Optically polarized alkali metal cell for muonic helium measurements

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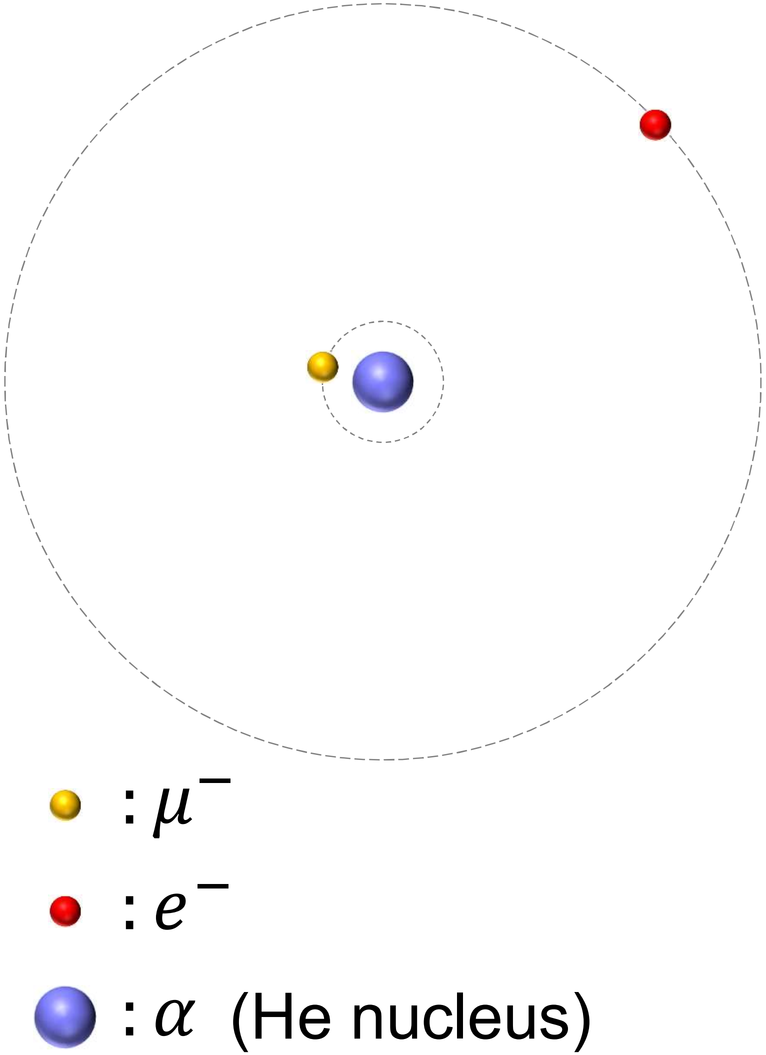
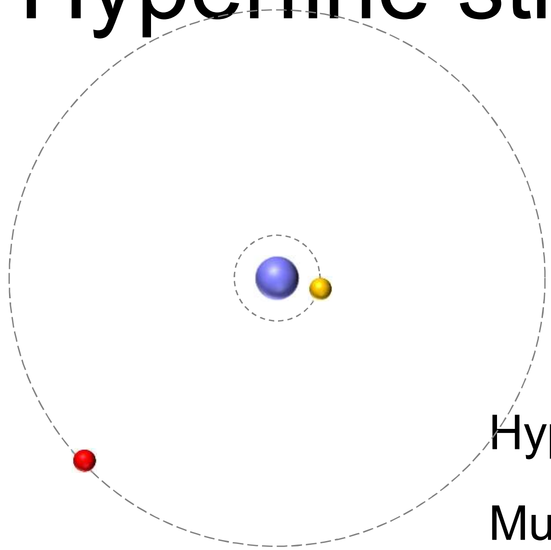
Muonic helium atom

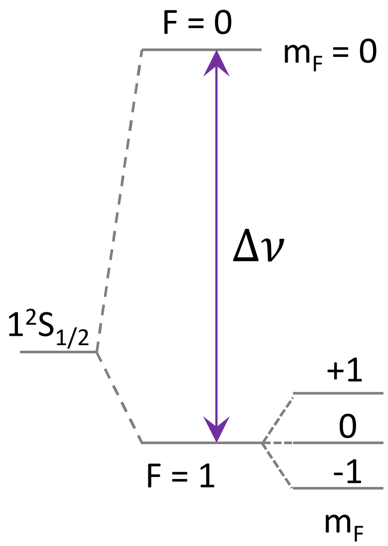


- He atom : α and $2e^-$
- Muonic He atom : α, e^-, and μ^-
- $r_\mu \approx r_e/400$
- Pseudo-nucleus (α & μ^-)
- Hydrogen-like atom
- Three body system
- Test of bound-state QED
- μ^- magnetic moment & mass

Hyperfine structure of muonic helium atom



$$\mathcal{H} = (-h\Delta\nu)\boldsymbol{I_\mu}\cdot\boldsymbol{J} + \left(\mu_B^e g_J\right)\boldsymbol{J}\cdot\boldsymbol{B} + \left(g'_\mu \mu_B^\mu\right)\boldsymbol{I_\mu}\cdot\boldsymbol{B}$$



Hyperfine structure interval $\Delta\nu = 4465.0\ \mathrm{MHz}$

Muon spin operator $\boldsymbol{I_\mu}$

Electron angular-momentum operator $\boldsymbol{J}$

Electron Bohr magneton $\mu_B^e = 5.78838 \times 10^{-5}\ \mathrm{eV}\cdot\mathrm{T}^{-1}$

Electron g-factor in μHe $g_J \approx g_e\left(1 - \frac{1}{3}\alpha^2 + O\left(\frac{m_e}{m_\mu}\right)\alpha^2\right)$

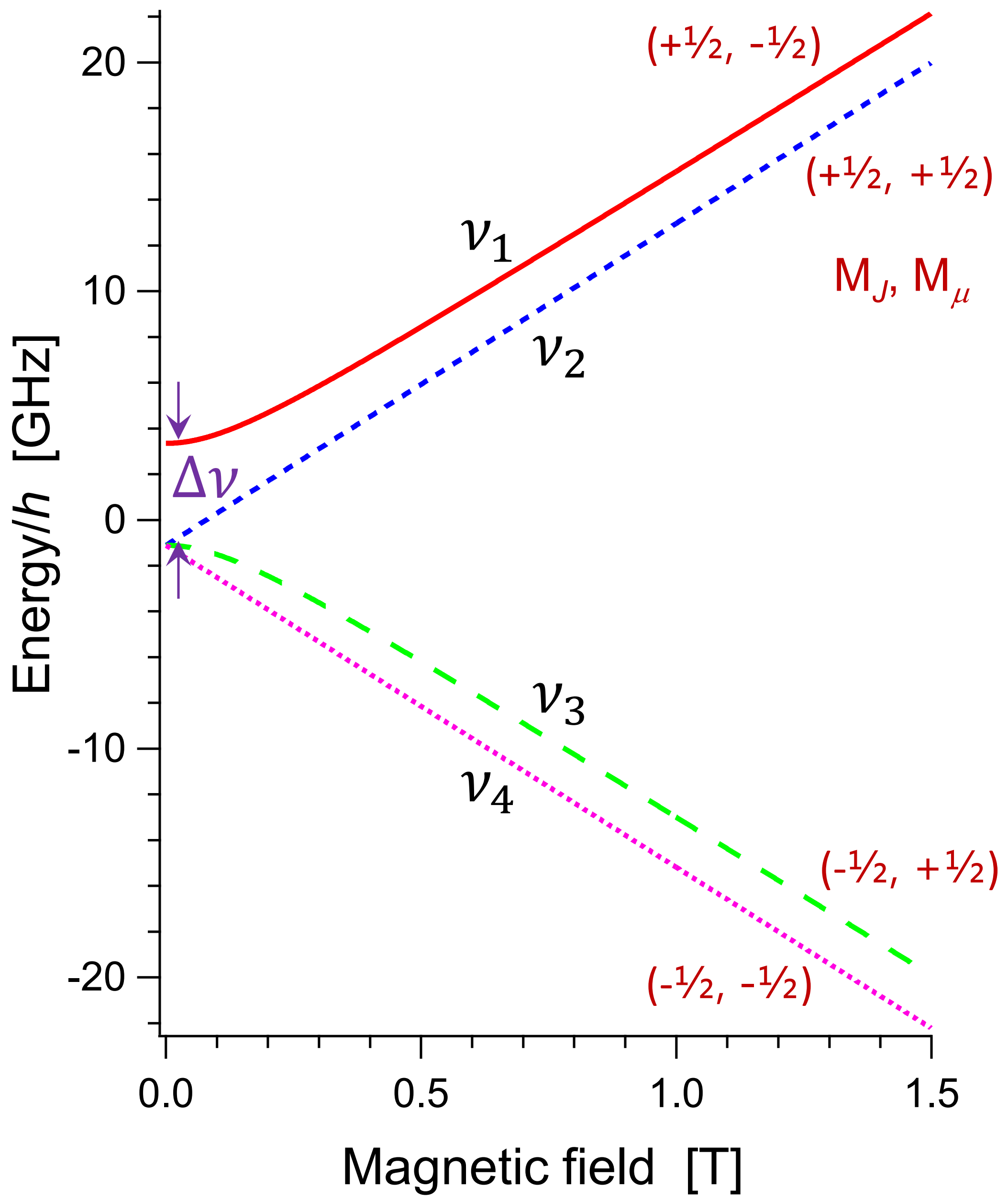
Muon Bohr magneton $\mu_B^\mu = 2.79945 \times 10^{-7}\ \mathrm{eV}\cdot\mathrm{T}^{-1}$

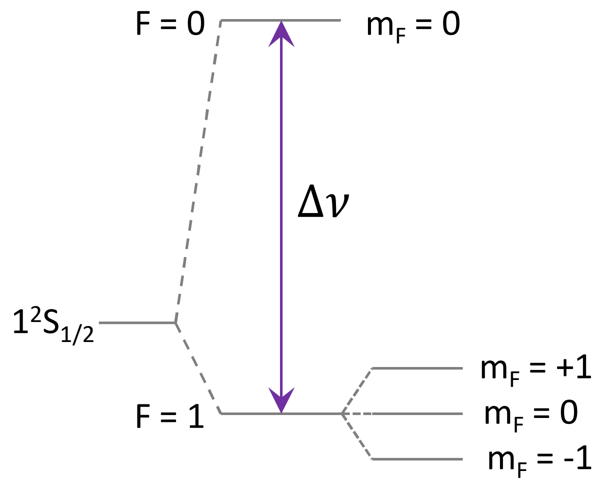
Muon g-factor in μHe $g'_\mu \approx g_\mu\left(1 - \frac{5}{3}\alpha^2 + O\left(\frac{m_e}{m_\mu}\right)\alpha^2\right)$

Static external magnetic field $\boldsymbol{B}$

P. A. Souder, *et al.*, Phys. Rev. A **22**, 33 (1980)

HFS of muonic helium atom





$$\nu_1 = \frac{\Delta\nu}{4} + \frac{\Delta\nu}{2}\sqrt{1+x^2}$$

$$\nu_2 = \frac{\Delta\nu}{4} + g'_\mu \mu_B^\mu \frac{B}{h} - \frac{\Delta\nu}{2}(1-x)$$

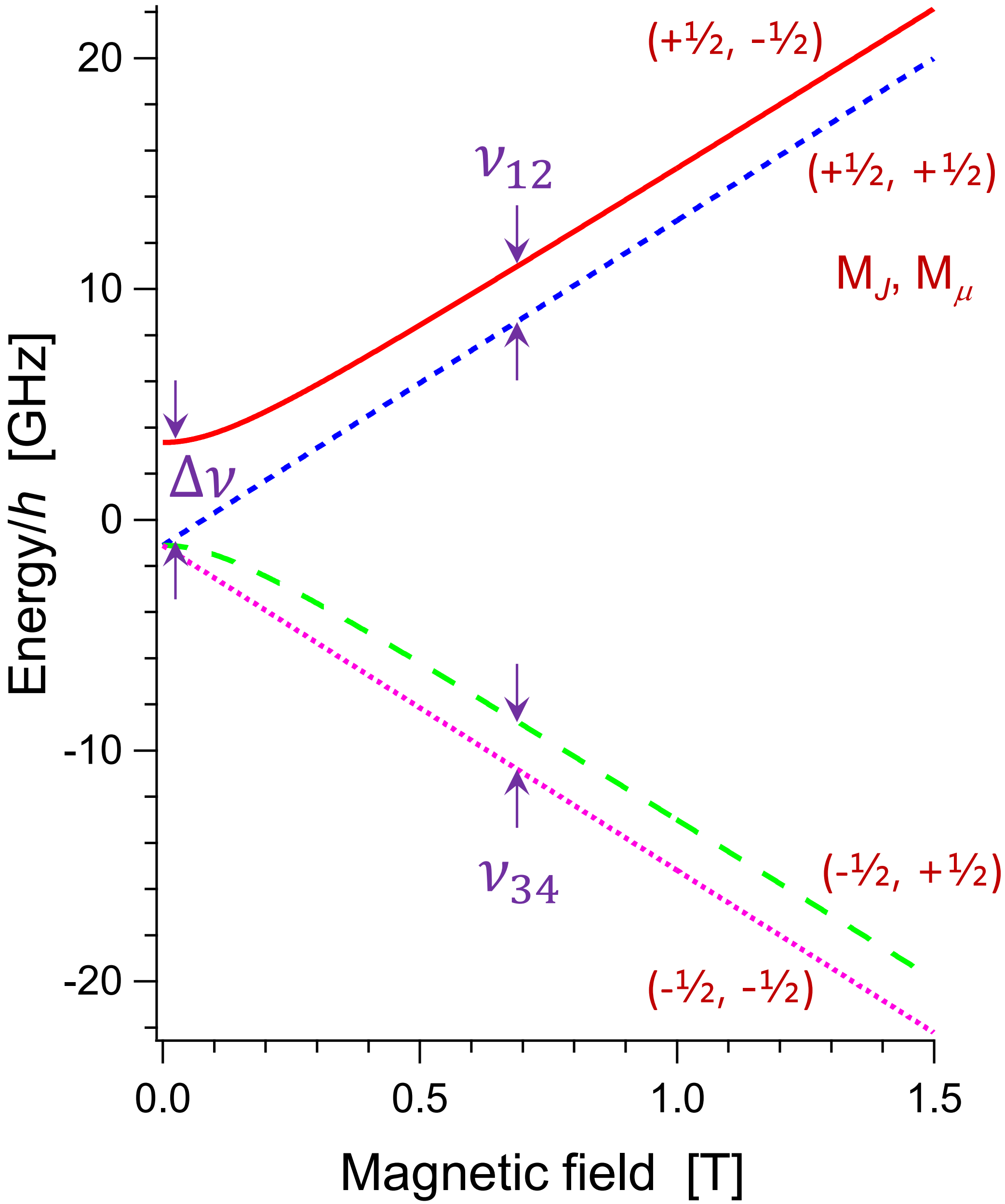
$$\nu_3 = \frac{\Delta\nu}{4} - \frac{\Delta\nu}{2}\sqrt{1+x^2}$$

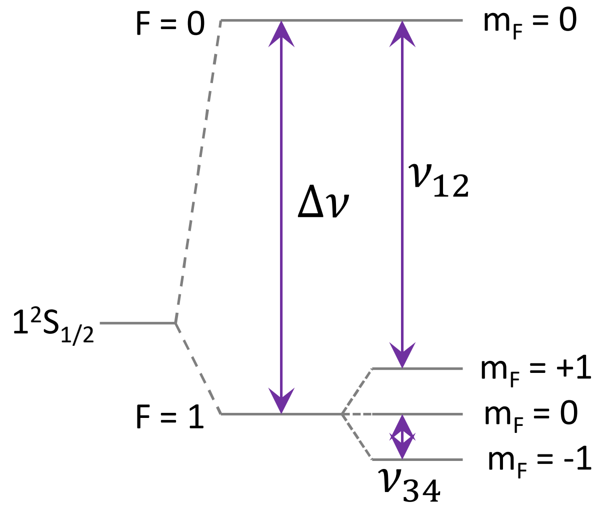
$$\nu_4 = \frac{\Delta\nu}{4} - g'_\mu \mu_B^\mu \frac{B}{h} - \frac{\Delta\nu}{2}(1+x)$$

$$x = \left(g_J \mu_B^e - g'_\mu \mu_B^\mu\right)\frac{B}{h\Delta\nu}$$

P. A. Souder, *et al.*, Phys. Rev. A **22**, 33 (1980)

HFS of muonic helium atom



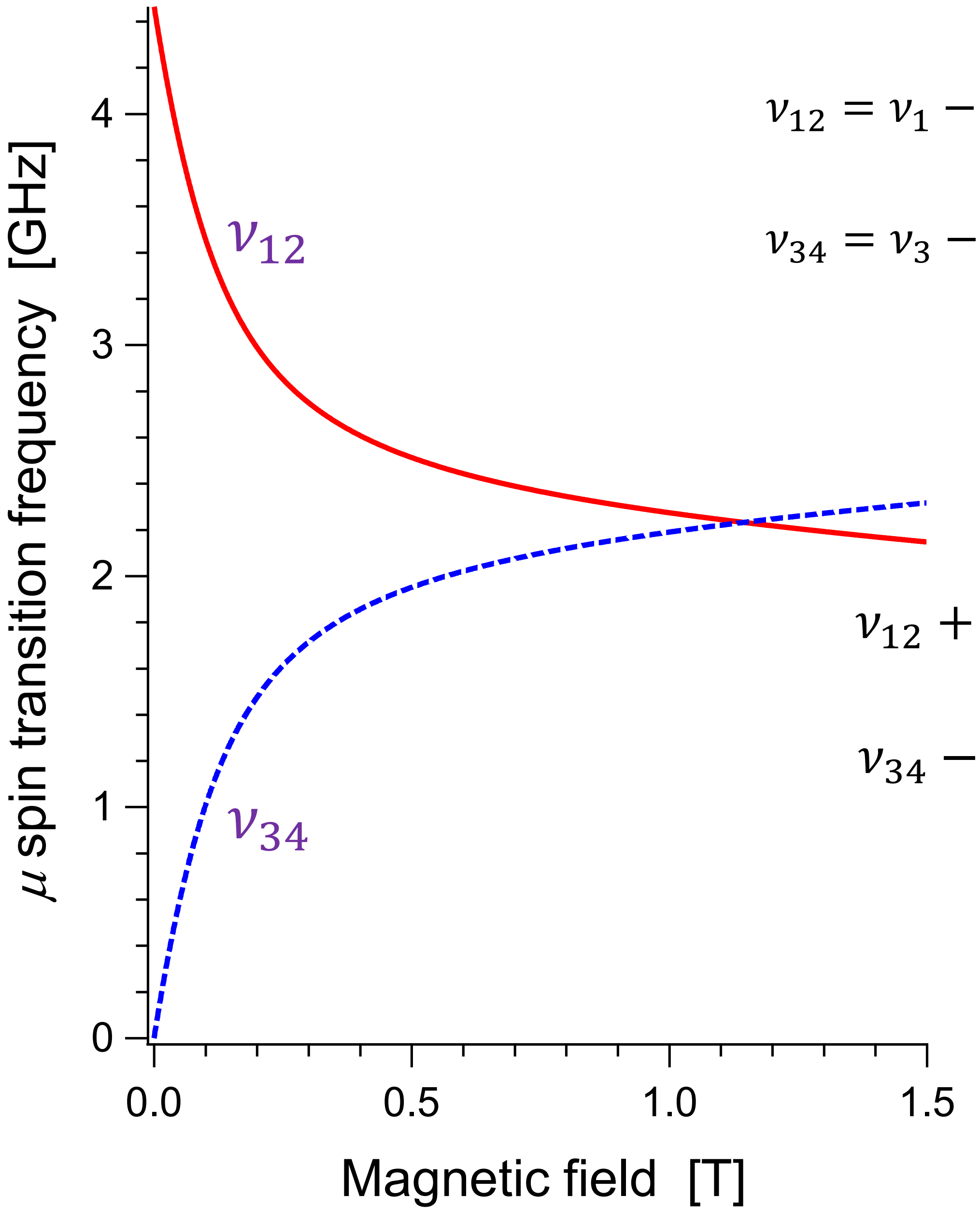


$$\nu_{12} = \nu_1 - \nu_2$$
$$= -g'_\mu \mu_B^\mu \frac{B}{h} + \frac{\Delta\nu}{2}\left(1 - x + \sqrt{1 + x^2}\right)$$

$$\nu_{34} = \nu_3 - \nu_4$$
$$= g'_\mu \mu_B^\mu \frac{B}{h} + \frac{\Delta\nu}{2}\left(1 + x - \sqrt{1 + x^2}\right)$$

$$x = \left(g_J \mu_B^e - g'_\mu \mu_B^\mu\right) \frac{B}{h\Delta\nu}$$

HFS of muonic helium atom



$$\nu_{12} = \nu_1 - \nu_2 = -g'_\mu \mu_B^\mu \frac{B}{h} + \frac{\Delta\nu}{2}\left(1 - x + \sqrt{1 + x^2}\right)$$

$$\nu_{34} = \nu_3 - \nu_4 = g'_\mu \mu_B^\mu \frac{B}{h} + \frac{\Delta\nu}{2}\left(1 + x - \sqrt{1 + x^2}\right)$$

$$x = \left(g_J \mu_B^e - g'_\mu \mu_B^\mu\right) \frac{B}{h\Delta\nu}$$

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

$$\nu_{34} - \nu_{12} = 2 g'_\mu \mu_B^\mu \frac{B}{h} + \Delta\nu\left(x - \sqrt{1 + x^2}\right)$$

$$\boxed{\mu_{\mu^-}/\mu_P}$$

$$\nu_P = g_P \mu_P \frac{B}{h}$$

B determined by proton NMR.

Most recent published results

$\Delta\nu = 4464.95(6)\ \mathrm{MHz}$ 13 ppm Zero magnetic field

H. Orth, *et al.*, Phys. Rev. Lett. **45**, 1483 (1980)

High magnetic field

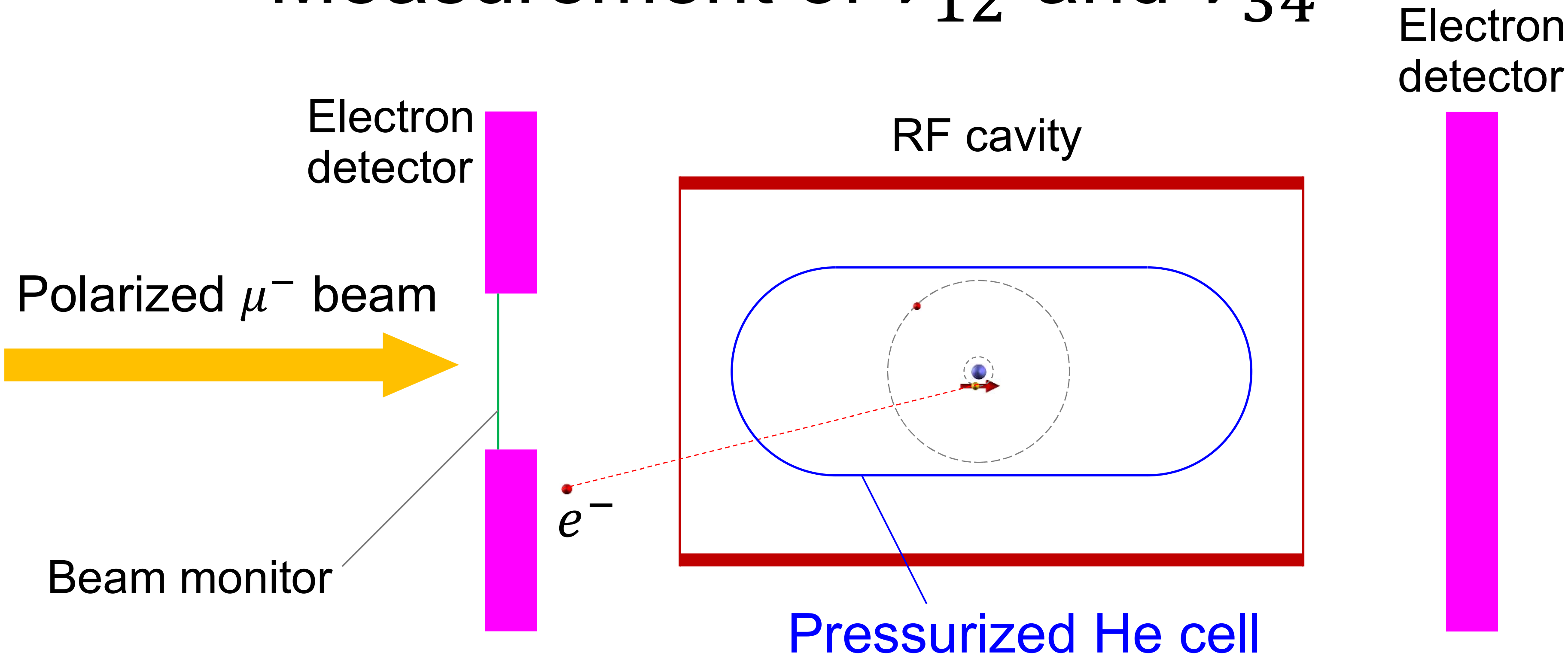
$\Delta\nu = 4465.004(29)\ \mathrm{MHz}$ 6.5 ppm

$\mu_{\mu^-}/\mu_P = 3.18328(15)$ 47 ppm

C. J. Gardner, *et al.*, Phys. Rev. Lett. **48**, 1168 (1982)

$\Longrightarrow$ Improve $\Delta\nu$ accuracy < 0.1 ppm

Measurement of ν_{12} and ν_{34}



Decay e^- preferentially emitted opposite to μ^- spin direction.

(1) Formation of muonic helium atoms.
(2) RF spin flip.
(3) Electron asymmetry measurement.

High μ^- polarization

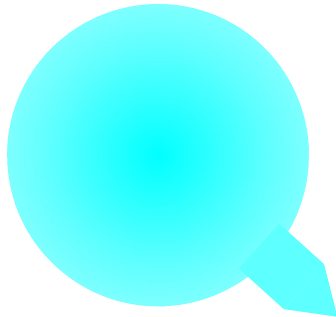
μ^- polarization is lost in formation of muonic helium atoms.

P. Strasser, *et al.*, JPS Conf. Proc. **21**, 011045 (2018)

Repolarization of muonic helium

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

Optically polarized Rb in He gas



$$\mathrm{Rb}\uparrow \;\Rightarrow\; \mu^{-}\uparrow$$

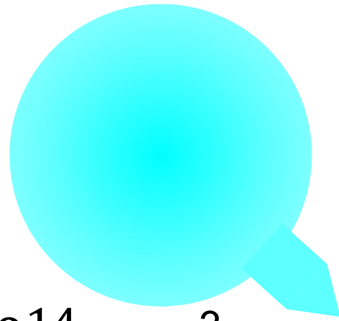
Similar to “SEOP” commonly used for rare gas polarization.

SEOP : spin exchange optical pumping

T. R. Gentile, *et al.*, Rev. Mod. Phys. **89**, 045004 (2017)

Repolarization of muonic helium

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

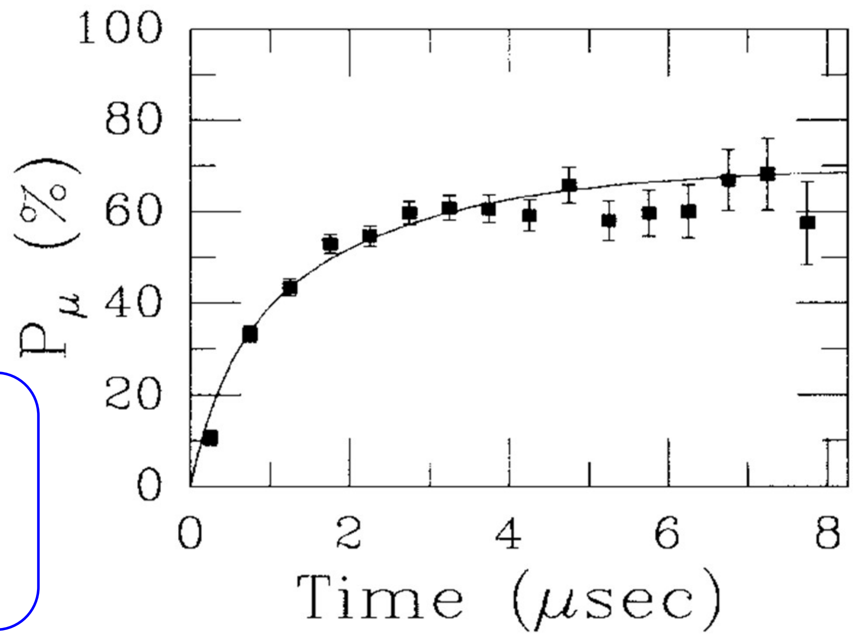


- He gas and Rb in a spherical glass cell
  He: 8 atm, cell: ϕ2.5 cm, wall: 0.1 mm thick

- Rb polarized by optical pumping
  Laser: 5 W, temperature: ~200°C, [Rb]: $\sim 4 \times 10^{14}$ cm^{-3}

- LAMPF, LANL
  23 MeV

- Average $P_\mu = 44\%$
  Spin transfer rate vs. μ lifetime



To get more polarized μHe,
- He gas volume and/or pressure
- Rb to μ spin transfer rate ∝ [Rb]

30 years of innovation

- High intensity muon source at J-PARC **2-3 orders**

- Time-differential muon spin resonance technique* **Several times**

- OP with ~100 W diode laser **One order**

- High alkali metal density with “alkali-hybrid OP” **Several times**

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

Alkali-hybrid optical pumping

$$P_{\mathrm{Rb}} = \frac{\gamma_{\mathrm{opt}}}{\gamma_{\mathrm{opt}} + \Gamma_{\mathrm{Rb}}}$$

γ_{opt} : Optical pumping rate

Γ_{Rb} : Rb-Rb spin destruction rate

$$P_{\mathrm{Rb}} \approx 100\% \leftarrow \gamma_{\mathrm{opt}} \gg \Gamma_{\mathrm{Rb}}$$

$$\gamma_{\mathrm{A}} \gg \Gamma_{\mathrm{A}}$$

Mixture of Rb and K

$$P_{\mathrm{A}} \approx \frac{\gamma_{\mathrm{opt}}}{\gamma_{\mathrm{opt}} + \Gamma_{\mathrm{A}}}$$

γ_{A} : A-A spin exchange rate

Γ_{A} : A-A spin destruction rate

$\Gamma_{\mathrm{Rb}} > \Gamma_{\mathrm{A}} > \Gamma_{\mathrm{K}}$ $\quad$ $\Gamma_{\mathrm{Rb}} : \Gamma_{\mathrm{K}} \approx 5:1$

$$\mathrm{Rb}\uparrow \;\Rightarrow\; \mathrm{K}\uparrow \;\Rightarrow\; \mu^{-}\uparrow$$

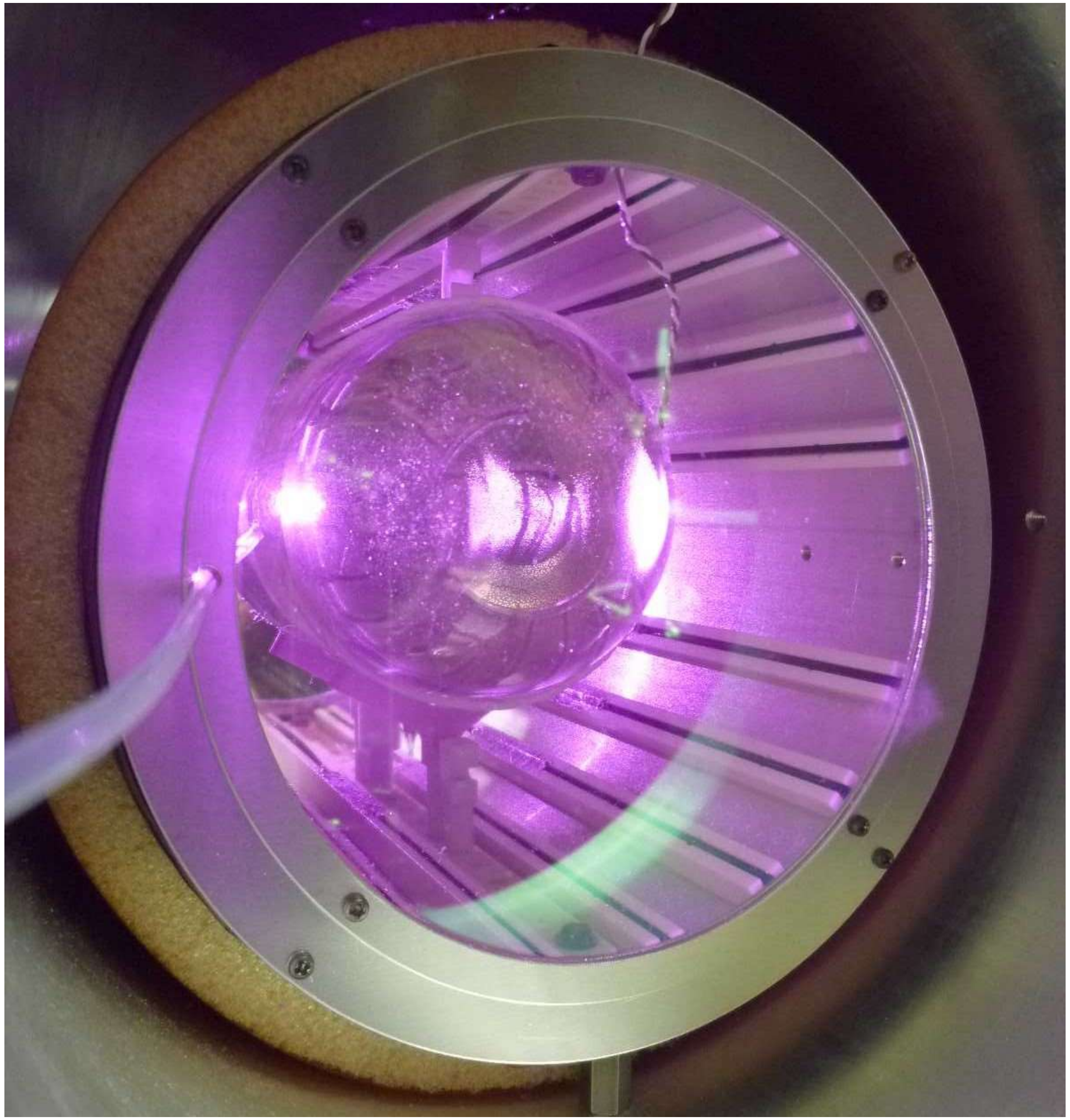
E. Babcock *et al.*, Phys. Rev. Lett. **91**, 123003 (2003)

He cell with a mixture of Rb & K

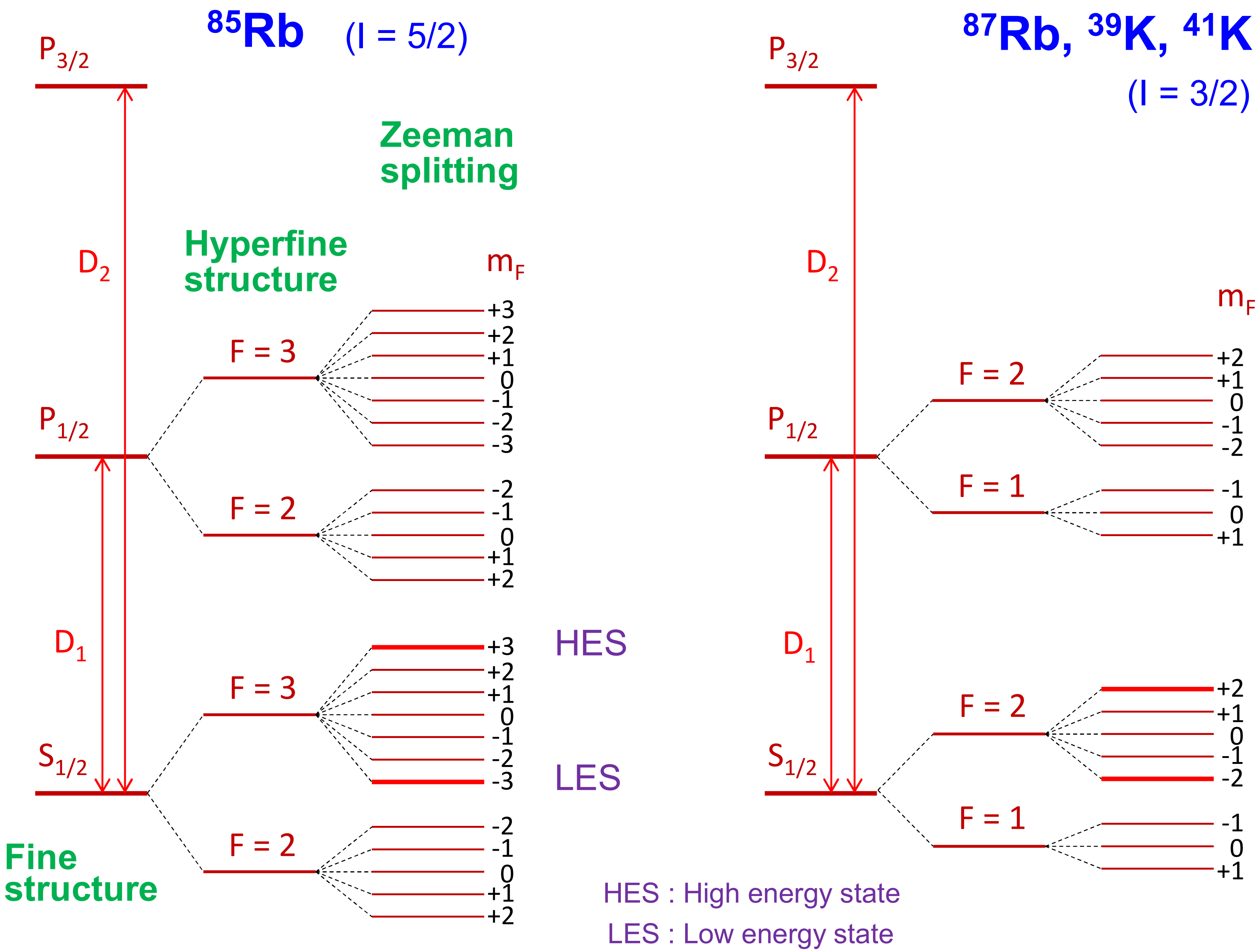
Pyrex glass	Wall thickness	Volume : 480 cm^3
Diameter : 72 mm	~1 mm (spherical)	He : 3.2 atm (0°C)
Length : 156 mm	~2 mm (cylindrical)	Rb & K

Optical pumping test

Estimation of alkali metal polarization by EPR



Atomic energy levels of Rb and K

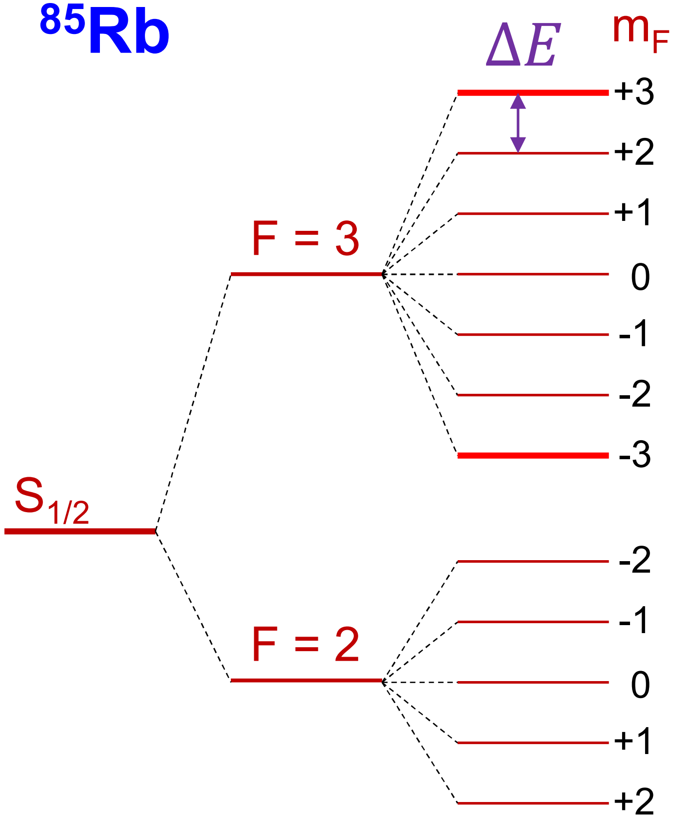


Transition energies

$$E = -\frac{h\nu_{\mathrm{hfs}}}{2(2I+1)} - g_{\mathrm{I}}\mu_{\mathrm{N}} B m_{\mathrm{F}} \pm \frac{h\nu_{\mathrm{hfs}}}{2}\sqrt{1 + \frac{4m_{\mathrm{F}}}{2I+1}x + x^2}$$

$$x = (g_{\mathrm{I}}\mu_{\mathrm{N}} - g_{\mathrm{S}}\mu_{\mathrm{B}})\frac{B}{h\nu_{\mathrm{hfs}}}$$

^{85}Rb



$B_{+3.+2} = 2.17860$ mT

$B_{+2,+1} = 2.16426$ mT

$B_{+1,0} = 2.15003$ mT

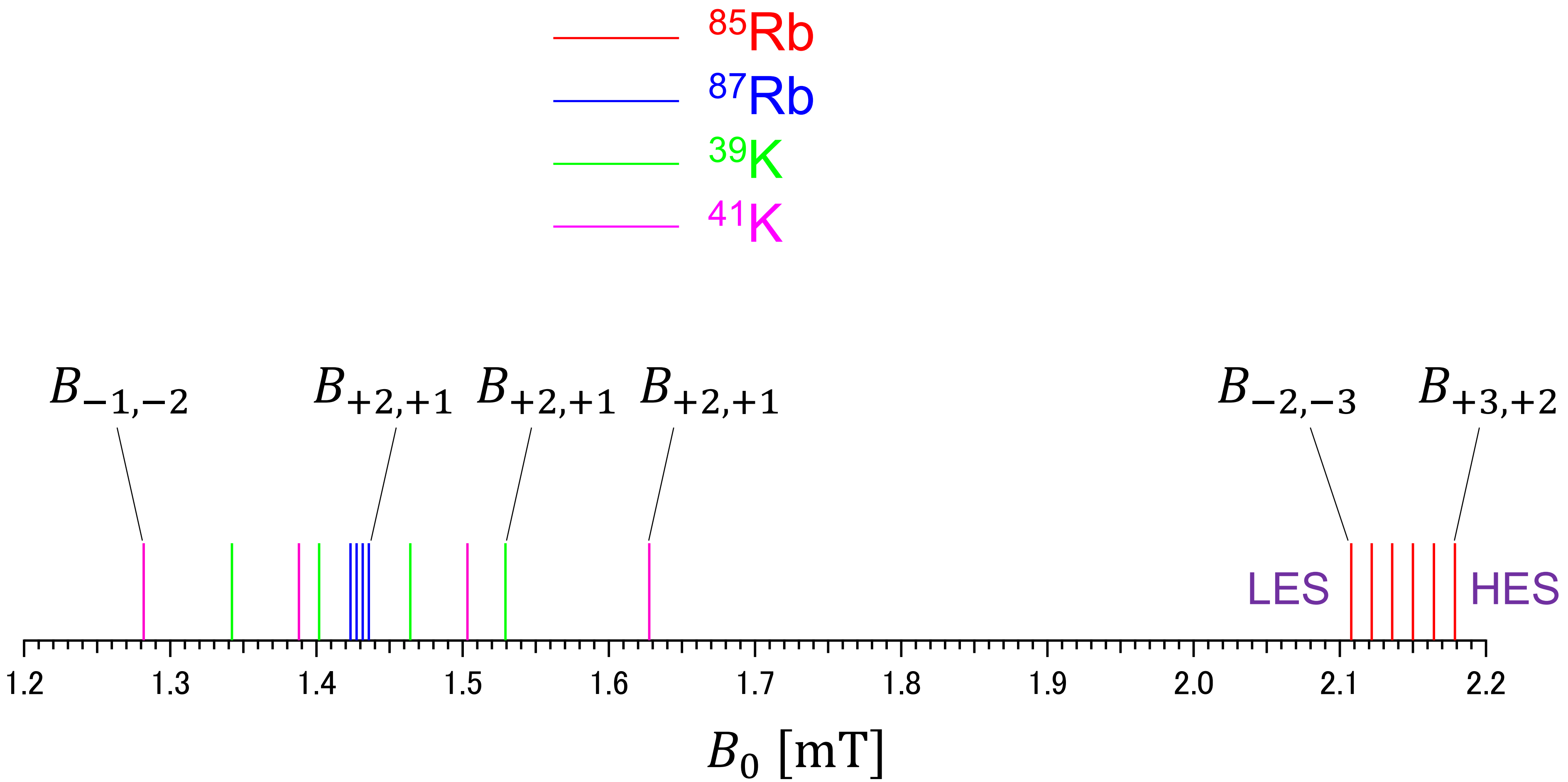
$B_{0,-1} = 2.13589$ mT

$B_{-1,-2} = 2.12183$ mT

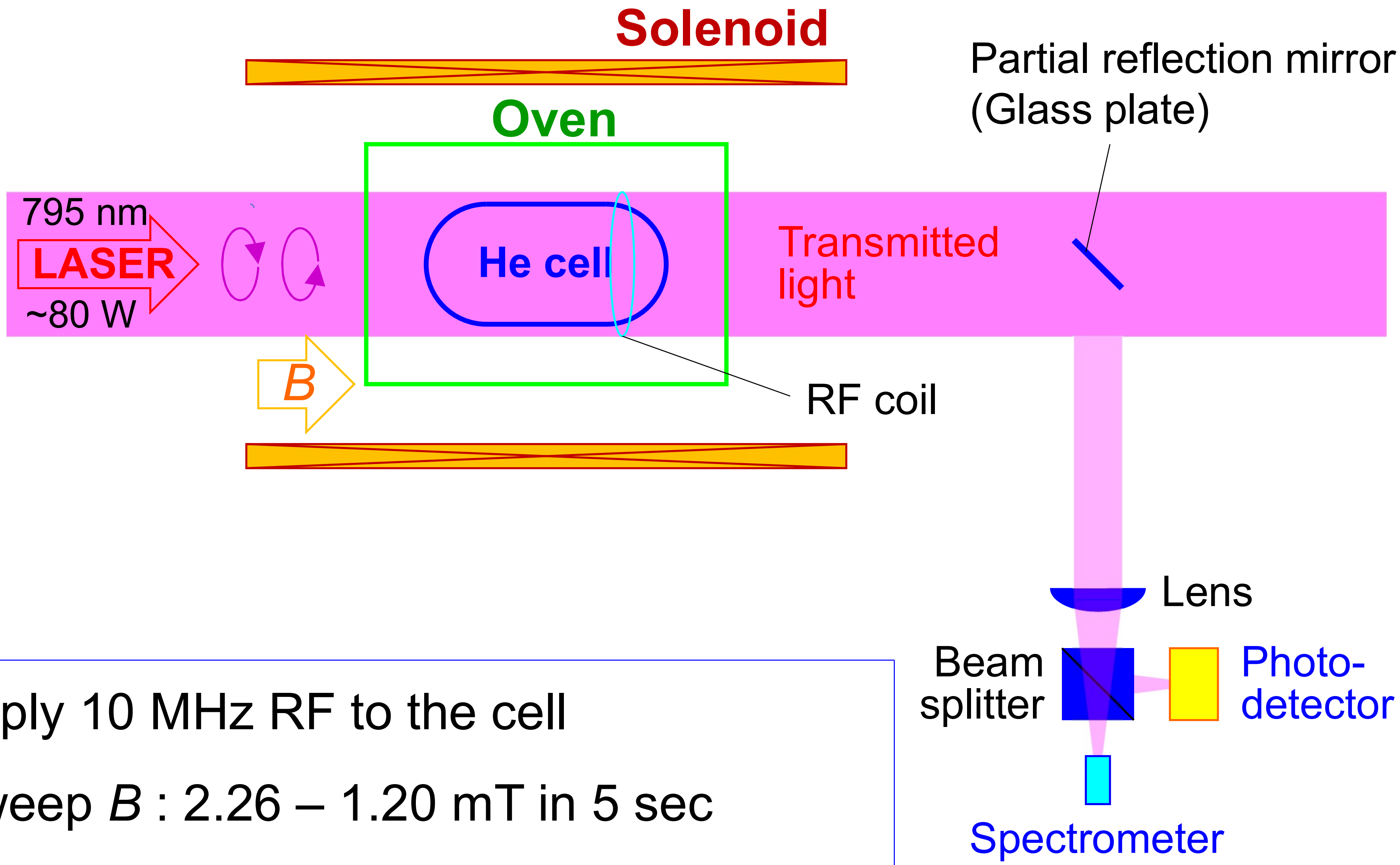
$B_{-2,-3} = 2.10785$ mT

$$\frac{\Delta E}{h} = 10\ \mathrm{MHz}$$

Resonance B at which $\Delta E/h = 10\ \mathrm{MHz}$



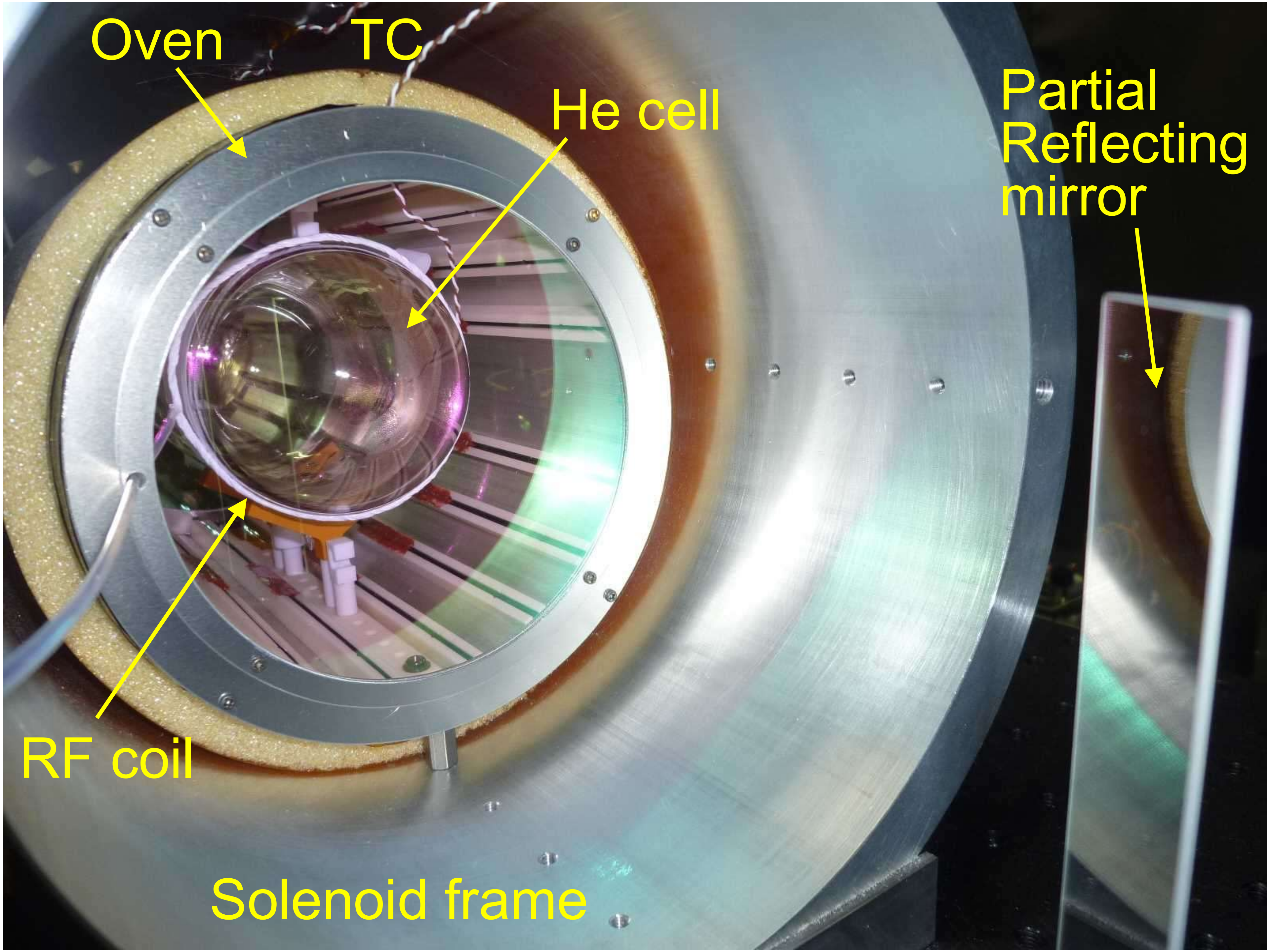
EPR measurement apparatus



Apply 10 MHz RF to the cell

Sweep *B* : 2.26 – 1.20 mT in 5 sec

Laser absorption increases at resonances
→ Lessen transmitted light



Oven
TC
He cell
Partial
Reflecting
mirror
RF coil
Solenoid frame

EPR signals

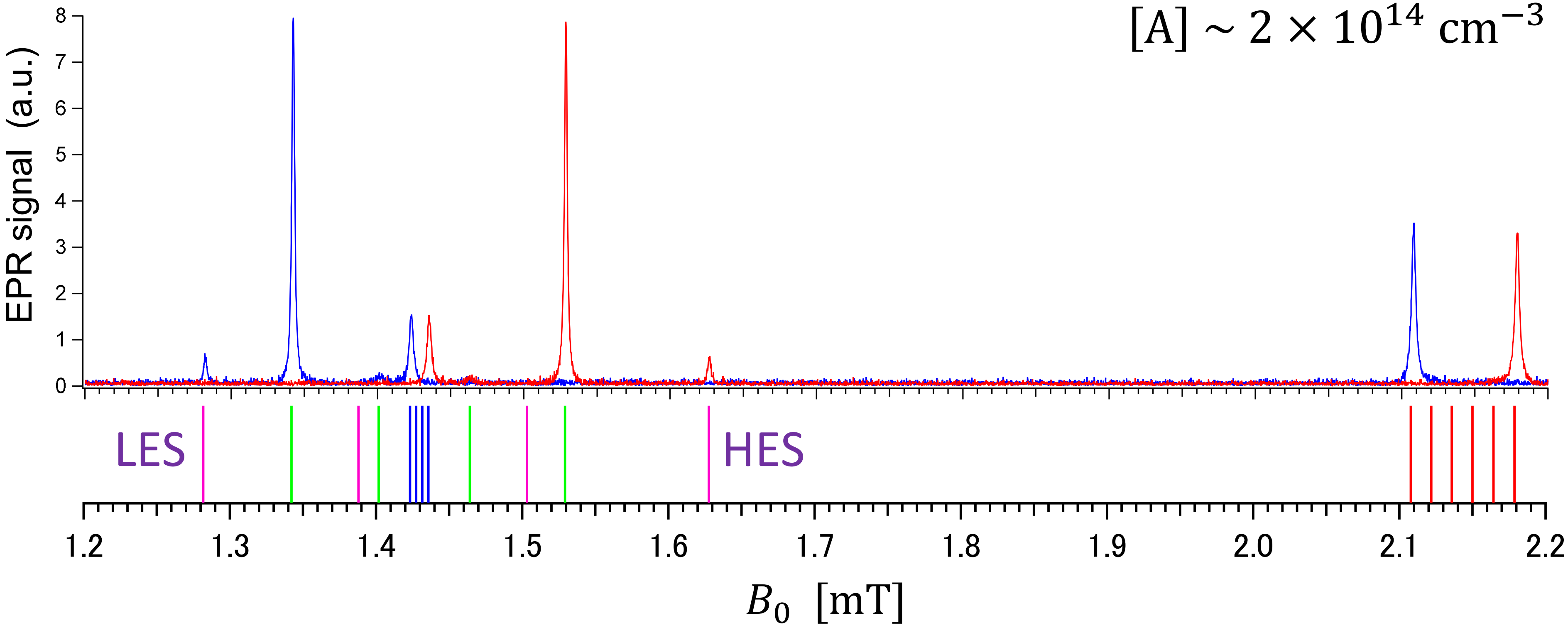
- LES
- HES

$P_A \approx 100\%$

Cell210308 at 200°C

$[K]/[Rb] = 1.3$

$[A] \sim 2 \times 10^{14}\ cm^{-3}$



^{85}Rb

^{87}Rb

^{39}K

^{41}K

Natural abundance

^{85}Rb : 72.2% ^{39}K : 93.3%

^{87}Rb : 27.8% ^{41}K : 6.7%

To aluminosilicate glass cells

OP at 160-220°C for 50 hrs

As pulled-off

Pyrex has reacted with alkali metal at ~200°C.

Aluminosilicate glass should be ok up to ~250°C.

Things to do

- Preparation of aluminosilicate glass He cells

- Measurements of P_A and $[\mathrm{A}]$

- Rb and K mixture optimization

- Optimization of He cell dimensions
  He pressure and glass wall thickness

Summary

- We have made and tested alkali metal cells made of Pyrex glass as prototype He cells for muonic Helium experiments.

- Alkali metals were optically polarized with a 80 W laser.

- $P_{\mathrm{A}} \approx 100\%$ was confirmed for a ~500 cm^3 cell with $[\mathrm{A}] \sim 2 \times 10^{14}$ cm^{-3}.

- After optical pumping at ~200˚C for 2 days, the glass changed color due to the reaction with alkali metal.

- Cell material needs to be changed to aluminosilicate glass, which is commonly used for ^{3}He spin polarizers, to improve alkali resistance.

- Need further studies.