MAX PLANCK INSTITUTE FOR NUCLEAR PHYSICS

Hirschegg 2012

“Precision Penning Trap Experiments with Exotic Ions”

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January 16, 2012

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

EMMI

GSI

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

MAX-PLANCK-GESELLSCHAFT

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Outline

- Introduction and motivation
- Principle of Penning traps
- Setup and measurement procedure
- Precision mass and *g*-factor measurements

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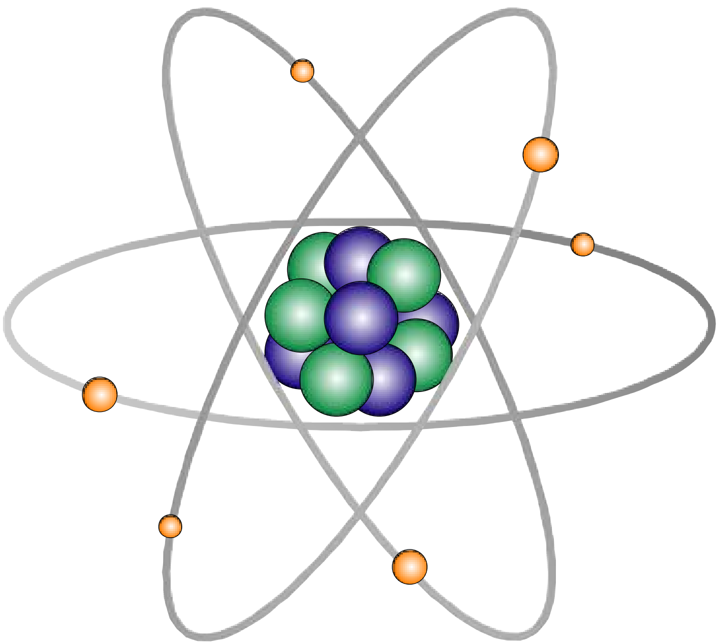
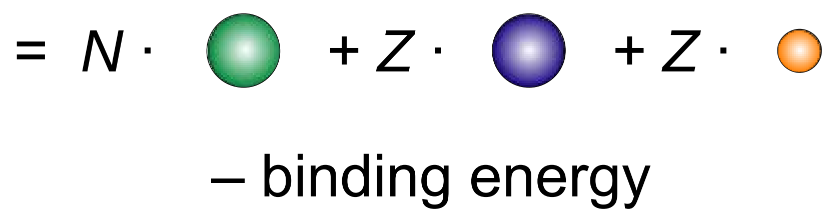
Part I

High-precision mass measurements

Applications of precision masses

High-accuracy mass measurements allow one to determine the atomic and nuclear binding energies reflecting all forces in the atom/nucleus.





$$M_{\mathrm{Atom}} = N \bullet m_{\mathrm{neutron}} + Z \bullet m_{\mathrm{proton}} + Z \bullet m_{\mathrm{electron}} - (B_{\mathrm{atom}} + B_{\mathrm{nucleus}})/c^2$$

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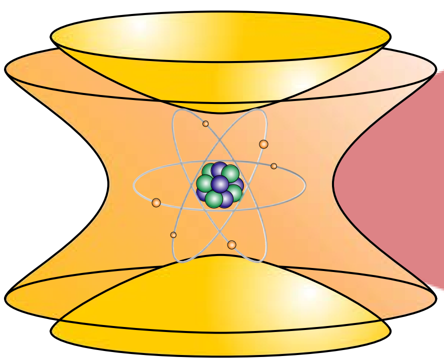
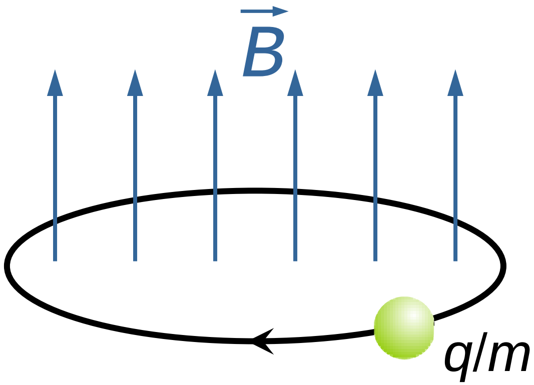
Why measuring atomic masses?

Atomic and nuclear binding energies reflect all forces acting in the atom/nucleus.



	$\delta m/m$
General physics & chemistry	$\leq 10^{-5}$
Nuclear structure physics - separation of isobars	$\leq 10^{-6}$
Astrophysics - separation of isomers	$\leq 10^{-7}$
Weak interaction studies	$\leq 10^{-8}$
Metrology - fundamental constants Neutrino physics	$\leq 10^{-9}$
CPT tests	$\leq 10^{-10}$
QED in highly-charged ions - separation of atomic states	$\leq 10^{-11}$

Principle of Penning trap mass spectrometry

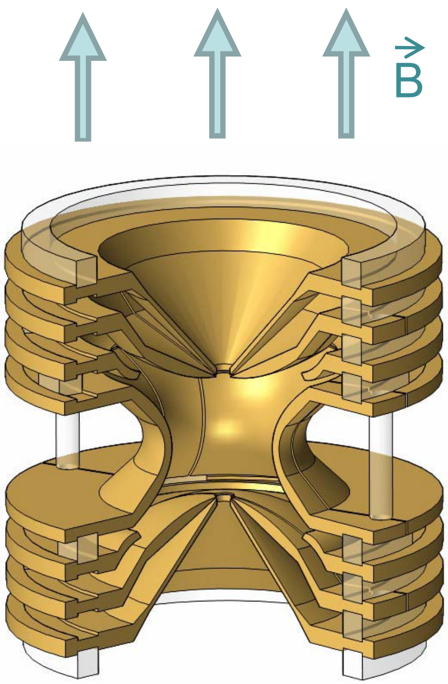


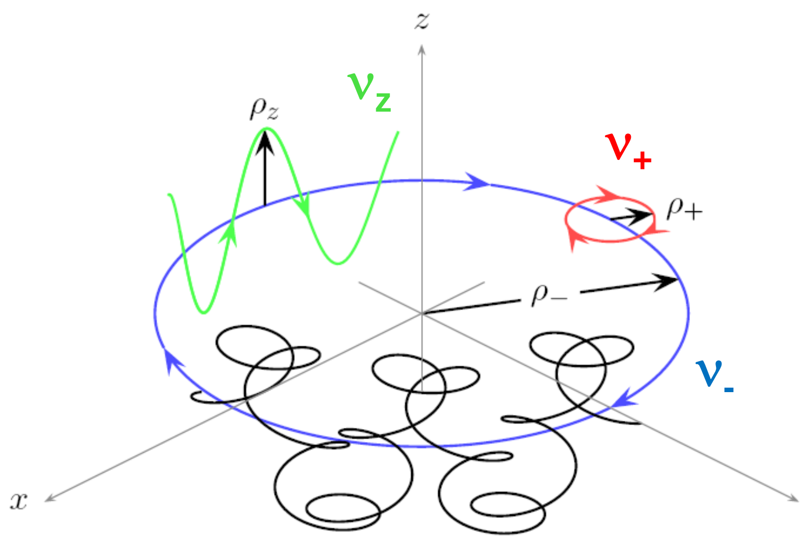
Cyclotron frequency:

$$f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$

PENNING trap

- Strong homogen. magnetic field
- Weak electric 3D quadrupole field

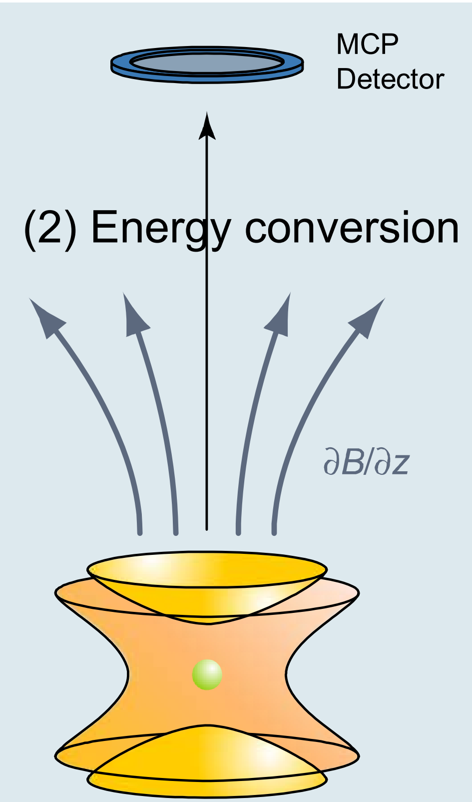




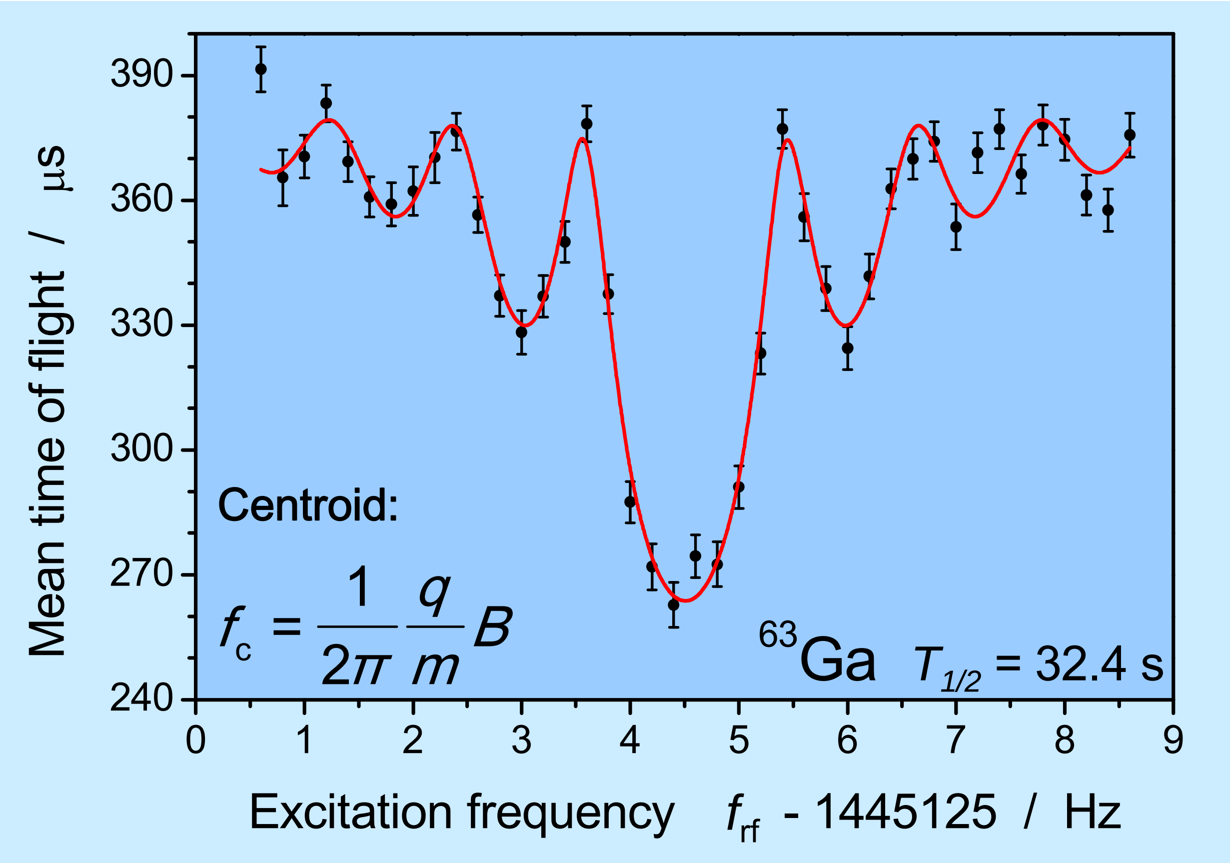
Typical freq.
q = e
m = 100 u
B = 6 T
$\Rightarrow$ $f_- \approx$ 1kHz
$f_+ \approx$ 1MHz

TOF cyclotron resonance detection

(3) TOF measurement



(1) Excitation of the ion motion



Determine atomic mass from frequency ratio with a well-known "reference mass".

$$\frac{f_{c,ref}}{f_c} = \frac{m - m_e}{m_{ref} - m_e}$$

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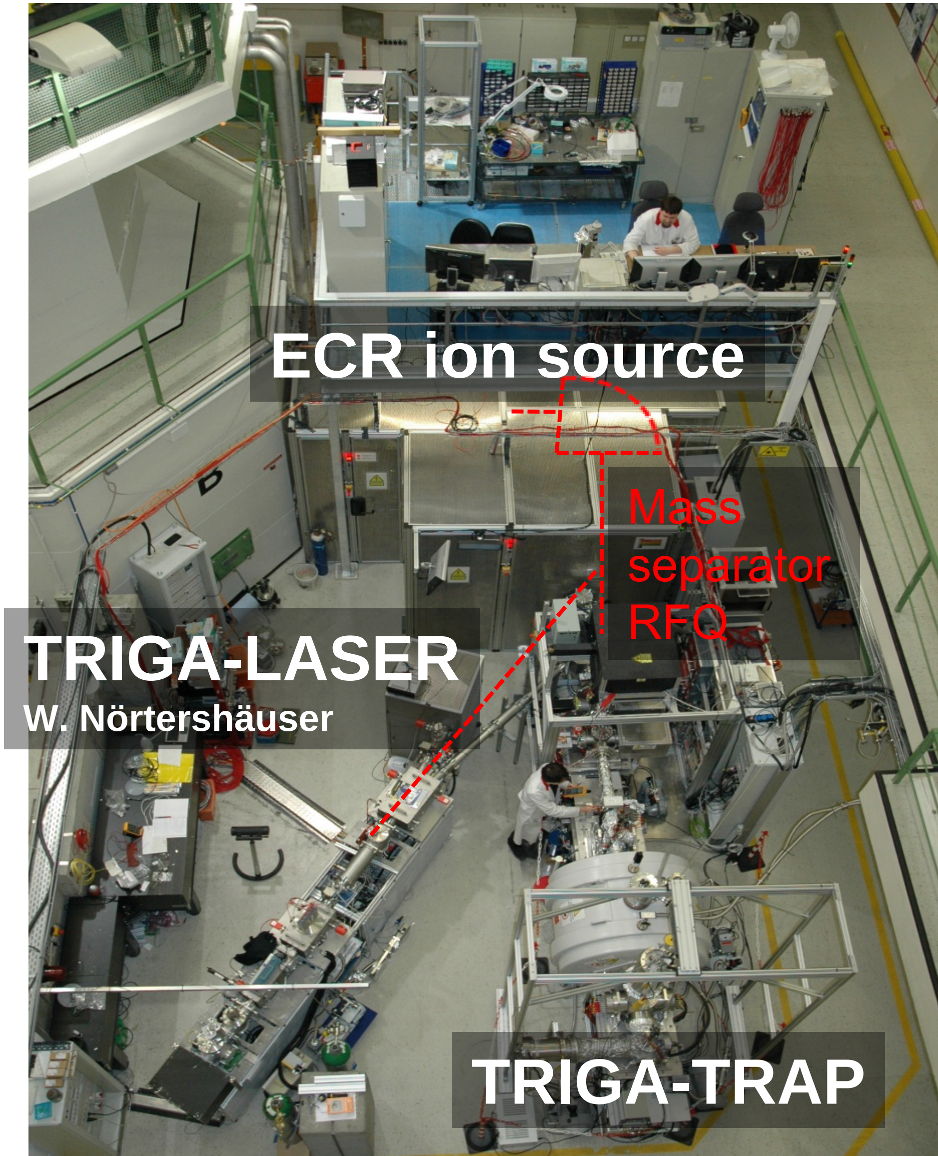
TRIGA-SPEC: TRIGA-LASER + TRIGA-TRAP

project start @ TRIGA: 01/08
start data taking: 05/09

steady 100 kW,
pulsed 250 MW,
neutron flux 1.8x10^{11} / cm^{2}s

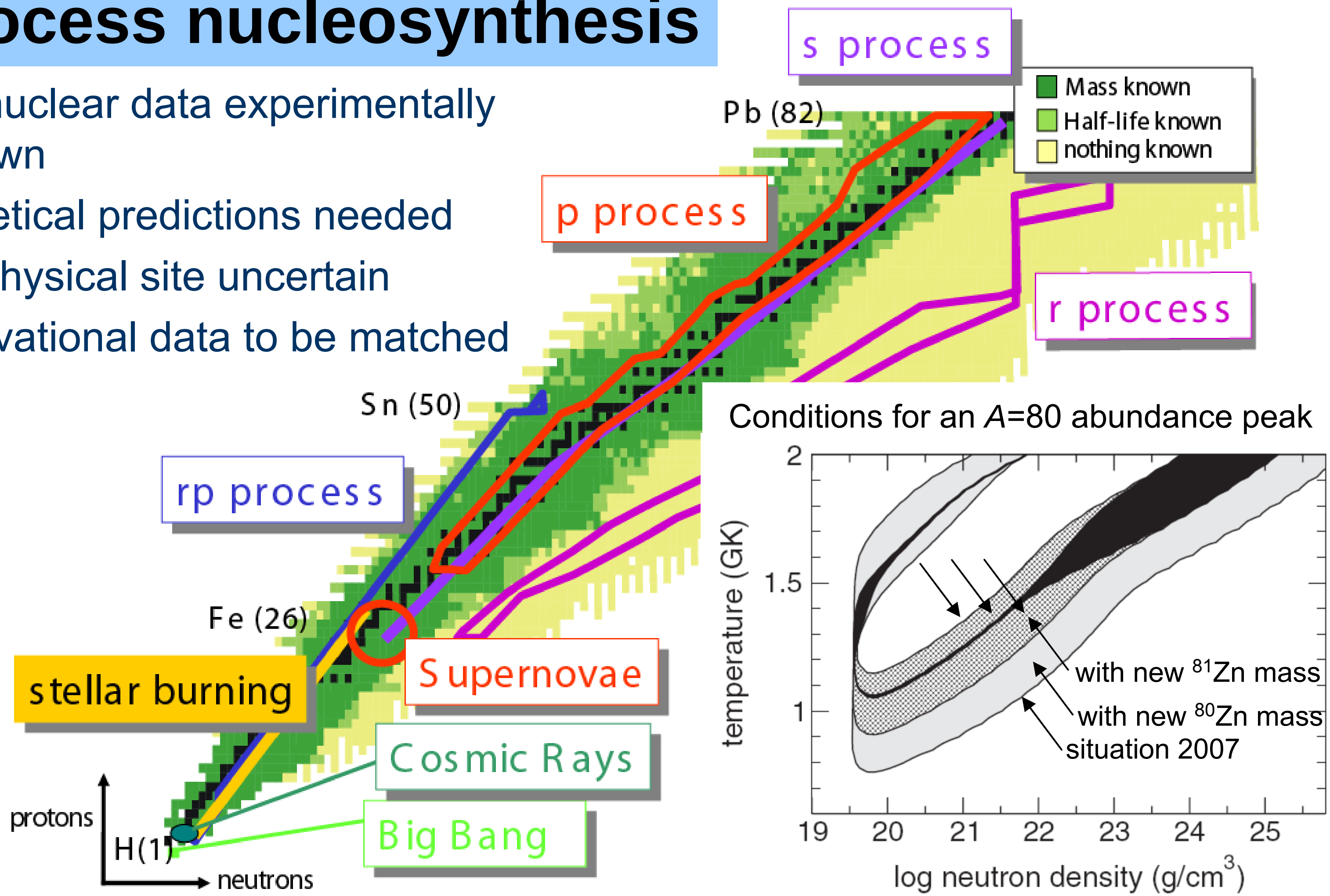
Nucl. Instrum. Meth. A 594, 162 (2008)



Making gold in nature

r-process nucleosynthesis

- Most nuclear data experimentally unknown
- Theoretical predictions needed
- Astrophysical site uncertain
- Observational data to be matched



D. Rodríguez *et al.*, Phys. Rev. Lett. 93, 161104 (2004)
S. Baruah *et al.*, Phys. Rev. Lett. 101, 262501 (2008)
X.L. Tu *et al.*, Phys. Rev. Lett. 106, 112501 (2011)
E. Haettner *et al.*, Phys. Rev. Lett. 106, 122501 (2011)

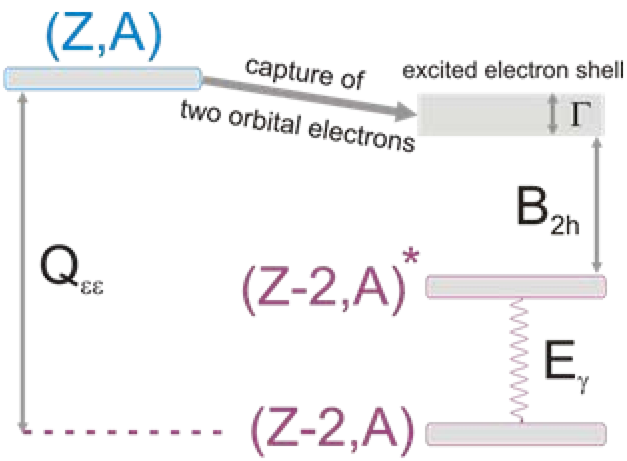
Neutrino-less double EC ($0\nu 2EC$)

Is the neutrino a Majorana or Dirac particle?

$2\nu 2EC$ ($T_{1/2}>10^{24}$y) $0\nu 2EC$ ($T_{1/2}>10^{30}$y)

$$\frac{1}{T_{1/2}} = C \times m_\nu^2 \times |M|^2 \times |\Psi_{1e}|^2 \times |\Psi_{2e}|^2 \times \frac{\Gamma}{(Q - B_{2h} - E_\gamma)^2 + \frac{1}{4}\Gamma^2}$$

$0\nu 2EC$ might be resonantly enhanced ($T_{1/2}$~10^{25}y)



Contribution of Penning traps:

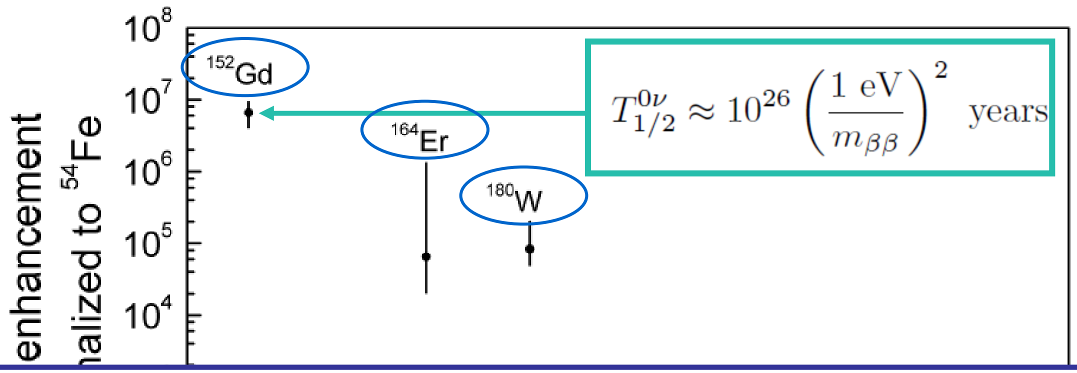
Search for nuclides with $\Delta=(Q_{\varepsilon\varepsilon}-B_{2h}-E_\gamma)$ < 1 keV

by measurements of $Q_{\varepsilon\varepsilon}$ –values

at ~100 eV accuracy level

Resonance enhancement factors

2EC - transition	*Δ* (old), keV	*Δ* (new), keV	$T_{1/2} \cdot m^2$, yr
$^{152}Gd \rightarrow {}^{152}Sm$	-0.2(3.5)	0.9(0.2)	10^{26}
$^{164}Er \rightarrow {}^{164}Dy$	5.2(3.9)	6.81(0.12)	10^{30}
$^{180}W \rightarrow {}^{180}Hf$	13.7(4.5)	12.4(0.2)	10^{27}

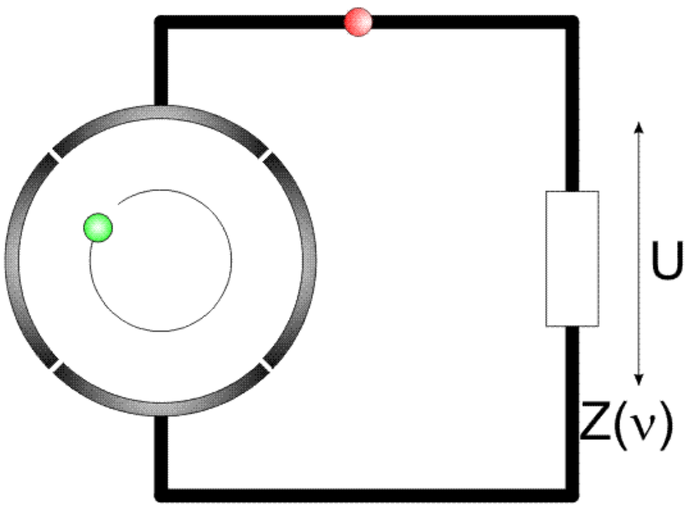


If $m_{\beta\beta}$ = 1 eV ⟹ 30 kg for 1 capture event a year

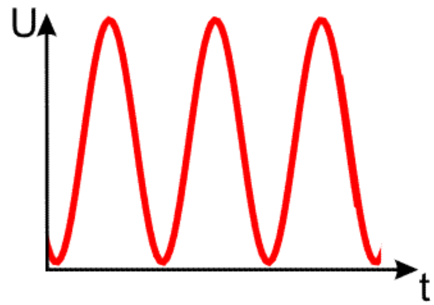
If $m_{\beta\beta}$ = 0.1 eV ⟹ 3 tons for 1 capture event a year

^{152}Gd can be used for a search for 0ν2EC

Non-destructive ion detection

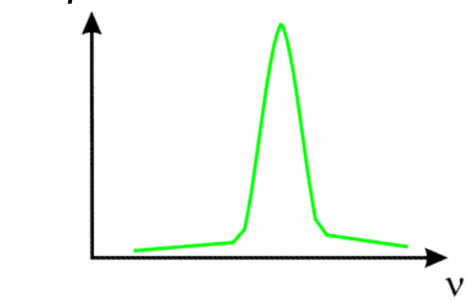


ion signal



very small signal ~fA

mass/frequency spectrum



„FT-ICR"
Fourier-**T**ransform-
Ion **C**yclotron **R**esonance

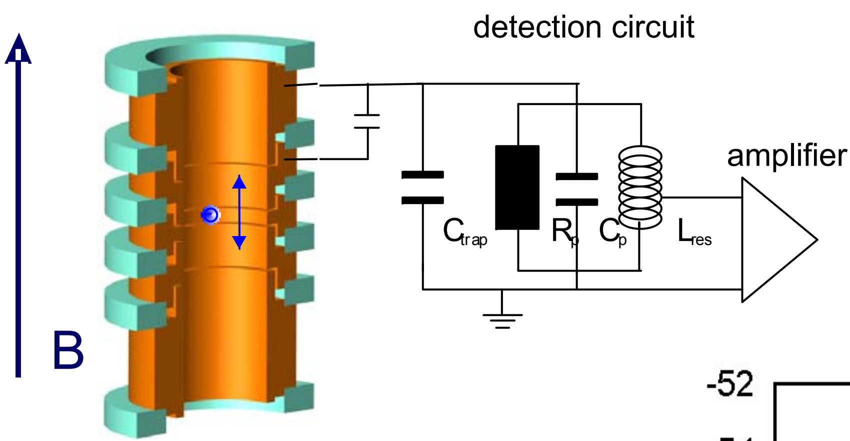
Induced current: $I_{eff} = 1/\sqrt{2} \cdot r_{ion}/ D \cdot \omega \cdot q$

(Schottky et al. ...)

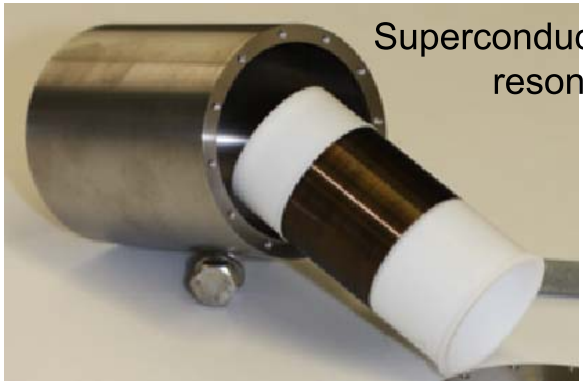
Signal / Noise $S/N \sim 1 / T^{1/2}$

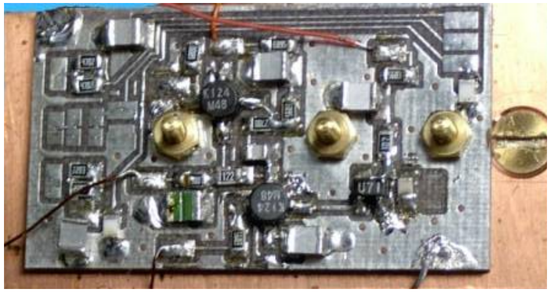
Operation of traps and electronics at **cryogenic** (4 K) temperature.

Single ion sensitivity



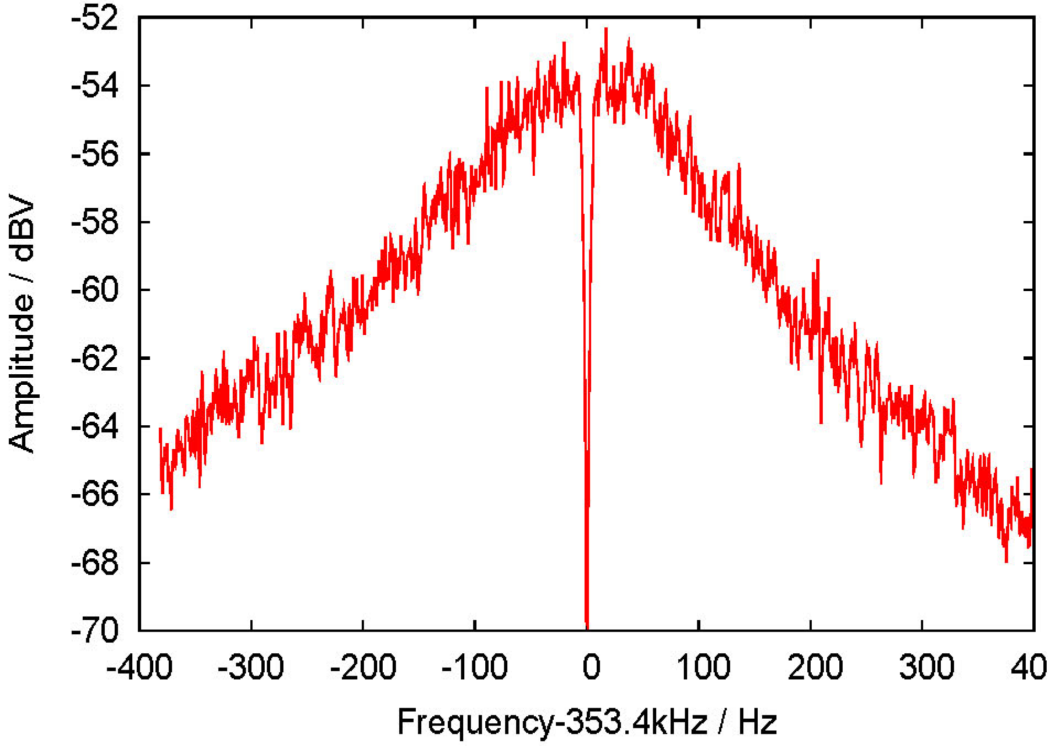
Penning trap





Ultra-low noise cryogenic amplifier

$$T = 4\ \mathrm{K}$$
$$P = 5.5\ \mathrm{mW}$$
$$e_n = 400\ \mathrm{pV}/\sqrt{\mathrm{Hz}}$$
$$i_n < 2\ \mathrm{fA}/\sqrt{\mathrm{Hz}}$$
$$\nu_z = 600\ \mathrm{kHz}$$



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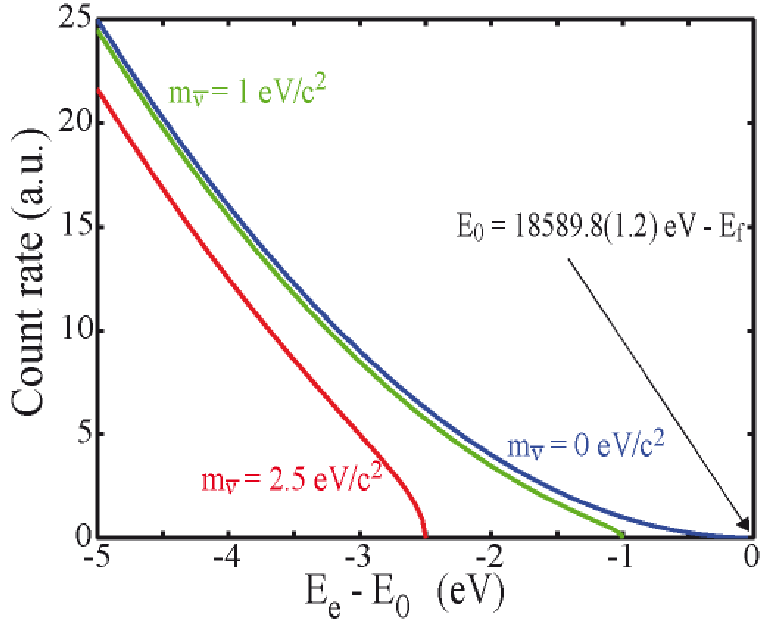
THe-TRAP for KATRIN

A high-precision $Q(^3T\text{-}^3He)$-value measurement



$^3_1H \rightarrow ^3_2He + e^- + \bar{\nu}$ Q_{lit} =18 589.8 (1.2) eV

We aim for: $\delta Q(^3T \rightarrow ^3He)$ = 20 meV
$\delta m/m = 7\cdot10^{-12}$

$\Delta T < 0.05$ K/d at 24°C
$\Delta B/B < 10$ ppt / h $\Delta x \leq 0.1$ µm

First $^{12}C^{4+}/^{16}O^{6+}$ mass ratio measurement at $\delta m/m_{stat} = 4\cdot10^{-11}$ performed.

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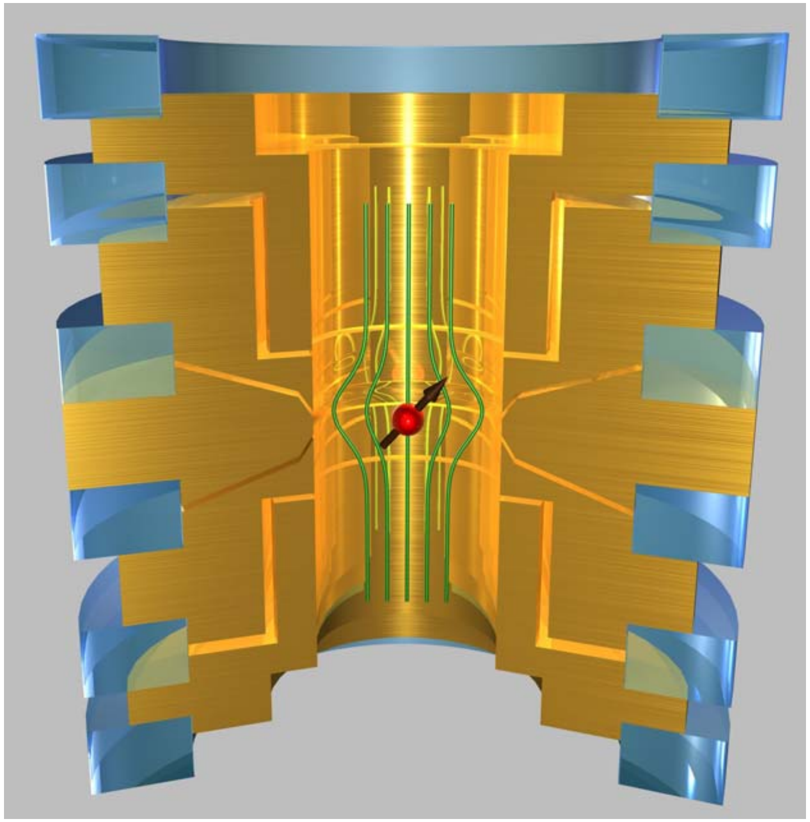
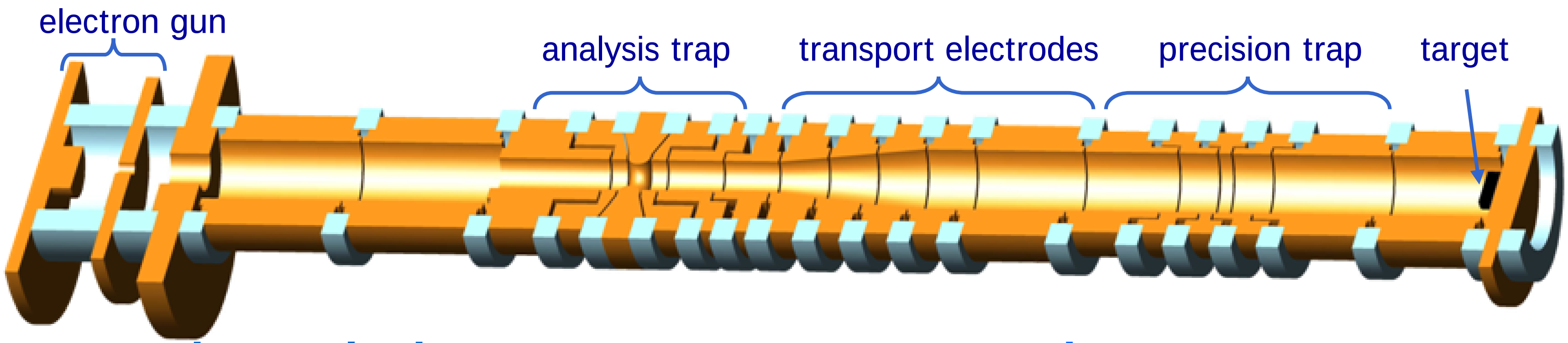
Part II

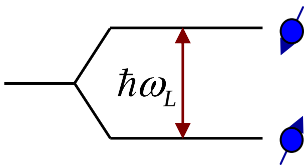
The *g* factor of a free proton



The *g*-factor (anti)proton experiment



The analysis trap



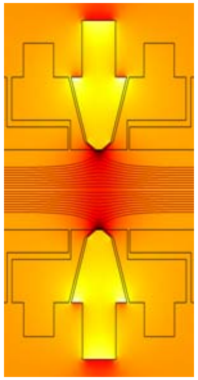
$$\omega_L = \frac{2\mu \cdot B}{\hbar} = g\frac{e}{2m_p}B$$

⇩

$$g = 2\frac{\omega_L}{\omega_c}$$

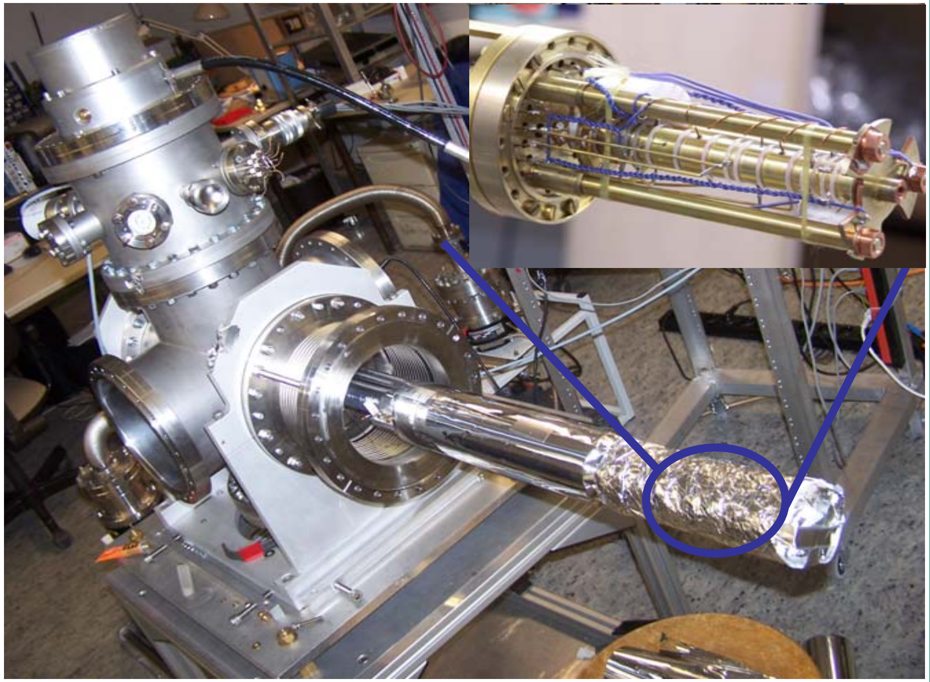
⇧

$$\omega_c = \frac{e}{m_p}B$$



COMSOL simulation

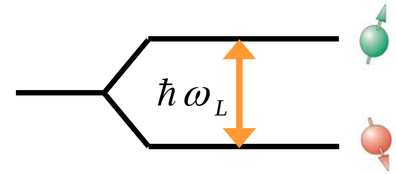
The cryostat



S. Ulmer *et al.*, Rev. Sci. Instrum. 80, 123302 (2009)

Continuous Stern-Gerlach effect

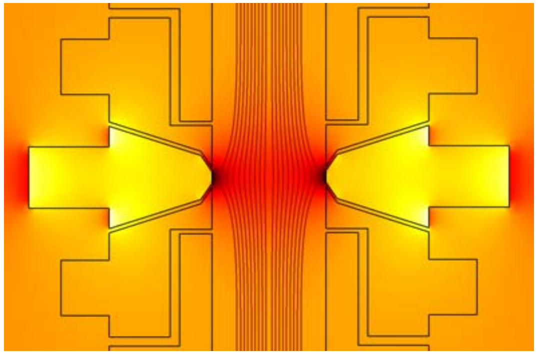
- Larmor-frequency cannot be directly measured



- Microwaves are irradiated to induce a spin flip
  → Spin direction has to be detectable

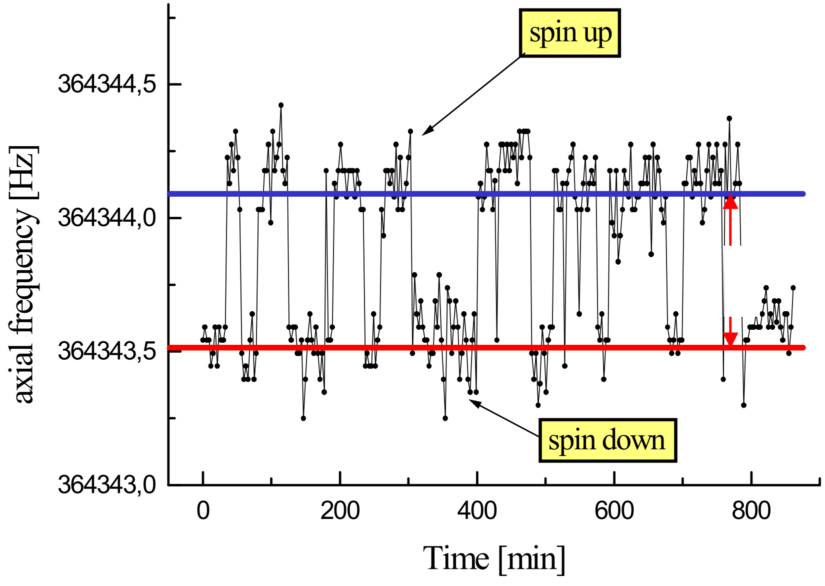
- Magnetic inhomogeneity produces an effective spin-dependent potential
  - Axial frequency depends on spin-direction
  - Small frequency difference between and :

$$\Delta\nu_z \cong \frac{g\cdot\mu_B\cdot B_2}{4\pi^2\cdot m_{ion}\cdot\nu_{z_0}} = 240mHz$$



COMSOL simulation

Ferromagnetic ring produces a magnetic bottle



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High-precision *g* factor measurement

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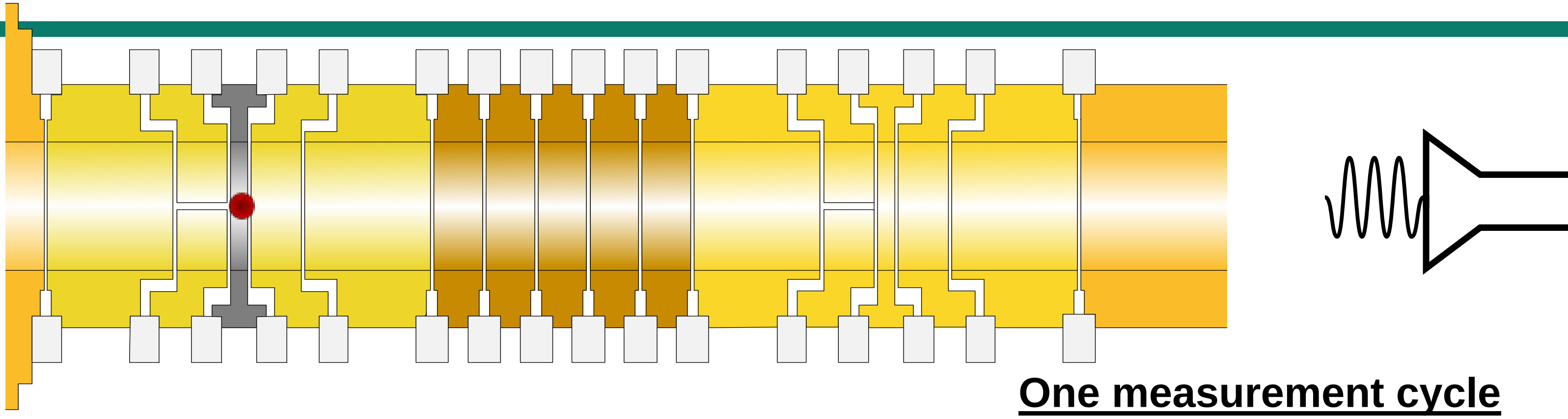
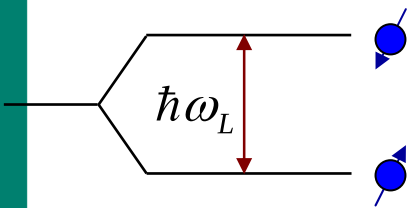




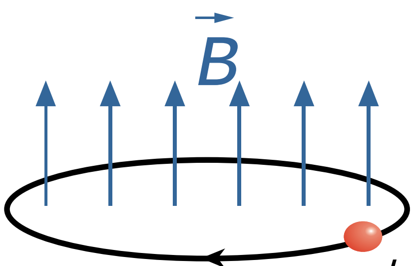
$$\omega_L = \frac{2\mu \cdot B}{\hbar} = g\frac{e}{2m_p}B$$

$$\Downarrow$$

$$g = 2\frac{\omega_L}{\omega_c}$$

$$\Uparrow$$

$$\omega_c = \frac{e}{m_p}B$$



One measurement cycle

i. Detection of spin-orientation in analysis trap — *10min*

ii. Transport to precision trap — *0.5min*

iii. Measurement of eigenfrequencies and simultaneous irradiation with microwaves — *5min*

iv. Transport to analysis trap — *0.5min*

v. Detection of spin orientation in analysis trap — *10min*

- Spin flip in the precision trap?

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g-factor resonance of a single proton

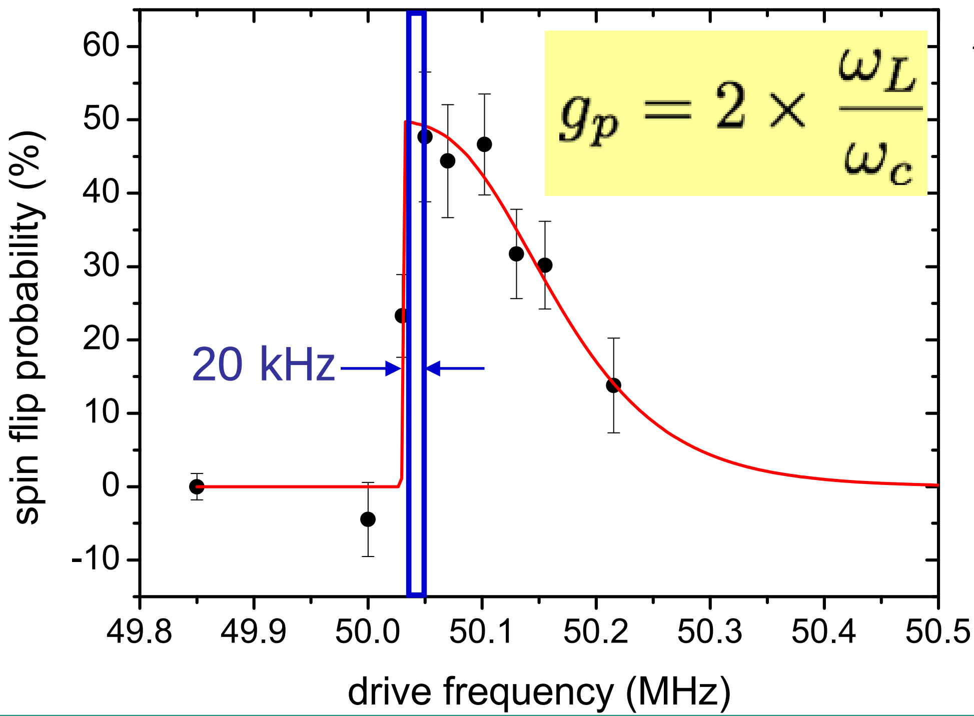
Compare *g*-factors of p and $\overline{\text{p}}$:

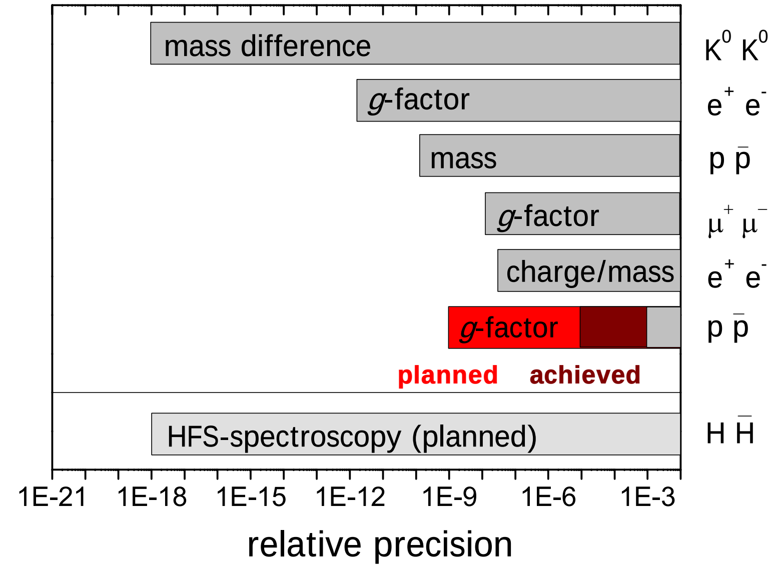
Test of matter-antimatter symmetry.

Highly challenging experiment since

$$\frac{\mu_p}{m_p} \times \frac{m_e}{\mu_e} = 8 \cdot 10^{-7}$$

one million times harder compared to e^-.





PDG:

$$g_p = 2 \times 2.792847337(29)$$
$$g_{\bar{p}} = 2 \times 2.800(8)$$

Larmor resonance based on first spin flip ever observed with a nuclear magnetic moment.

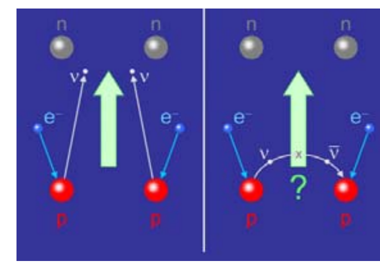
We aim for $\delta g/g = 10^{-9}$.

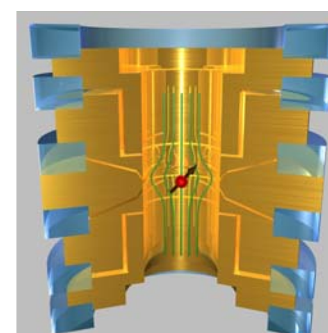
S. Ulmer *et al.*, Phys. Rev. Lett. 106, 253001 (2011)

Summary

Exciting results in high-precision experiments with stored and cooled exotic ions have been achieved!

- Accurate masses have been obtained for reliable nucleosynthesis calculations.
- High-precision mass measurements with strong impact on neutrino physics research.
- Discovery of a suitable candidate for 0ν2EC search.
- First direct observation of a spin-flip of a single proton
- Development of novel and unique storage devices.
- … and many more!





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Thanks

Thanks a lot for the invitation and your attention!

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