Muonic helium atom hyperfine splitting measurement at J-PARC

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On behalf of the MuSEUM Collaboration

Muonic Atoms at PSI2022
Satellite Workshop on “Proton structure in and out of muonic hydrogen — the ground-state hyperfine splitting”
PSI, Villigen, Switzerland, October 14–15, 2022

MuSEUM Collaboration

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

Muonic Helium HFS Experiment Collaborators:

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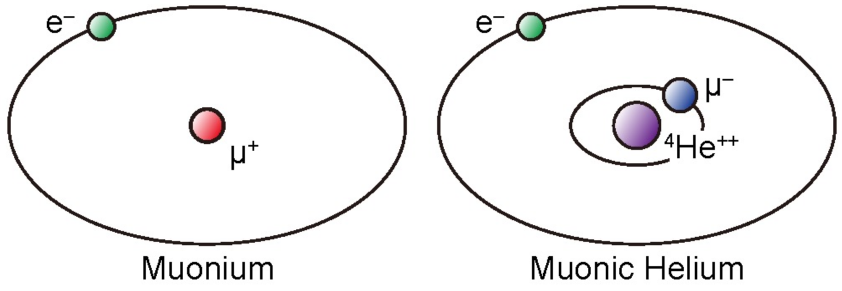
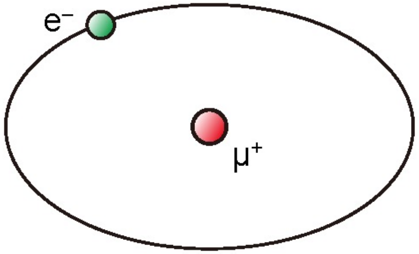
On behalf of the MuSEUM Collaboration

Muonic Helium Atom

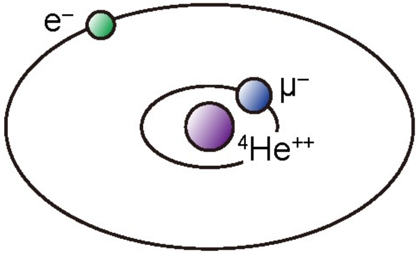


- System composed of a helium atom in which one of the two electrons is replaced by a negative muon (μ^-) (bound muon Bohr radius: **$r_\mu \cong 1/400\ a_o$**).
- Hydrogen-like atom very similar to muonium (Mu).
- Ground state hyperfine structure (HFS) results from the interaction of the remaining electron 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** theory, and determine fundamental constants of the **negative muon magnetic moment** and **mass** to test **CPT invariance** with **2nd generation lepton**.

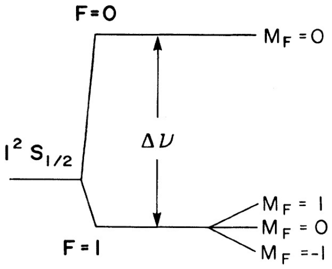
Mu & µHe HFS Comparison



Muonium

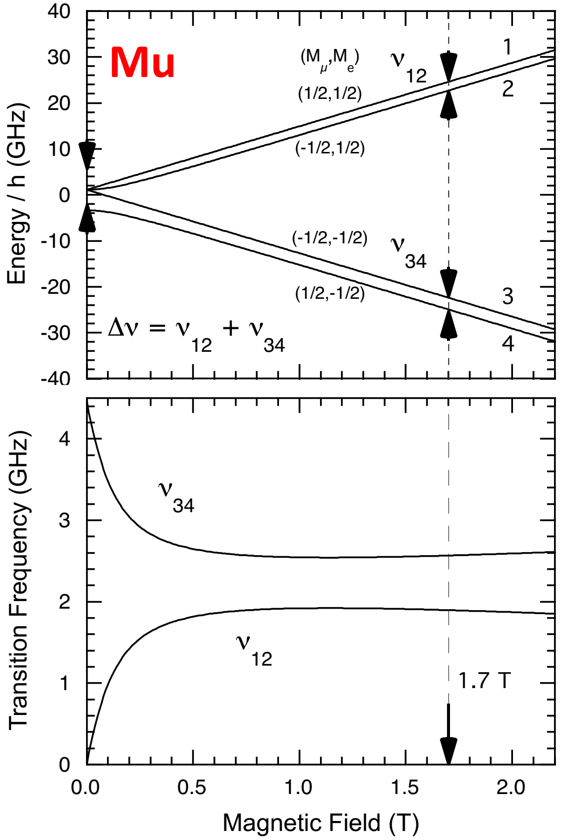


Muonic Helium

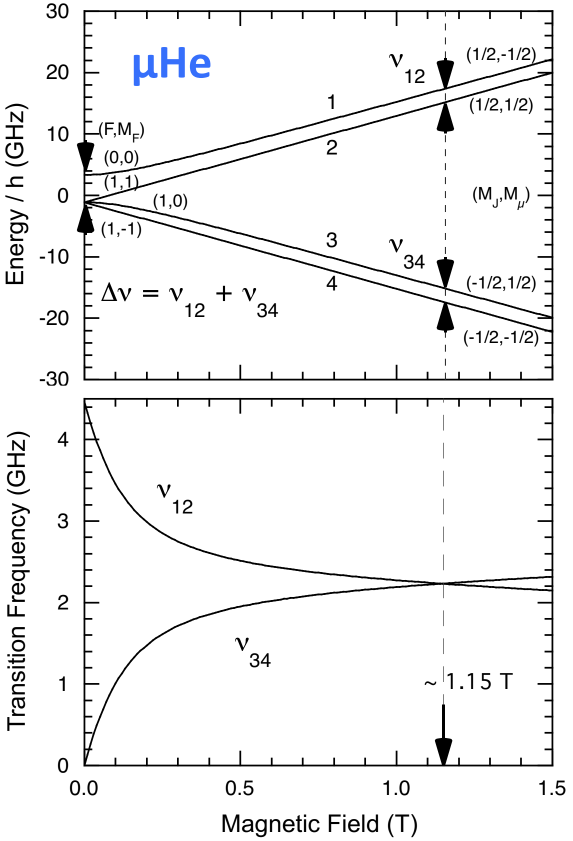


Ground state muonic helium HFS structure and low field Zeeman splitting

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



$\Delta\nu$(µHe) = 4465.004(29) MHz

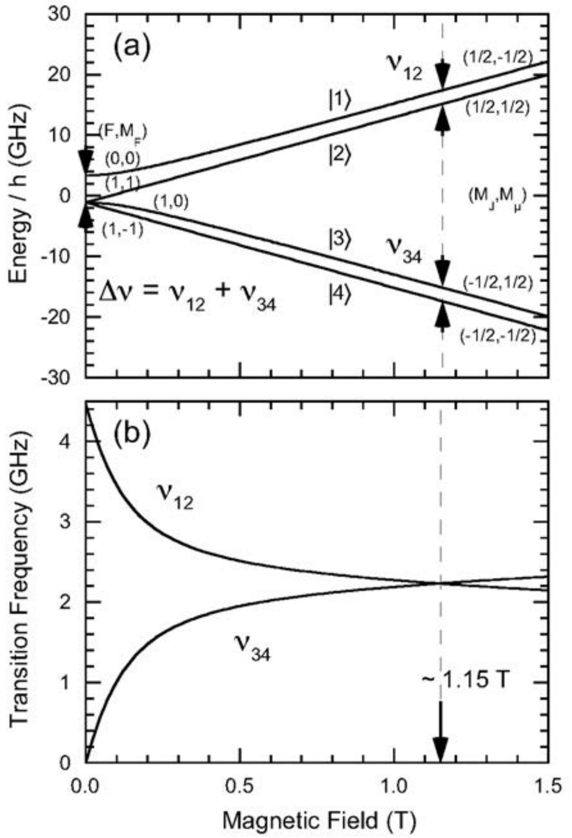


Breit-Rabi energy level diagrams

Muonic Helium Atom HFS

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

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



where g_J and g'_μ are the g-factors of the electron and muon bound in $^4He\mu^-e^-$, respectively.

The transitions frequencies ν_{12} and ν_{34} are given by the Breit-Rabi formula

$$\nu_{12} = -g'_\mu \mu_B^\mu \frac{H}{h} + \frac{\Delta\nu}{2}\left(1 - x + \sqrt{1 + x^2}\right)$$

$$\nu_{34} = g'_\mu \mu_B^\mu \frac{H}{h} + \frac{\Delta\nu}{2}\left(1 + x - \sqrt{1 + x^2}\right)$$

with $x = \left(g_J \mu_B^e - g'_\mu \mu_B^\mu\right) H / h\Delta\nu$

(a) Breit-Rabi energy level diagram
(b) HFS transition frequencies for muonic helium ($\Delta\nu \cong 4.465$ GHz).

C. J. Gardner *et al.*, Phys. Rev. Lett. **48**,1168 (1982); PhD Thesis, Yale University, 1983 (unpublished)

Muonic Helium Atom HFS

Same as with muonium,

- The sum of the two transition frequencies ν_{12} and ν_{34} is constant, and equal to the ground state hyperfine splitting $\Delta\nu$ at zero field:

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

- The difference is directly related to the ratio of the negative muon and proton magnetic moments μ_{μ}–/μ_{p}:

$$\boxed{\nu_{34} - \nu_{12} = g'_{\mu}\mu_{B}^{\mu}\,\nu_{p}/\mu_{p} + \Delta\nu\left(x - \sqrt{1 + x^{2}}\right)}$$

and by using $r'_{e} = g_{J}\mu_{B}^{e}/2\mu_{p}$ and $r'_{\mu} = g'_{\mu}\mu_{B}^{\mu}/2\mu_{p}$ we can get

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

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

Note: The g-factors of the electron and muon bound in ^{4}He$\mu^{-}e^{-}$ (g_{J} and g'_{μ}) have recently been calculated up to the 3rd order by S. G. Karshenboim.

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

Muonic Helium Atom HFS

Precise determination of $\Delta\nu$

- The precision of $\Delta\nu$ only depends on the experimental statistics and systematics of the measured frequencies ν_{12} and ν_{34} (QED test).

Precise determination of μ_{μ^-}/μ_p

- The precision of μ_{μ^-}/μ_p depends on the experimental statistics and systematics of the measured frequencies ν_{12} and ν_{34}, and on the uncertainties of the known parameters
  - g_e : free-electron g-value (1.7×10^{-13})
  - α : fine structure constant (1.5×10^{-10})
  - μ_p/μ_B^e : proton magnetic moment to Bohr magneton ratio (3.0×10^{-10})

from CODATA 2018

- Presently, those parameters contribute to the order of **1 ppb** to the final μ_{μ^-}/μ_p value (negligible compared to the foreseen experimental accuracy).

Previous μHe HFS Experiments

Zero Field (SIN)

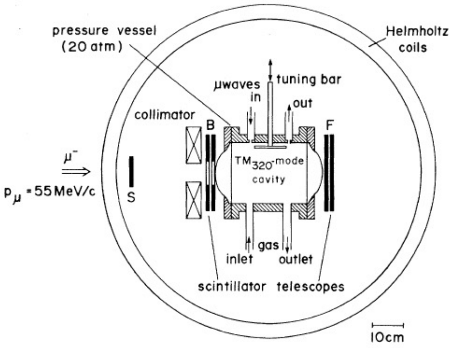


FIG. 2. Schematic view of the apparatus. The Helmholtz coils are used for muon-spin rotation. A cylindrical high-permeability metal shield (diameter 50 cm, length 100 cm) was installed (not shown in the figure) during the microwave magnetic-resonance experiment to reduce the stray magnetic fields.

$\Delta\nu = 4464.95(6)$ MHz

[13 ppm]

pressure: 20 atm

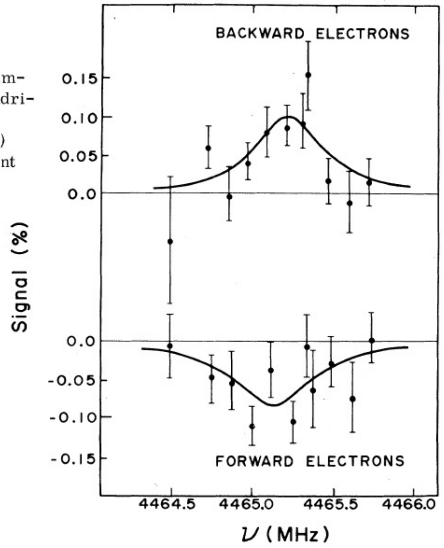


FIG. 3. Resonance curves for the $\Delta F = \pm 1$, $\Delta M_F = \pm 1$ hfs transitions in $({}^4\mathrm{He}^{++}\mu^- e^-)^0$, simultaneously observed in the backward (upper graph) and forward (lower graph) electron telescopes as a function of the microwave resonance frequency.

High Field (LAMPF)

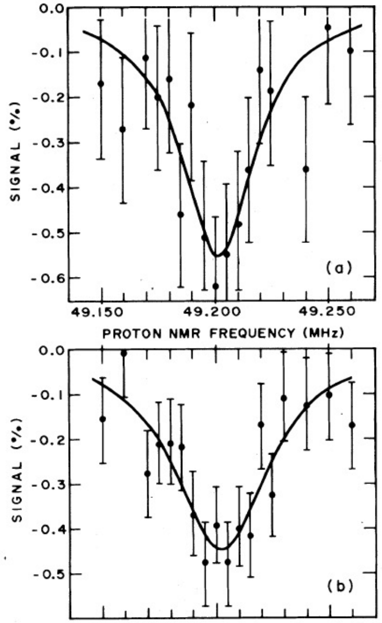


FIG. 1. Typical resonance curves for the ν_{12} transition obtained with the forward telescope at (a) 15 atm and (b) 5 atm. The data for these curves were obtained in (a) 24 h and (b) 100 h. For each curve obtained with the forward telescope there is a corresponding curve for the backward telescope.

pressure: 5 & 15 atm

$\Delta\nu = 4465.004(29)$ MHz

[6.5 ppm]

$\mu_{\mu^-}/\mu_p = 3.18328(15)$

[47 ppm]

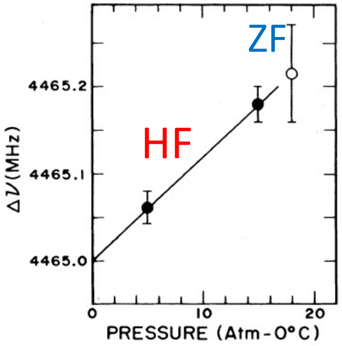


FIG. 2. $\Delta\nu$ as a function of He+Xe(1.5%) gas pressure. Closed circles show the results of this experiment; the open circle is the result of Ref. 3. The straight line shows the linear extrapolation used to extract $\Delta\nu(0)$.

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.

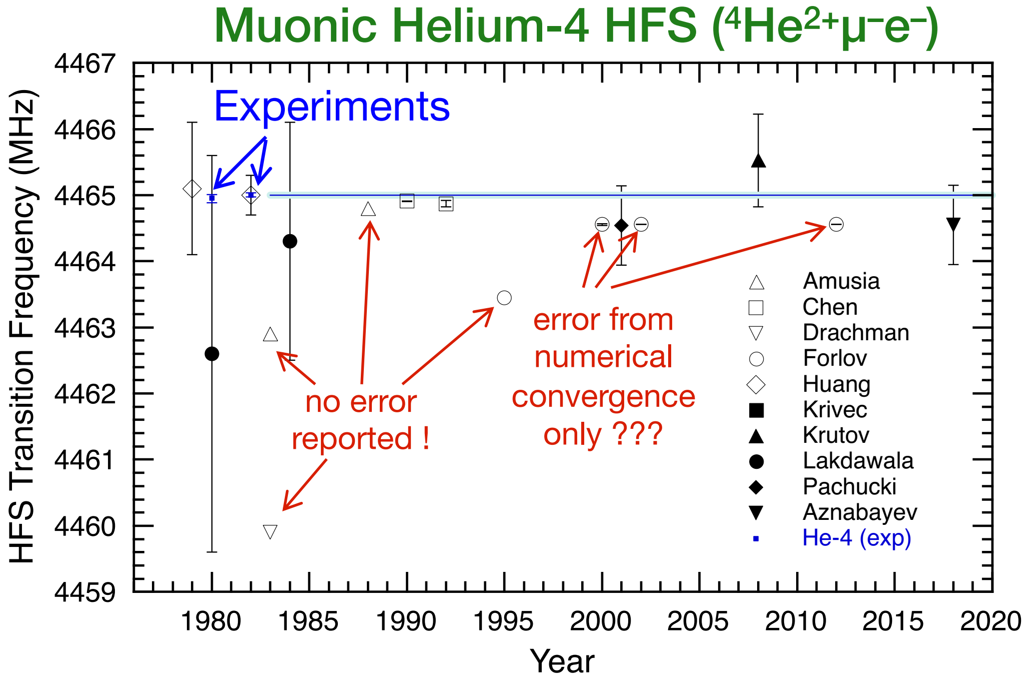
$\Delta\nu$: Experiment vs. Theory

- Ground state HFS of muonic helium very similar to muonium, however …
- Muonic helium is in reality complicated, because three-body interaction has to be considered, thus theoretical approach has been limited.
- Calculations performed since the late 1970s mainly on the basis of the perturbation theory (PT), variational approach (VA) and Born-Oppenheimer (BO) theory.

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

Need ways of theoretical improvement to test QED !

maybe …


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

Experiments

no error reported !

error from numerical convergence only ???

- Pachucki suggested that calculation of QED effects in 3-body systems could be performed more precisely in **higher orders of perturbation theory**.

CPT with 2nd 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] (maybe soon at Fermilab).

[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 !

Why so difficult compared to Mu?

Muonic helium atom residual polarization

- Depolarization during muon cascade → ~6% expected for most I = 0 atoms.
- 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 the Z-law.
- Recently **methane** (**CH_4**) 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.

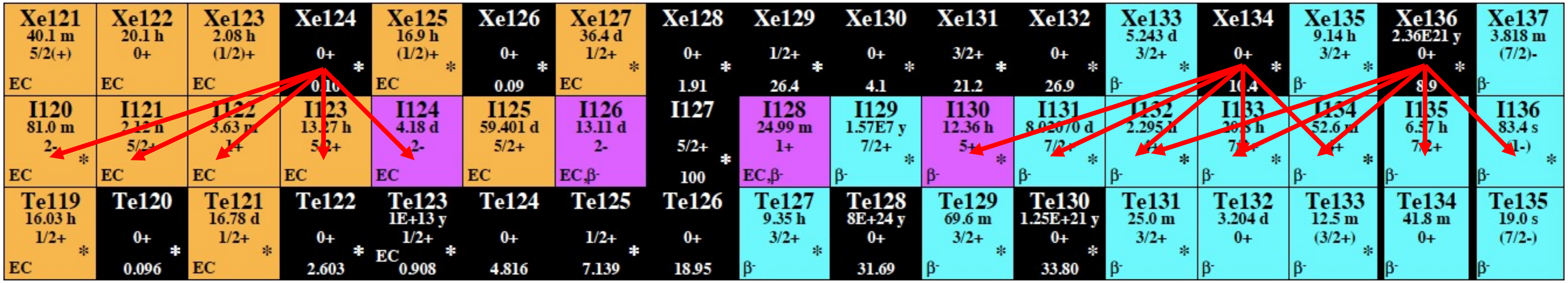
Negative Muon Beam Intensity

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

Theoretical calculation of muonic helium ground state HFS ($\Delta\nu$)

- Very similar to Mu, but in reality complicated because of interaction and QED effects in three-body systems, thus theoretical approach has been limited.
- 1980s experimental values by far still outweigh any theoretical calculations.

Xenon Muon Capture



Xe121 40.1 m 5/2(+) EC	Xe122 20.1 h 0+ EC	Xe123 2.08 h (1/2)+ EC	Xe124 0+ * 0.10	Xe125 16.9 h (1/2)+ * EC	Xe126 0+ * 0.09	Xe127 36.4 d 1/2+ * EC	Xe128 0+ * 1.91	Xe129 1/2+ * 26.4
I120 81.0 m 2- * EC	I121 2.12 h 5/2+ EC	I122 3.63 m 1+ EC	I123 13.27 h 5/2+ EC	I124 4.18 d 2- EC	I125 59.401 d 5/2+ EC	I126 13.11 d 2- EC,β-	I127 5/2+ * 100	I128 24.99 m 1+ EC,β-
Te119 16.03 h 1/2+ * EC	Te120 0+ * 0.096	Te121 16.78 d 1/2+ * EC	Te122 0+ * 2.603	Te123 1E+13 y 1/2+ EC * 0.908	Te124 0+ * 4.816	Te125 1/2+ * 7.139	Te126 0+ 18.95	Te127 9.35 h 3/2+ * β-

Xe130 0+ * 4.1	Xe131 3/2+ * 21.2	Xe132 0+ * 26.9	Xe133 5.243 d 3/2+ * β-	Xe134 0+ * 10.4	Xe135 9.14 h 3/2+ * β-	Xe136 2.36E21 y 0+ * 8.9	Xe137 3.818 m (7/2)- β-
I129 1.57E7 y 7/2+ * β-	I130 12.36 h 5+ * β-	I131 8.02070 d 7/2+ * β-	I132 2.295 h 4+ * β-	I133 20.8 h 7/2+ * β-	I134 52.6 m 4+ * β-	I135 6.57 h 7/2+ β-	I136 83.4 s (1-) * β-
Te128 8E+24 y 0+ 31.69	Te129 69.6 m 3/2+ * β-	Te130 1.25E+21 y 0+ * 33.80	Te131 25.0 m 3/2+ * β-	Te132 3.204 d 0+ β-	Te133 12.5 m (3/2+) * β-	Te134 41.8 m 0+ β-	Te135 19.0 s (7/2-) β-

Xenon: 9 isotopes (natural abundance, $P_{Xe(i)}$)

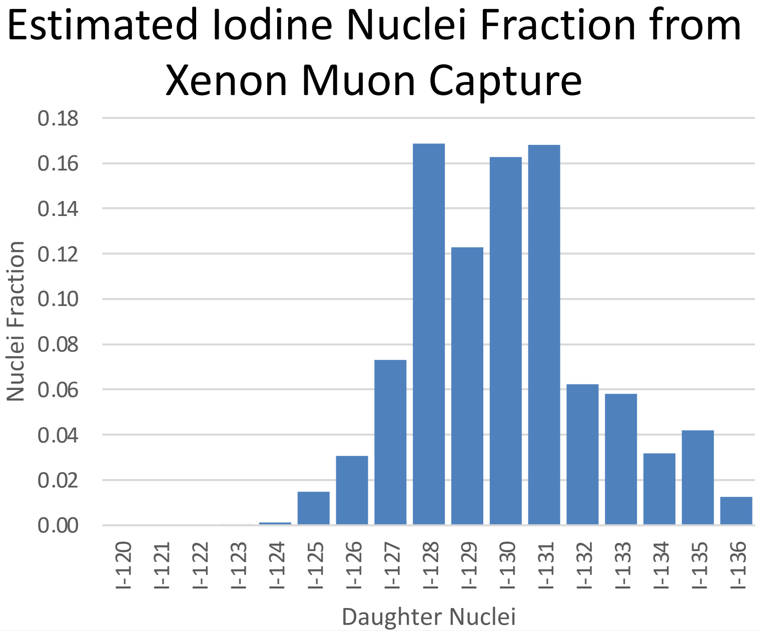
Muon capture probability (Z=54): **~95%** (P_C)

Typical muon capture branching ratio (BR):

Xenon Nuclei	Muon Capture Reaction	Daughter Nuclei	Branching Ratio (BR)
Xe^A	(μ^-,ν)	I^A	**15%**
Xe^A	$(\mu^-,n+\nu)$	I^{A-1}	**50%**
Xe^A	$(\mu^-,2n+\nu)$	I^{A-2}	**20%**
Xe^A	$(\mu^-,3n+\nu)$	I^{A-3}	**10%**
Xe^A	$(\mu^-,4n+\nu)$	I^{A-4}	**5%**

A: atomic number

$$P_{I(i)} = P_C \sum_{j=124}^{136} P_{Xe(j)}\, BR_{Xe(j)\rightarrow I(i)}$$



Estimated Iodine Nuclei Fraction from Xenon Muon Capture

Up to 16 Iodine radioisotopes produced !

Activity up to several kBq depending on Xe concentration and measurement time !!!

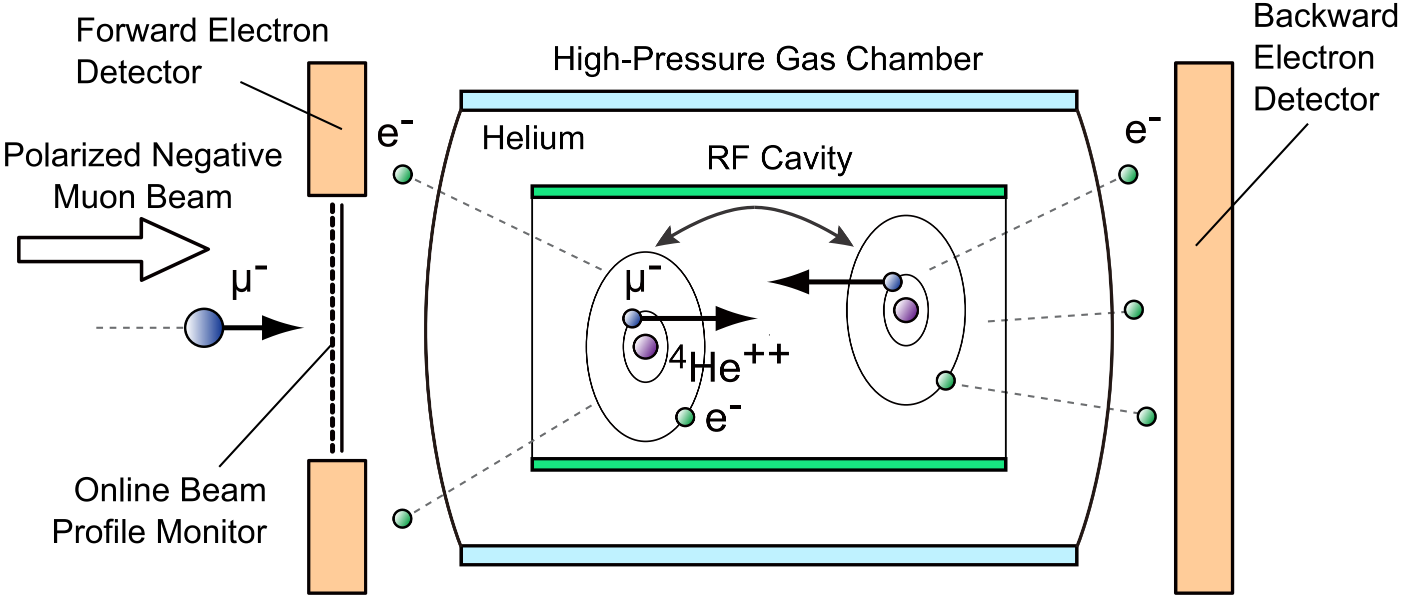
New MuHe HFS at J-PARC MUSE

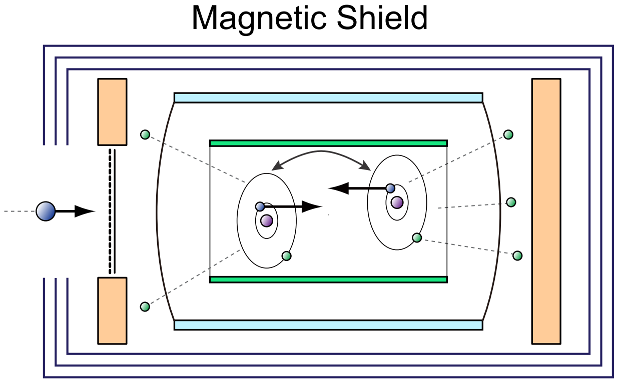
New precise HFS measurements are being planned at the Muon Science Facility (MUSE) of the Japan Proton Accelerator Research Complex (J-PARC).

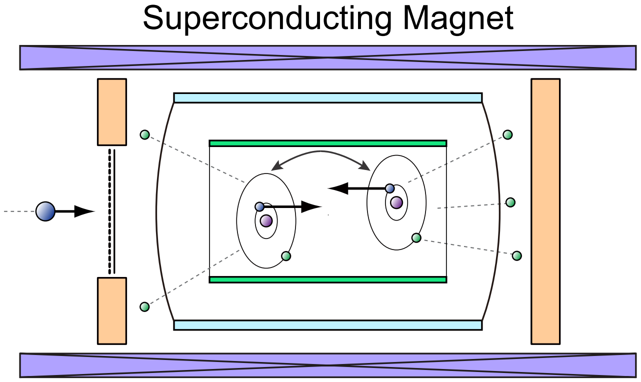
Three key components for improvement:

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 SEOP.

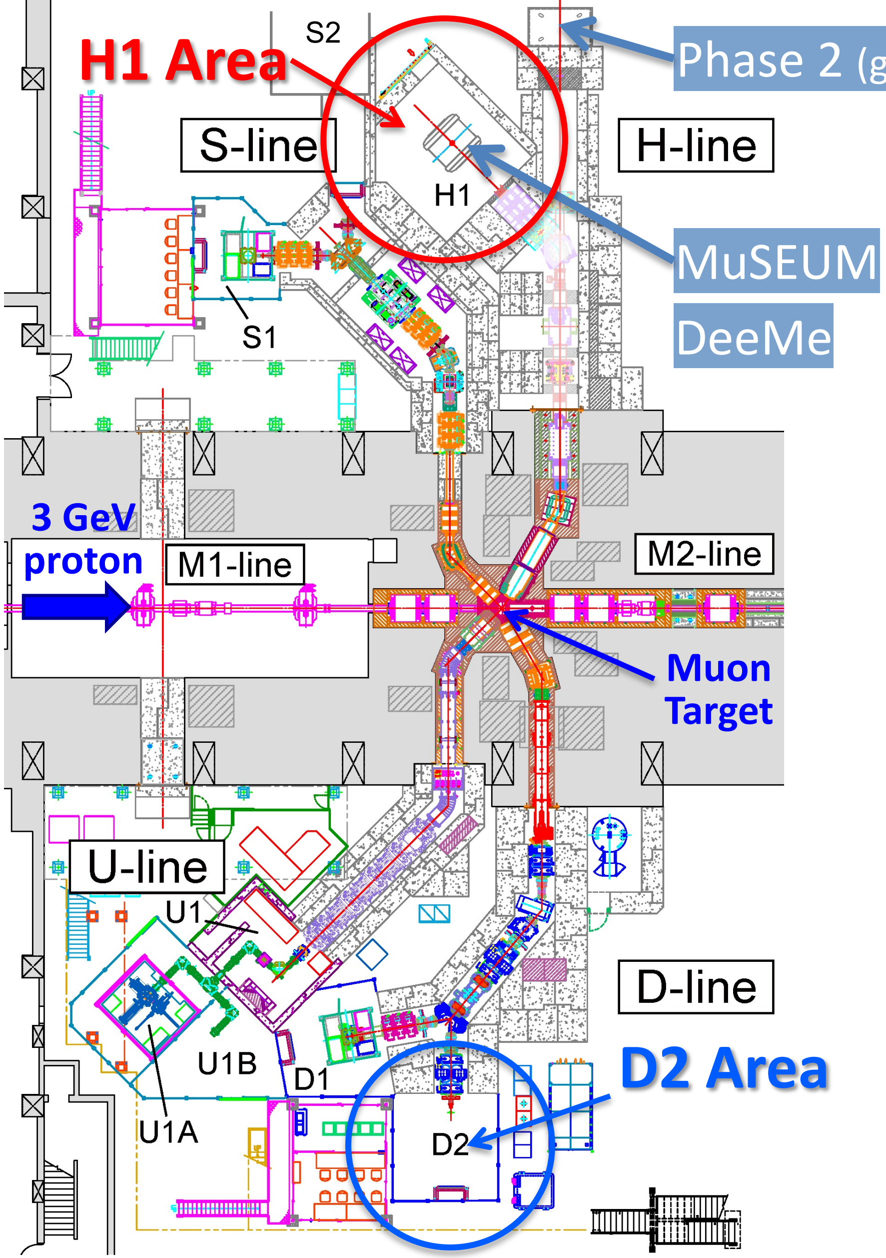
Experimental Arrangement


(a) Experiment apparatus


(b) Zero-field measurement


(c) High-field measurement

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, …)

MLF Experimental Hall No. 1 (2018)

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.

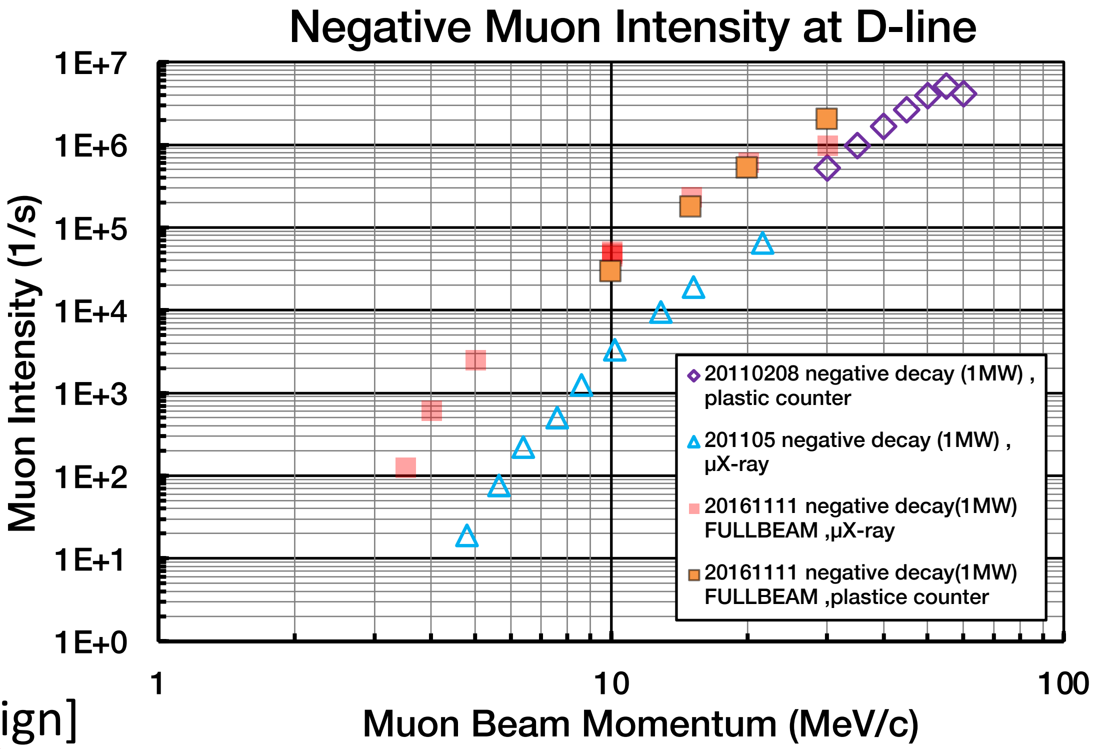
Negative Muon Source at MUSE

D-line:

decay negative muon

Intensity: 2–4 × 10^6 μ^-/s

Polarization: > 90%



H-line:

surface (positive) muon [design]

Intensity: 1 × 10^8 μ^+/s

Polarization: 100%

cloud negative muon

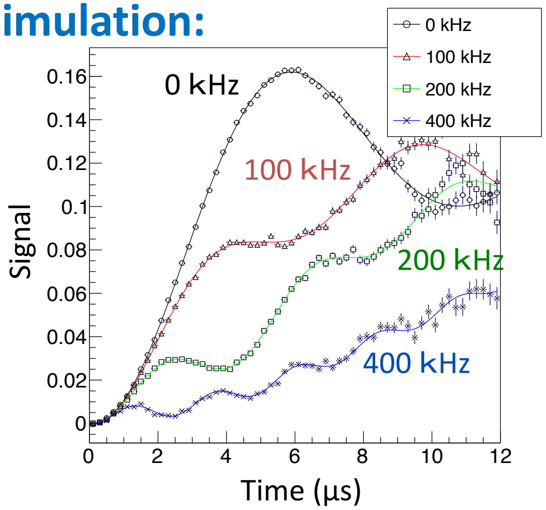
Intensity: ~ 10^7 μ^-/s at 30 MeV/c [estimation]

Polarization: 40~50% [measured at S-line]

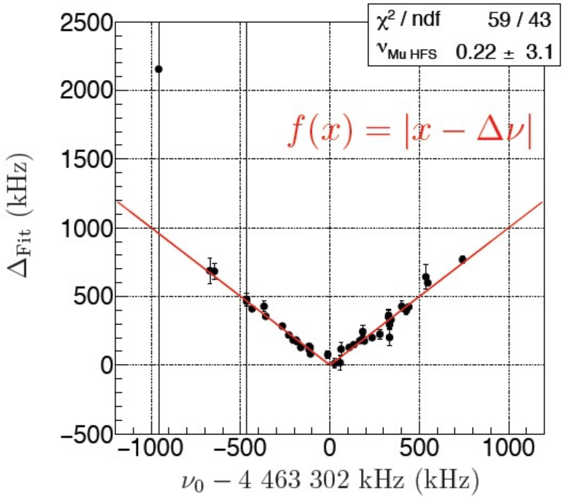
Rabi-Oscillation Spectroscopy Technique

Developed by Nishimura for **MuSEUM experiment** !!!

Simulation:



Nishimura et al., Phys. Rev. A104 (2021) L020801

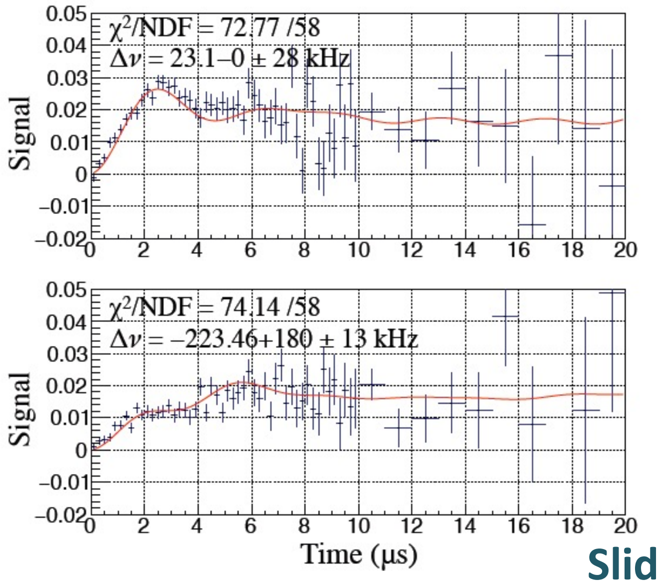


$\Delta\nu_{HFS}$ (0) = 4 463 301.61

±0.71 kHz

(160 ppb)

Experiment (2017 June):



Possible advantages of this method:

- Each detuning frequency data fitted individually.
- Can determine $\Delta\nu_{HFS}$ with only one frequency data.
- Most sensitive detuning frequency is ~60 kHz.
- Can improve statistical uncertainty by **3.2 times** compared to the conventional method.
- Can reduce systematics of RF power variation (free fitting parameter).
- Need high-statistics data.

Slide from MuSEUM experiment

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)
  $\rightarrow$ ~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)	30 ppb	350 ppb
Highly-Polarized μ^-He (×7)	4 ppb	50 ppb

Very Very Preliminary !!!

Systematic uncertainties:

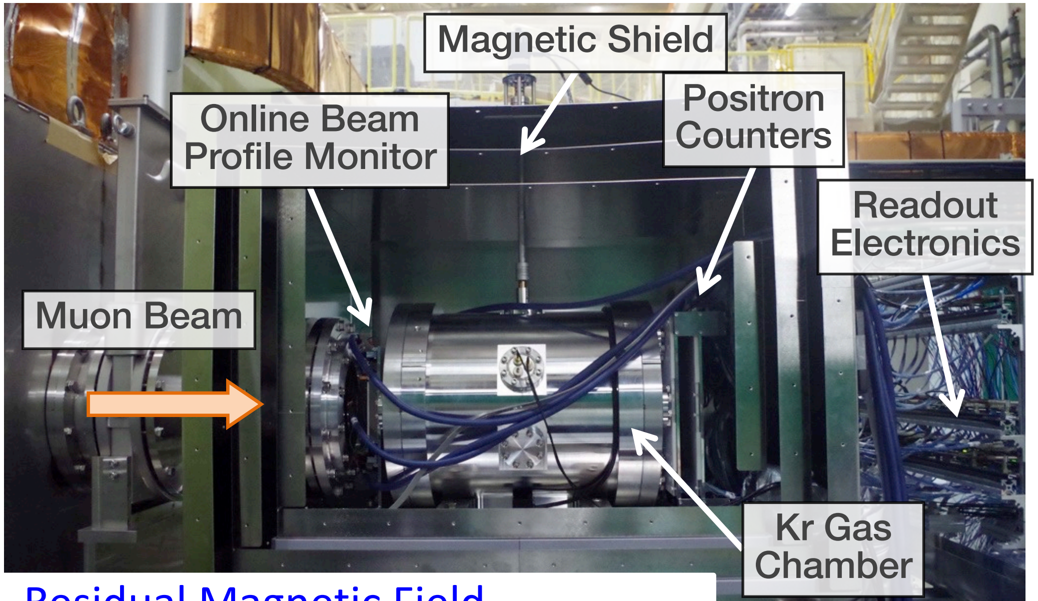
- MuSEUM experiment has similar systematical errors.
- Present estimation: ~2 ppb for $\Delta\nu$ and ~20 ppb for μ_{μ^-}/μ_p.

D-line: (zero field)

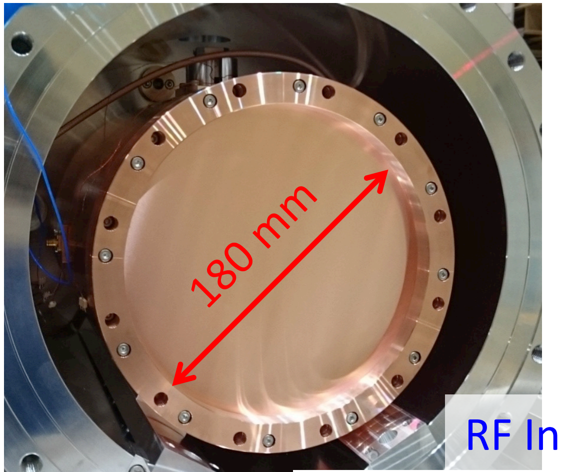
$\rightarrow$ 10^2–10^3 times more statistics (depending on beamtime allocation)

Mu Zero Field Measurements (D-Line)

Experimental Setup

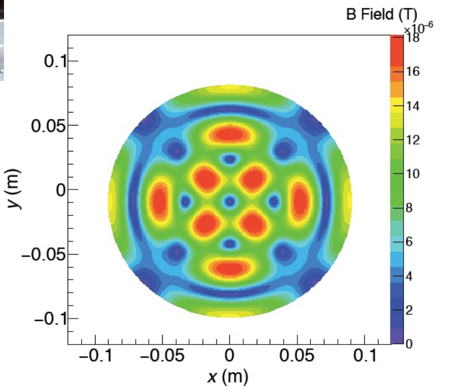


New RF Cavity for Zero Field



$\Delta\nu$ = 4.463 GHz

RF Intensity



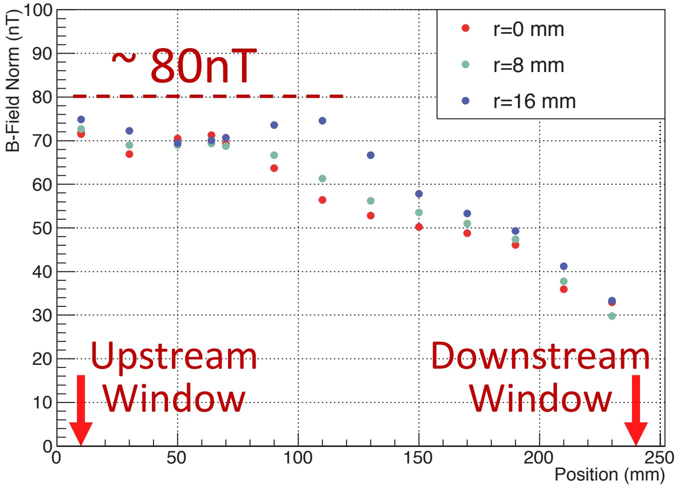
TM220 mode

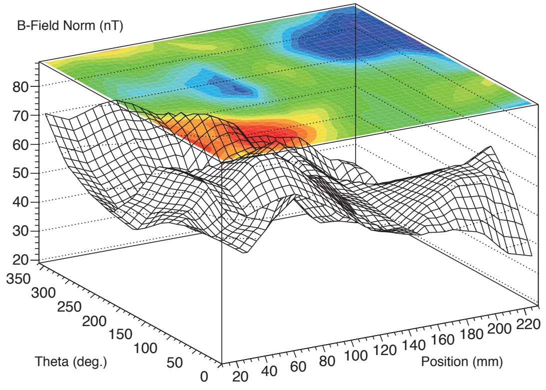
Larger cavity

More muon stop

Q-Value: 20,000 (calc.)

Residual Magnetic Field



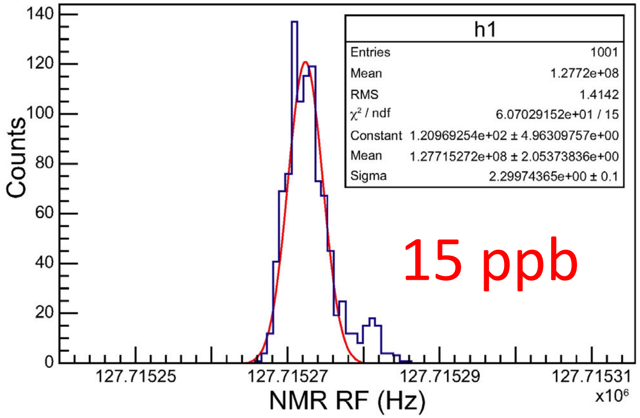


Slide from MuSEUM experiment

MRI Magnet for High-Field Experiment

Second-hand 2.9 T MRI magnet

CW-NMR Field Monitoring System

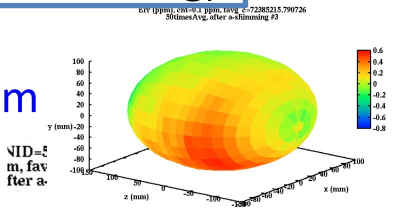


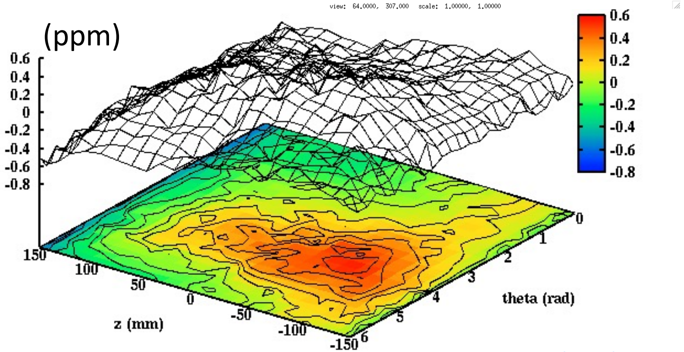
15 ppb

Field Homogeneity (after shimming)

Spheroid :
r=100 mm, z=300 mm

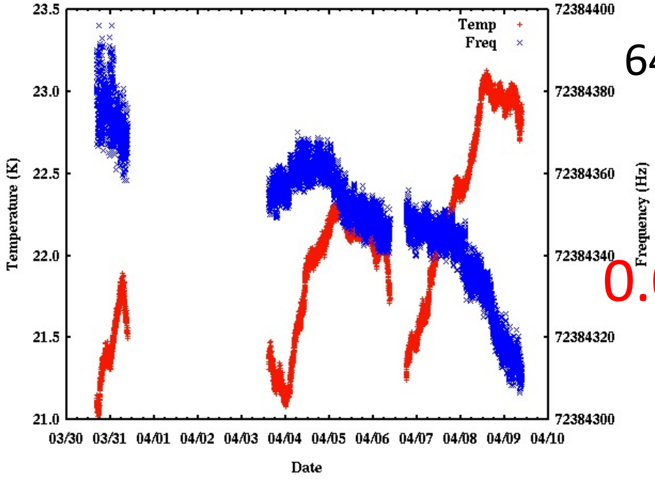
0.2 ppm (p-p)





these data: 1.4 ppm (p-p)

Long Term Stability



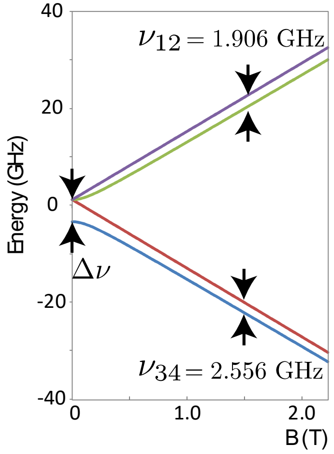
64 Hz / 9.7 days

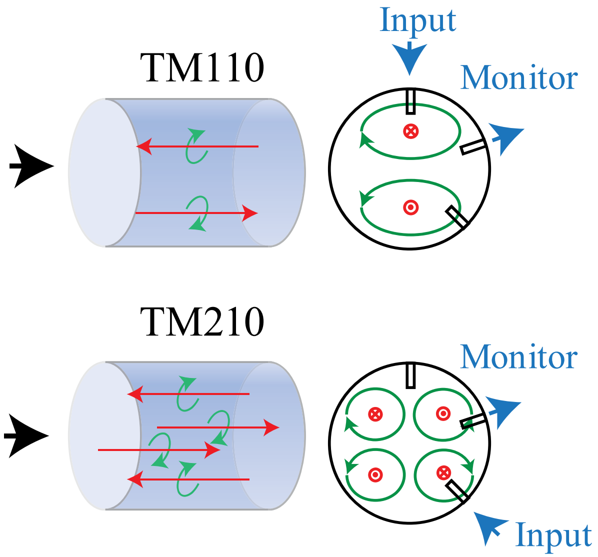
0.003 ppm /h

Slide from MuSEUM experiment

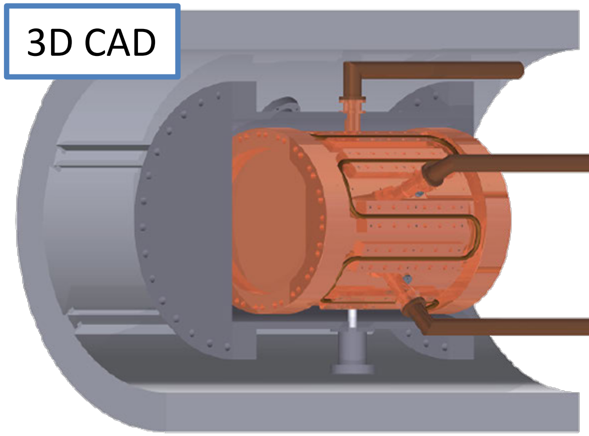
Microwave Cavity (High-Field)

Muonium HFS

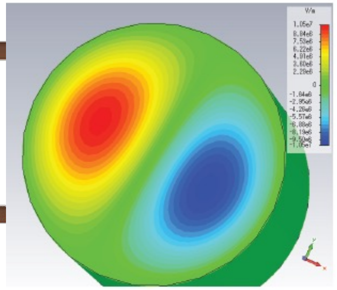




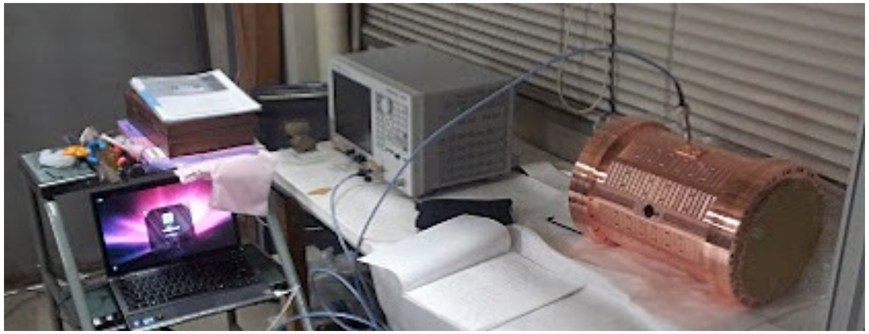
3D CAD



MWS Simulation



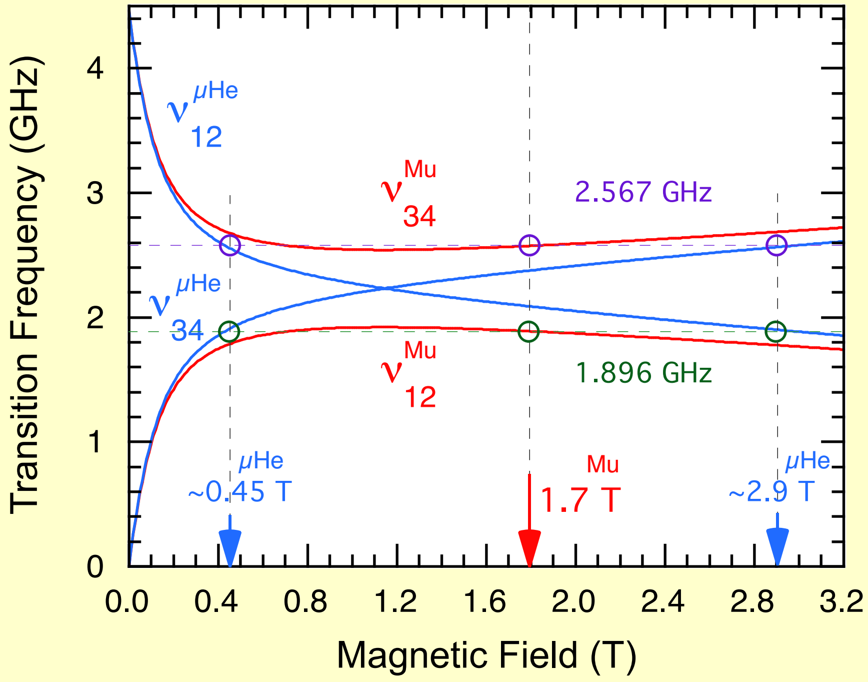
Cavity Test



Q Value

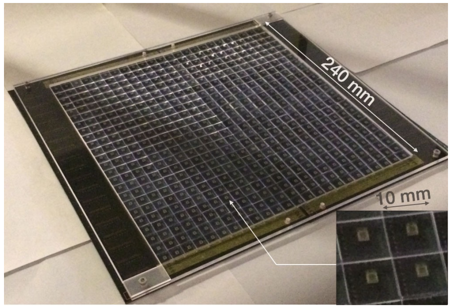
Modes	Q (measured)	Q (simulation)
TM110	1.13×10^4	2.97×10^4
TM210	8.05×10^3	2.89×10^4

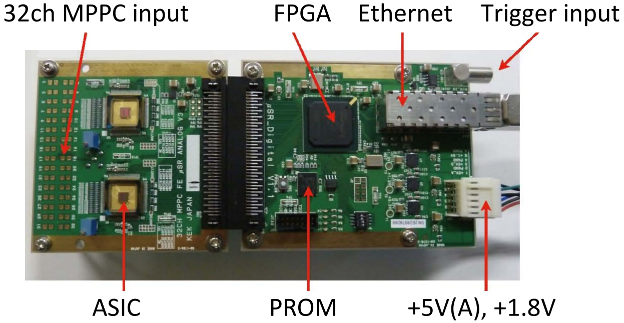
Comparison Muonium & μHe



Counter Development

Positron Counter (1): Segmented Scintillation Detector



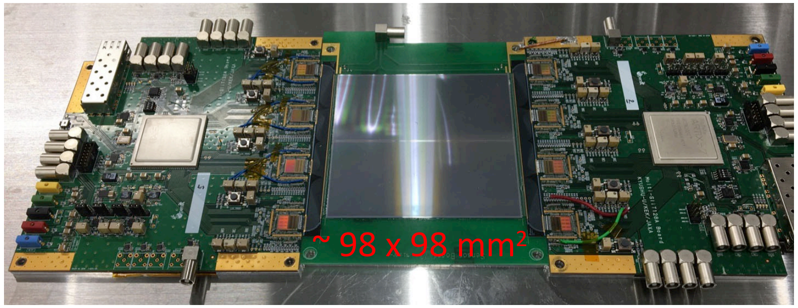


Plastic scintillator + MPPC(SiPM) + Kaliope readout circuit

- 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%

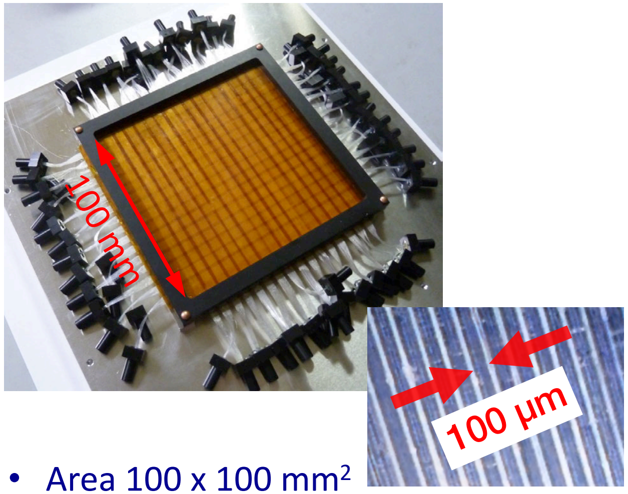
Positron Counter (2): Silicon Strip Detector



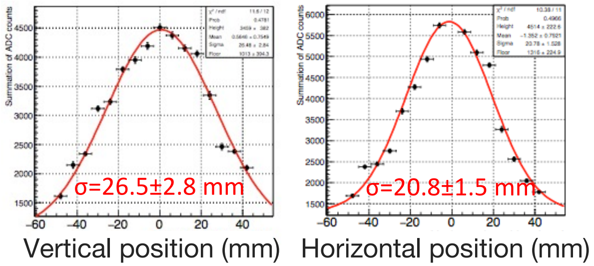
- Readout chips (SliT128A, 128 ch/chip)
- Developed for J-PARC g−2/EDM experiment
- Highly-segmented
- High-rate capability (S/N ~ 21)

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



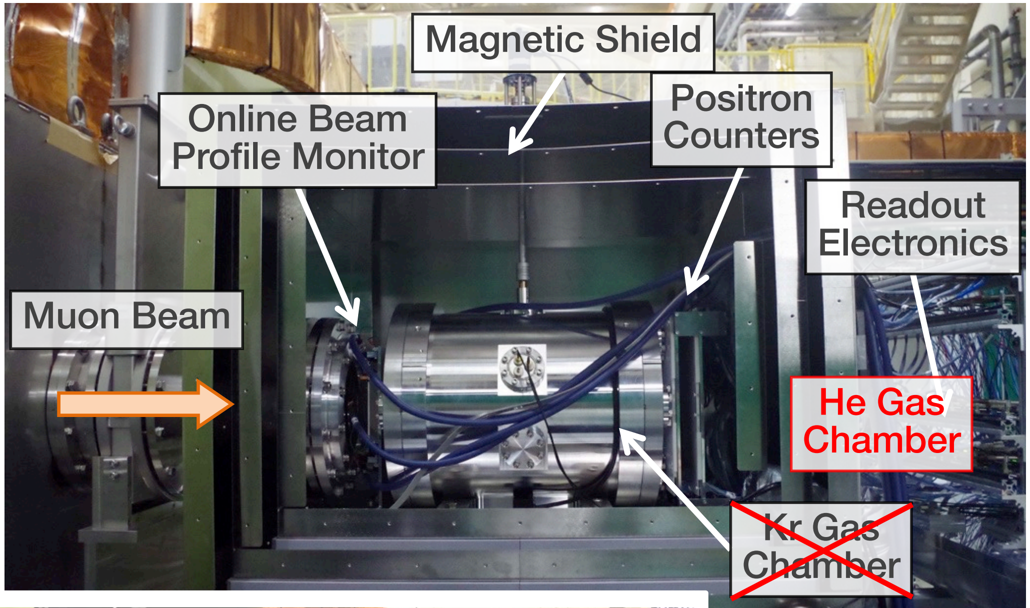
Recent Developments

First µHe HFS Measurements at D-Line

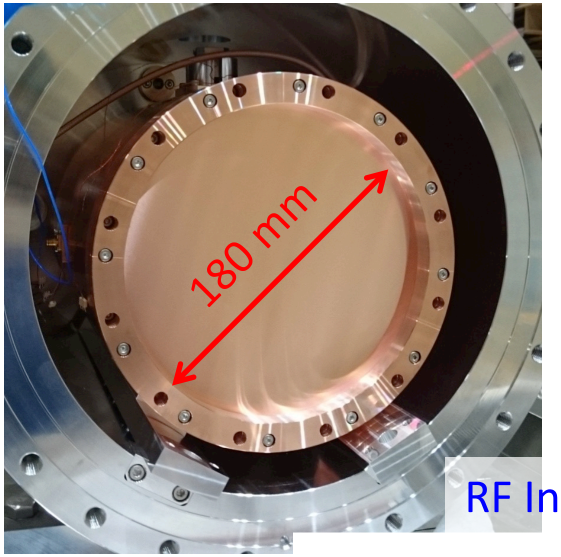
[2019B0318]

at Zero Field

MuSEUM Experimental Setup

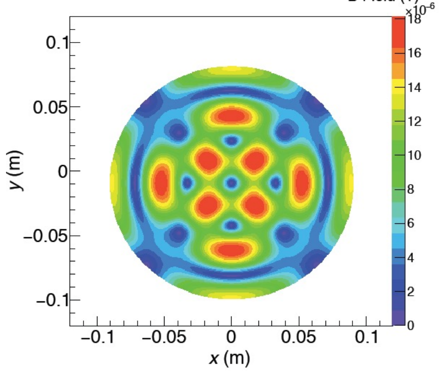


RF Cavity

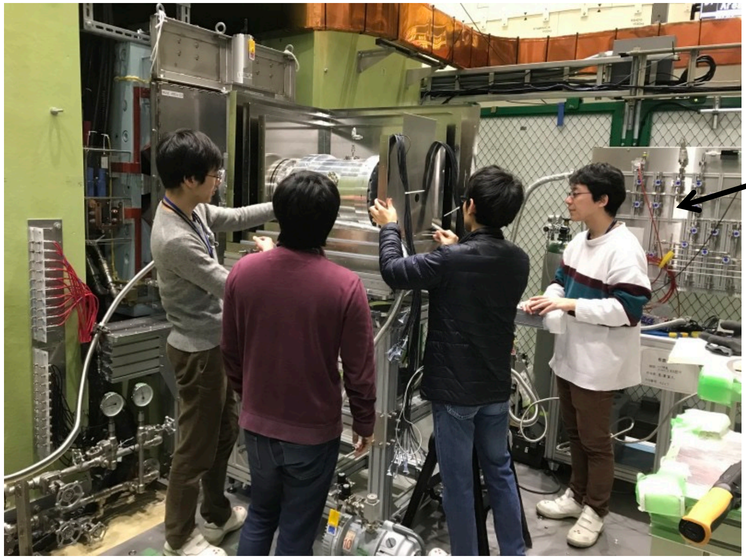


$\Delta\nu = 4.465$ GHz

RF Intensity

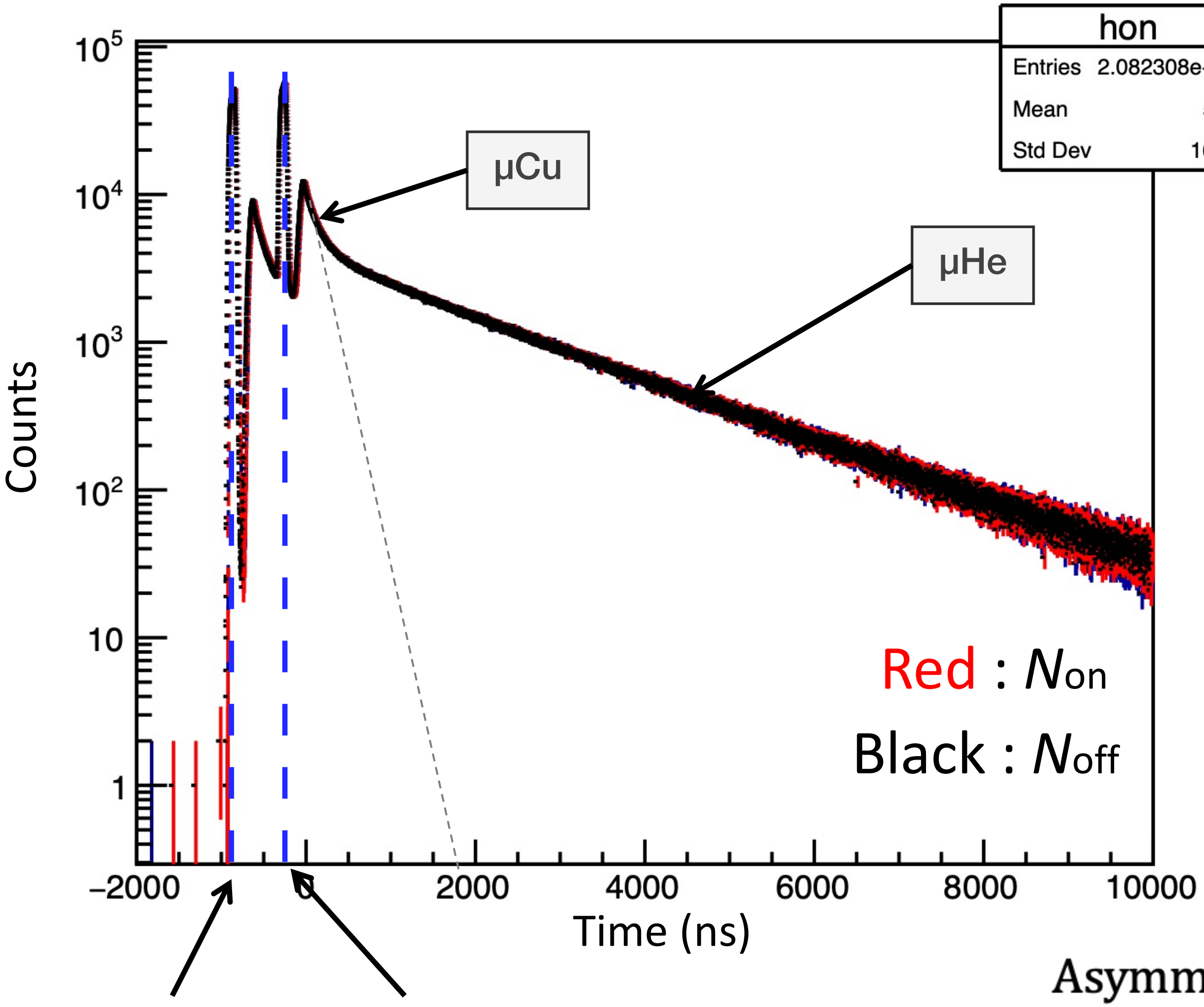


TM220 mode
Larger cavity
More muon stop
Q-Value: 20,000 (calc.)



Preparation of MuSEUM apparatus in D2 area
(students from Nagoya University and the University of Tokyo).

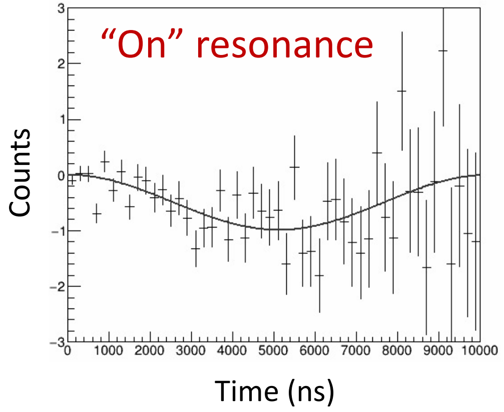
Decay Electron Time Spectra



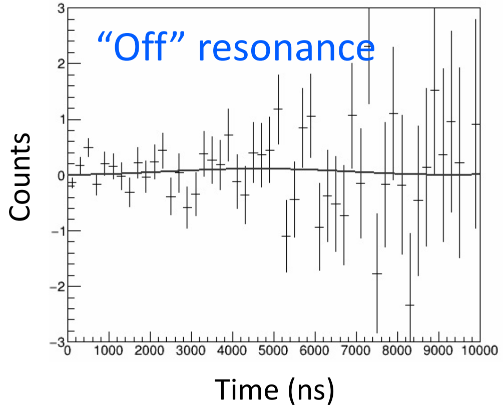
1st muon peak
(-600 ns)

2nd muon peak
(0 ns)

Frequency = 4465000 + 0 kHz



Frequency = 4465000 + 600 kHz



$$\text{Asymmetry} = \frac{N_{\text{off}}}{N_{\text{on}}} - 1$$

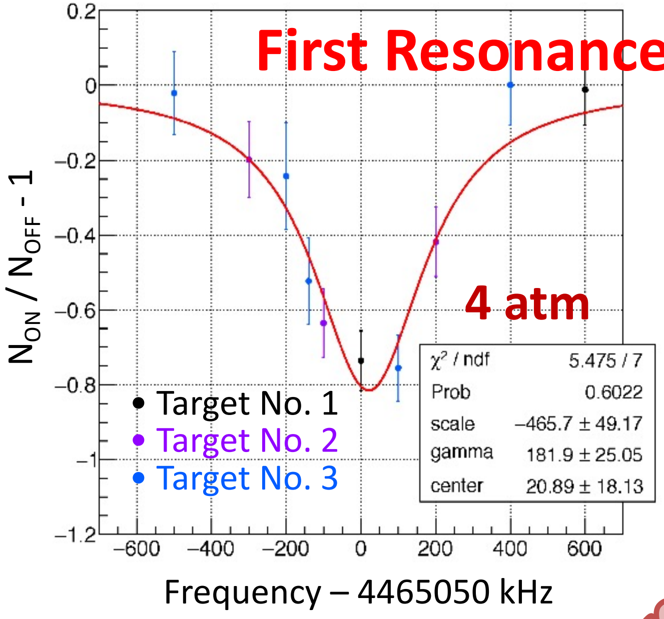
N_{on}: Number of detected e^- with microwave

N_{off}: Number of detected e^- without microwave

MuHe HFS Resonance Curve

March 11–17, 2021 Beamtime

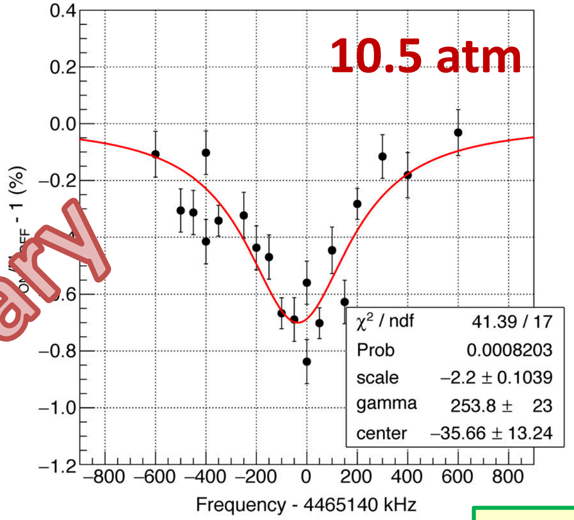
First Resonance Observed



[2020B0333]

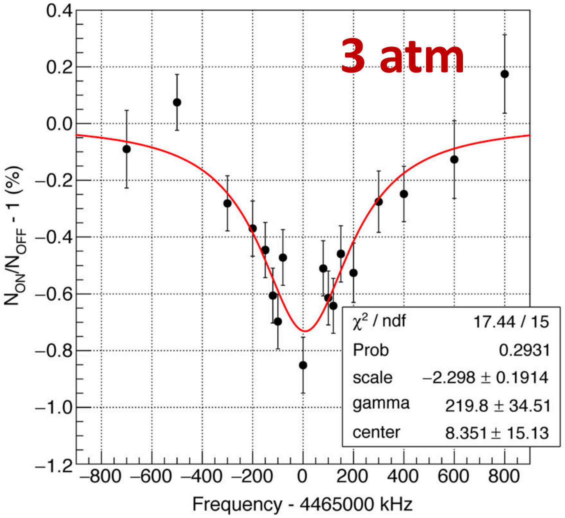
Very Preliminary

February 2022 Beamtime



[2021B0169]

May 2022 Beamtime

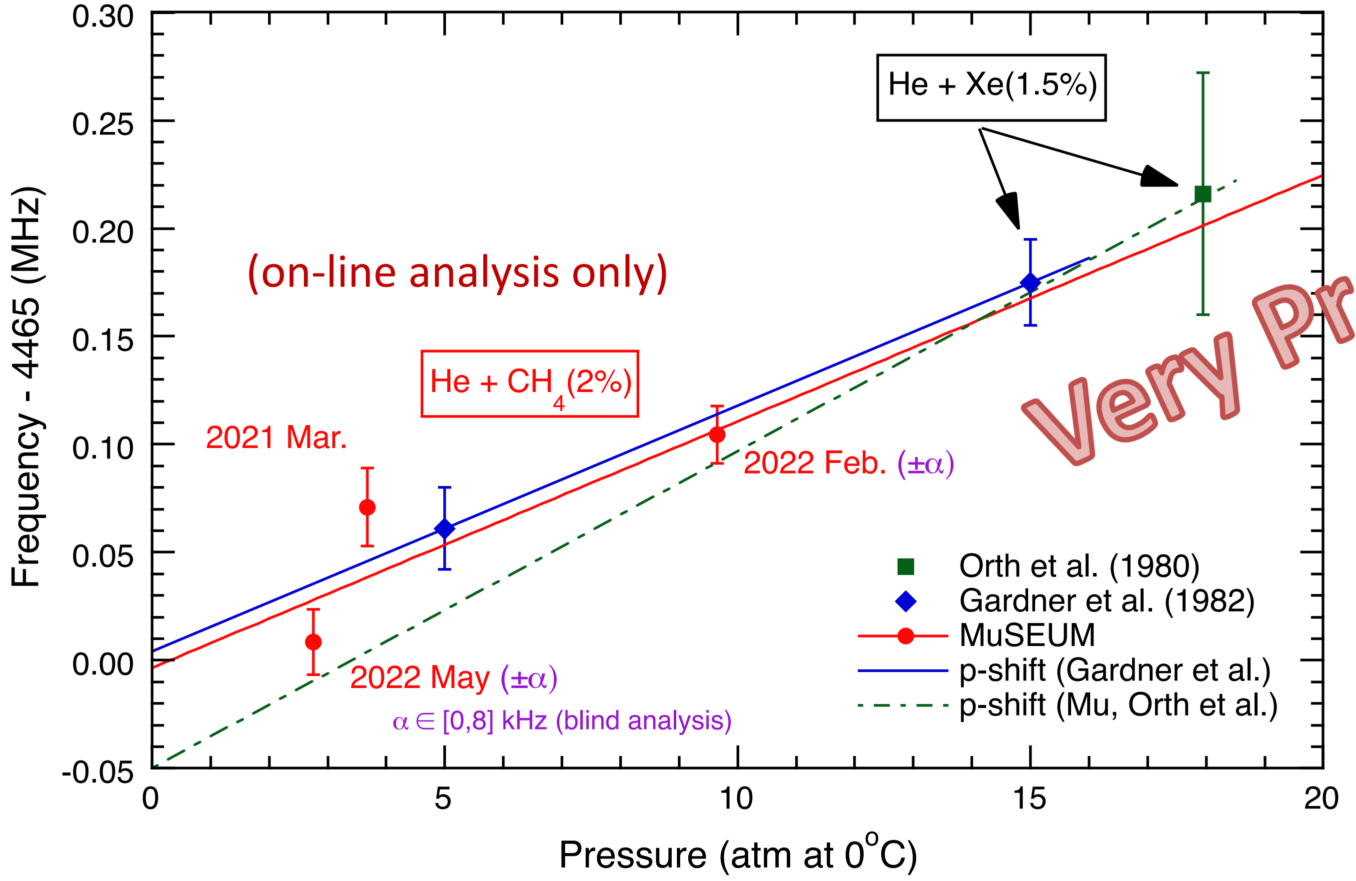


(on-line analysis only)

[2022A0159]

Time cut: electron data from 2 μs after second μ^- pulse !

Extrapolation to Zero Pressure



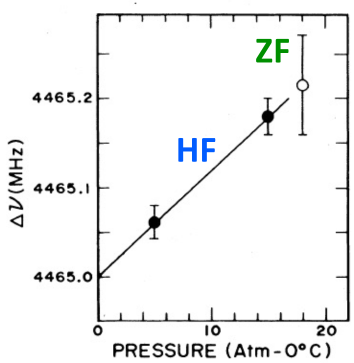


FIG. 2. Δν as a function of He+Xe(1.5%) gas pressure. Closed circles show the results of this experiment; the open circle is the result of Ref. 3. The straight line shows the linear extrapolation used to extract Δν(0).

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

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

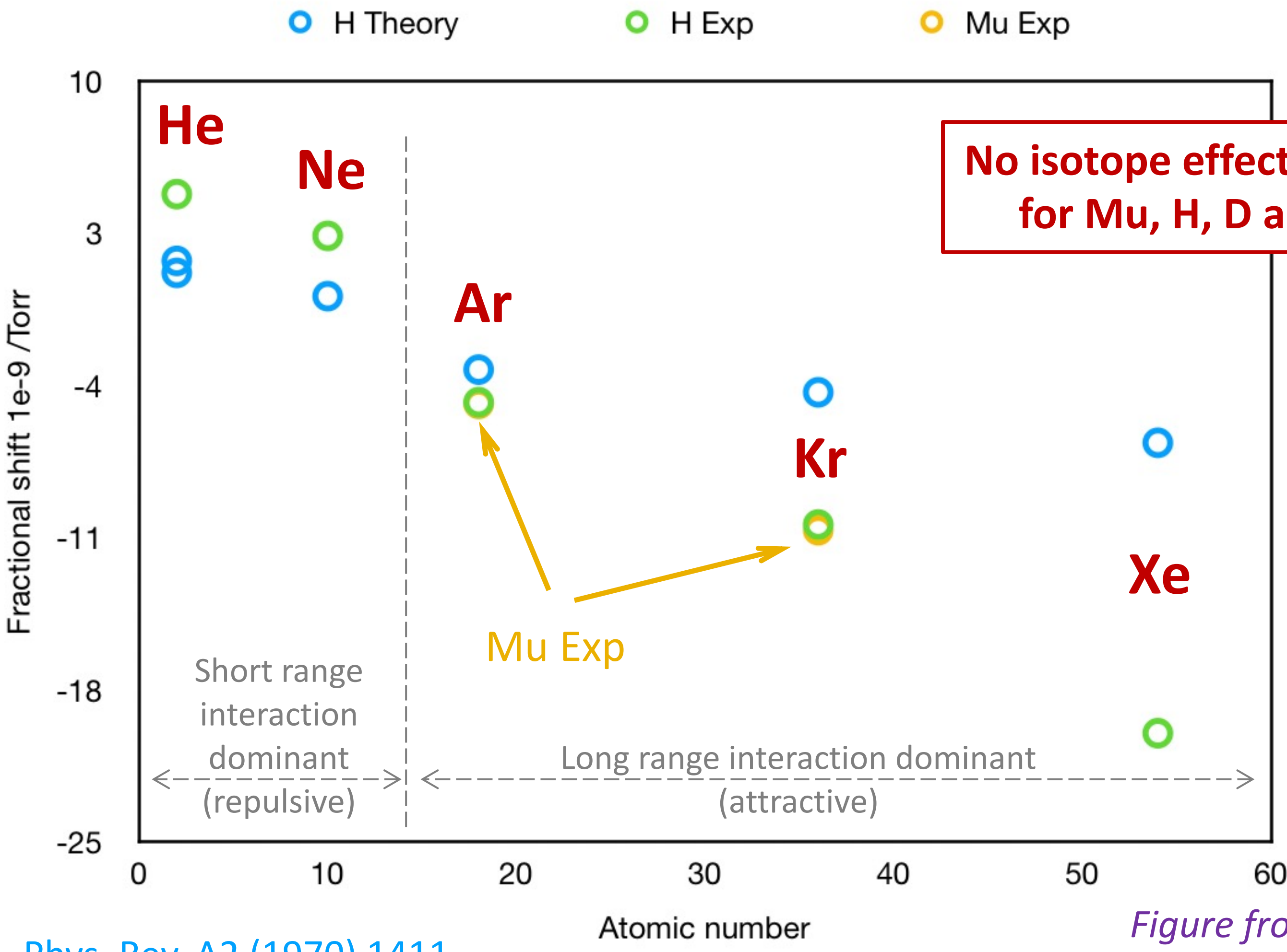
Δν = 4464.997(18) MHz (MuSEUM) [4ppm] zero field

Tentative Result !!
"Blind" Analysis
in progress

- **Probably a New World Record**

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

Pressure Shift Comparison: Mu vs. H



No isotope effect observed for Mu, H, D and T !!!

Figure from Kanda

- B.K. Rao *et al.*, Phys. Rev. A2 (1970) 1411
- D.E. Casperson *et al.*, Phys. Lett. 59B (1975) 397
- F.M. Pipkin *et al.*, Phys. Rev. 127 (1962) 787
- E.S. Ensberg *et al.*, Phys. Lett. 28A (1968) 106

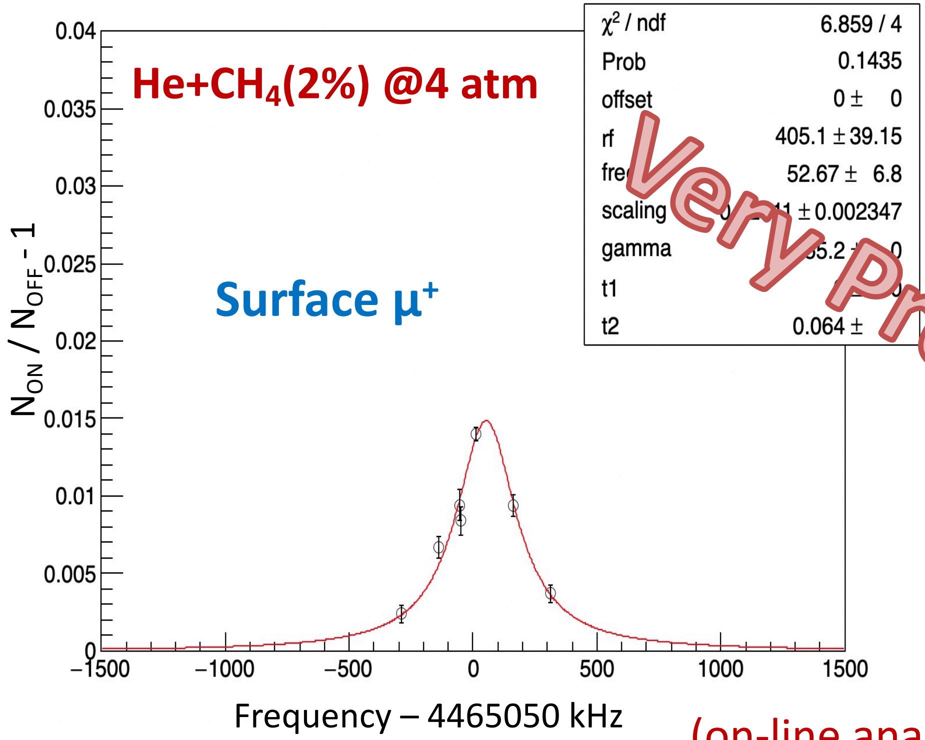
Hydrogenic pressure shift:
no isotope effect observed for H, D, T

Muonium HFS Resonance Curve

MuSEUM Beamtime

(May 2021)

$\Delta\nu_{Mu}(4\text{ atm, RT}) - \Delta\nu_{Mu}(0) = 52.7 \pm 6.8$ kHz

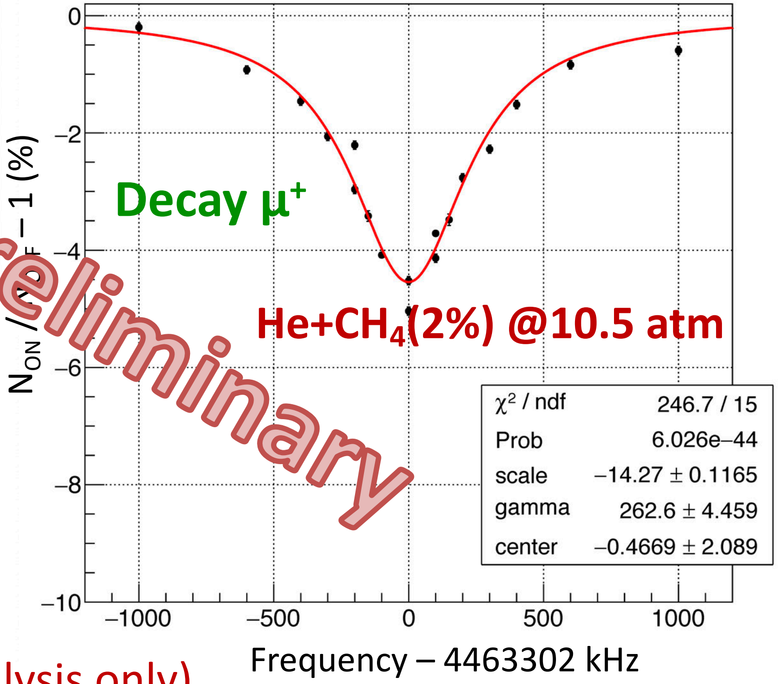


MuHe Beamtime

(February - March 2022)

Blind analysis: α

$\Delta\nu_{Mu}(10.5\text{ atm, RT}) - \Delta\nu_{Mu}(0)$
$= 139.5 \pm 2.1$ kHz $+ \alpha$



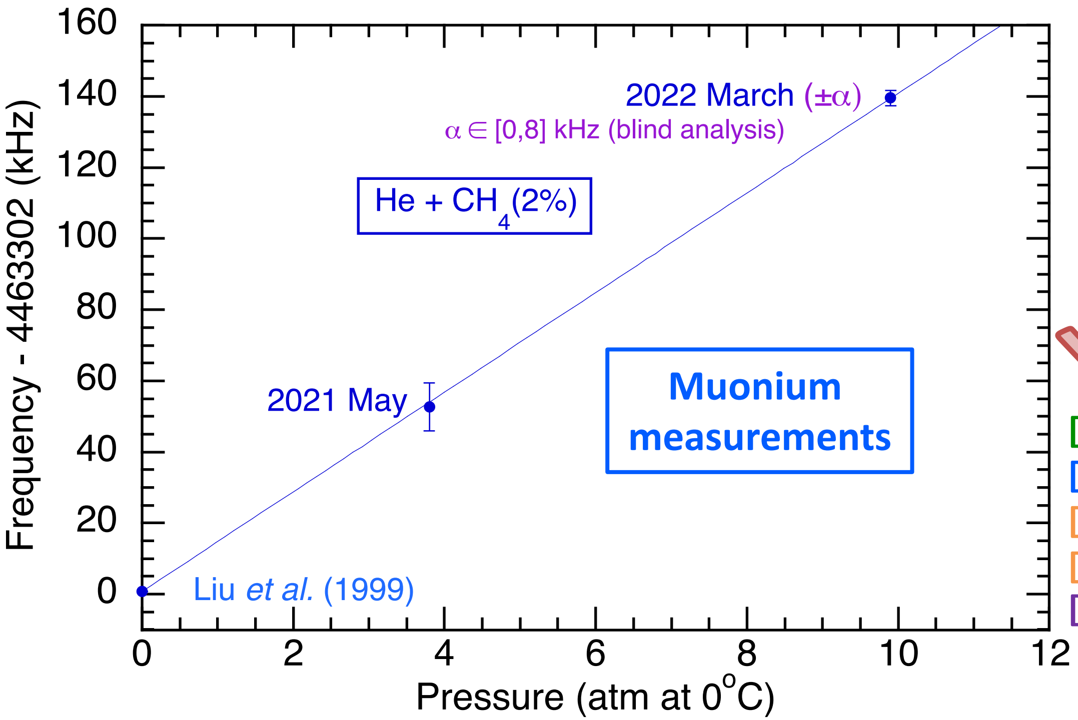
Very Preliminary

(on-line analysis only)

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

- **Determination of Mu pressure shift in He+CH$_4$(2%)**
- **Comparision with μHe pressure shift**

Pressure Shift Comparison (Update)



Very Preliminary

[1] H. Orth et al., PRL 45 (1980) 1483
[2] C. J. Gardner et al., PRL48 (1982) 1168
[3] F. M. Pipkin et al., Phys. Rev. 127 (1962) 787
[4] E. S. Ensberg et al., Phys. Lett. 28A (1968) 106
[5] D. E. Casperson et al., Phys. Lett. 59B (1975) 397

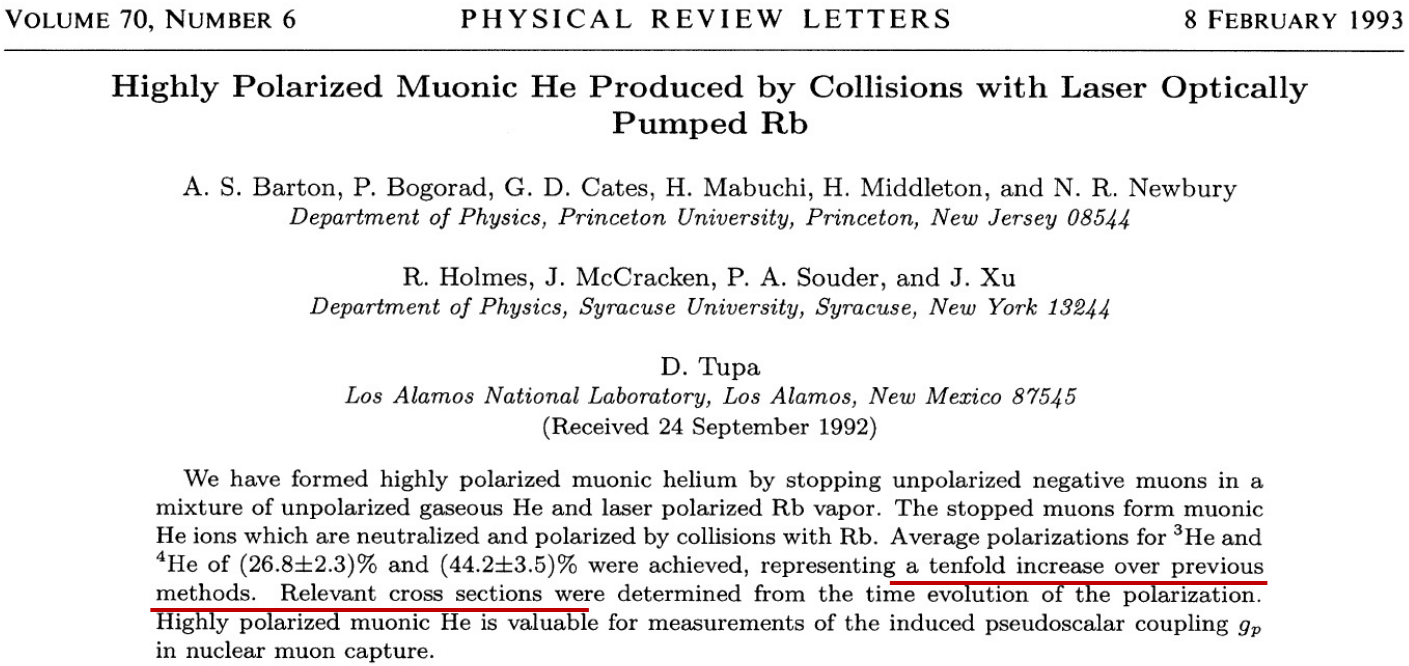
(blind analysis)

	He + Xe(1.5%)	He + CH_4(2%)	Pure He
Mu	14.7 ± 0.9 kHz/atm [1]	**14.0 ± 0.2 kHz/atm (b.a.)**	n/a
^{4}He	11.4 ± 2.7 kHz/atm [2]	**11.4 ± 2.7 kHz/atm (b.a.)**	n/a
H	15.0 ± 0.3 kHz/atm [3,4]	–	16.3 ± 0.3 kHz/atm [3]

Pressure shift in noble gases: on isotopic effect observed for H, D, T [3,4] & Mu [5]

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^4He: 6% → 44%

Improvement by a factor 7 achieved !

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

Polarization of Muonic He Atom

By spin exchange optical pumping (SEOP) with Rb vapors:

$(\mu^{-}He)^{+}$ ion will form molecular ion in few ns in high-pressure He gas (~10 atm).

(1) Polarization through dissociation of molecular ion $He(\mu^{-}He)^{+}$ via:

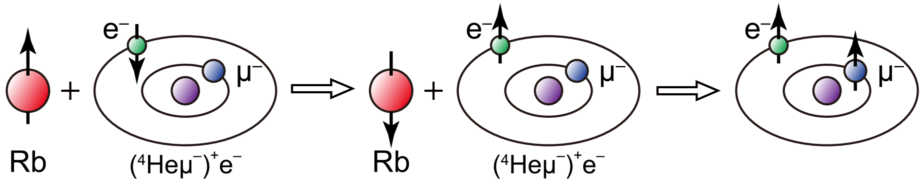
$$\boxed{Rb\uparrow + He(\mu^{-}He)^{+} \rightarrow Rb^{+} + He + (\mu^{-}He)^{+}\, e^{-}\uparrow}$$

After the charge exchange, the "*pseudo-nucleus*" $(He\mu^{-})^{+}$ and the polarized e^{-} are coupled through the HFS interaction, thus polarizing the muon.

(2) After neutral muonic helium atom is formed, further polarization via:

$$\boxed{Rb\uparrow + (\mu^{-}He)^{+} e^{-}\downarrow \rightarrow Rb\downarrow + (\mu^{-}He)^{+}\, e^{-}\uparrow}$$

After short-lived collisions the polarization of the transferred e^{-} is shared with the "*pseudo-nucleus*" $(He\mu^{-})^{+}$.



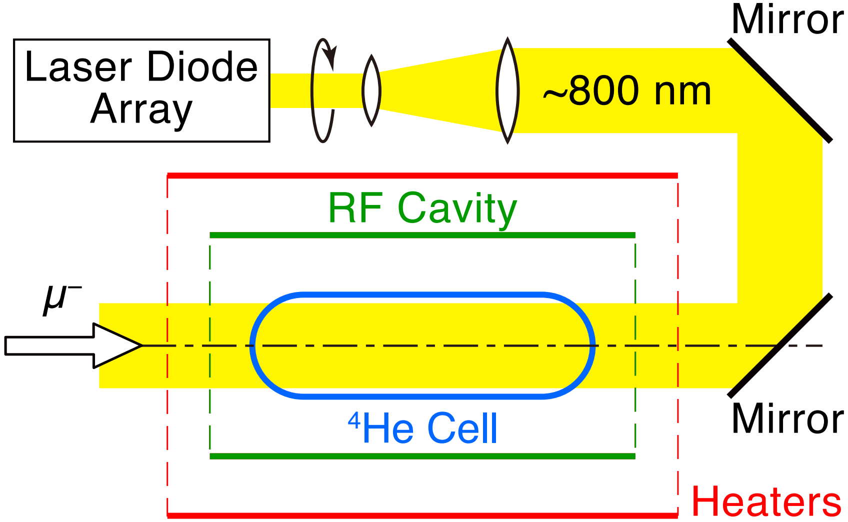
A. S. Barton et al., Phys. Rev. Lett. **70**, 758 (1993)

SEOP for μHe HFS Measurements

New MuSEUM-SEOP collaboration just started !

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

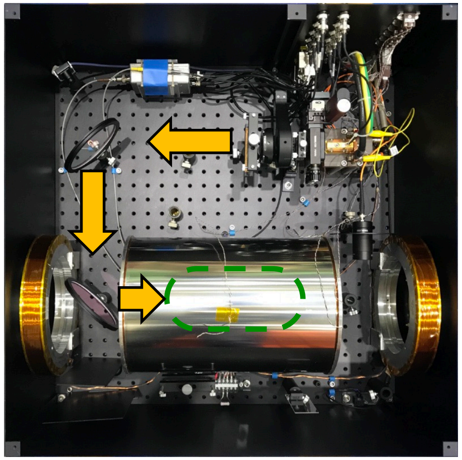
Schematic layout



Prototype Gas Cell
Ø74 mm x 152 mm
(picture from T. Ino)

Experimental Challenges:

- RF field inside glass cell
- SEOP in high magnetic field
- Magnetic field uniformity
- Gas pressure and temperature stability
- New systematics …



Example:
^{3}He gas spin filter of POLANO (MLF BL23) by T. Ino et al. (KEK)

μHe SEOP Objectives

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

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

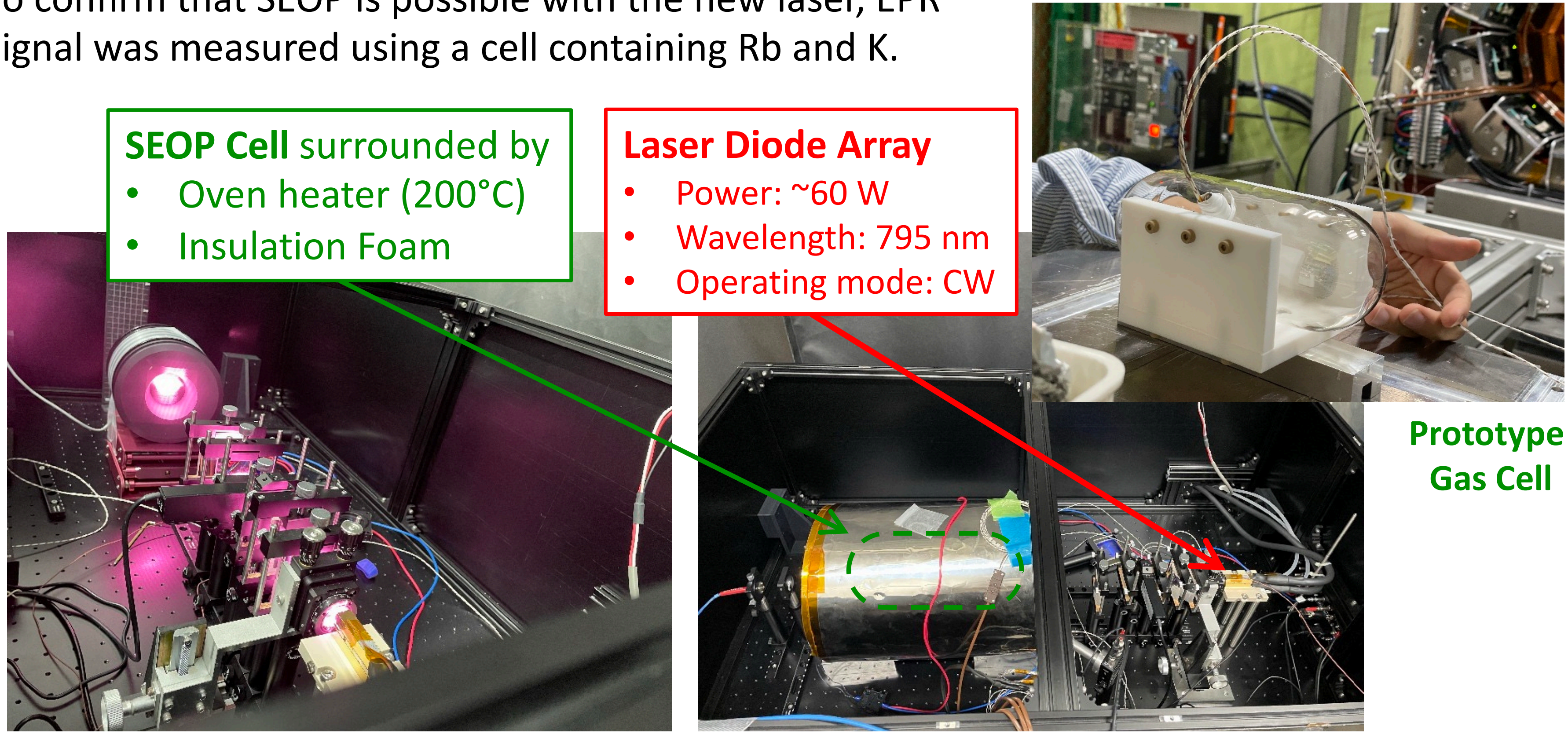
3) Demonstrate **SEOP technique** can be applied to **muonic helium HFS** measurements
   - Simulation (in progress)
   - Test experiment

New Laser System for µHe SEOP

S. Fukumura
T. Okudaira

A laser system for muonic helium SEOP has been constructed:

To confirm that SEOP is possible with the new laser, EPR signal was measured using a cell containing Rb and K.



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

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

Prototype Gas Cell

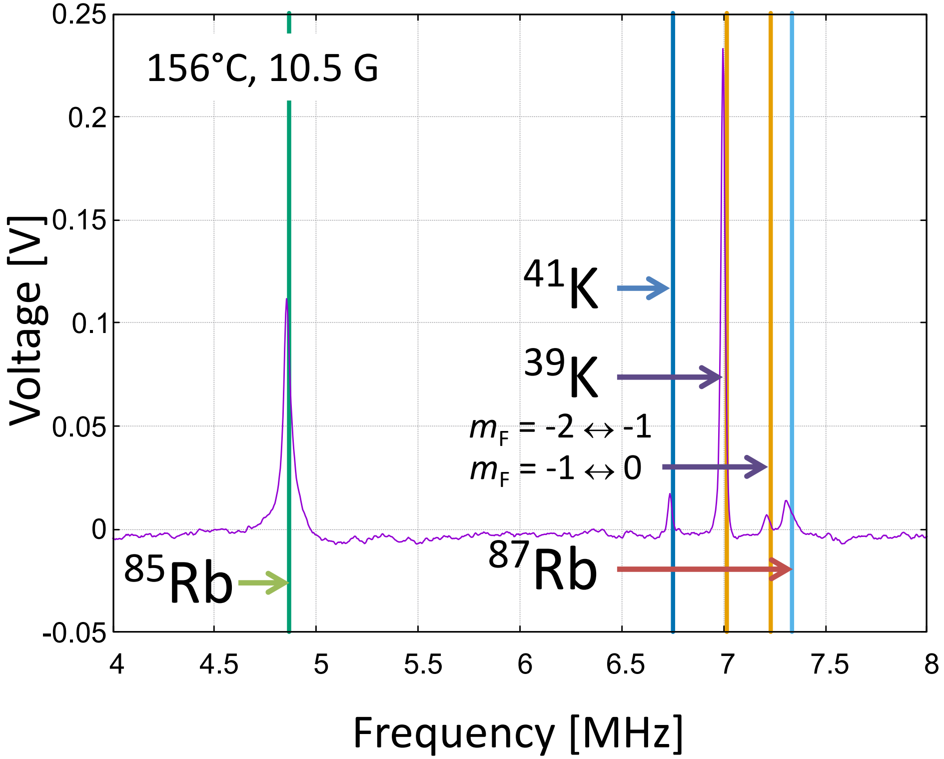
EPR: Electron Paramagnetic Resonance

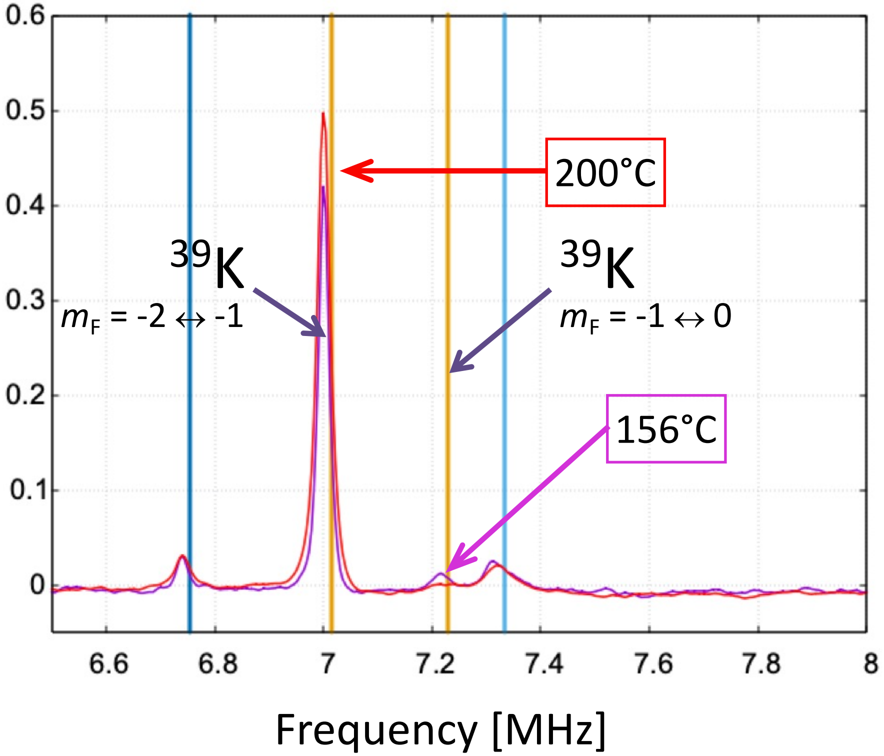
- Excite Rb and K with RF and measure the de-excitation light intensity.
- The population of each sub-level can be estimated from the de-excitation light intensity and the applied RF frequency.

EPR Measurements

S. Fukumura
T. Okudaira

EPR signal was clearly observed !

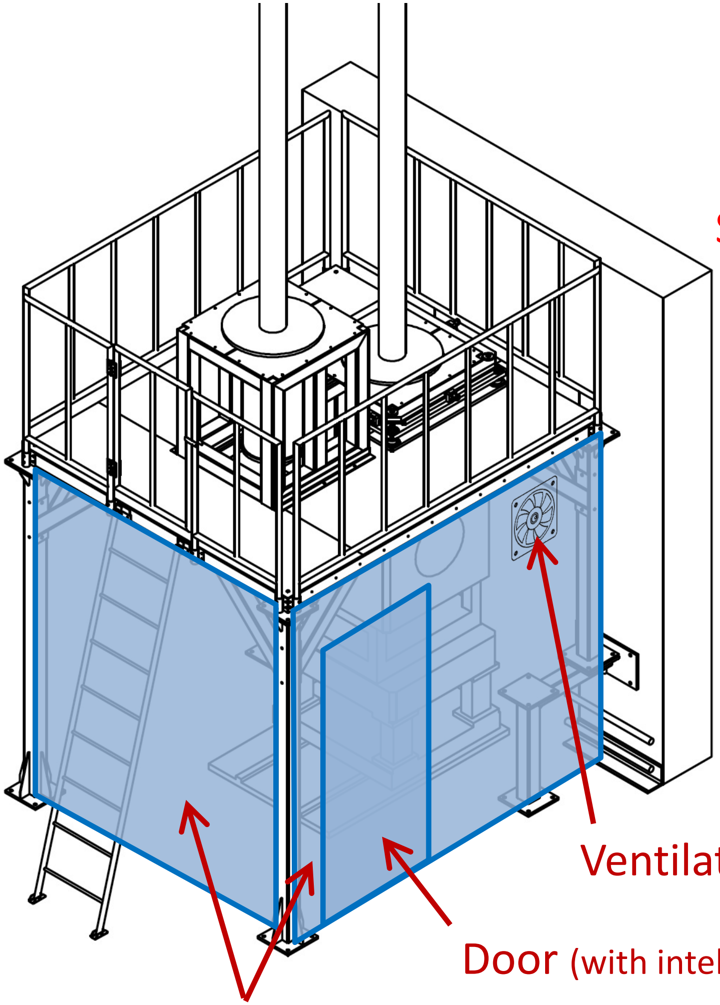


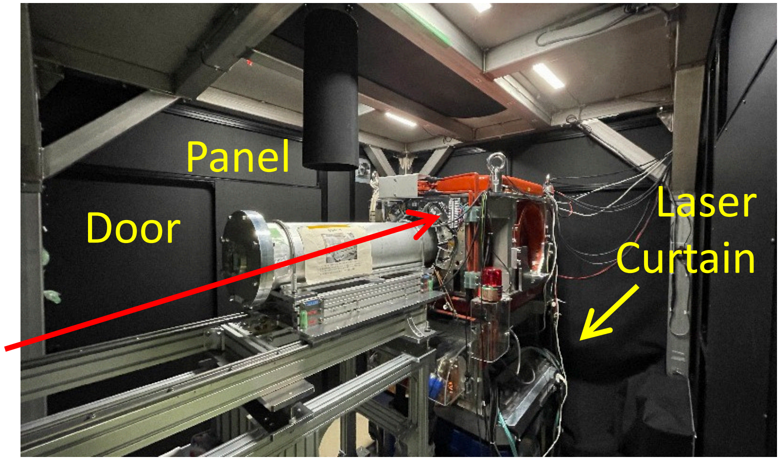


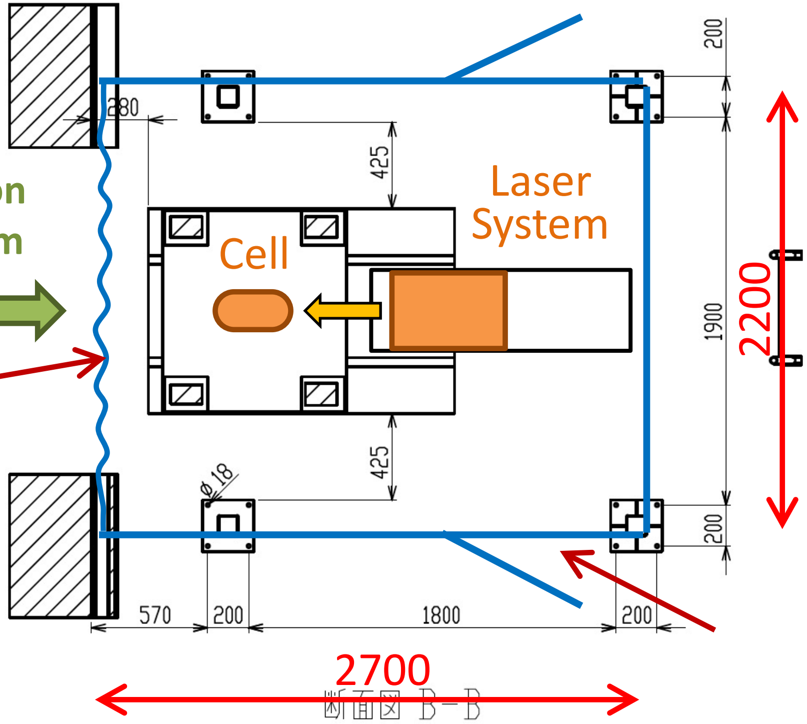
- The line broadening caused by the doppler effect was confirmed.
- For each atom, the population is concentrated in one state, i.e., Rb and K have high polarization.
- At 156°C the different signal intensity of the two peaks from ^{39}K indicates that the alkali metals are not fully polarized but close to 100%.

Laser Enclosure at D1 Area

A removable laser enclosure for SEOP experiment at D1 area was constructed !







µHe SEOP Experiment in Preparation

New results coming soon !!!

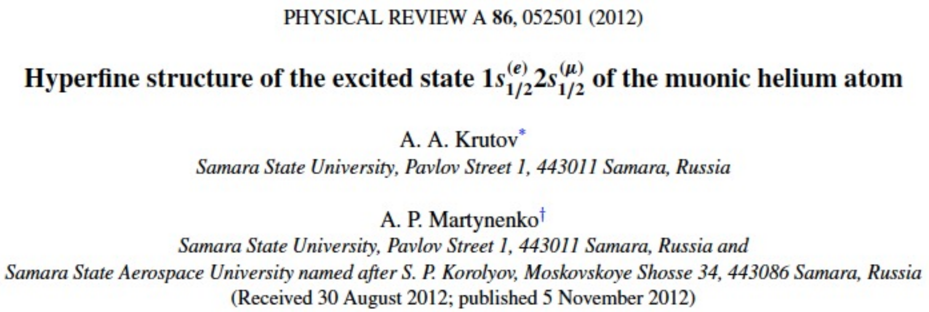
Picture from S. Fukumura

Future Perspectives

Excited State HFS in Muonic He Atoms

(1) HFS transition with the muon in the 2s excited state:

- During the muon cascade, few percent of μHe atoms are formed in a metastable 2s state with a lifetime of ~1 μs (below 0.01 MPa) [1].
- 2s level lifetime decreases rapidly with pressure (radiative quenching).
- HFS transition with the muon in 2s excited state attracted theoreticians since early 1980s. Recent calculations results by Krutov [2].



PHYSICAL REVIEW A 86, 052501 (2012)

Hyperfine structure of the excited state $1s^{(e)}_{1/2}2s^{(\mu)}_{1/2}$ of the muonic helium atom

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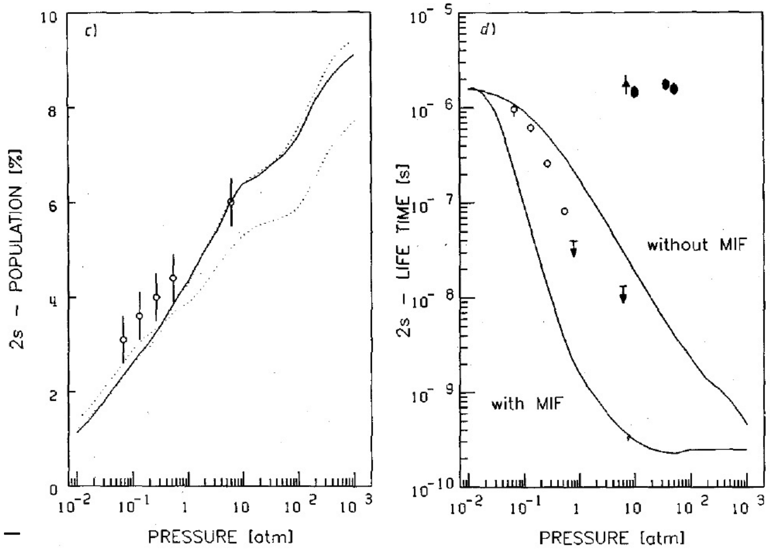
Samara State Aerospace University named after S. P. Korolyov, Moskovskoye Shosse 34, 443086 Samara, Russia
(Received 30 August 2012; published 5 November 2012)



Population and lifetime of the 2s state in μHe

Experimental challenge:

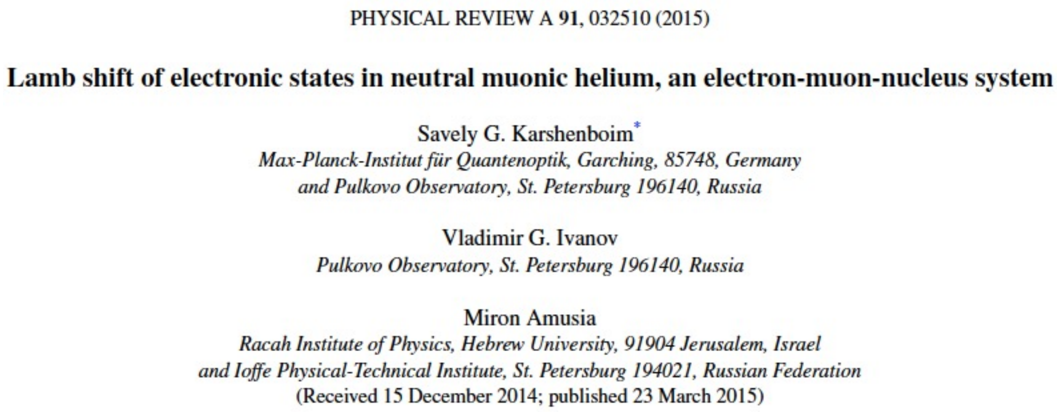
Measurements at low He pressure to maximize 2s level lifetime require intense low energy polarized μ⁻.

[1] G. Reifenröther, E. Klempt, and R. Landua, Phys. Lett. B **191**, 15 (1987)
[2] A. A. Krutov and A. P. Martynenko, Phys. Rev. A **86**, 052501 (2012).

Excited State HFS in Muonic He Atoms

(2) Electronic 1s–2s transition in neutral μ^{3}He and μ^{4}He atoms:

- The 1s–2s transition measured in hydrogen and muonium, but not yet in μ^{3}He or μ^{4}He (with the muon in the ground state).
- The 1s–2s transition in neutral muonic helium (similar to that in hydrogen) has been calculated by Karshenboim.
- The **experiment** is **feasible:** 1s–2s excitation in neutral μHe achievable via Doppler-free two-photon pulsed laser spectroscopy (similar as H and Mu).
- Karshenboim proposed using a double resonance technique: appearance of the 2s excited state and/or disappearance of the 1s ground state HFS transition.



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Lamb shift of electronic states in neutral muonic helium, an electron-muon-nucleus system

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(Received 15 December 2014; published 23 March 2015)

S. G. Karshenboim, V. G. Ivanov, and M. Amusia, Phys. Rev. A **91** , 032510 (2015)

Summary & Future Plans

- We are now proposing precise measurements of ground state HFS splittings of muonic helium atom at J-PARC MUSE.
- **Key components for improvement:**
  - **High-intensity negative muon beam** at J-PARC MUSE
  - **Rabi-oscillation spectroscopy technique**
  - **Highly-polarized muonic helium atom formation**
- **Preparation in progress:**
  - **µHe HFS measurements** at **zero field** using MuSEUM apparatus at D2
    - Already new results were obtained.
    - Pressure shift in He + CH_4 measured for µHe and muonium.
    - Analysis is in progress (blind analysis).
  - SEOP development for µHe measurements is on-going.
- **Future perspectives:** μ^3He HFS, excited states HFS measurements, …
- This project is supported by a Kakenhi grant (FY2021-2023)

  "High-precision measurement of the negative muon mass by muonic helium atom hyperfine structure spectroscopy"

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