NEW DEVELOPMENTS FOR LAMB-SHIFT POLARIMETER

26TH FEBRUARY 2024 NICOLAS FAATZ

SPIN PHYSICS

- Precision physics
- Nuclear magnetic resonance (NMR)
- Nuclear fusion

LSP USED FOR DIFFERENT EXPERIMENTS

- Los Alamos → invention of the first spin filter

J. McKibben et.al., Phys. Rev. Lett. **20**, (1968)

A. Solovev et.al., JINST., **15,** (2020)

LSP USED FOR DIFFERENT EXPERIMENTS

- Los Alamos → invention of the first spin filter

J. McKibben et.al., Phys. Rev. Lett. **20**, (1968)

- Moscow State University → pulsed polarized proton source

A. Belov et.al., NIM., **255**, (1987)

LSP USED FOR DIFFERENT EXPERIMENTS

- Los Alamos → invention of the first spin filter

J. McKibben et.al., Phys. Rev. Lett. **20**, (1968)

- Moscow State University → pulsed polarized proton source

A. Belov et.al., NIM., **255**, (1987)

- TUNL → hydrogen and deuterium ion beams

S. Lemieux et.al., NIM., **333**, (1993)

LSP USED FOR DIFFERENT EXPERIMENTS

- Los Alamos → invention of the first spin filter

J. McKibben et.al., Phys. Rev. Lett. **20**, (1968)

- Moscow State University → pulsed polarized proton source

A. Belov et.al., NIM., **255**, (1987)

- TUNL → hydrogen and deuterium ion beams

S. Lemieux et.al., NIM., **333**, (1993)

- University of Cologne → polarized atomic and ion beams

R. Engels et.al., Rev. Sci. Instrum., **74,** (2003)

LSP USED FOR DIFFERENT EXPERIMENTS

- Los Alamos → invention of the first spin filter

J. McKibben et.al., Phys. Rev. Lett. **20**, (1968)

- Moscow State University → pulsed polarized proton source

A. Belov et.al., NIM., **255**, (1987)

- TUNL → hydrogen and deuterium ion beams

S. Lemieux et.al., NIM., **333**, (1993)

- University of Cologne → polarized atomic and ion beams

R. Engels et.al., Rev. Sci. Instrum., **74,** (2003)

- RHIC → optically pumped polarized H^{-} source

A. Zelenski et.al., Pol. At RHIC., **15,** (2013)

LSP USED FOR DIFFERENT EXPERIMENTS

- Los Alamos → invention of the first spin filter

J. McKibben et.al., Phys. Rev. Lett. **20**, (1968)

- Moscow State University → pulsed polarized proton source

A. Belov et.al., NIM., **255**, (1987)

- TUNL → hydrogen and deuterium ion beams

S. Lemieux et.al., NIM., **333**, (1993)

- University of Cologne → polarized atomic and ion beams

R. Engels et.al., Rev. Sci. Instrum., **74,** (2003)

- RHIC → optically pumped polarized H^- source

A. Zelenski et.al., Pol. At RHIC., **15,** (2013)

- FZ Jülich → H and D atomic beam source for ANKE

M. Mikirtychyants et.al., NIM., **721**, (2013)

LSP USED FOR DIFFERENT EXPERIMENTS

- Los Alamos → invention of the first spin filter

J. McKibben et.al., Phys. Rev. Lett. **20**, (1968)

- Moscow State University → pulsed polarized proton source

A. Belov et.al., NIM., **255**, (1987)

- TUNL → hydrogen and deuterium ion beams

S. Lemieux et.al., NIM., **333**, (1993)

- University of Cologne → polarized atomic and ion beams

R. Engels et.al., Rev. Sci. Instrum., **74,** (2003)

- RHIC → optically pumped polarized H^- source

A. Zelenski et.al., Pol. At RHIC., **15,** (2013)

- FZ Jülich → H and D atomic beam source for ANKE

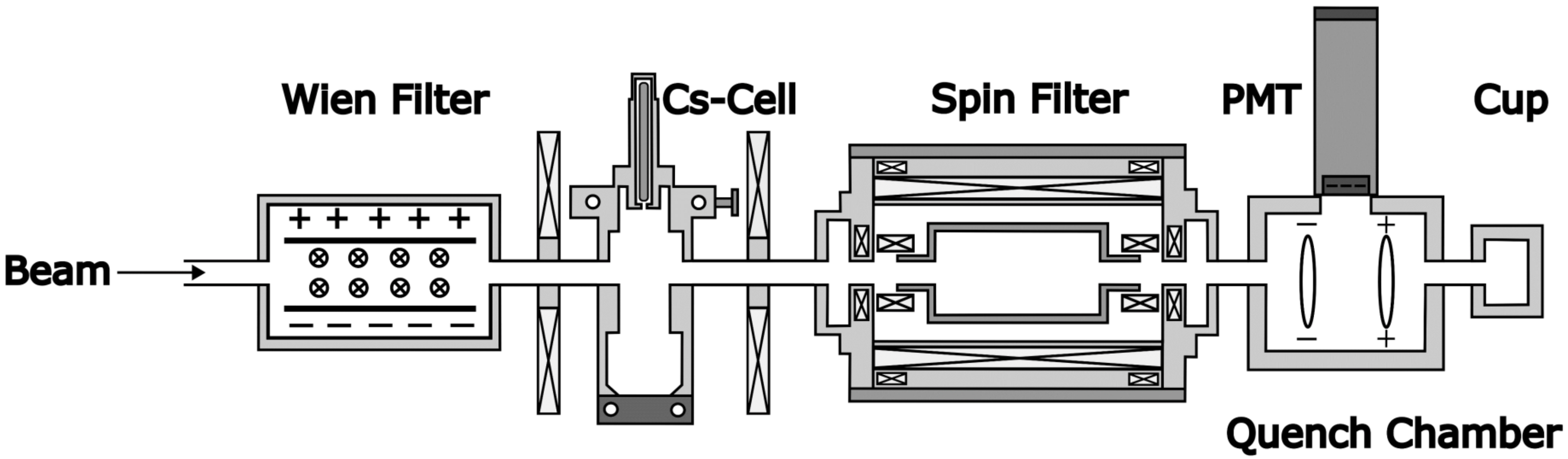
M. Mikirtychyants et.al., NIM., **721**, (2013)

- PNPI → investigations for double-polarized DD-fusion

A. Solovev et.al., JINST., **15,** (2020)

GSI JÜLICH Forschungszentrum

START IN JÜLICH

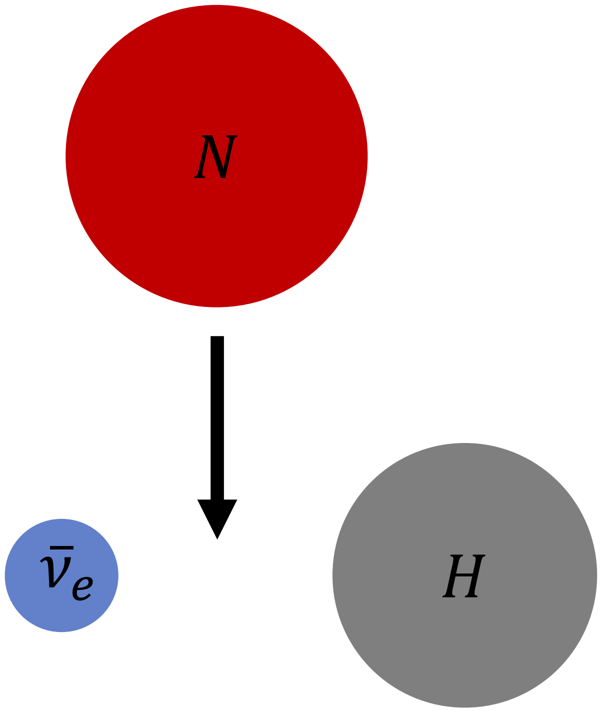


- Measuring the nuclear polarization created by the ABS
- Simple and cheap detection method
- Working for hydrogen atoms their isotopes molecules and ions

MOTIVATION

- Nuclear polarized sources
- Bound beta decay (BoB) $n \rightarrow {H^*}_{2S_{1/2}} + \bar{\nu}_e$
- Parity violation $2S_{1/2} \rightarrow 2P_{1/2}$

  $P = (-1)^l \colon 0 \rightarrow 1$
- Sona transition unit



HYDROGEN-LIKE WAVEFUNCTIONS

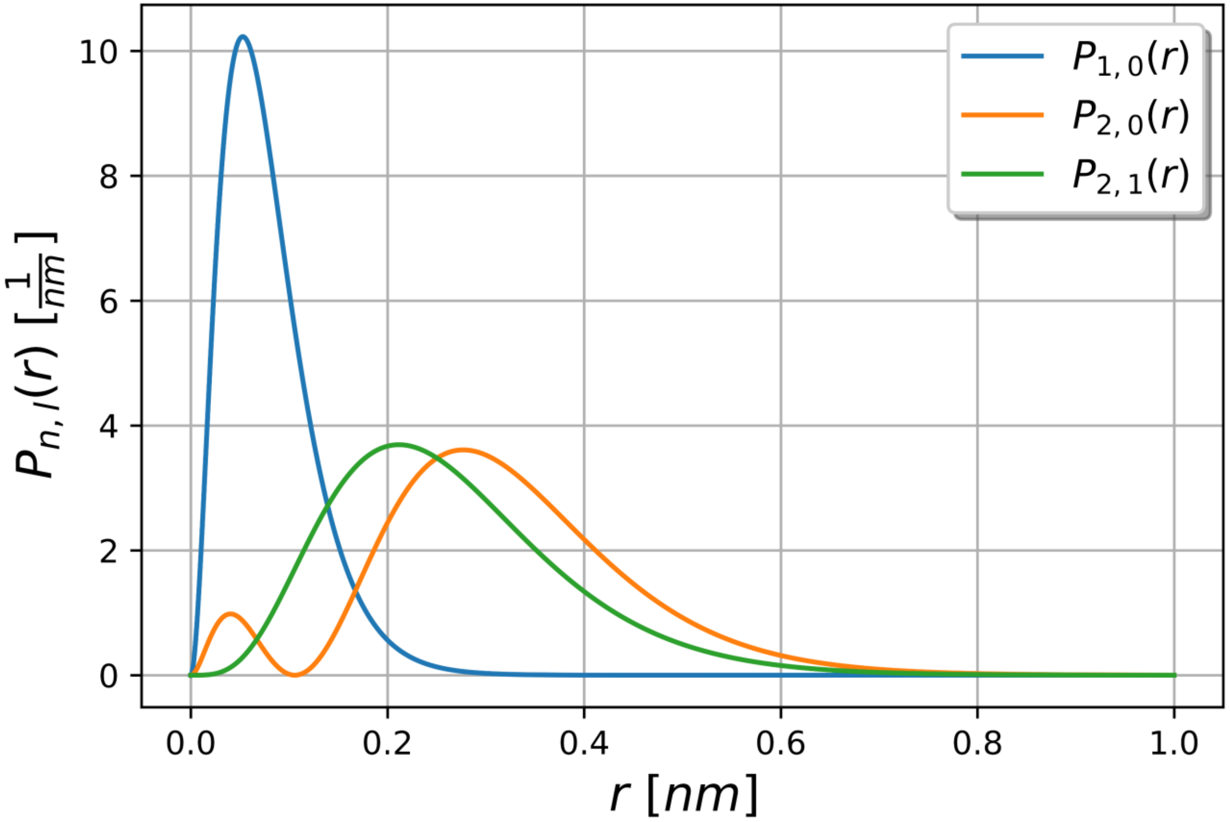
$$\psi_{100} = \sqrt{\frac{4Z^3}{{a_0}^3}} e^{-\frac{Zr}{a_0}} \frac{1}{\sqrt{4\pi}}$$

$$\psi_{200} = \sqrt{\frac{Z^3}{32\pi {a_0}^3}} \left(-\frac{Zr}{a_0} + 2\right) e^{-\frac{Zr}{2a_0}}$$

$$\psi_{210} = \sqrt{\frac{Z^3}{32\pi {a_0}^3}} \left(-\frac{Zr}{a_0}\right) e^{-\frac{Zr}{2a_0}} \cos(\theta)$$

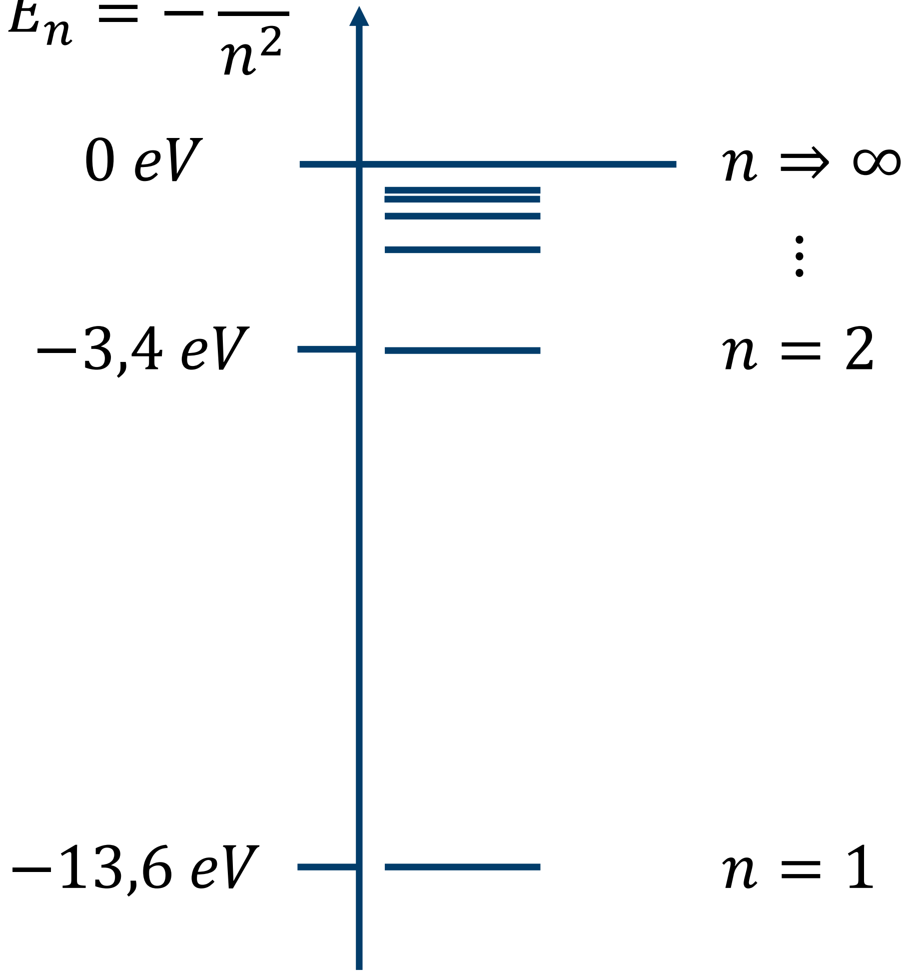
$$\psi_{21\pm1} = \mp\sqrt{\frac{Z^3}{64\pi {a_0}^3}} \left(-\frac{Zr}{a_0}\right) e^{-\frac{Zr}{2a_0}} \sin(\theta) e^{\pm i\phi}$$

$$P_{n,l}(r) = r^2 \left|R_{n,l}(r)\right|^2$$



HYDROGEN-LIKE WAVEFUNCTIONS

$$E_n = -\frac{E_R}{n^2}$$



$$\psi_{100} = \sqrt{\frac{4Z^3}{{a_0}^3}}\, e^{-\frac{Zr}{a_0}} \frac{1}{\sqrt{4\pi}}$$

$$\psi_{200} = \sqrt{\frac{Z^3}{32\pi {a_0}^3}} \left(-\frac{Zr}{a_0} + 2\right) e^{-\frac{Zr}{2a_0}}$$

$$\psi_{210} = \sqrt{\frac{Z^3}{32\pi {a_0}^3}} \left(-\frac{Zr}{a_0}\right) e^{-\frac{Zr}{2a_0}} \cos(\theta)$$

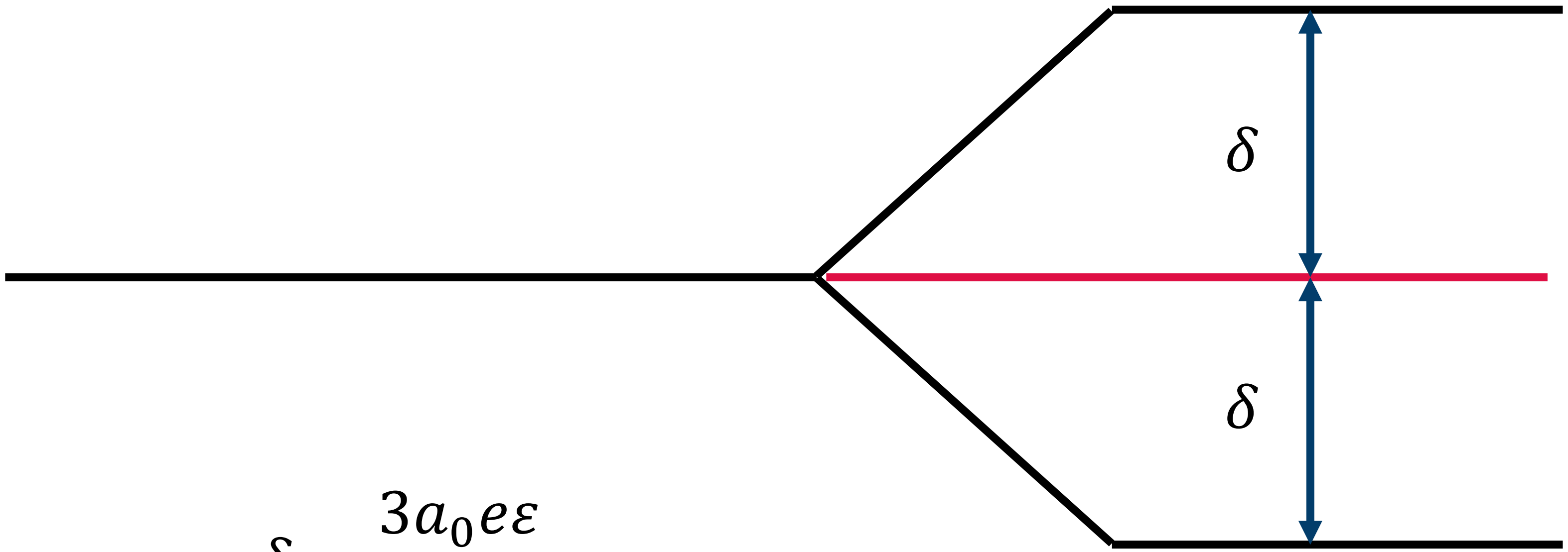
$$\psi_{21\pm1} = \mp\sqrt{\frac{Z^3}{64\pi {a_0}^3}} \left(-\frac{Zr}{a_0}\right) e^{-\frac{Zr}{2a_0}} \sin(\theta) e^{\pm i\phi}$$

STARK EFFECT

$$V_{Stark}(t) = e\vec{E}(t) \cdot \vec{r}$$

$$|\psi_+\rangle = \frac{1}{\sqrt{2}}(|2,0,0\rangle - |2,1,0\rangle)$$

$$E_2 = -\frac{E_R}{4}$$

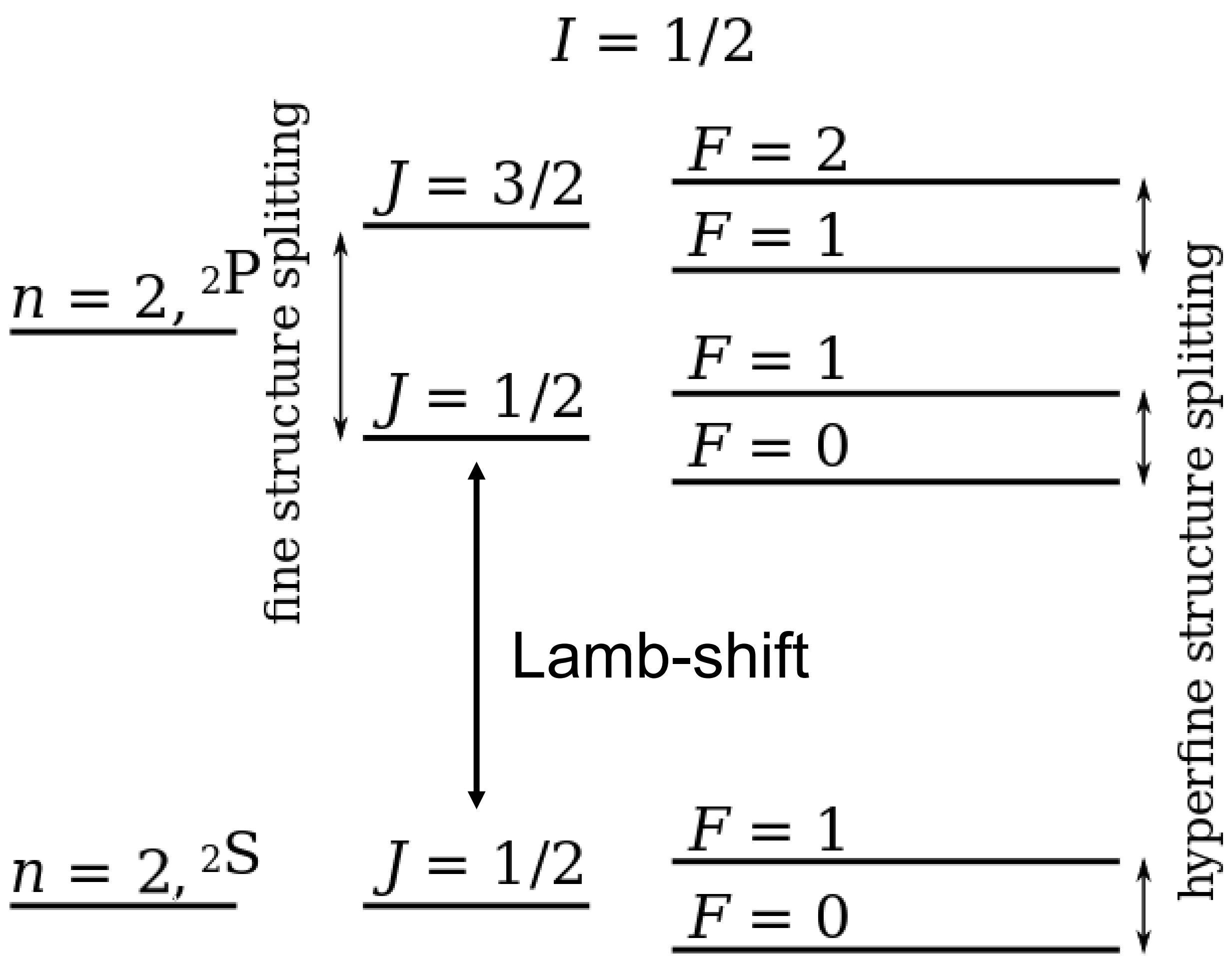


$$|\psi_{1,2}\rangle = |2,1,\pm1\rangle$$

$$\delta = \frac{3a_0 e\varepsilon}{Z}$$

$$|\psi_-\rangle = \frac{1}{\sqrt{2}}(|2,0,0\rangle + |2,1,0\rangle)$$

ENERGY SPLITTINGS



$$\vec{J} = \vec{L} \otimes 1 + 1 \otimes \vec{S}$$

$$\vec{F} = \vec{J} \otimes 1 + 1 \otimes \vec{I}$$

https://en.wikipedia.org/wiki/Hyperfine_structure

BREIT-RABI FORMULAS

$$H = \Delta E_{Lamb} \frac{\vec{L} \cdot \vec{S}}{\hbar^2} + A \frac{\vec{J} \cdot \vec{I}}{\hbar^2} + \left(g_j \mu_B \frac{\vec{J}}{\hbar} - g_I \mu_k \frac{\vec{I}}{\hbar} \right) \cdot \vec{B}$$

BREIT-RABI FORMULAS

$$H = \Delta E_{Lamb} \frac{\vec{L} \cdot \vec{S}}{\hbar^2} + A \frac{\vec{J} \cdot \vec{I}}{\hbar^2} + \left(g_j \mu_B \frac{\vec{J}}{\hbar} - g_I \mu_k \frac{\vec{I}}{\hbar} \right) \cdot \vec{B}$$

Example for $2S_{1/_2}$

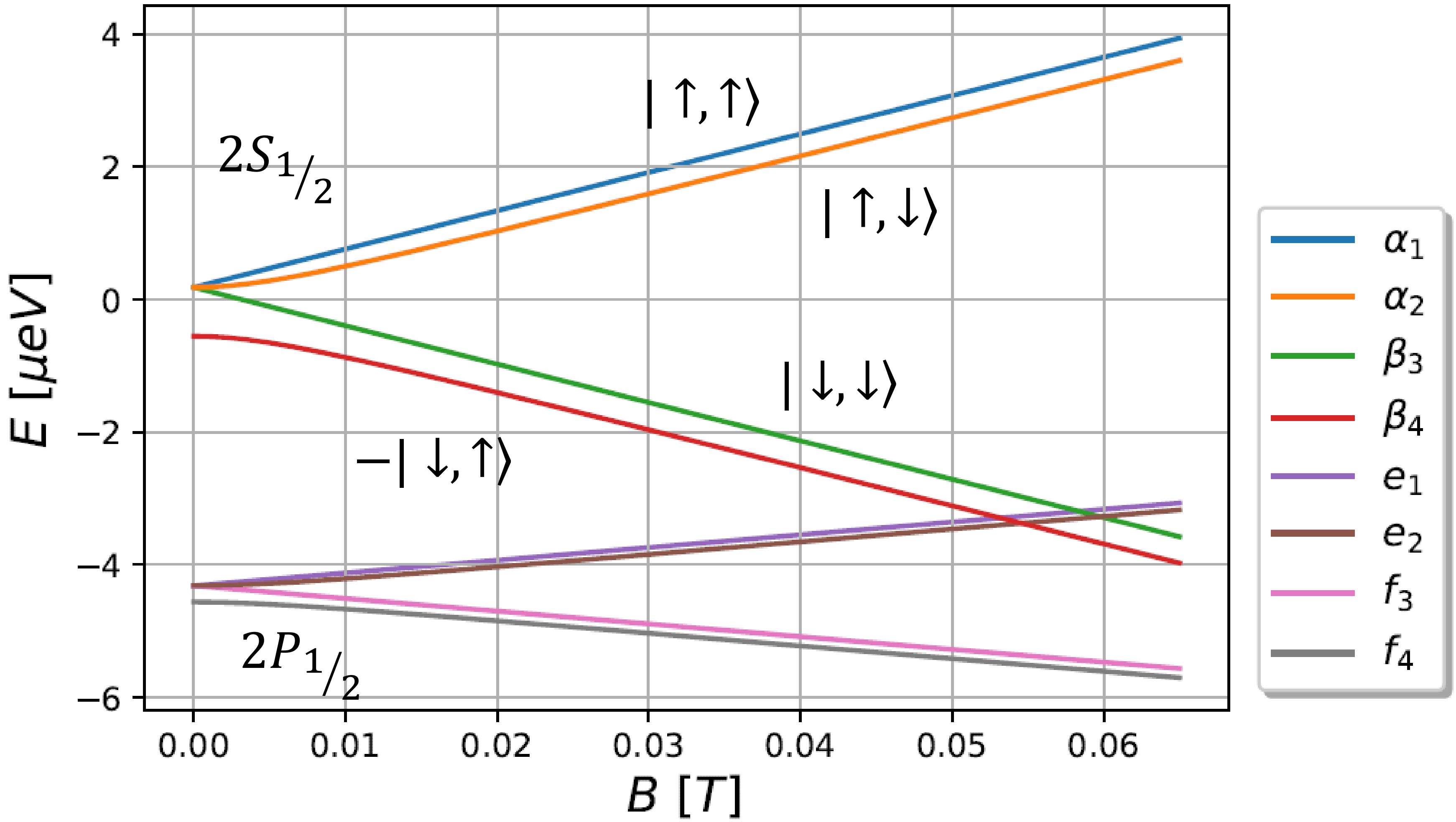
$$E_{\alpha_1} = \frac{A}{4} + \frac{1}{2}\left(g_j \mu_B - g_I \mu_k\right) B$$

$$E_{\alpha_2} = -\frac{A}{4} + \frac{1}{2}\sqrt{A^2 + \left(g_j \mu_B + g_I \mu_k\right)^2 B^2}$$

$$E_{\beta_3} = \frac{A}{4} - \frac{1}{2}\left(g_j \mu_B - g_I \mu_k\right) B$$

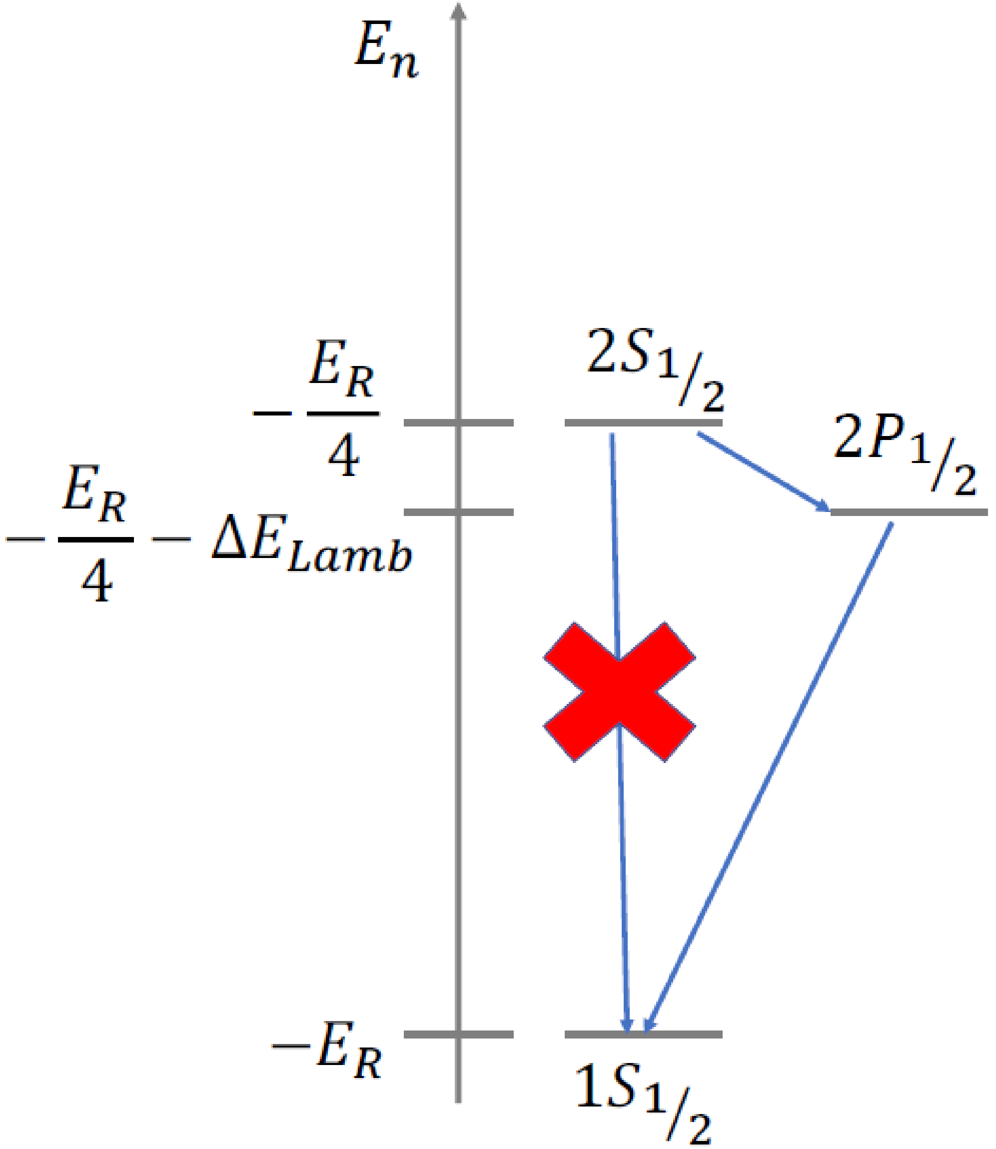
$$E_{\beta_4} = -\frac{A}{4} - \frac{1}{2}\sqrt{A^2 + \left(g_j \mu_B + g_I \mu_k\right)^2 B^2}$$

BREIT-RABI DIAGRAM



METASTABLE ATOMS

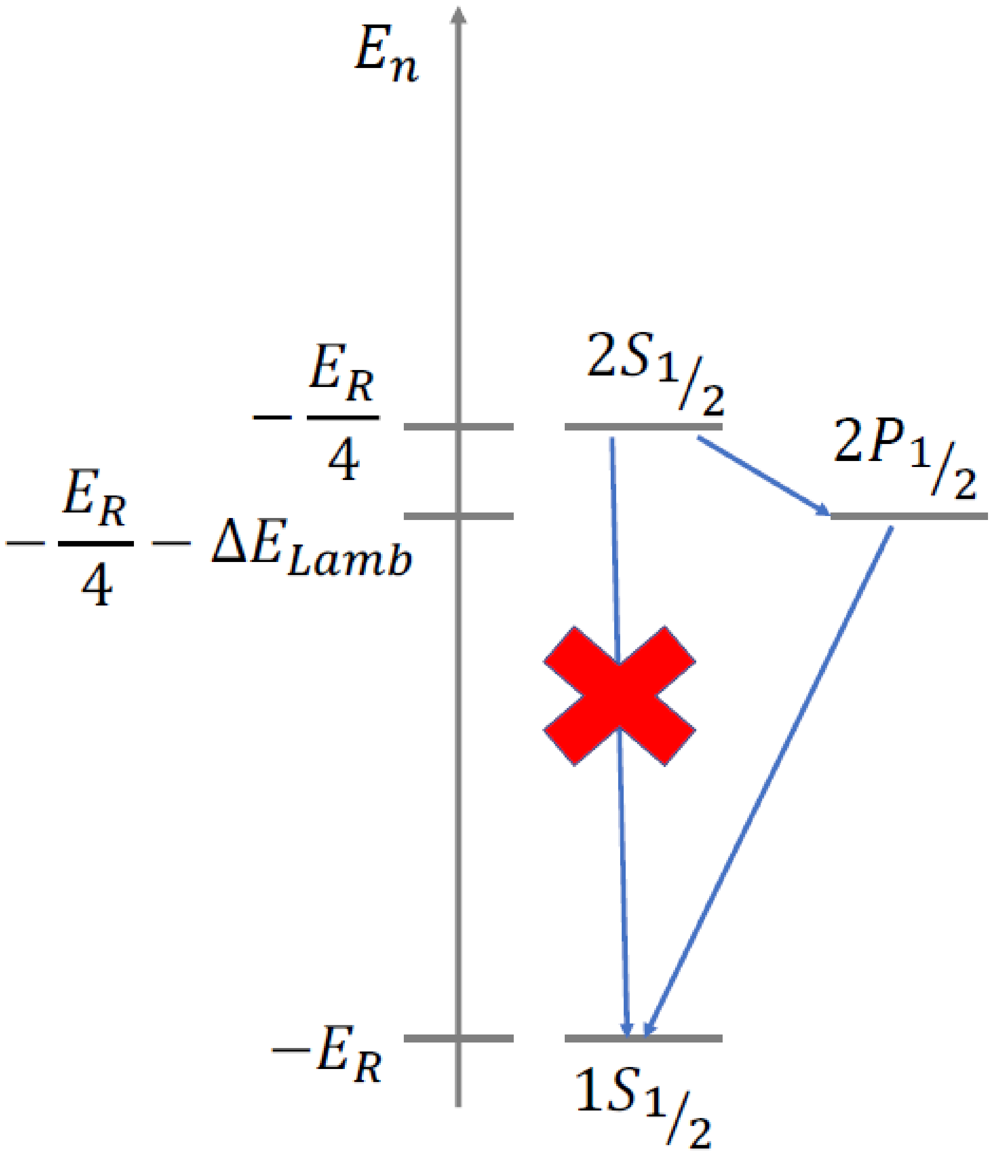
$$V_{Life} = -i\frac{\hbar}{2\tau}$$



METASTABLE ATOMS

$$V_{Life} = -i\frac{\hbar}{2\tau}$$

$$i\hbar\frac{\partial}{\partial t}|\psi_n(t)\rangle = \left(H + V_{Life}\right)|\psi_n(t)\rangle$$

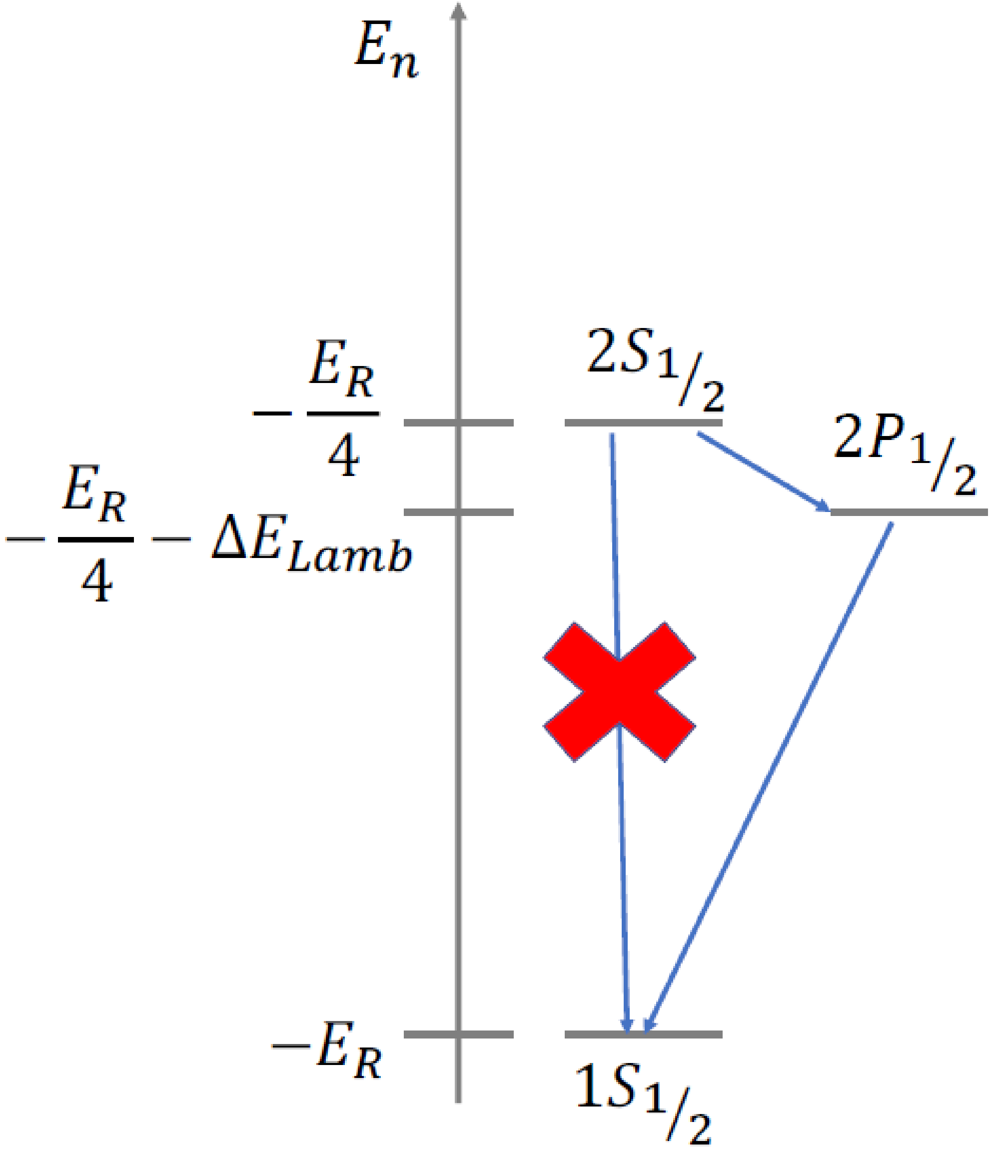


METASTABLE ATOMS

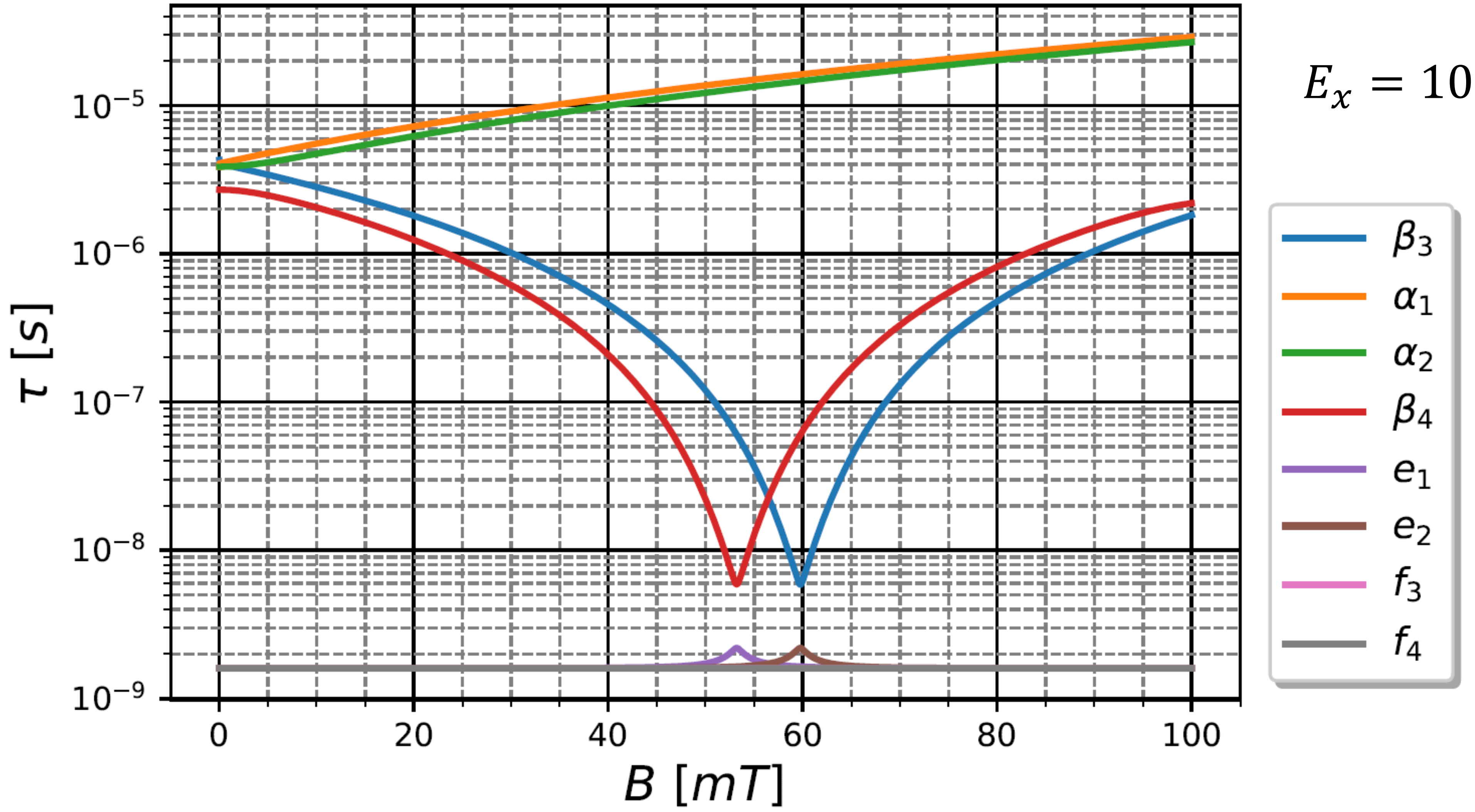
$$V_{Life} = -i\frac{\hbar}{2\tau}$$

$$i\hbar\frac{\partial}{\partial t}|\psi_n(t)\rangle = \left(H + V_{Life}\right)|\psi_n(t)\rangle$$

$$\langle\psi_n(t)|\psi_n(t)\rangle = |C(t)exp\left(-i\frac{\left(E_n - i\frac{\hbar}{2\tau}\right)}{\hbar}\right)|^2 = e^{-\frac{t}{\tau}}$$



LIFETIME

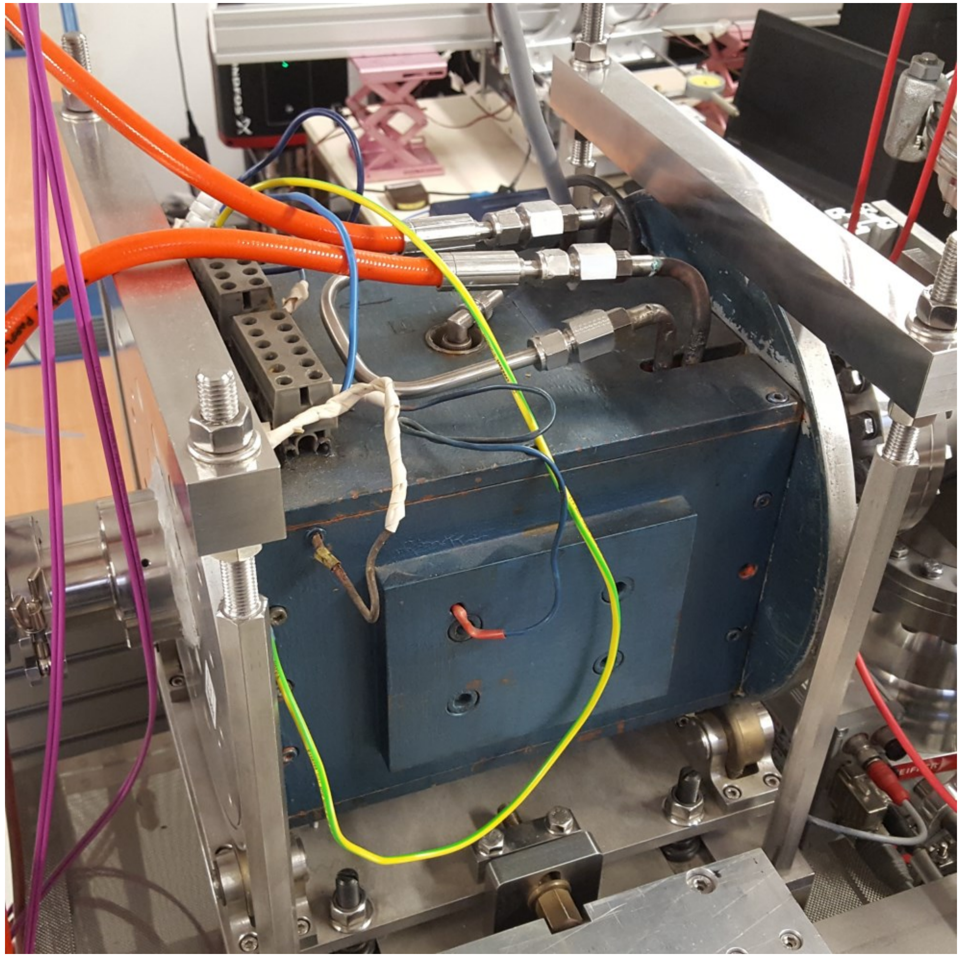


$$E_x = 10^3 \frac{V}{m}$$

WIEN-FILTER

- Electric and magnetic field perpendicular to beam direction

$$\vec{v} \perp \vec{\varepsilon} \perp \vec{B}$$



JÜLICH Forschungszentrum

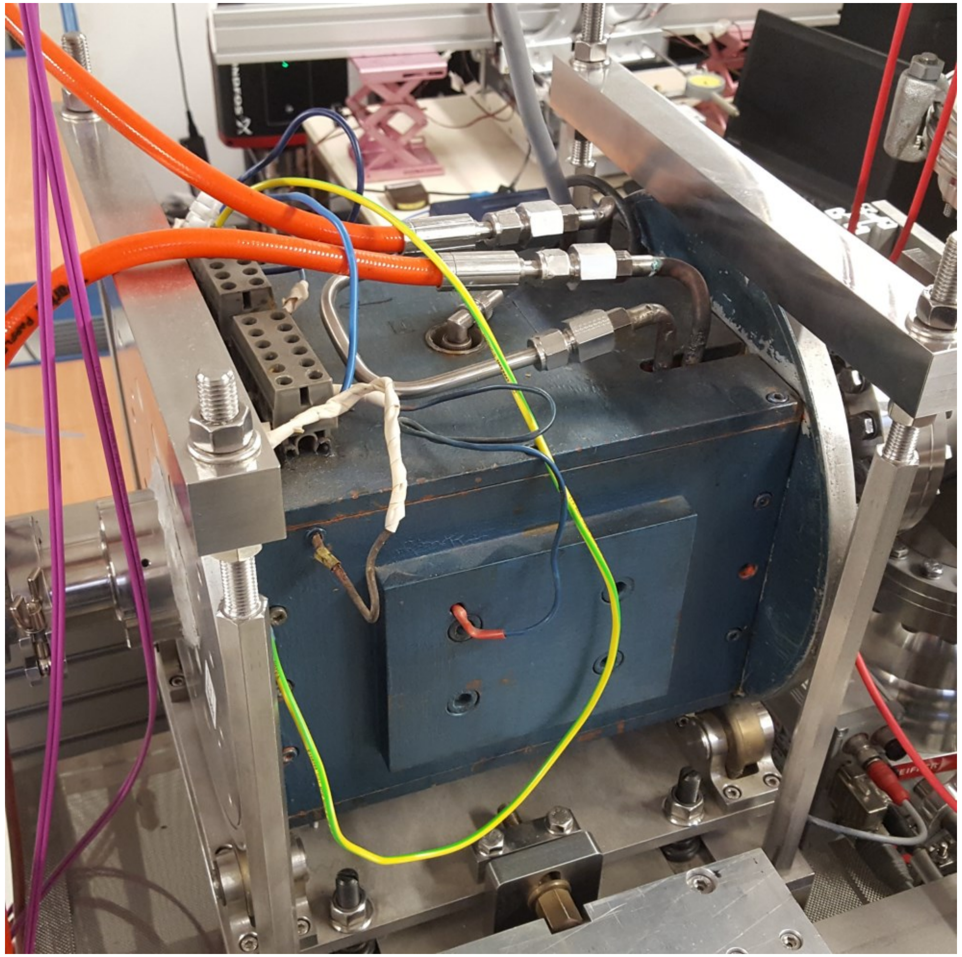
WIEN-FILTER

- Electric and magnetic field perpendicular to beam direction

$$\vec{v} \perp \vec{\varepsilon} \perp \vec{B}$$

- Sharpening the beam velocity

$$\vec{F}_{el.} = q\vec{\varepsilon} = q\left(\vec{v} \times \vec{B}\right) = \vec{F}_{Lorentz} \qquad |v| = \frac{|\varepsilon|}{|B|}$$



WIEN-FILTER

- Electric and magnetic field perpendicular to beam direction

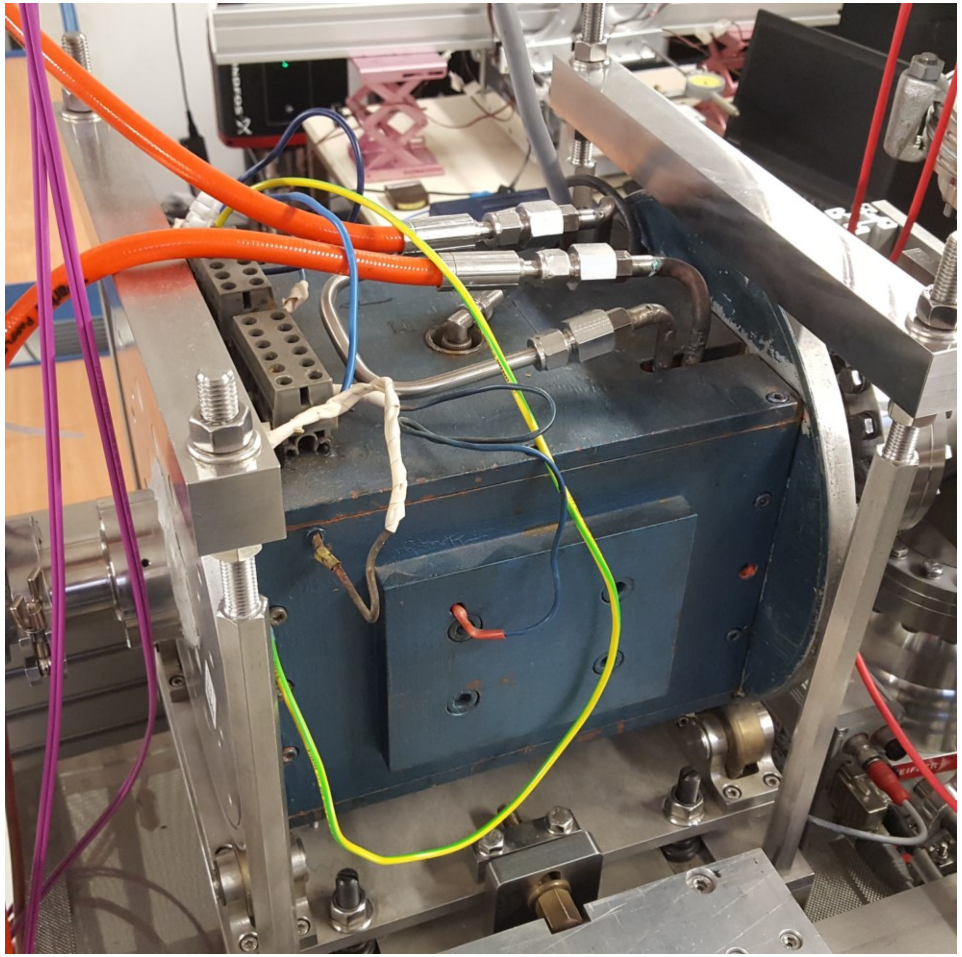
$$\vec{v} \perp \vec{\varepsilon} \perp \vec{B}$$

- Sharpening the beam velocity

$$\vec{F}_{el.} = q\vec{\varepsilon} = q\left(\vec{v} \times \vec{B}\right) = \vec{F}_{Lorentz} \qquad |v| = \frac{|\varepsilon|}{|B|}$$

- For a fixed beam energy then works as a mass filter

$$E_{kin} = \frac{1}{2}mv^2 \qquad m = \frac{2E_{kin}B^2}{\varepsilon^2}$$

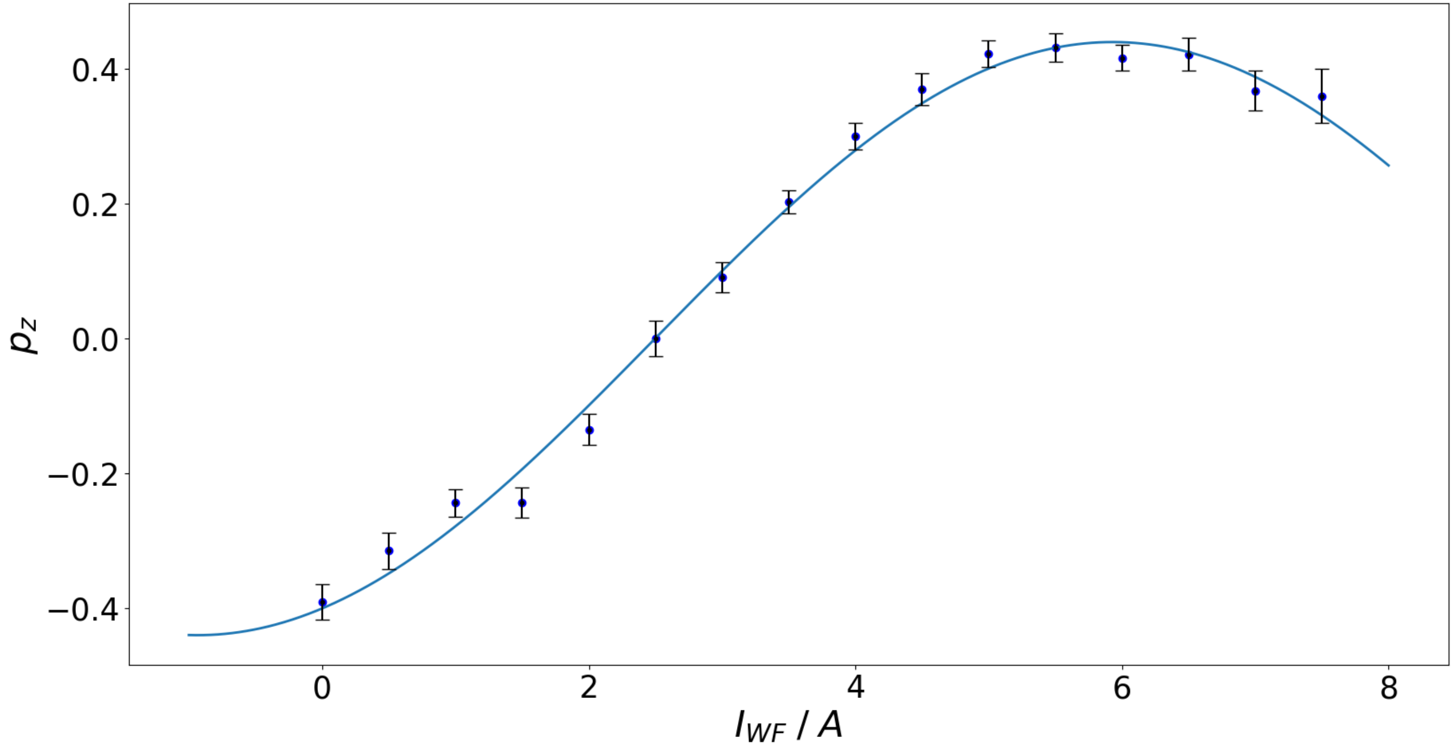


JÜLICH Forschungszentrum

WIEN-FILTER

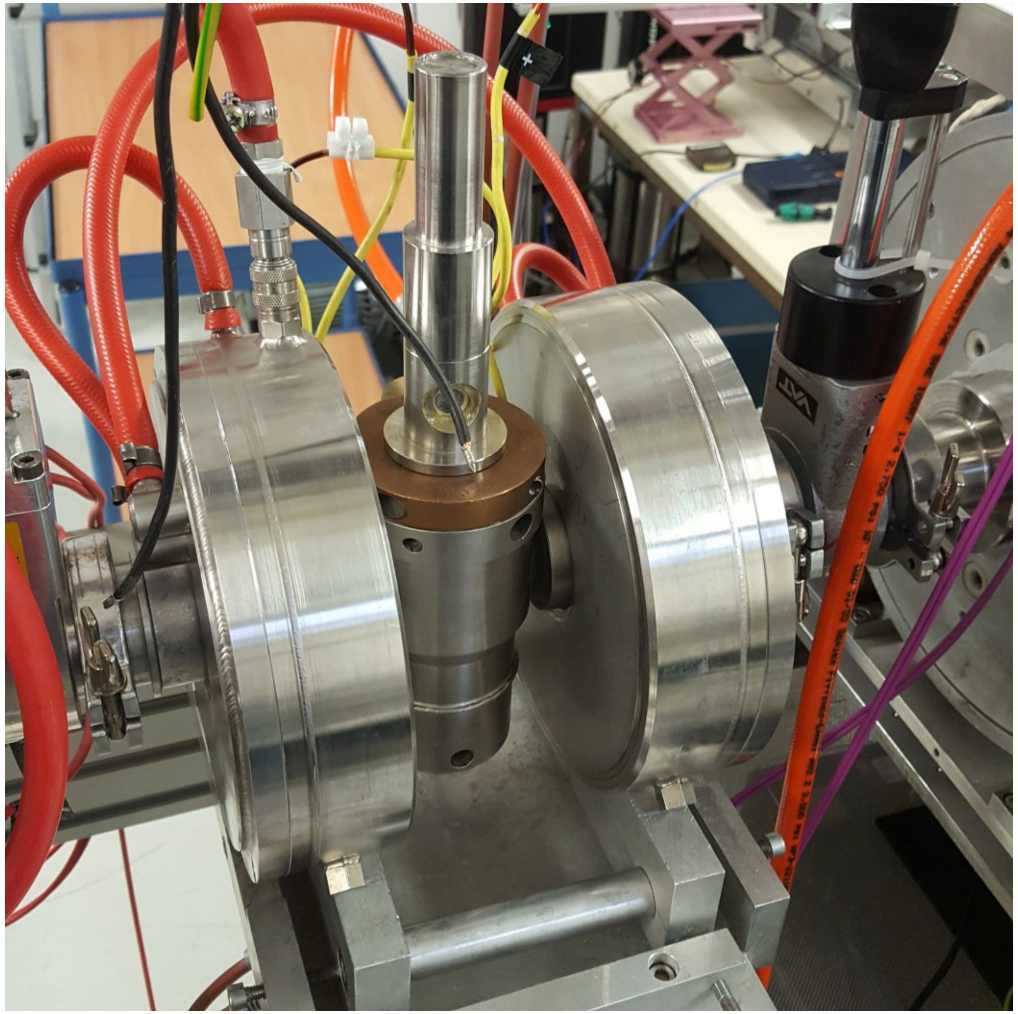
- Spins of the particles interact with the magnetic field

$$\omega_{Larmor} = -\frac{gqB}{2m}$$



CAESIUM CELL

- Using the properties of alkali metals for charge exchange

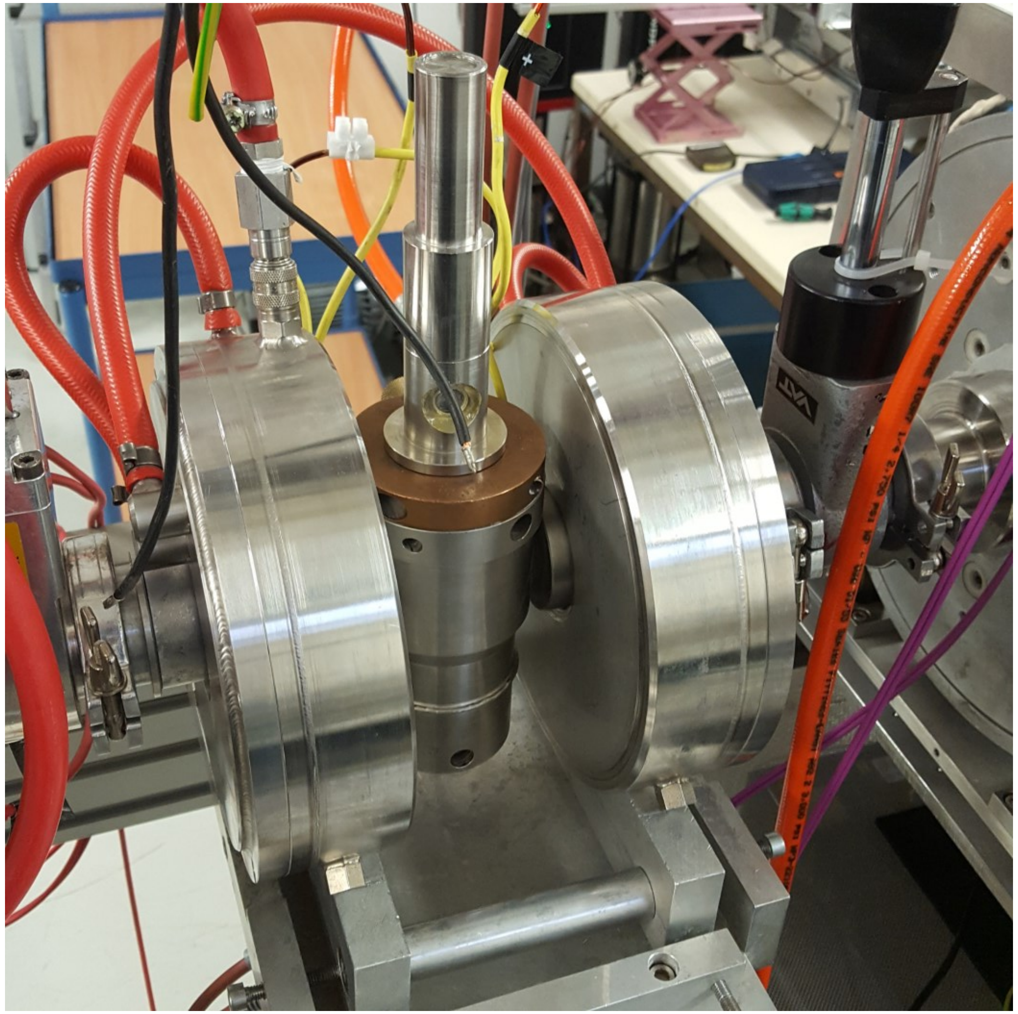


CAESIUM CELL

- Using the properties of alkali metals for charge exchange

- Creating metastable hydrogen

$$H^{+} + Cs \rightarrow H_{2S}^{*} + Cs^{+}$$

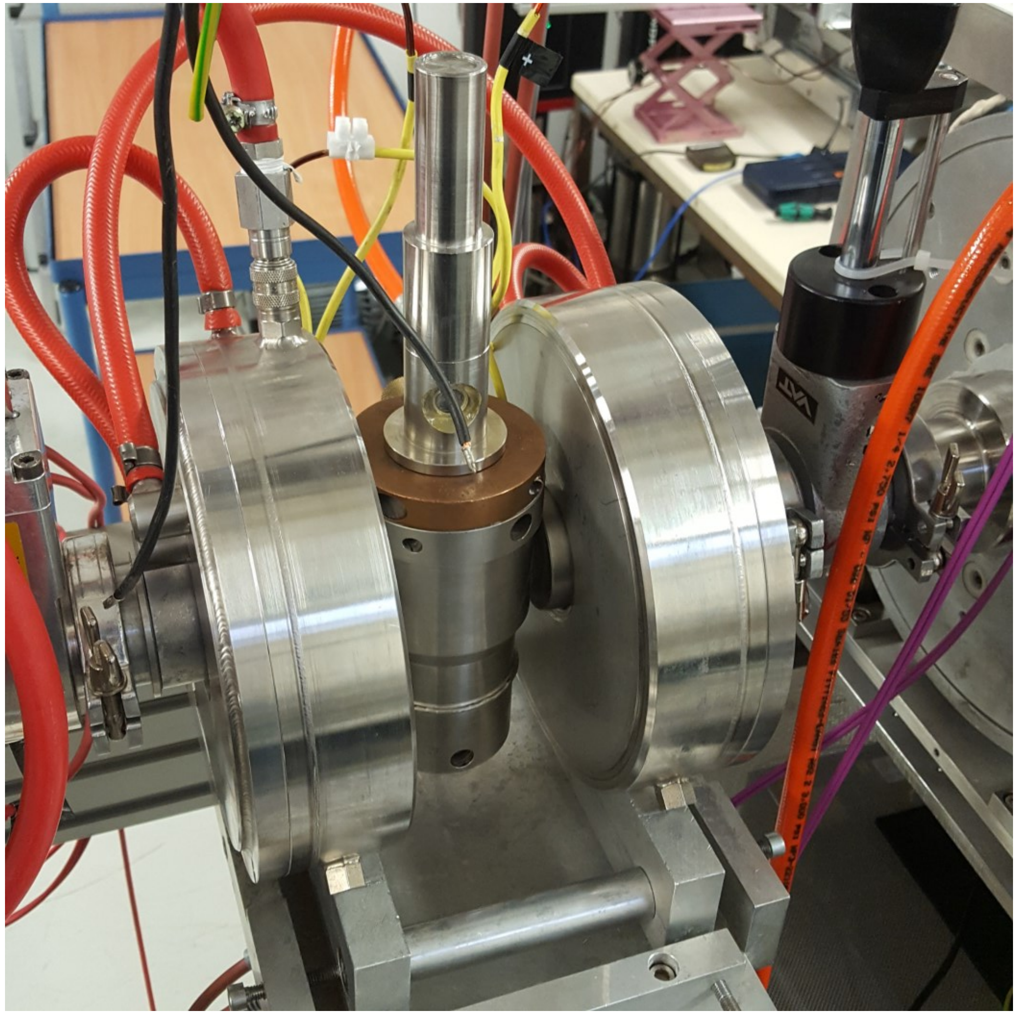


CAESIUM CELL

- Using the properties of alkali metals for charge exchange

- Creating metastable hydrogen

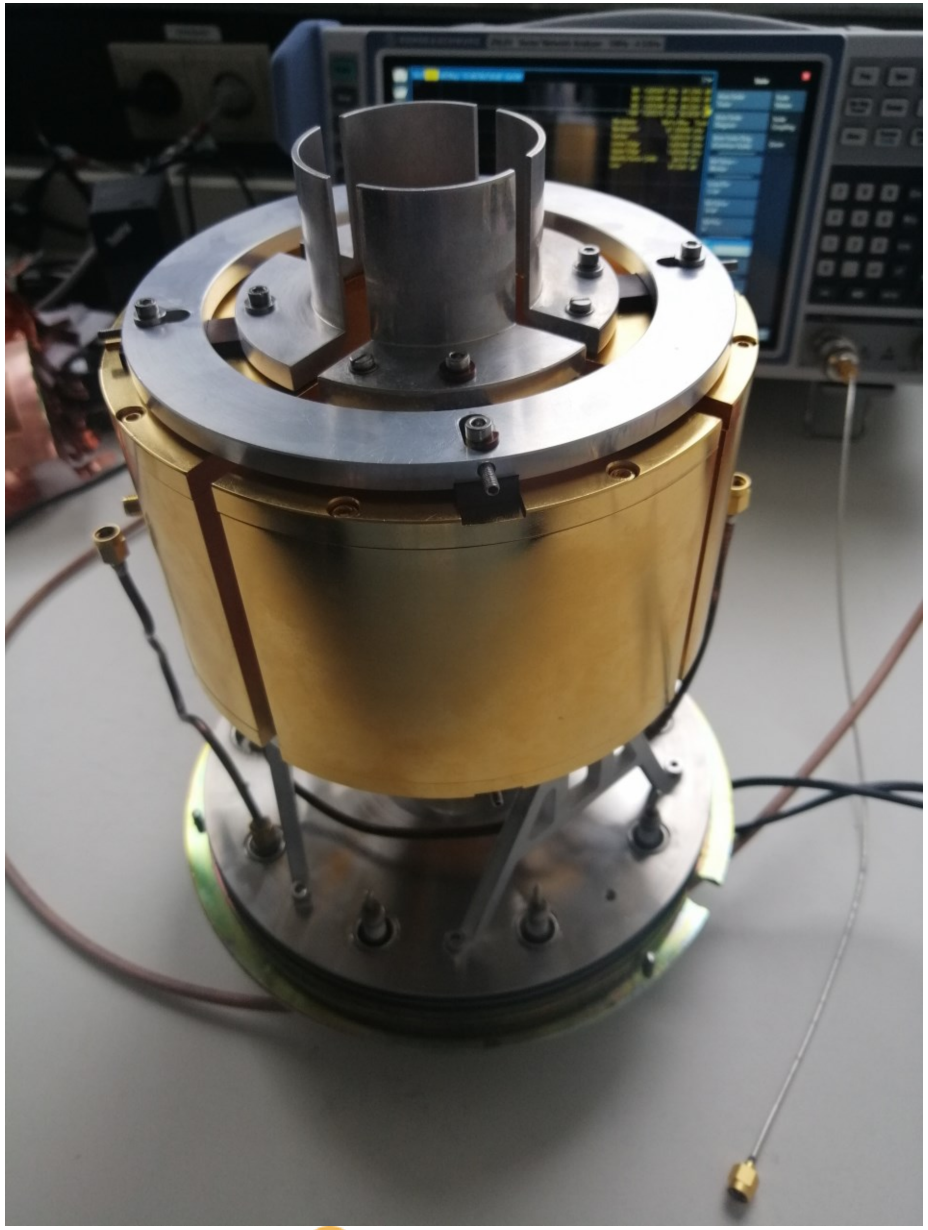
$$H^{+} + Cs \rightarrow H^{*}_{2S} + Cs^{+}$$



- Lower temperature (Cs: 160 °C / Na: 350 °C)

SPIN FILTER

- Aim to separate the different Breit-Rabi states
- Contains several coils producing a homogeneous static magnetic field in beam direction
- Embedded sits a cavity in which a radio frequency as well as a static electric field is induced



GSI JÜLICH Forschungszentrum

THEORY FOR THE SPIN FILTER

$$H_{SF} = H_{BR} + \underbrace{V_{Life} + V_{Stark} + V_{RF}(t)}_{= V(t)}$$

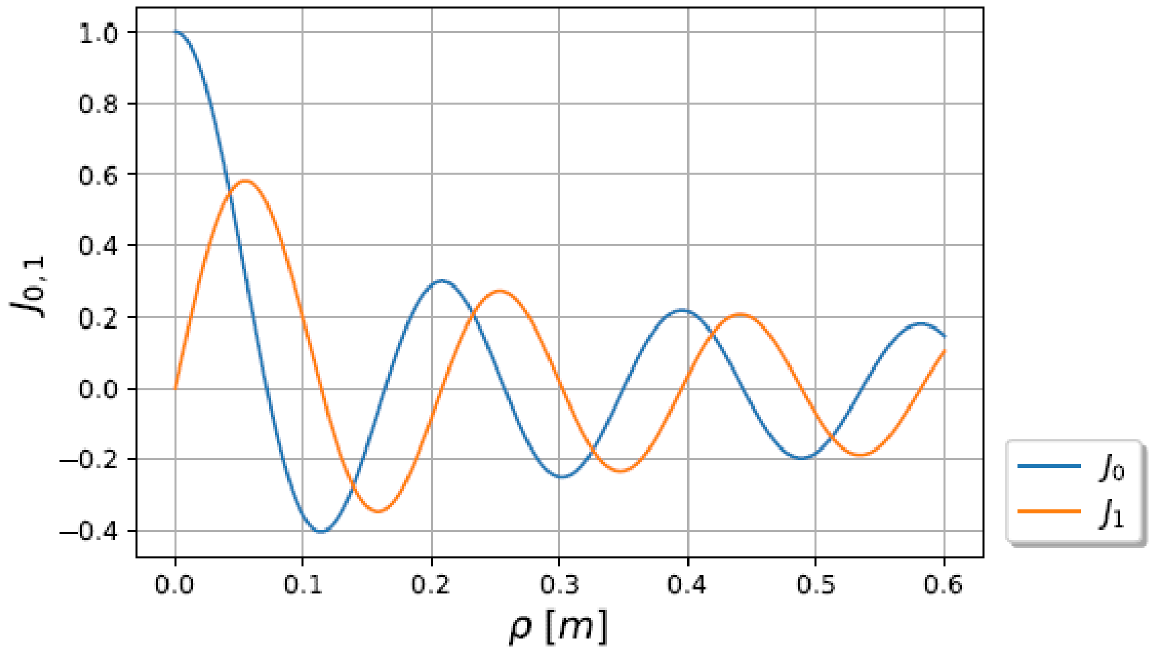
THEORY FOR THE SPIN FILTER

$$H_{SF} = H_{BR} + \underbrace{V_{Life} + V_{Stark} + V_{RF}(t)}_{= V(t)}$$

$$\omega_{0,1,0} = \frac{2.405c}{R}$$

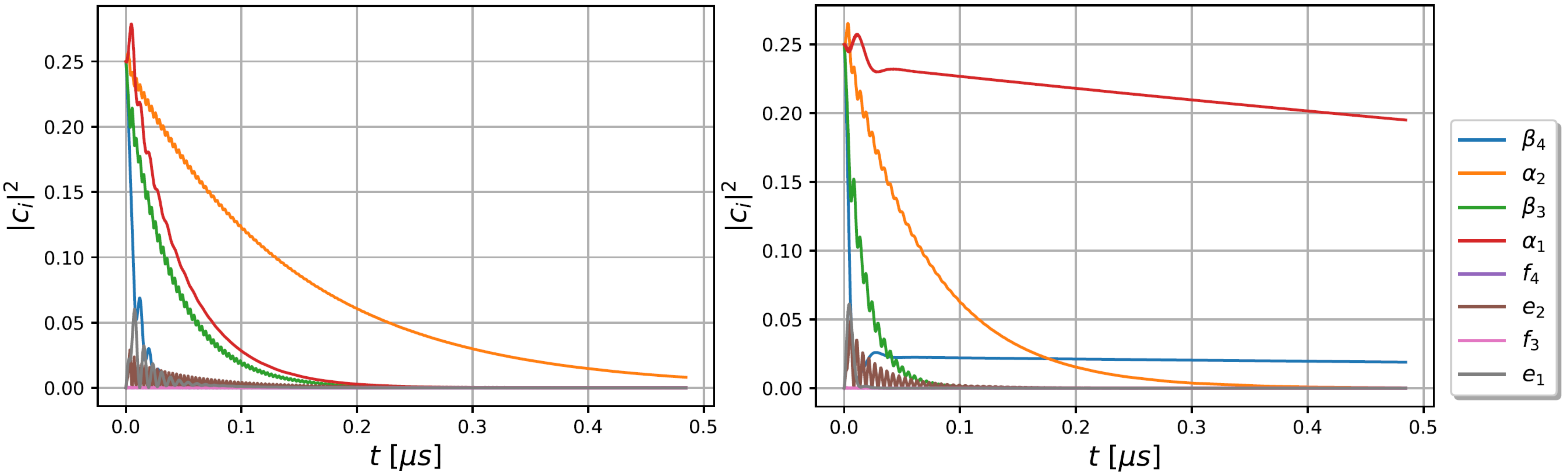
$$\vec{E} = Re\left[E_0 J_0\left(\frac{2.405\rho}{R}\right) e^{-i\omega_{0,1,0}t}\hat{e}_z\right]$$

$$\vec{B} = Im\left[-\frac{E_0}{c} J_1\left(\frac{2.405\rho}{R}\right) e^{-i\omega_{0,1,0}t}\hat{e}_\phi\right]$$



JÜLICH Forschungszentrum

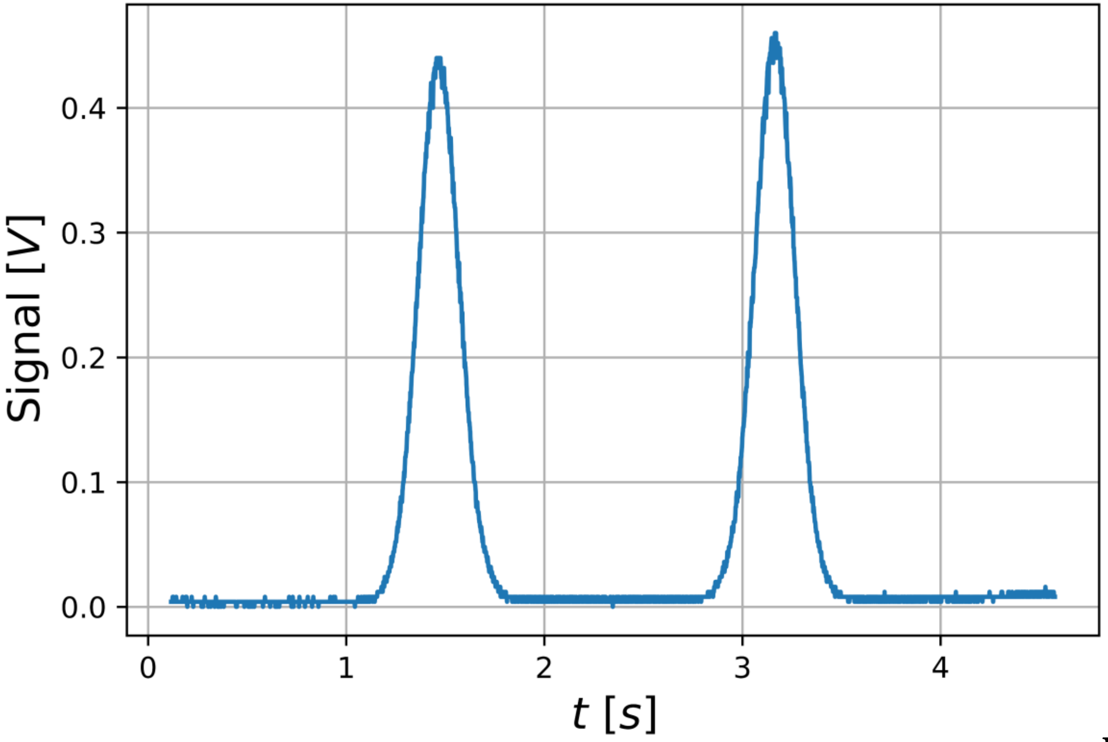
EVOLUTION IN TIME



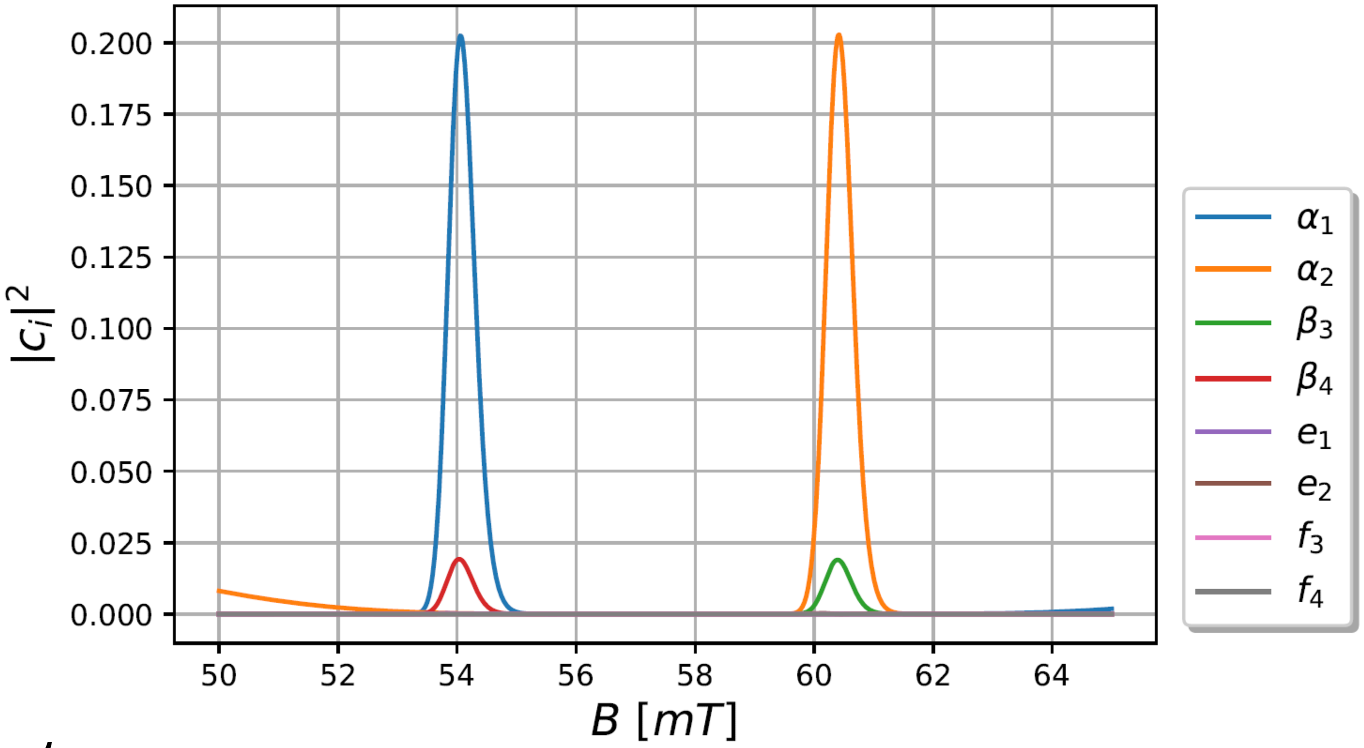
$$B = 50\ mT \qquad \left|c_{2S_{1/2}}\right|^2 = 0.25 \qquad B = 54\ mT$$

RAMPED MAGNETIC FIELD

Measurement



Simulation



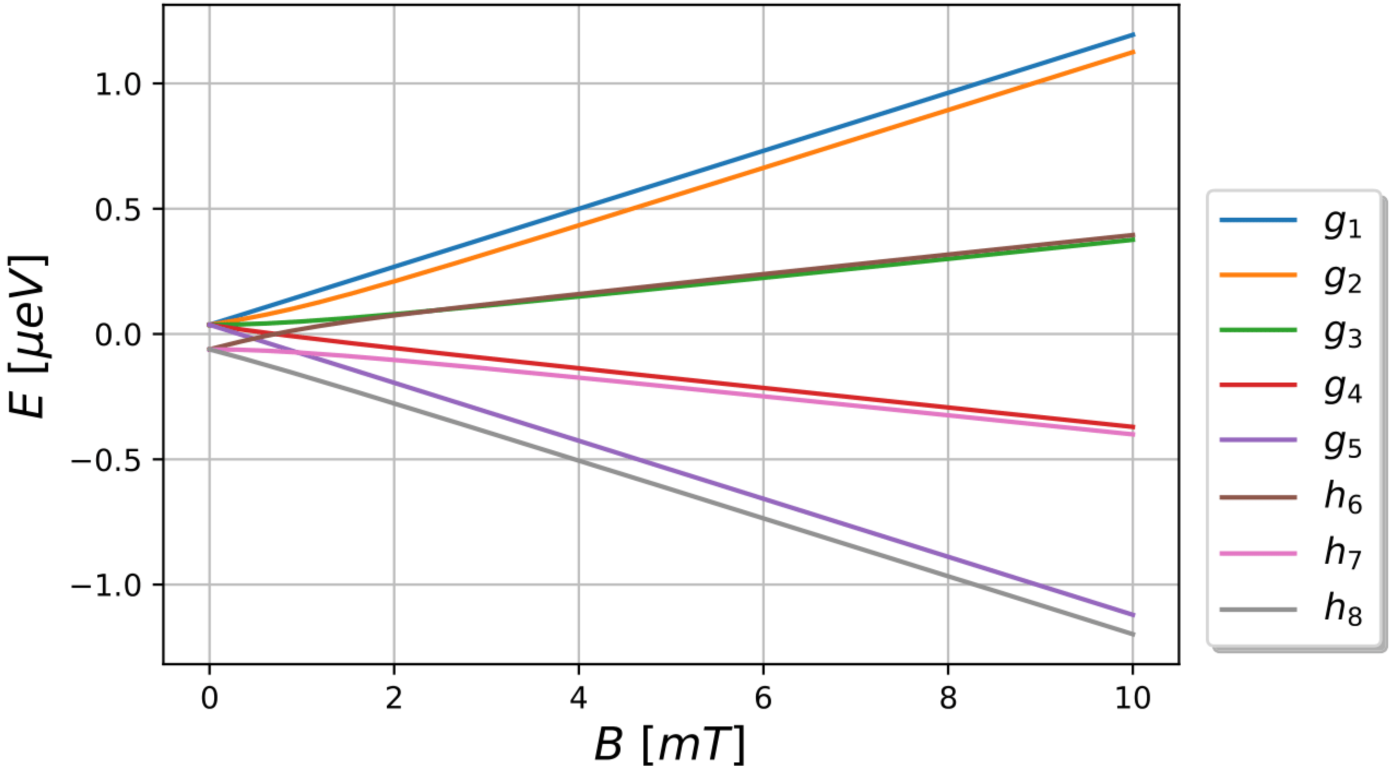
$B \sim t$

GSI JÜLICH Forschungszentrum

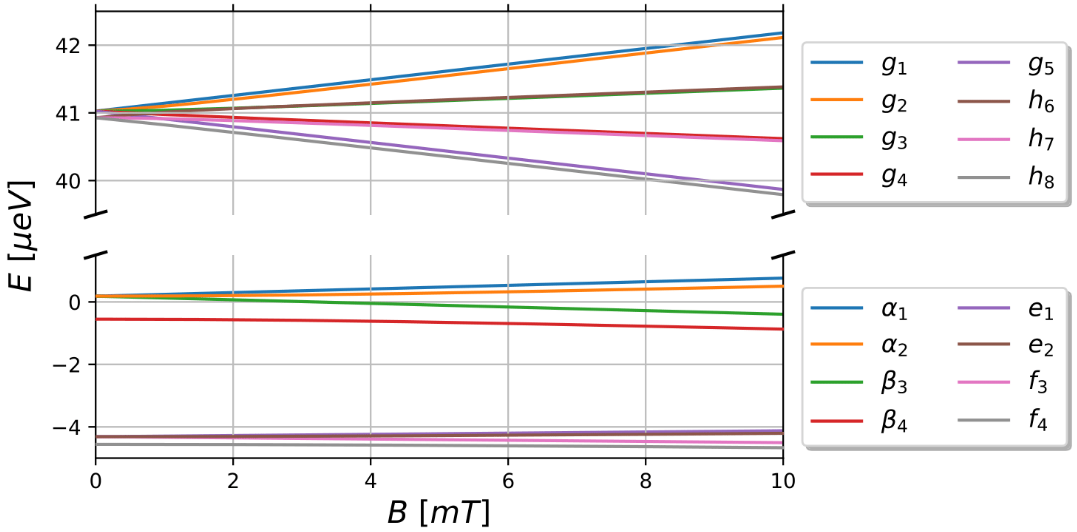
SECOND GENERATION SPIN FILTER

- Extend the spin filter such that also β states can be selected

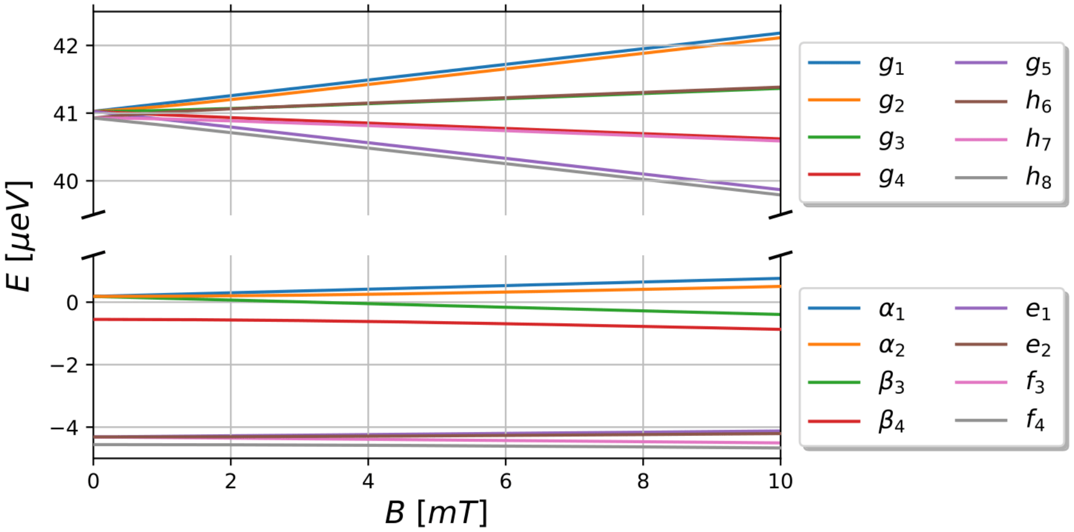
- Use the interaction with the $2P_{3/2}$ set

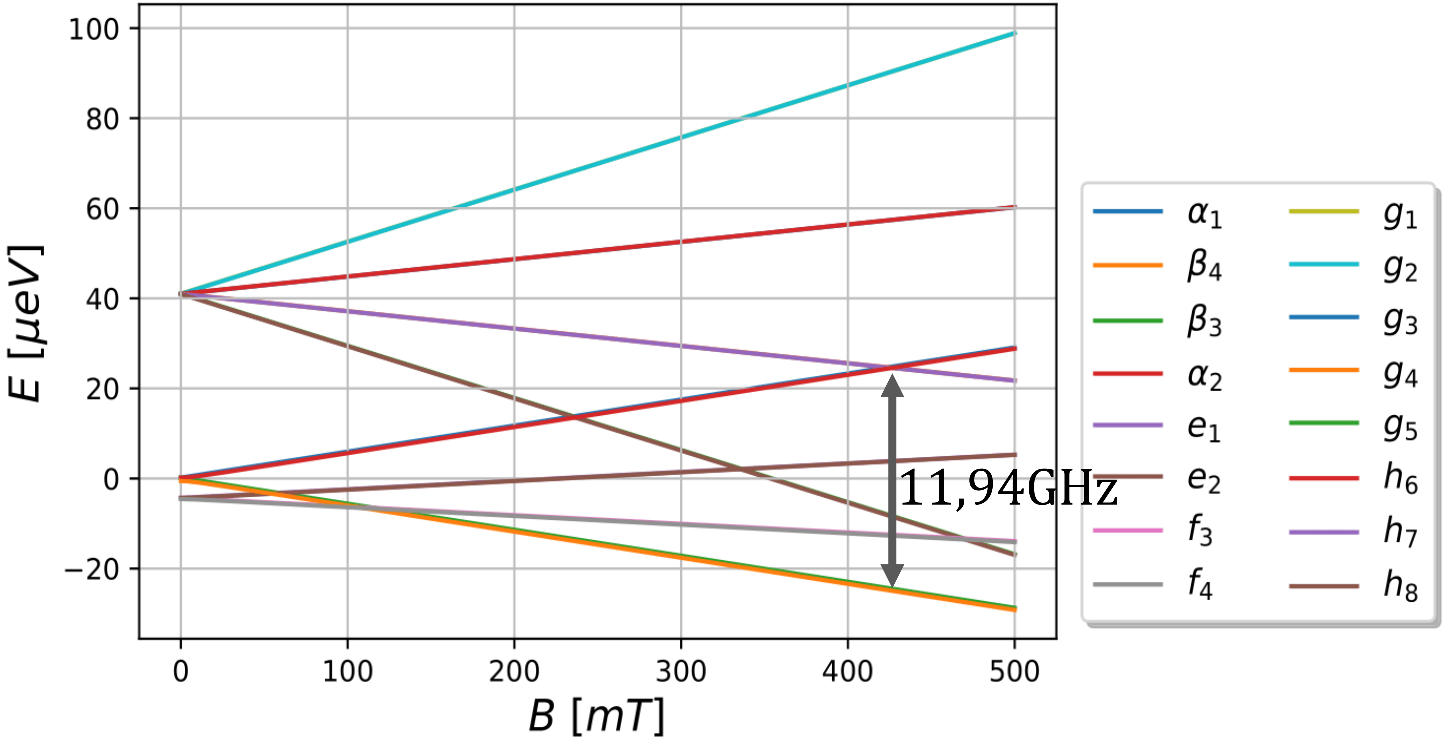


SECOND GENERATION SPIN FILTER



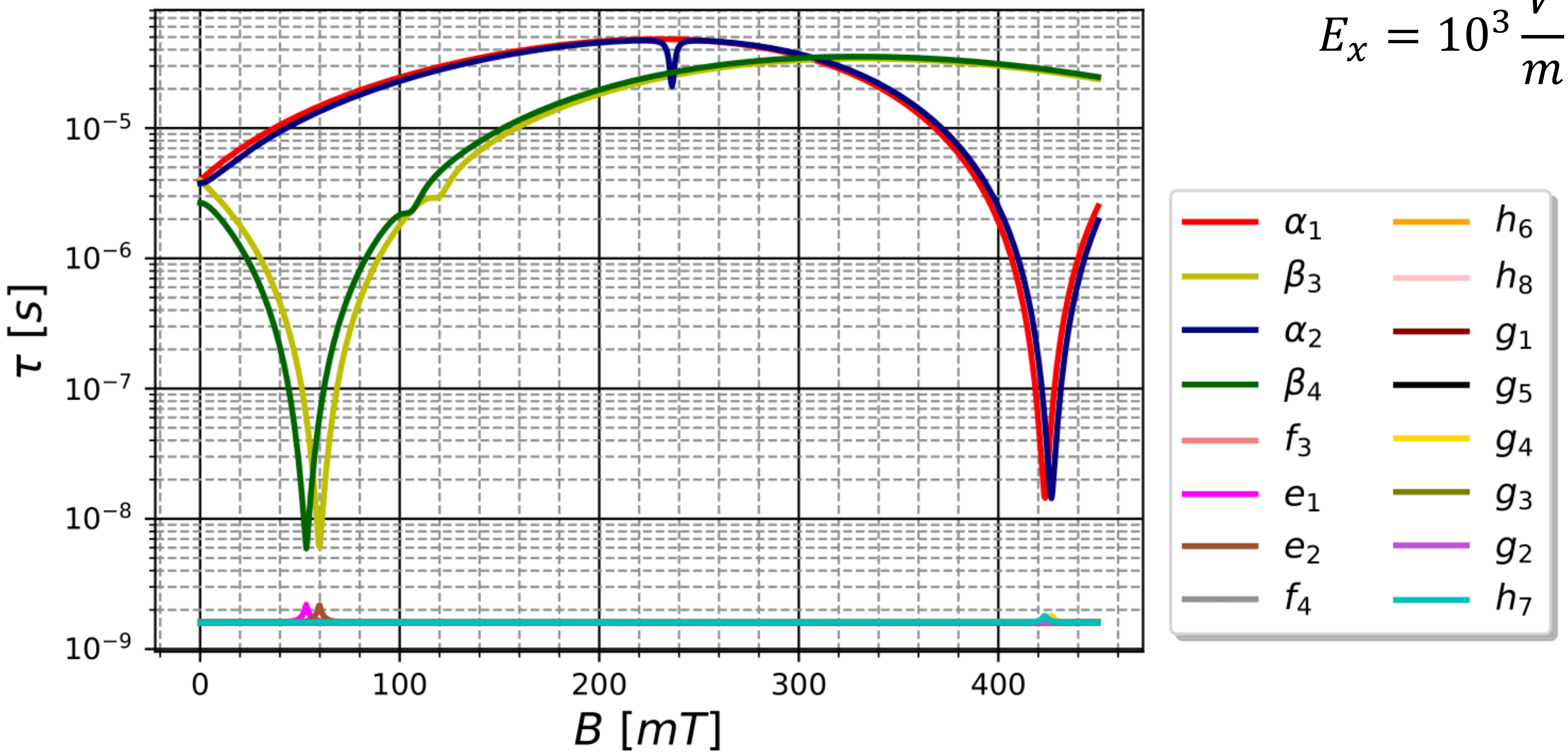
SECOND GENERATION SPIN FILTER





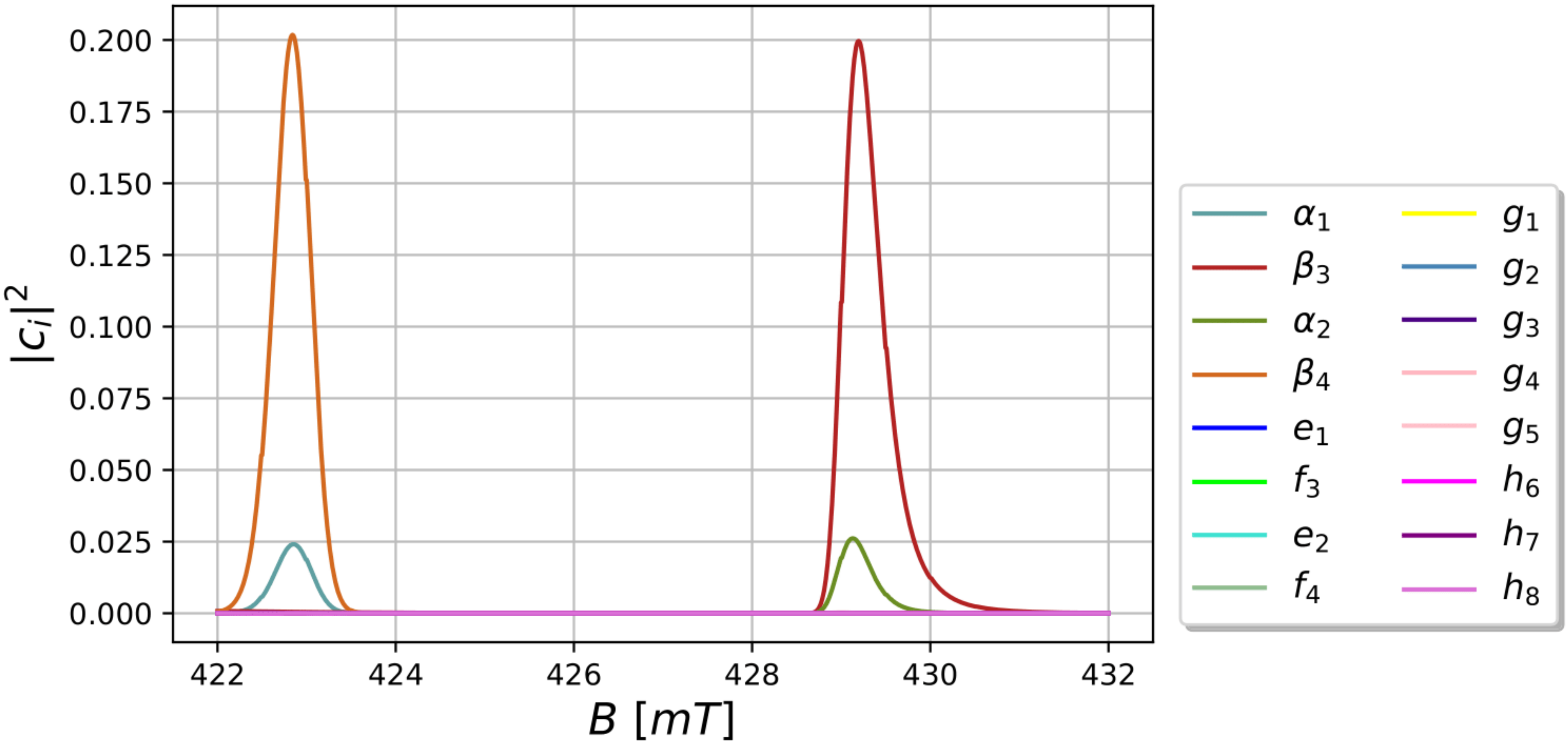
JÜLICH
Forschungszentrum

LIFETIMES INCLUDING $2P_{3/2}$

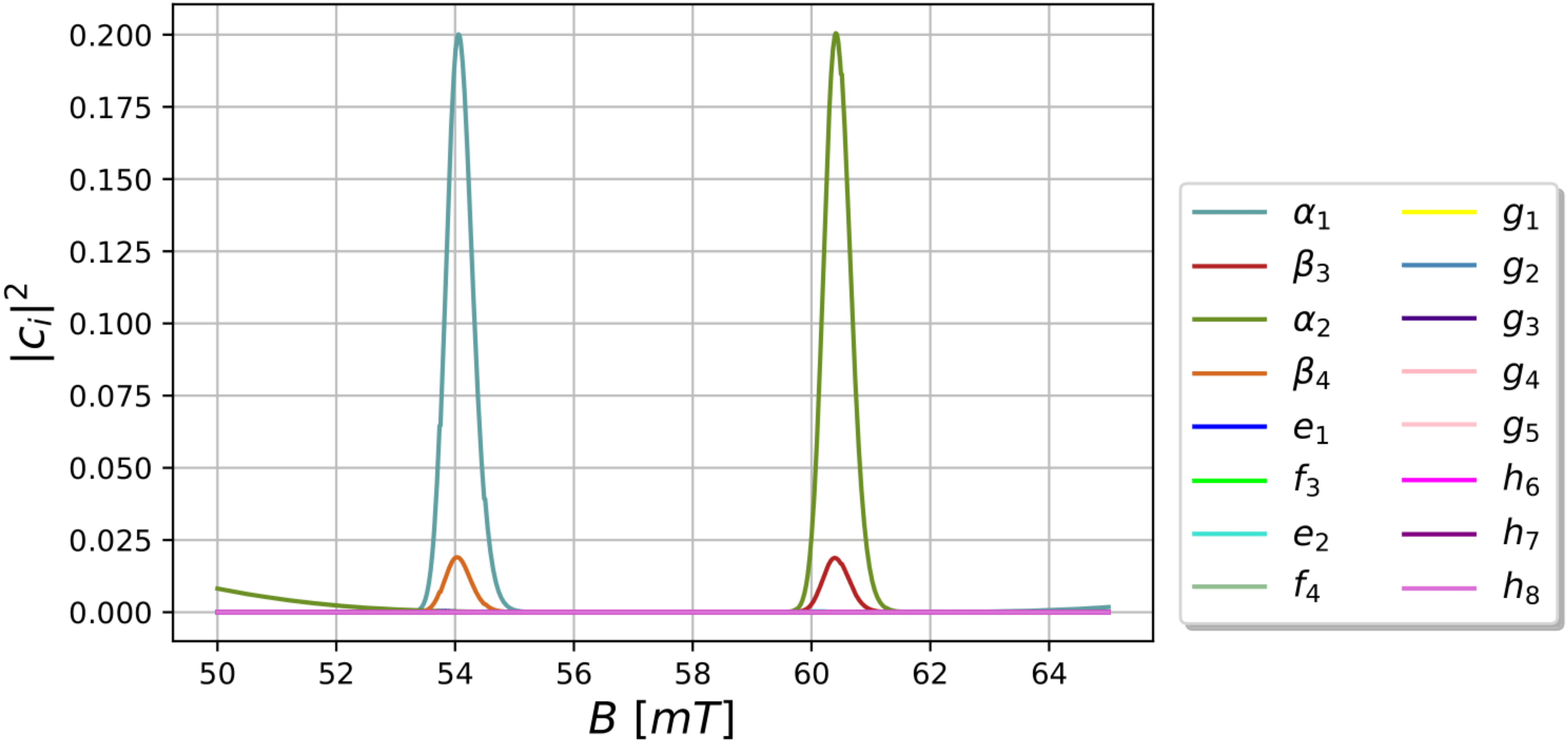


$$E_x = 10^3 \frac{V}{m}$$

METASTABLE HYDROGEN



METASTABLE HYDROGEN



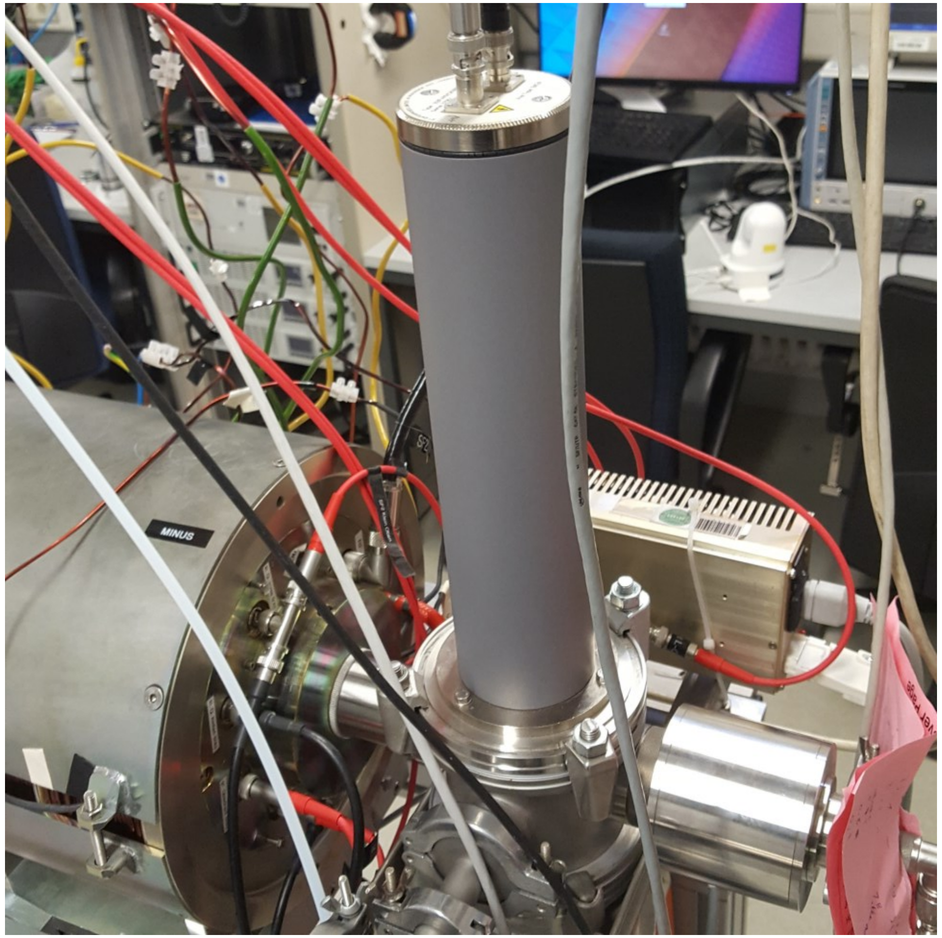
JÜLICH Forschungszentrum

QUENCHING CHAMBER

- Using Stark effect to quench all metastable into the ground state

- Created Ly-α photons are detected by a photomultiplier

- Directly observing the metastable occupation numbers



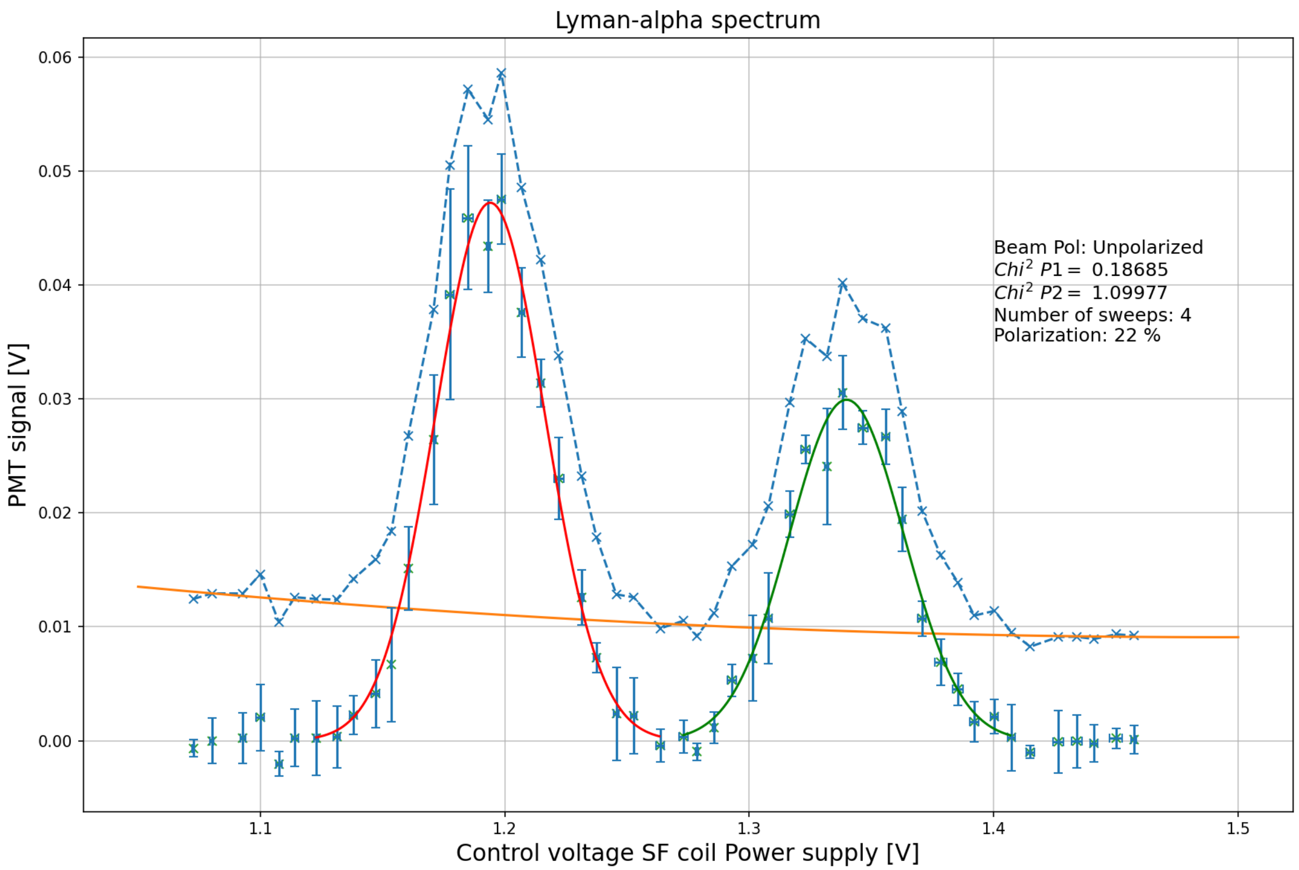
GSI JÜLICH Forschungszentrum

PULSED H^- SOURCE

- Direct nuclear polarization measurement

- Pulsed sources detectable

- Uncertainty in the beam transport and polarization preservation and creation

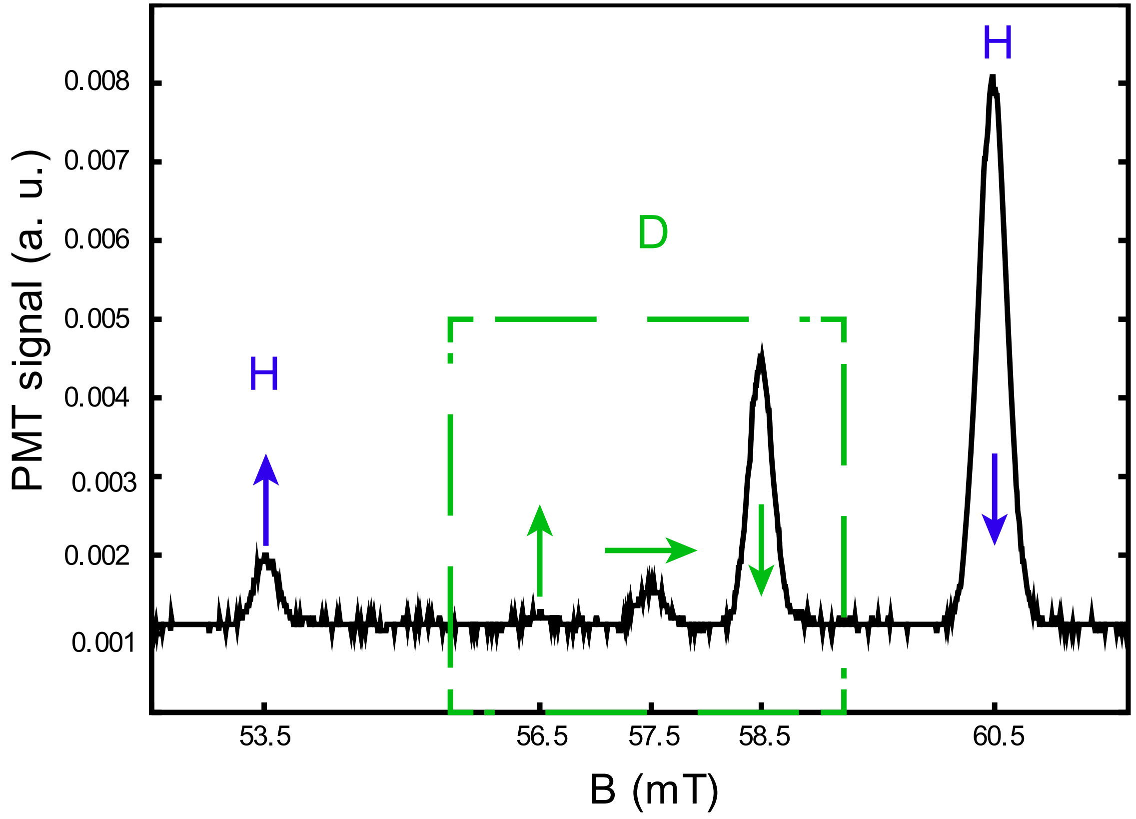


JÜLICH
Forschungszentrum

OUTLOOK AND CONCLUSION

- Lamb-shift is a simple and consistent tool to verify nuclear and electron polarization

- Continuous and pulsed sources detectable



R. Engels et al. , Phys. Rev. Lett. **124**, (2020)

- Usage for hydrogen and its isotopes in atomic, ionic and molecular form