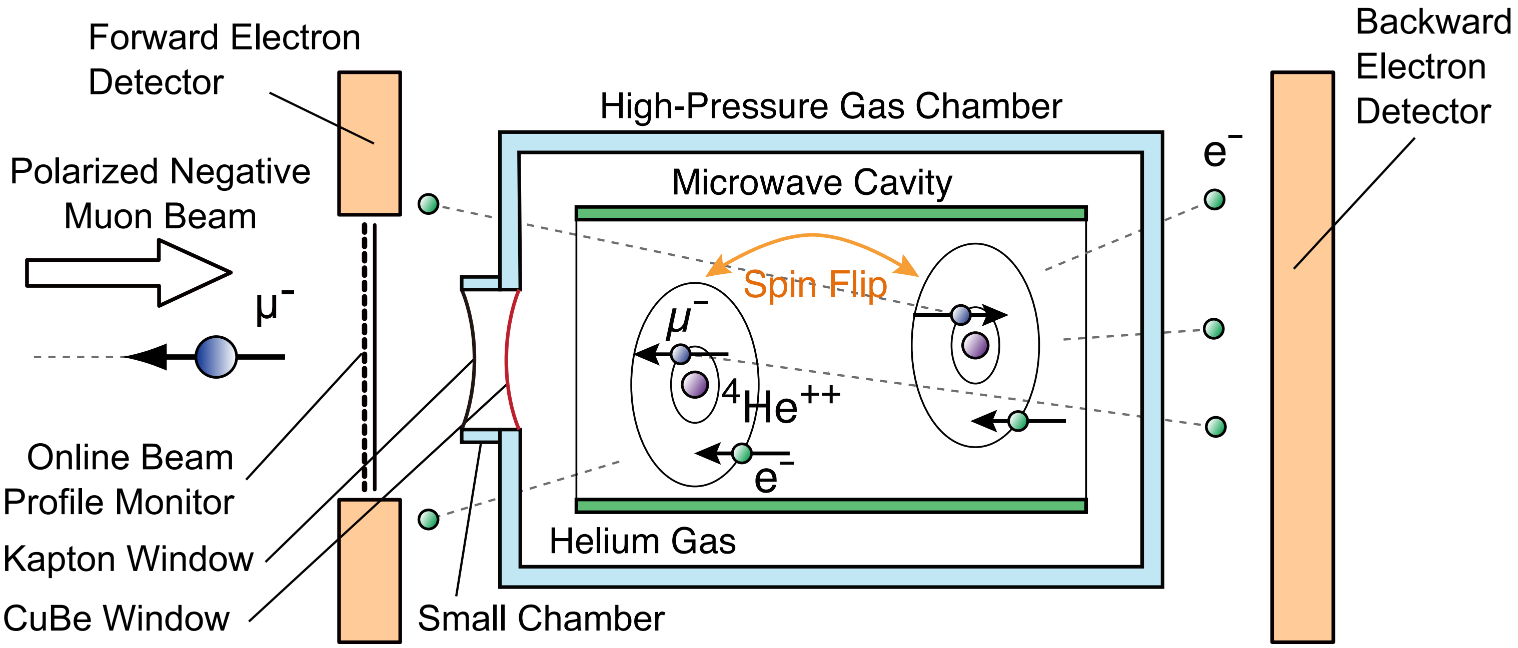
2) Applying **Rabi-oscillation spectroscopy technique** to HFS measurements.



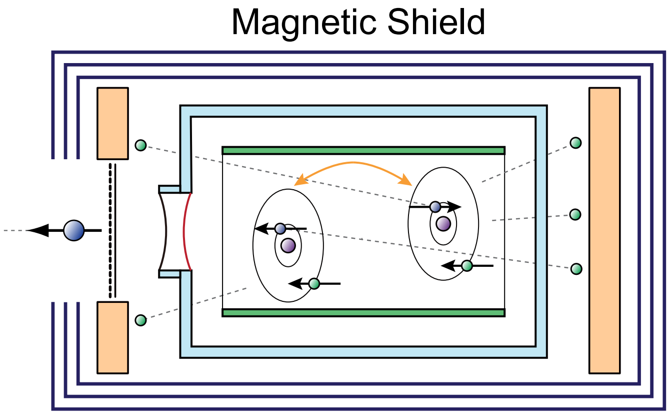
3) Producing **highly-polarized muonic helium atoms** to improve the µ⁻ residual polarization in helium by Spin Exchange Optical Pumping (SEOP).



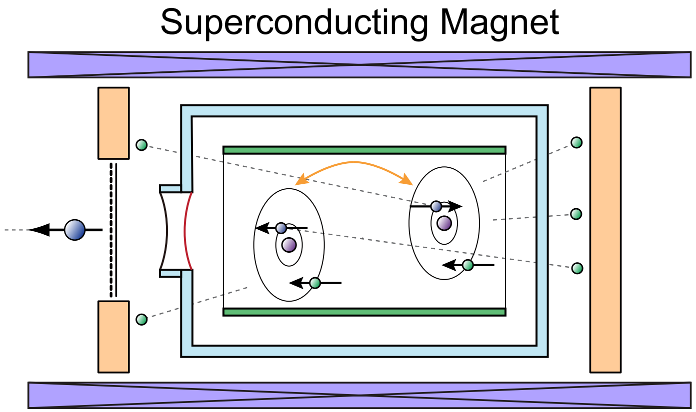
Experimental Arrangement



Zero-Field Measurements



High-Field Measurements



Expected Improvements

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

- $5 \times 10^4\ \mu^-/s$ at 55 MeV/c (low field), $4 \times 10^4\ \mu^-/s$ at 35 MeV/c (high field)

H-line:

- $\sim 10^7\ \mu^-/s$ 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:

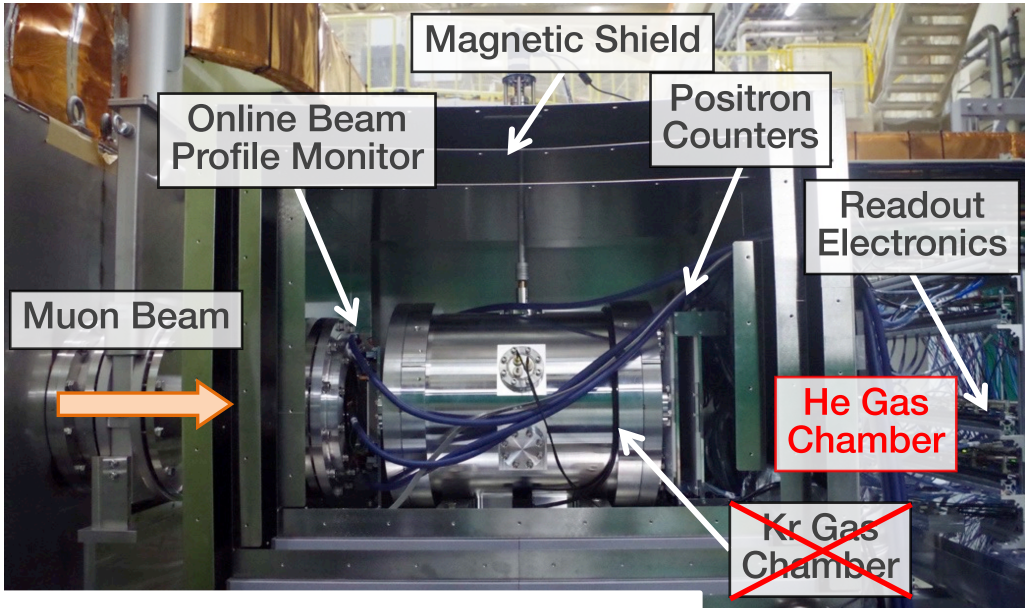
- MuSEUM experiment has similar systematical errors.
- Present estimation: ~2 ppb for $\Delta\nu$ and ~20 ppb for $\mu_\mu - /\mu_p$.

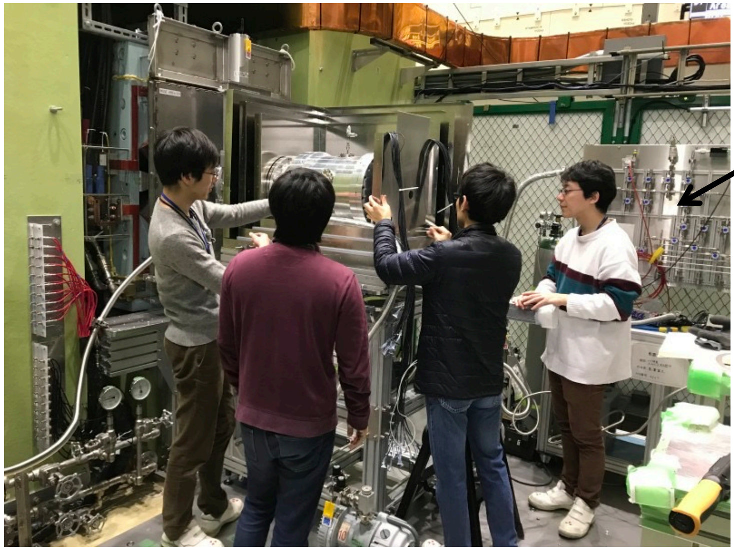
D-line: (zero field)
$\rightarrow \sim 10^2$ times more statistics (depending on beamtime allocation)

General User Program

μHe HFS Measurements at Zero-Field

Experimental Setup



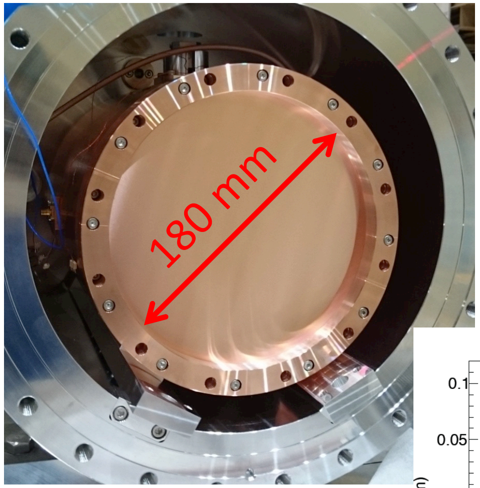


[2019B0318]

Preparation of MuSEUM apparatus in D2 area

(students from
Nagoya University and
the University of Tokyo)

Microwave Cavity (zero field)

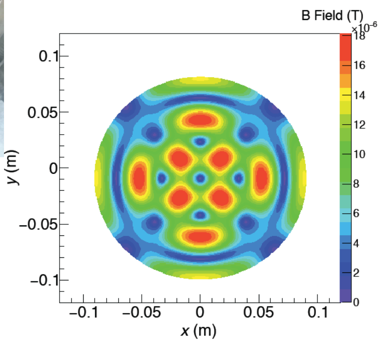


TM220 mode
Larger cavity
More muon stop
Q-Value:
20,000 (calc.)

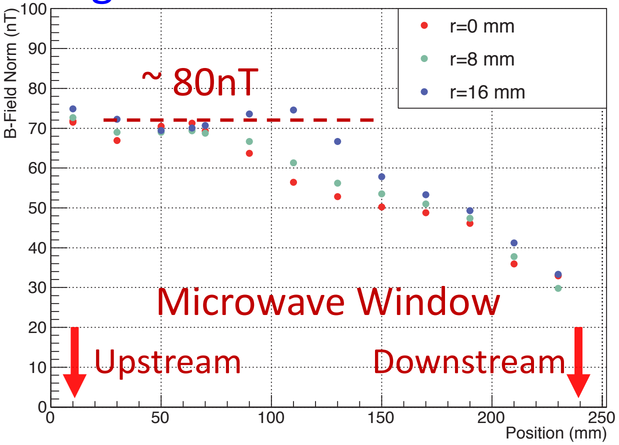
~~Δν = 4.463 GHz~~

Δν = 4.465 GHz

MW Intensity

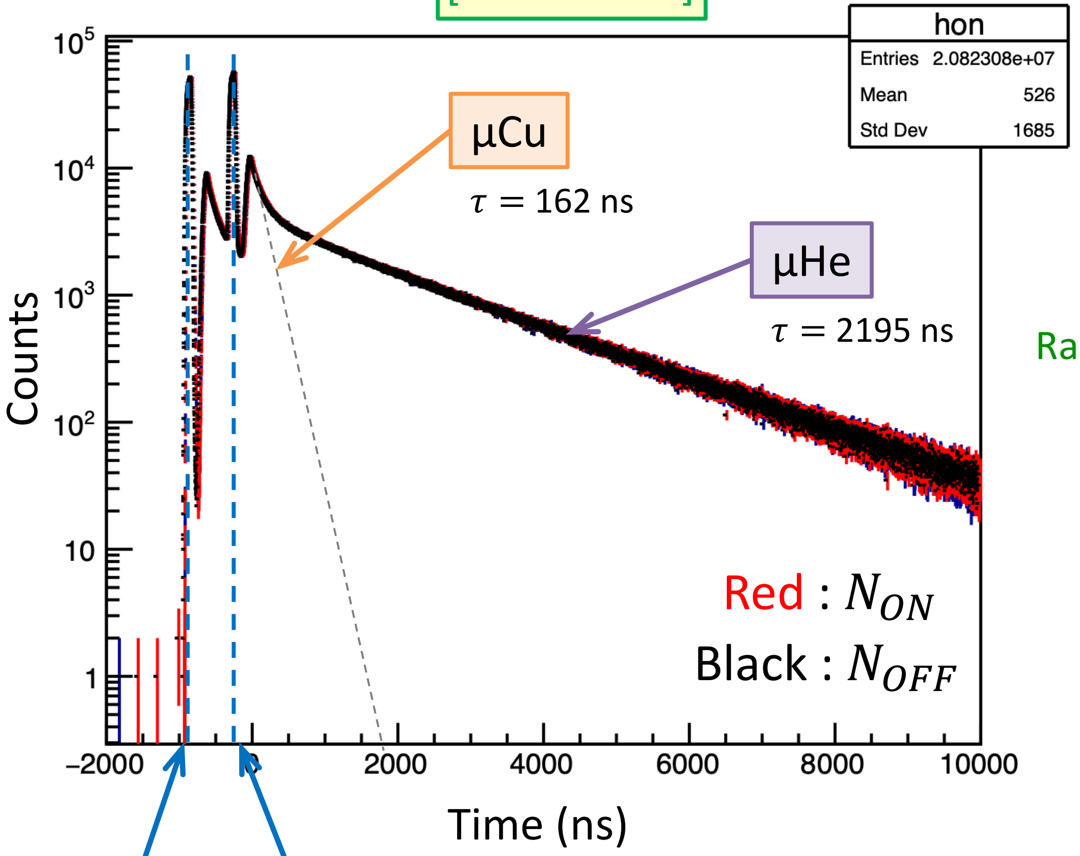


Residual Magnetic Field



Decay Electron Time Spectra

[2020B0333]



µCu

$\tau = 162$ ns

µHe

$\tau = 2195$ ns

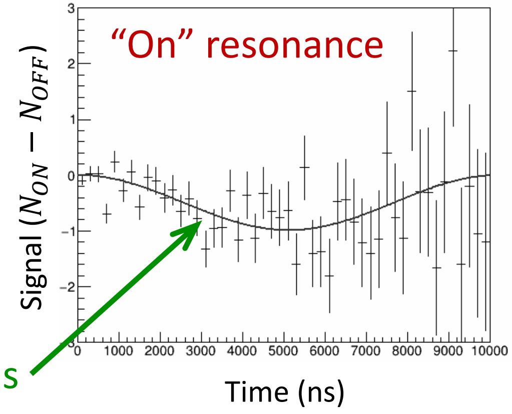
Red : N_{ON}

Black : N_{OFF}

1st Muon Peak (-600 ns)

2nd Muon Peak (0 ns)

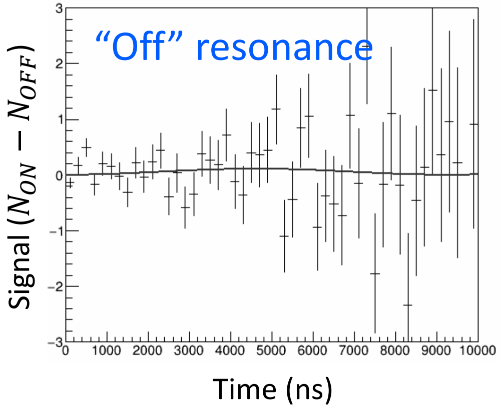
Frequency = 4465000 + 0 kHz



"On" resonance

Rabi Oscillations

Frequency = 4465000 + 600 kHz

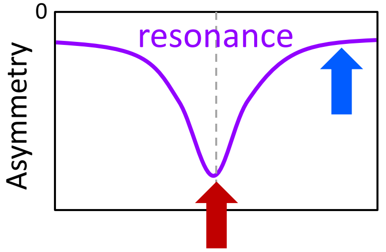


"Off" resonance

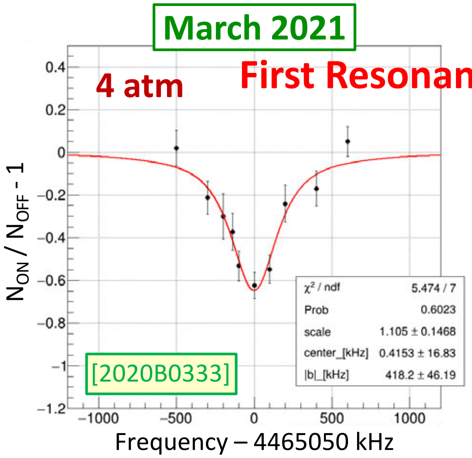
$$\text{Asymmetry} = \frac{N_{OFF}}{N_{ON}} - 1$$

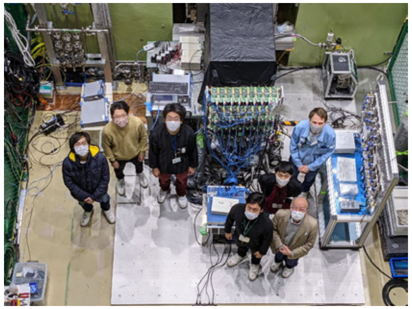
N_{ON} : Number of e⁻ with microwave

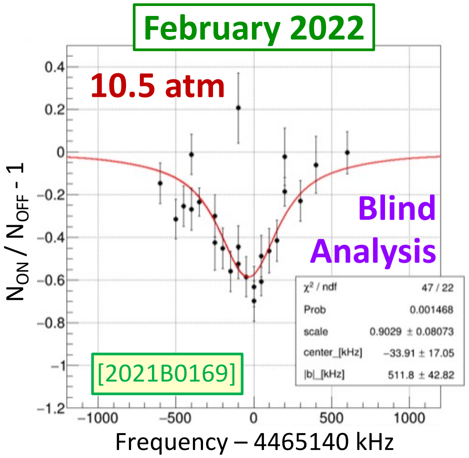
N_{OFF} : Number of e⁻ without microwave

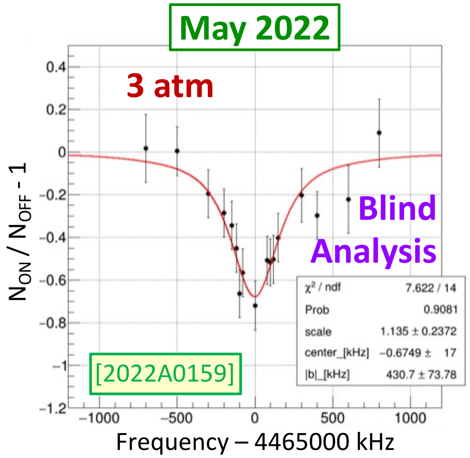


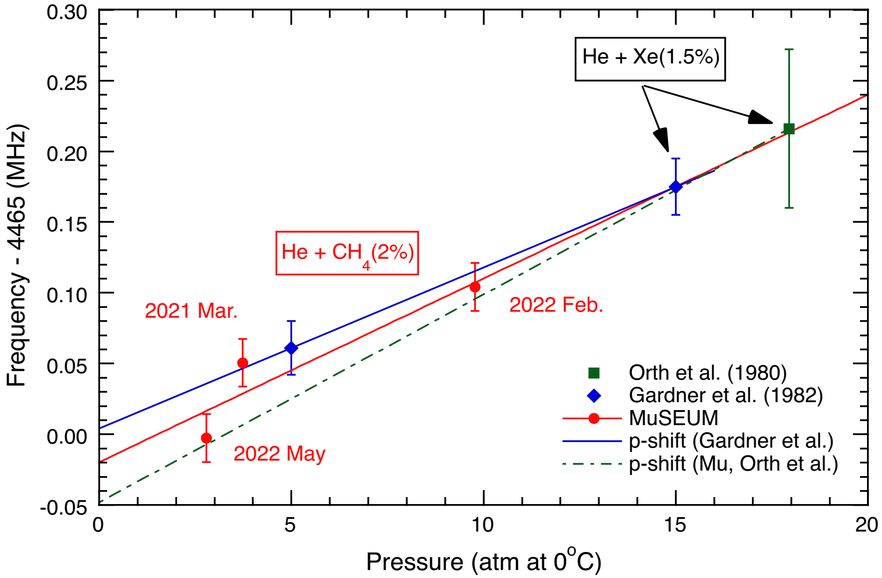
μHe HFS Resonance Curve











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!

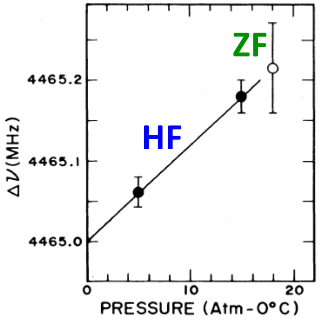


FIG. 2. $\Delta\nu$ as a function of He+Xe(1.5%) gas pressure. Closed circles show the results of this experiment; the open circle is the result of Ref. 3. The straight line shows the linear extrapolation used to extract $\Delta\nu(0)$.

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

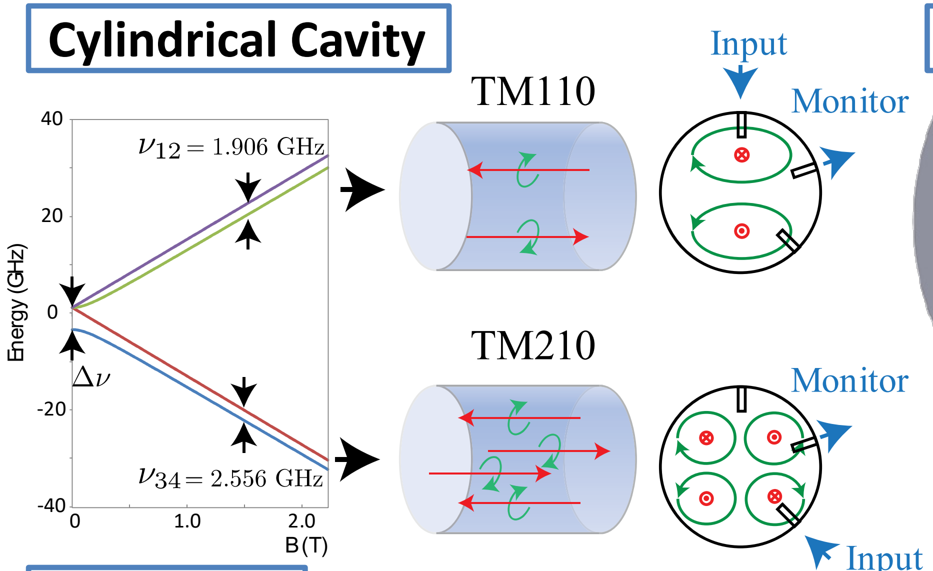
$\Delta\nu$ = 4465.004(29) MHz (Gardner et al.) [6.5 ppm] high field (HF)

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

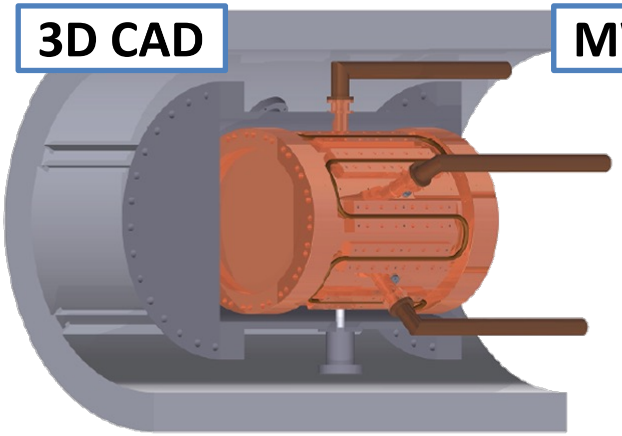
P. Strasser et al., Phys. Rev. Lett. **131** (2023) 253003

High-Field Microwave Cavity (Mu&µHe)

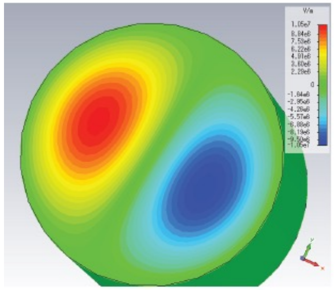
Cylindrical Cavity



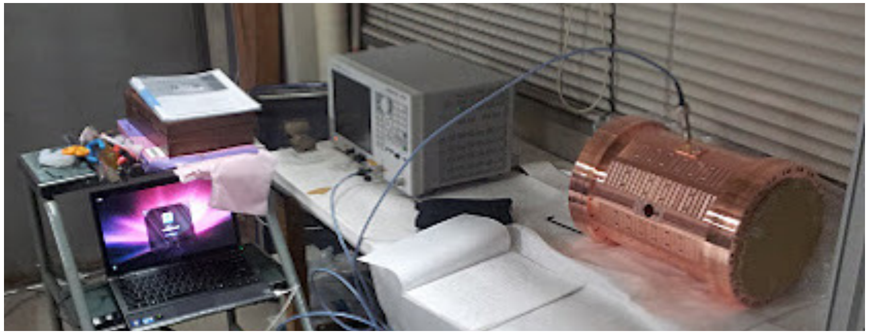
3D CAD



MWS Simulation



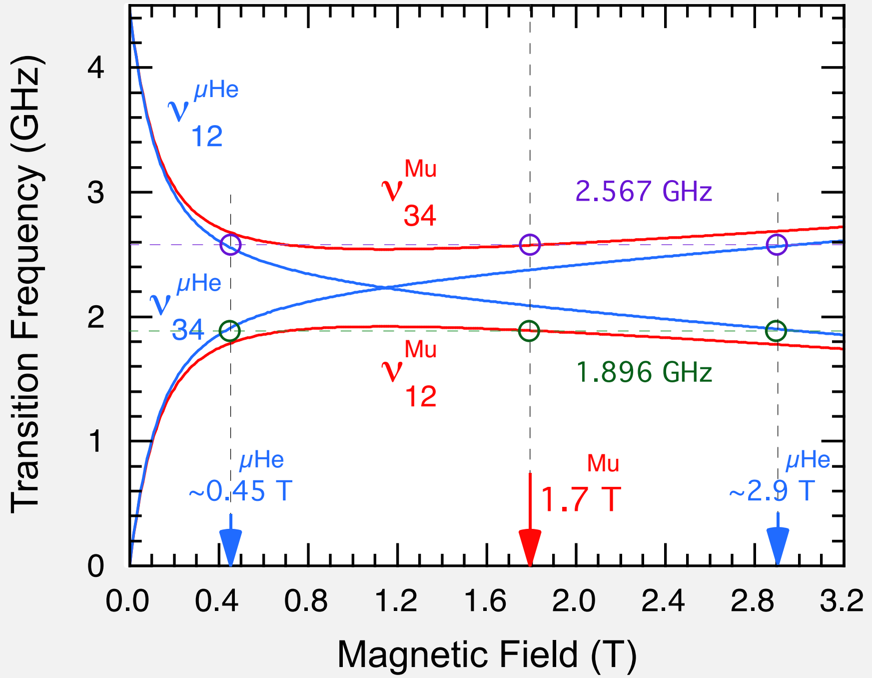
Cavity Test



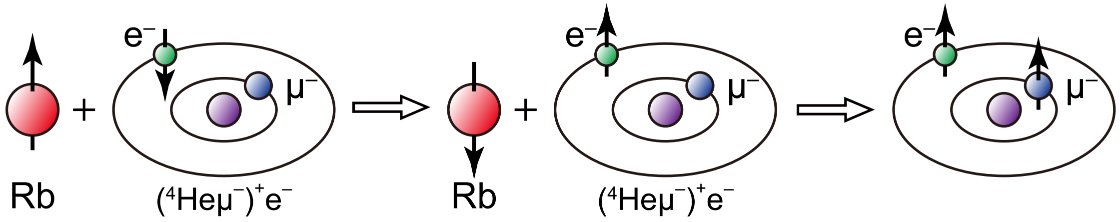
Q Value

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

Comparison between **Muonium** & **µHe**

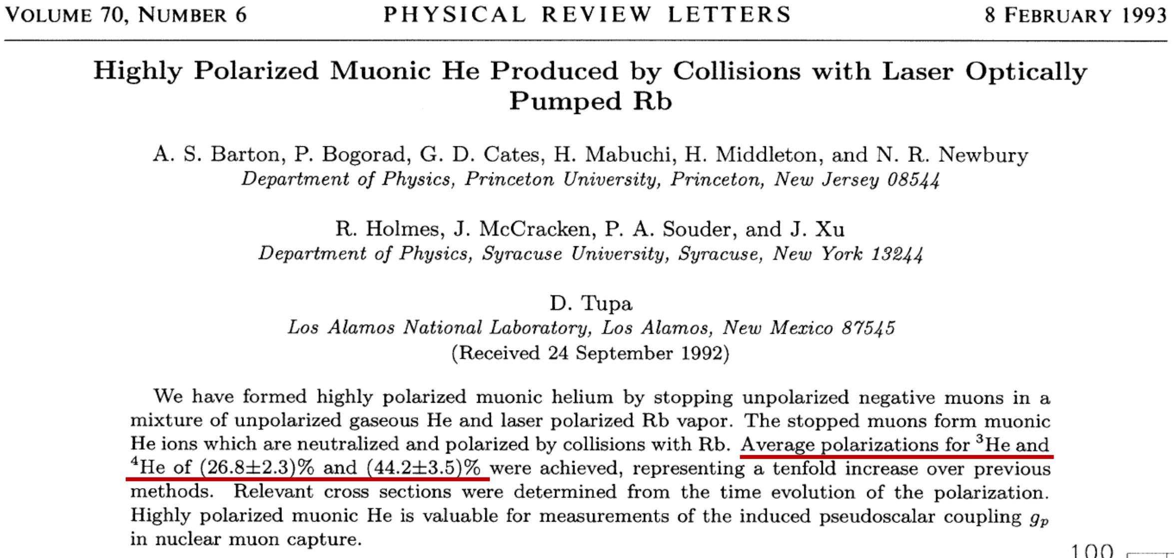


Highly-Polarized Muonic Helium Atom



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)

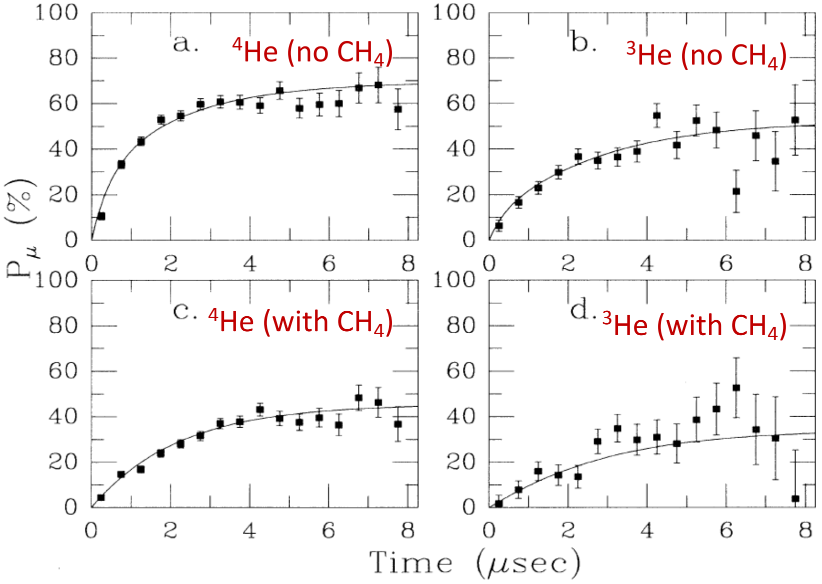
Glass cell target: (T ≈ 200°C)

- 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%

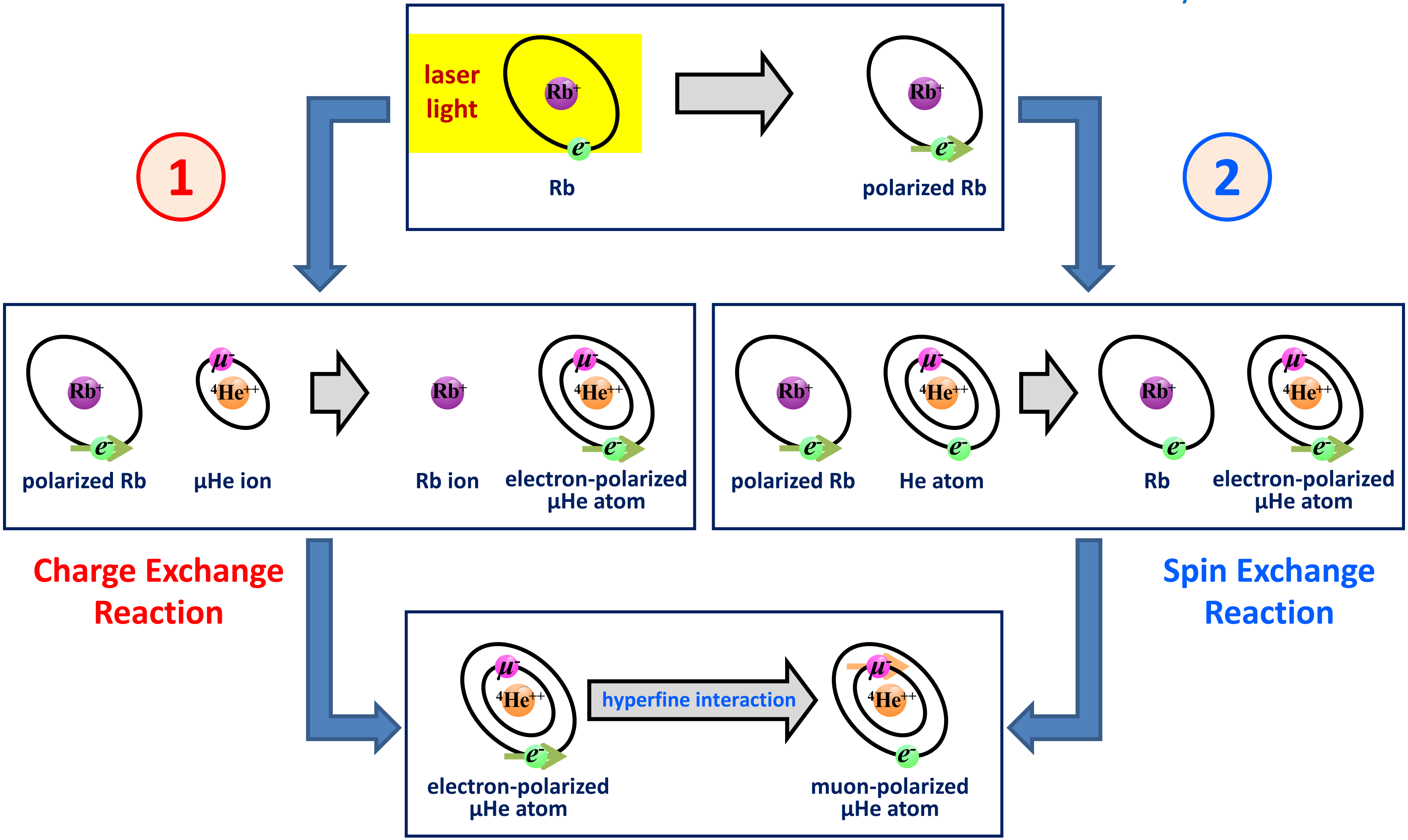
Improvement by a factor 7 achieved !

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



Polarization of Muonic He Atom

by S. Fukumura



laser light

Rb

polarized Rb

①

polarized Rb

μHe ion

Rb ion

electron-polarized μHe atom

Charge Exchange Reaction

②

polarized Rb

He atom

Rb

electron-polarized μHe atom

Spin Exchange Reaction

electron-polarized μHe atom

muon-polarized μHe atom

μHe SEOP Objectives

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

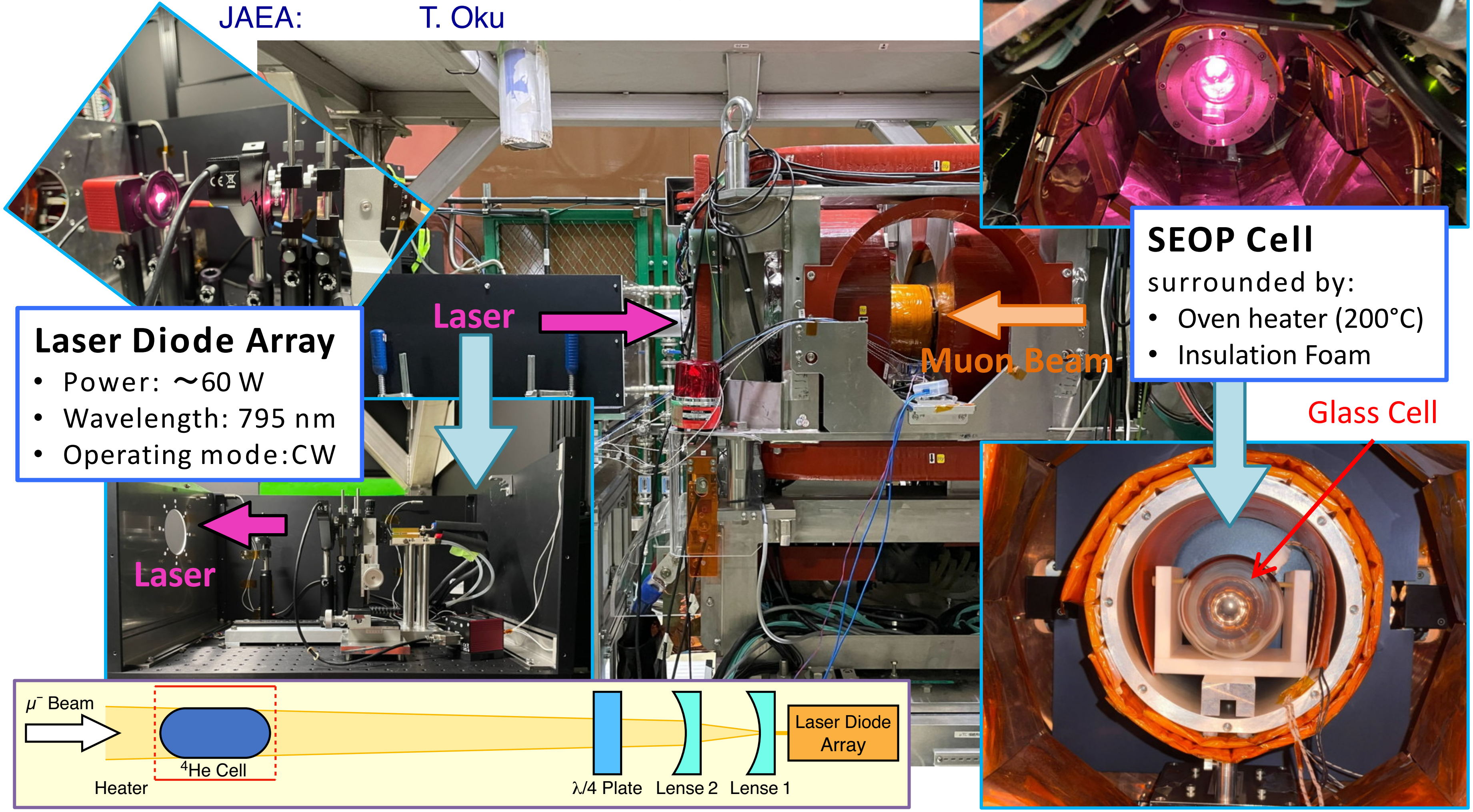
2) Further improvements expected with a **hybrid-SEOP technique**
   - Use **K/Rb** to enhance the spin-exchange efficiency
   - Rb is used as a spin-transfer agent to K, to prevent depolarization of Rb due to Rb-Rb collision.
   - K-He transfers the angular momentum with much greater efficiency than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



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

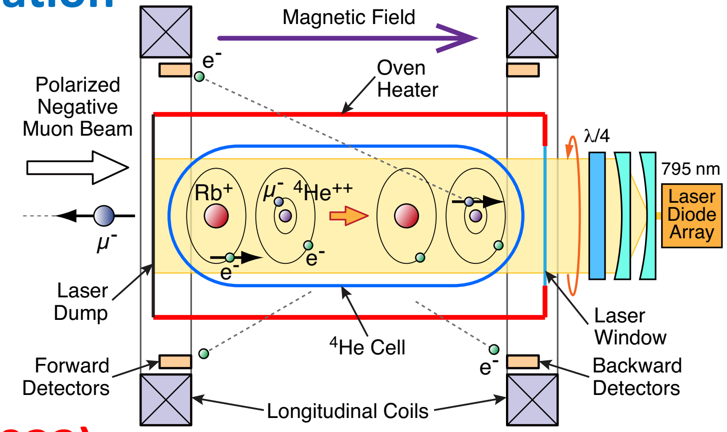
SEOP Cell

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

First Laser Experiment at D1 Area

Muonic helium atom polarization

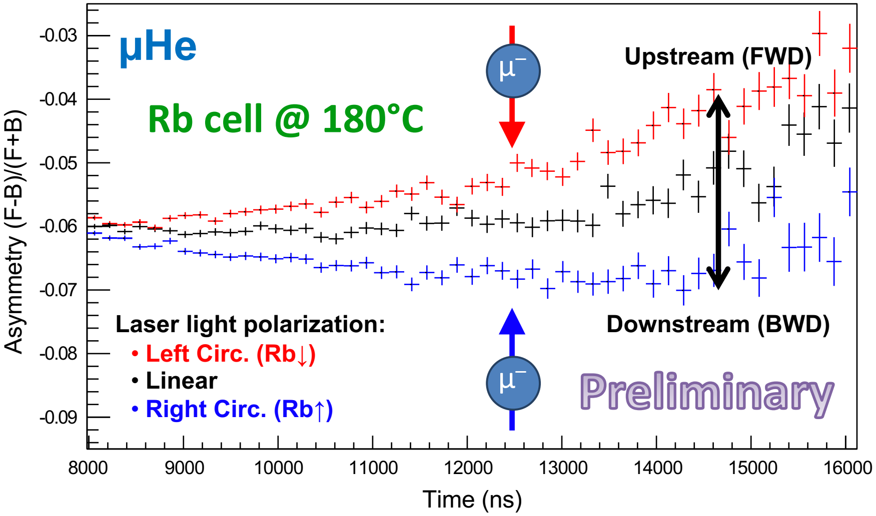
- Depolarization during the muon cascade ↘ ~5%
- Re-polarization of μHe atom by Spin-Exchange Optical Pumping (SEOP)

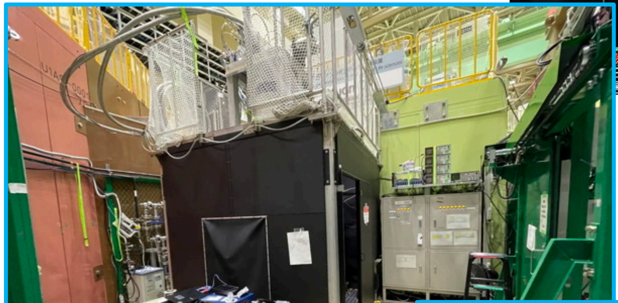


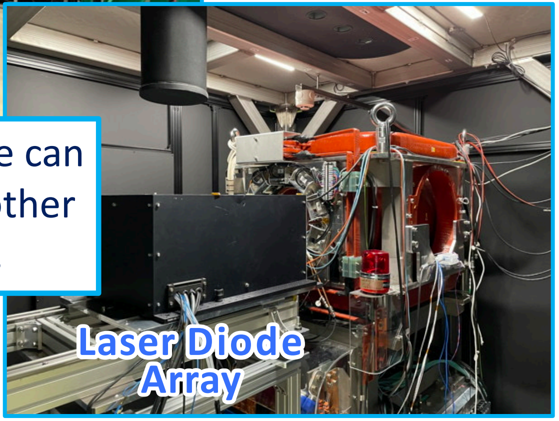
[2022B0314]

S. Fukumura,
T. Okudaira
(Nagoya Univ.)

μHe SEOP Beamtime (Feb. 2023)







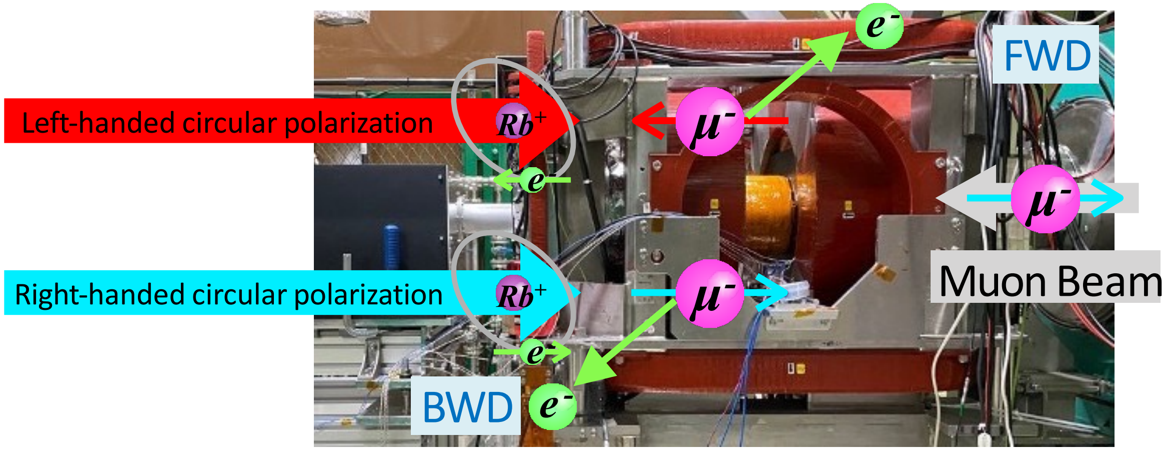
D1 laser enclosure can also be used by other experiments.

&

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

Glass Cell Development

by S. Fukumura



Asymmetry:

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

Old Pyrex Cell

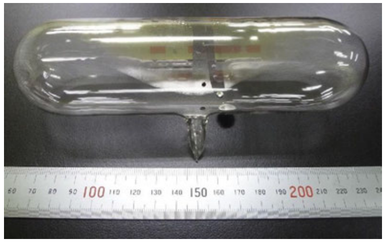
Size: Ø75 mm x 150 mm
Wall (front): 1 mm
Wall (side): 1 mm

Glass Cells:

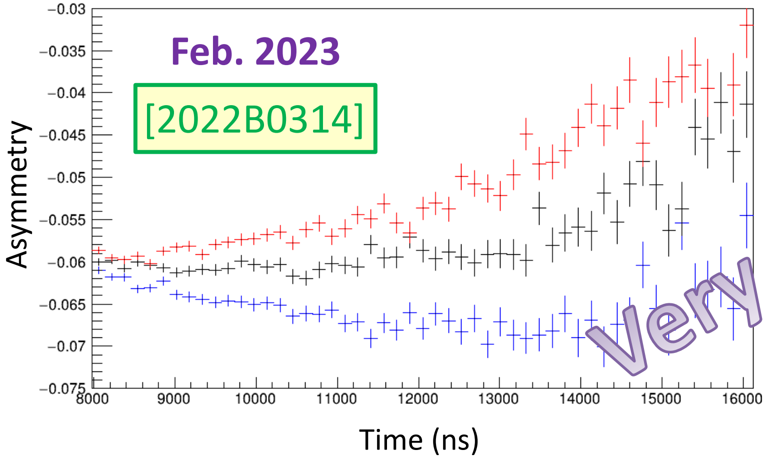
- Blown at the Glass Workshop of Tohoku University
- Filled and tested by Takashi Ino (KEK)

Rb cell: 180°C

New GE-180 Cell



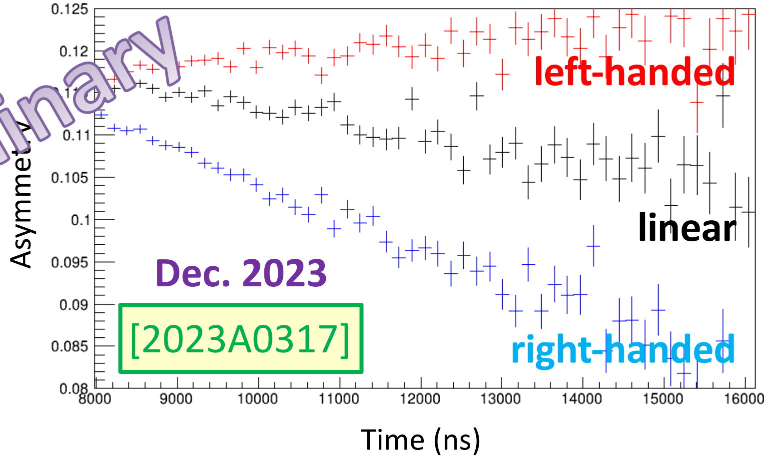
Size: Ø50 mm x 180 mm
Wall (front) : 0.5 mm
Wall (side) : 1.0 mm



Upstream (FWD)

↕

Downstream (BWD)



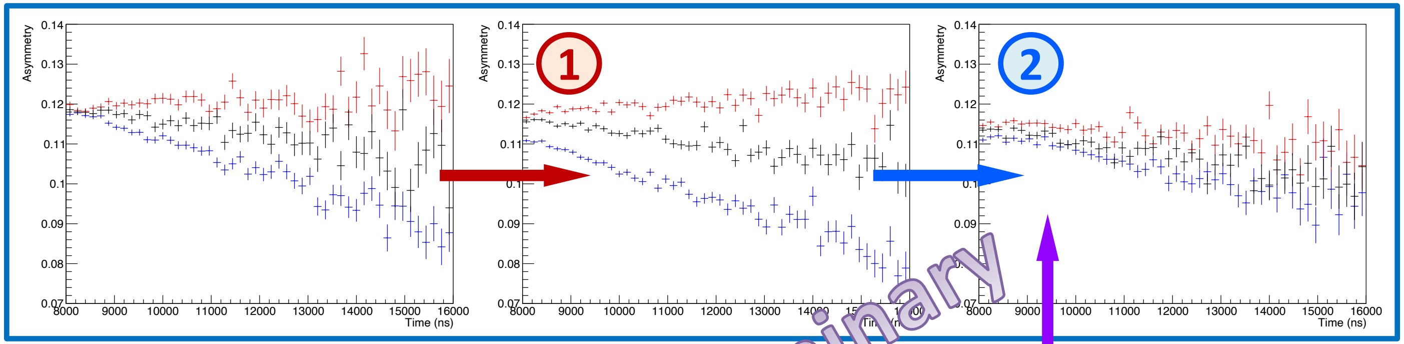
µHe SEOP vs. Hybrid-SEOP

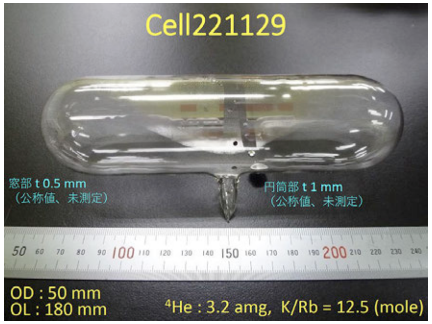
160 °C 180 °C 200 °C 240°C

Rb Pure Cell

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

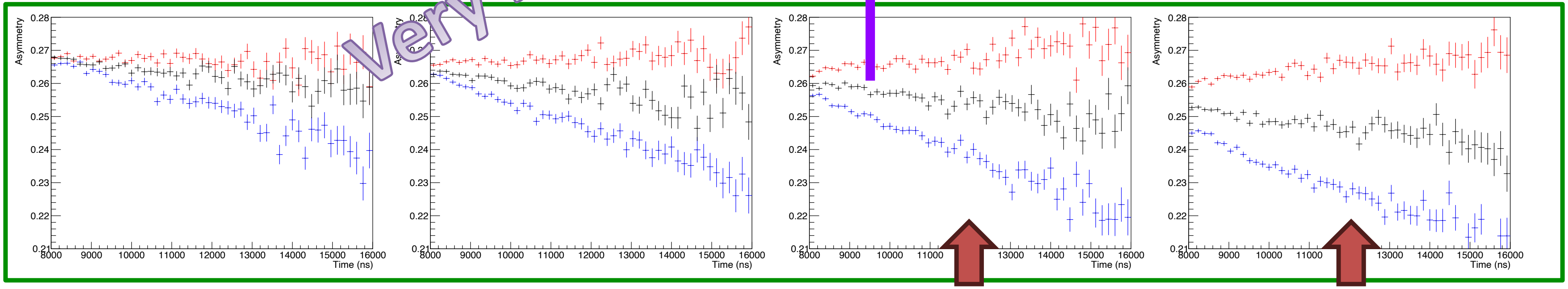
Hybrid Cell
[K]/[Rb] = 12.5 (mole)





Hybrid K/Rb Cell

Decrease in polarization efficiency due to spin relaxation



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

(on-line analysis only)

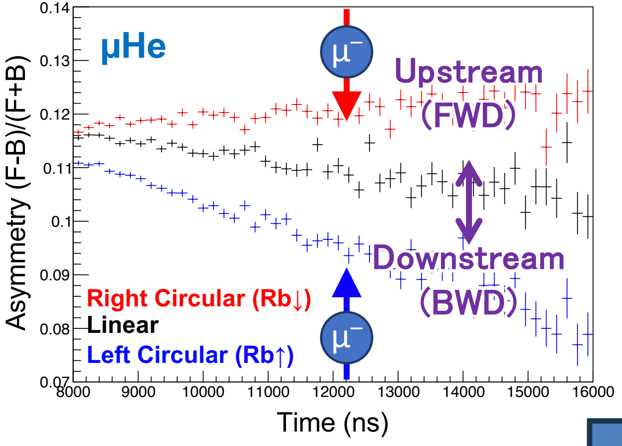
Comparison: Pure & Hybrid Cell

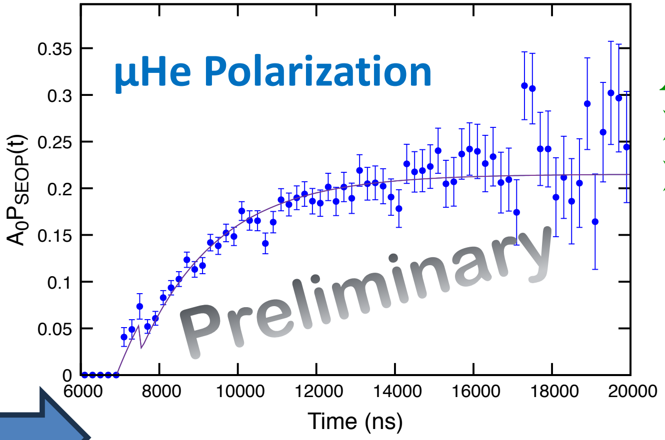
Asymmetry: $$A(t) = \frac{F(t) - B(t)}{F(t) + B(t)}$$

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

Muons stopped in He

Pure Rb cell @180°C



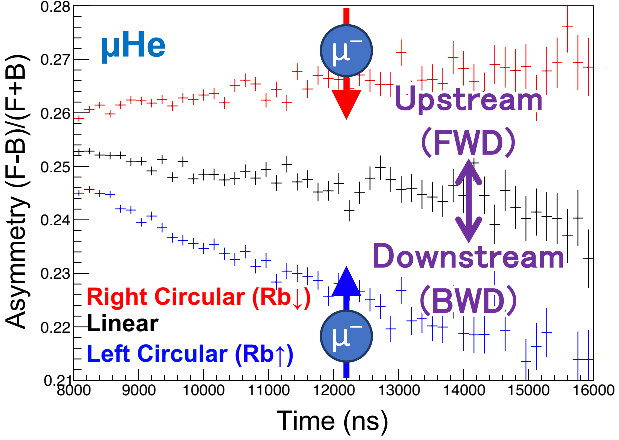


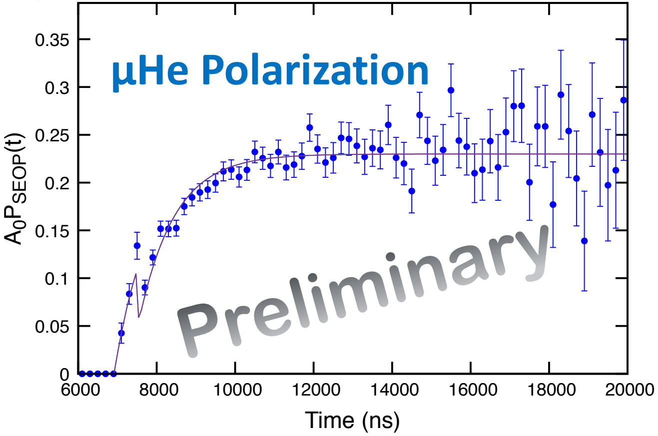
A_0 : Experimental asymmetry

- 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%

Hybrid K/Rb cell @240°C





- Geant4 simulations needed to determine A_0

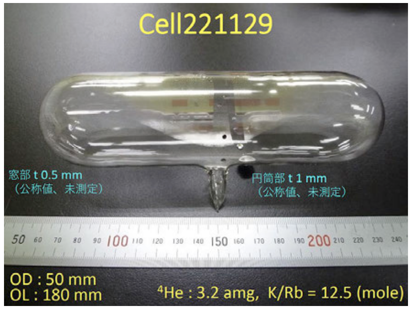
Analysis in progress

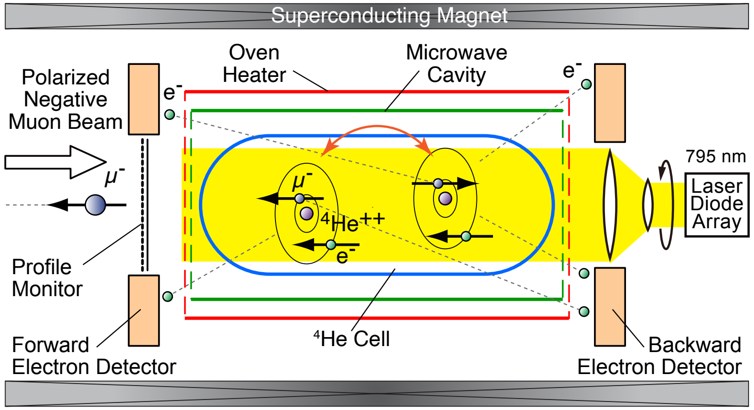
- High polarizing rate with high polarization efficiency achieved with “Hybrid” at 240°C

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

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Abstract

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

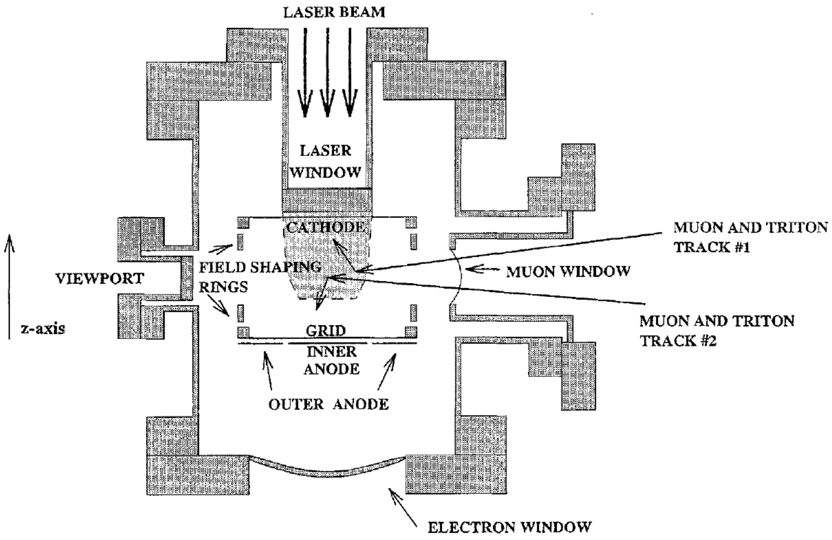

Fig. 1. Diagram of the polarized target/drift chamber.

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

Summary & Future Plans

- **Muonium HFS precision measurement**
  - Precise bound-state QED test
  - Muon $g-2$ & Muonium $1s-2s$
- **Zero-Field Experiment**
  - Development of Rabi-oscillation spectroscopy
  - World's highest precision in ZF measurement: **160 ppb**
- **High-Field Experiment (H1 area)**
  - Field uniformity: **0.20 ppm** achieved
  - Development of CW-NMR magnetic probe: **15 ppb** precision achieved
  - Field measurements and adjustment with all components in progress
  - First test result at high field with low proton beam power (100 kW)
  - Next **commissioning run**: October 30 ~ November 7, 2025
  - First **physics run** (TBD): February ~ March 2026 period
- **Muonic Helium HFS Measurement**
  - Zero-Field experiment successful; world's highest precision: **4.5 ppm**
  - Highly-polarized μHe formation by SEOP under development
  - High-field experiment planned after muonium

MuSEUM Collaboration

(Muonium Spectroscopy Experiment Using Microwave)

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