MAX PLANCK INSTITUTE
FOR NUCLEAR PHYSICS

EMMI Physics Days 2011, GSI Darmstadt

“Precision Penning Trap Experiments with Exotic Ions”

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November 08, 2011

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Outline

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

  (see also talk by Sven Sturm yesterday)

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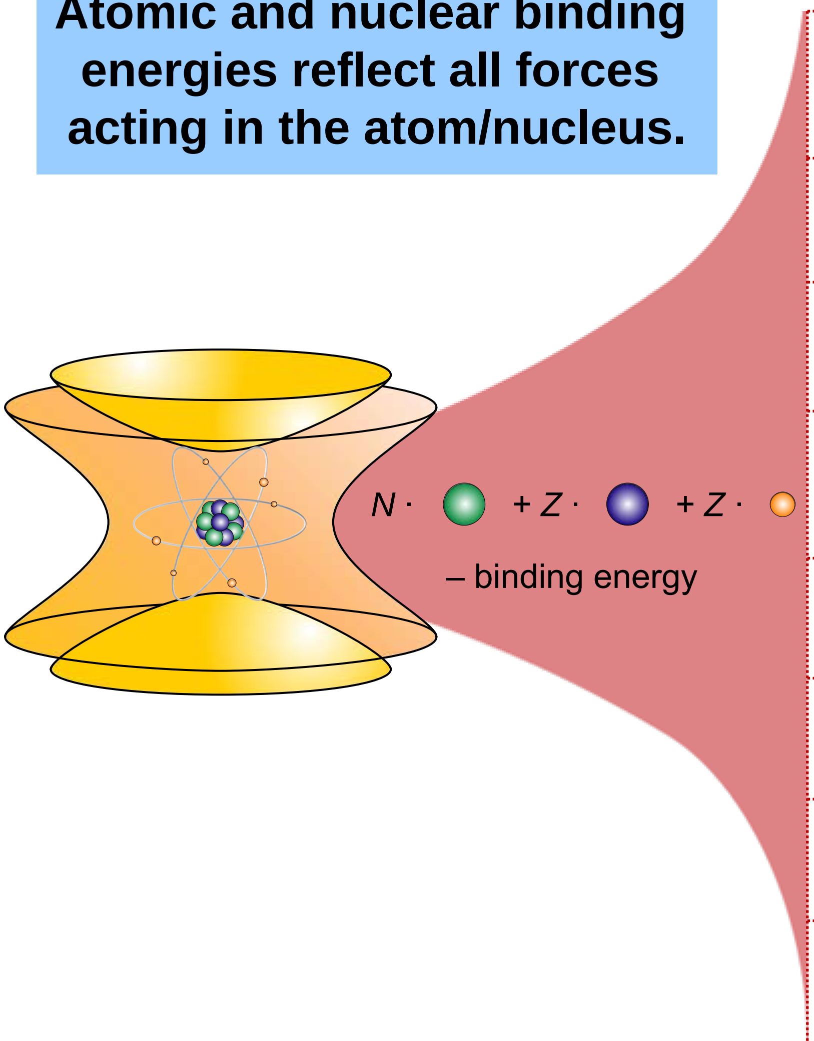
Part I

High-precision mass measurements

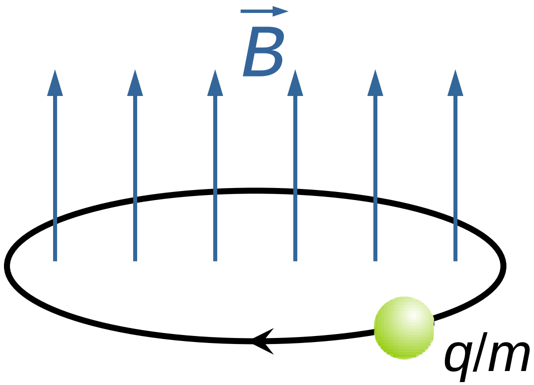
Why measuring atomic masses?

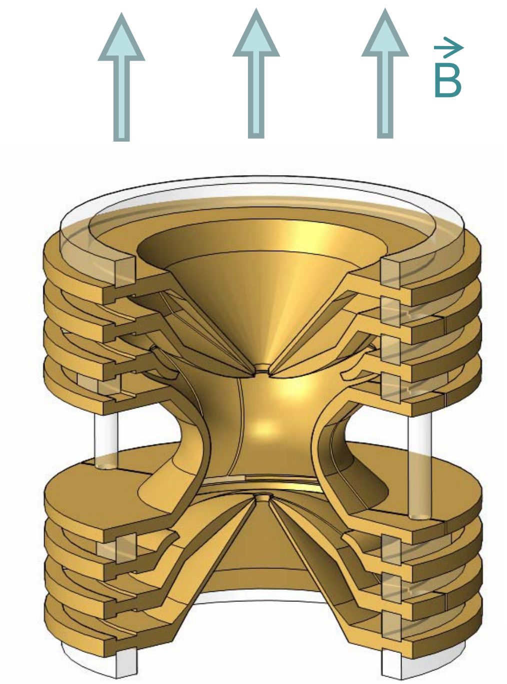
Atomic and nuclear binding energies reflect all forces acting in the atom/nucleus.



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

Principle of Penning trap mass spectrometry



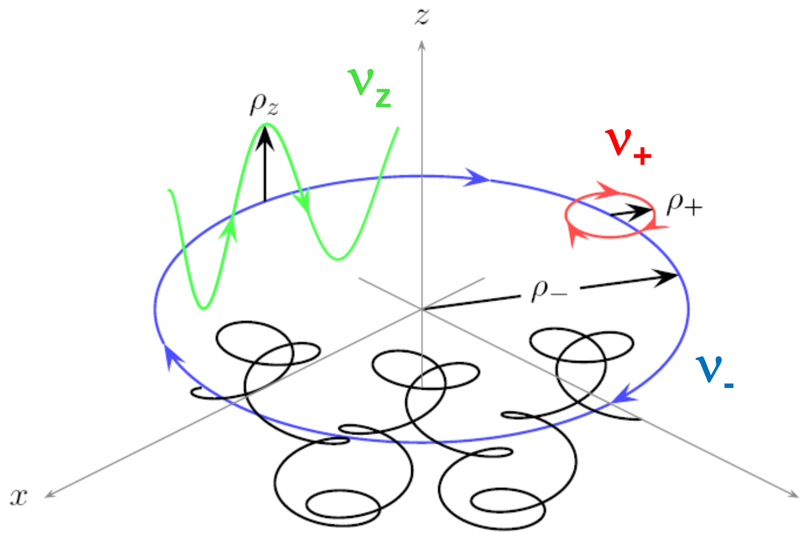


Cyclotron frequency:

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

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

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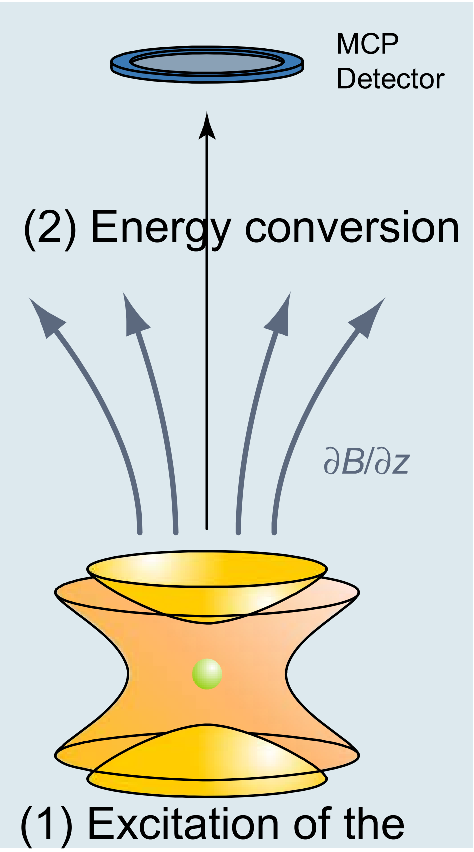
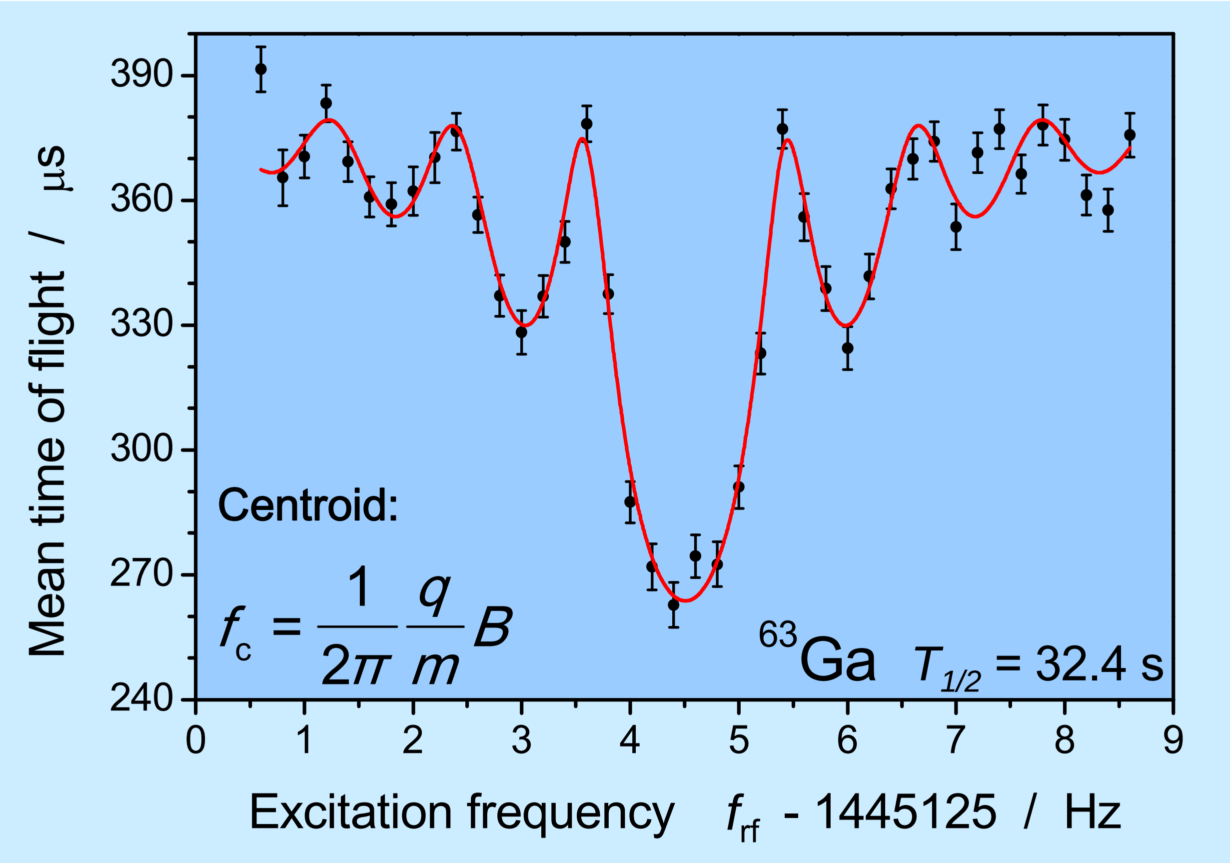
(3) TOF measurement



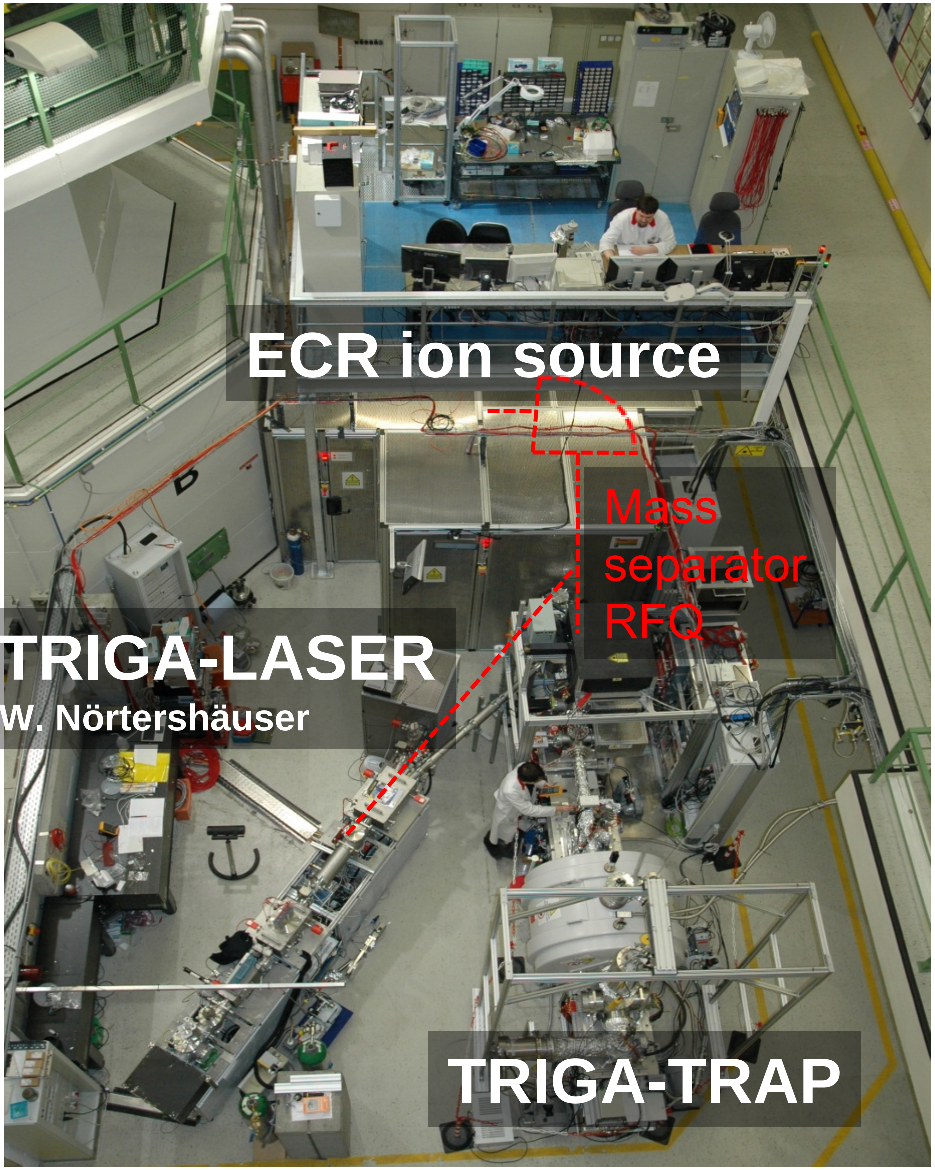


Determine atomic mass from frequency ratio with a well-known “reference mass”.

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

TRIGA-SPEC: TRIGA-LASER + TRIGA-TRAP

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



steady 100 kW,
pulsed 250 MW,
neutron flux 1.8×10^{11} / $cm^2 s$

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

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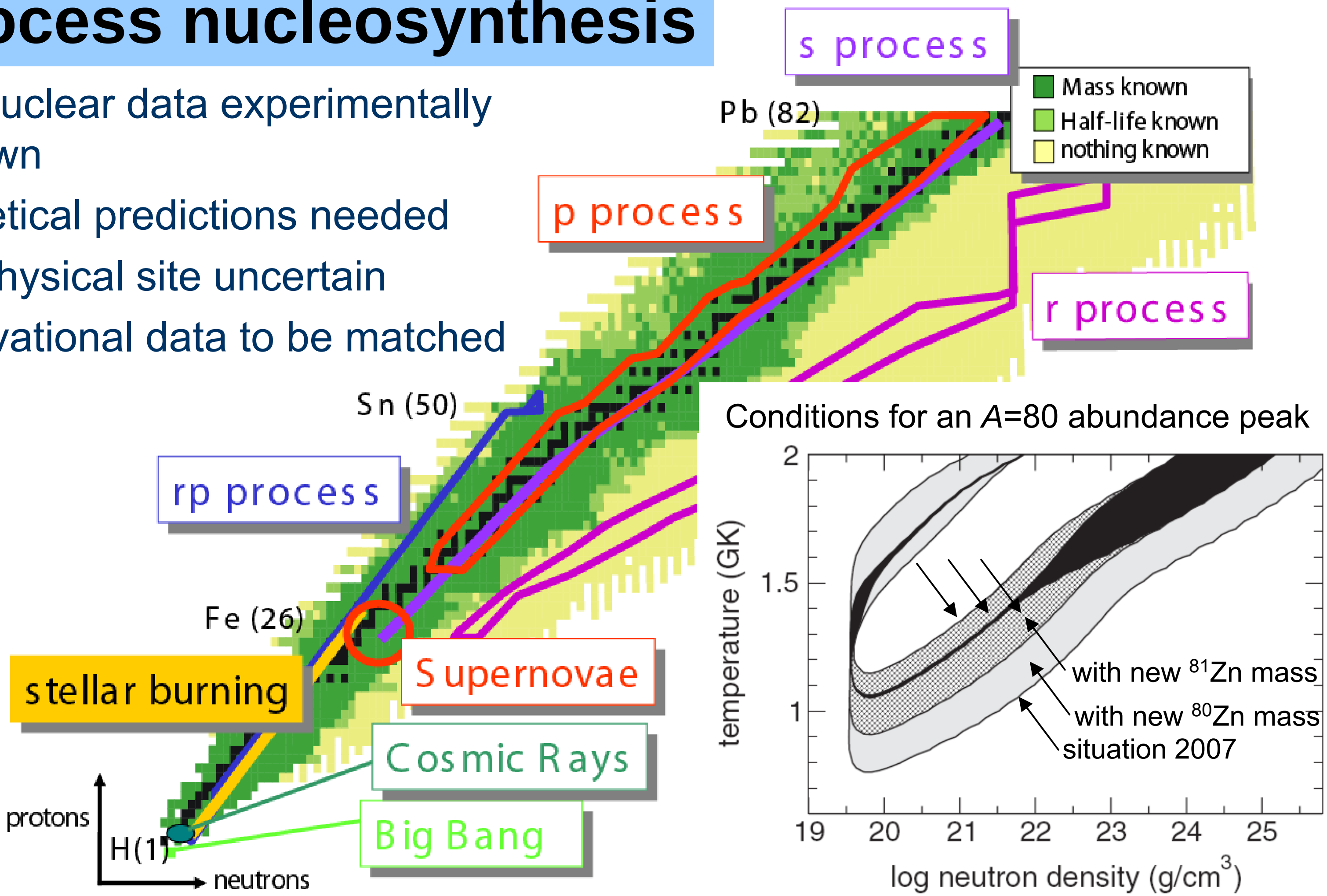
Making gold in nature

r-process nucleosynthesis

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



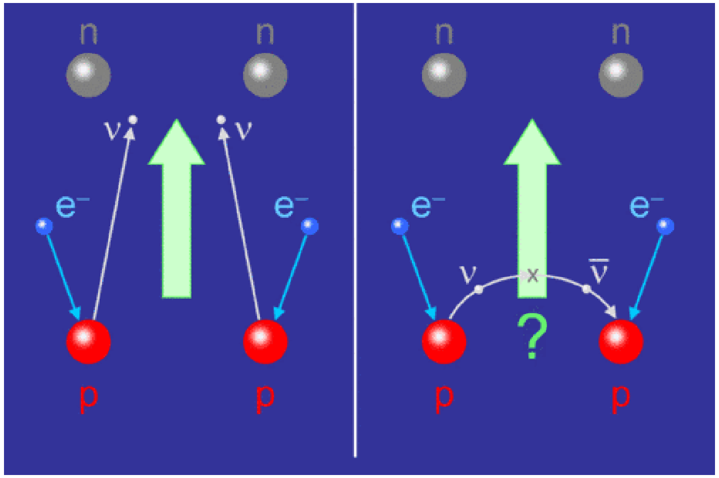
D. Rodríguez *et al.*, Phys. Rev. Lett. 93, 161104 (2004)
S. Baruah *et al.*, Phys. Rev. Lett. 101, 262501 (2008)
X.L. Tu *et al.*, Phys. Rev. Lett. 106, 112501 (2011)
E. Haettner *et al.*, Phys. Rev. Lett. 106, 122501 (2011)

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

Is the neutrino a Majorana or Dirac particle?

2ν2EC ($T_{1/2}$>10^{24}y)   *0ν2EC* ($T_{1/2}$>10^{30}y)

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



Measurements triggered by Prof. Y. Novikov, EMMI Professorship 2011

Neutrino-less double EC (0ν2*EC*)

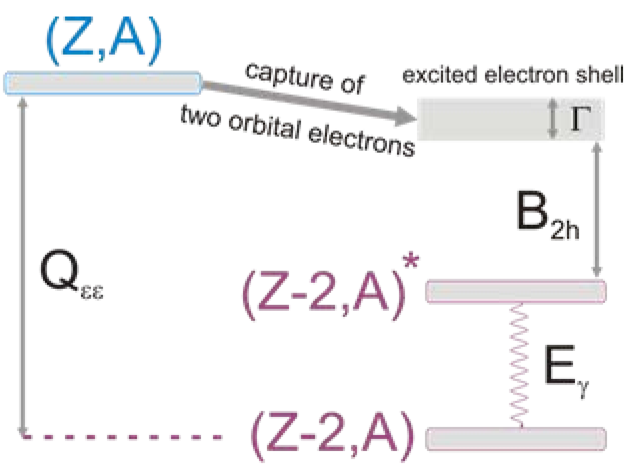
Is the neutrino a Majorana or Dirac particle?

2ν2EC **($T_{1/2}$>10^{24}y)**

0ν2EC **($T_{1/2}$>10^{30}y)**

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

0ν2EC 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

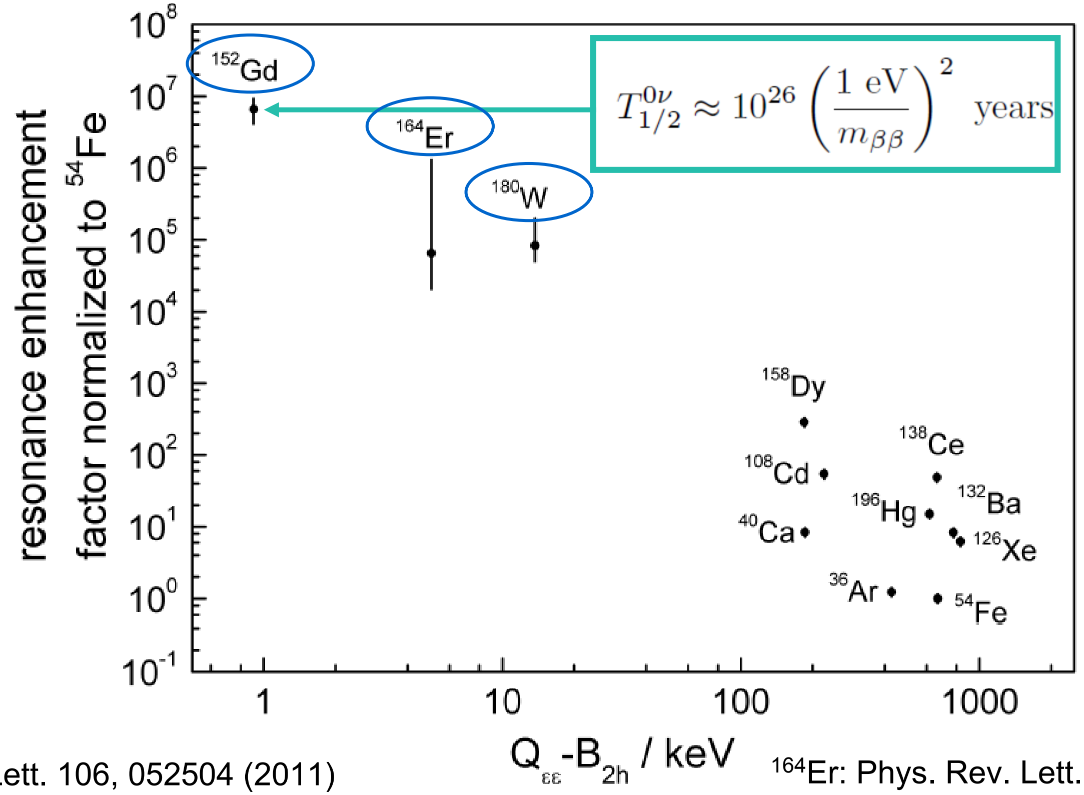
by measurements of $Q_{\varepsilon\varepsilon}$ –values

at ~100 eV accuracy level

Measurements triggered by Prof. Y. Novikov, EMMI Professorship 2011

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}



$$T^{0\nu}_{1/2} \approx 10^{26} \left(\frac{1\ \mathrm{eV}}{m_{\beta\beta}}\right)^2 \ \text{years}$$

^{152}Gd: Phys. Rev. Lett. 106, 052504 (2011)

^{164}Er: Phys. Rev. Lett. 107, 152501 (2011)

Resonance enhancement factors

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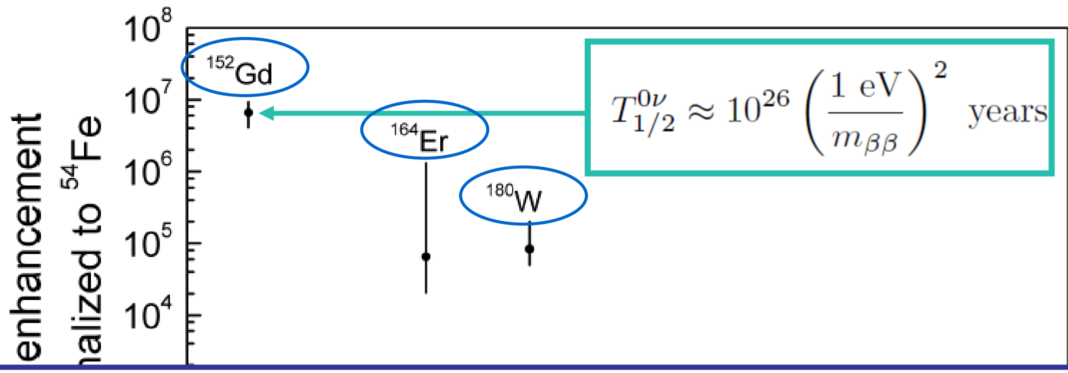

If $m_{\beta\beta}$ = 1 eV ⇒ 30 kg for 1 capture event a year

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

A breakthrough: Octupolar excitation

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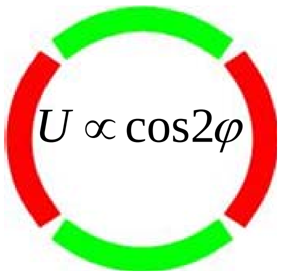
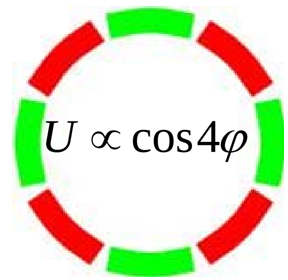
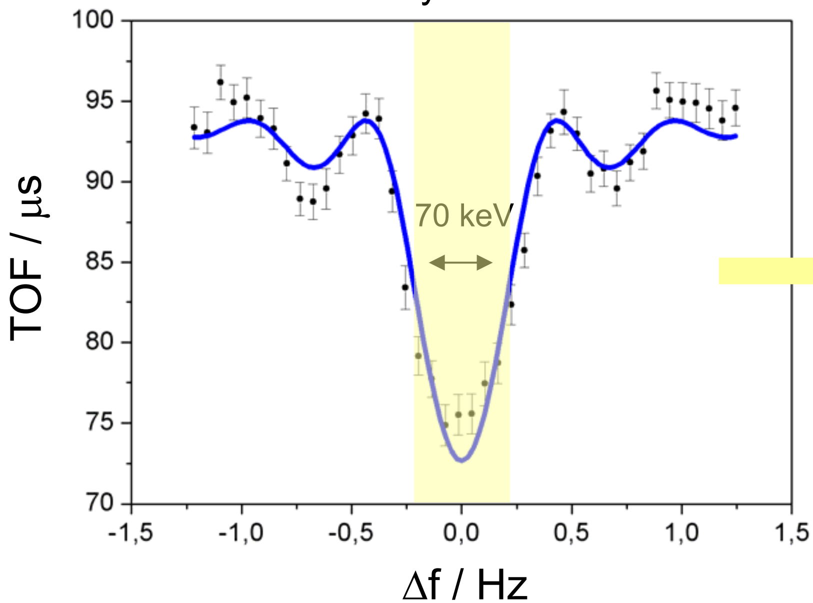
Quadrupolar excitation



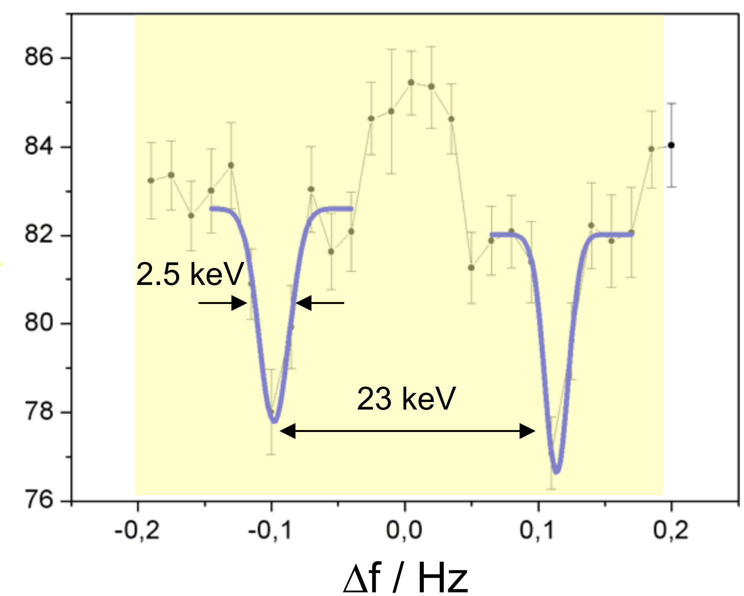
Octupolar excitation



^{164}Er and ^{164}Dy are *not* resolved



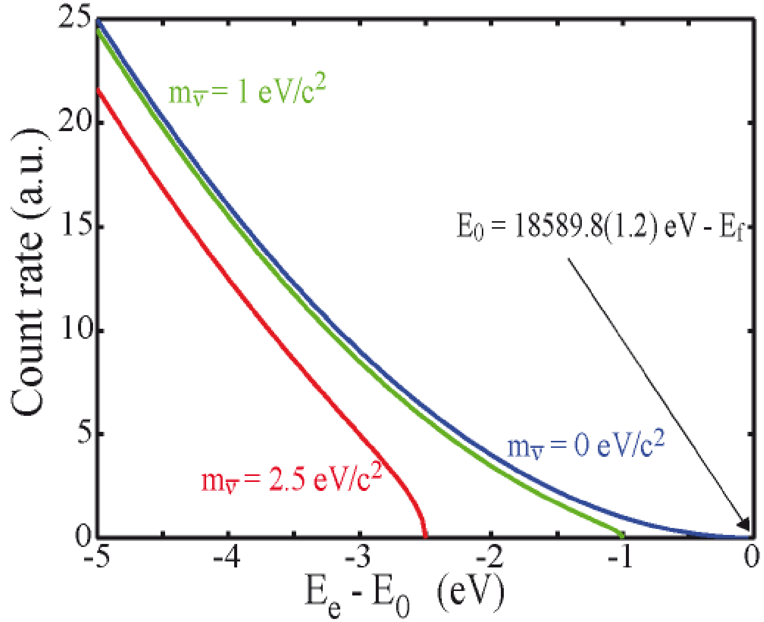
^{164}Er and ^{164}Dy are resolved



At least 20-fold improvement in resolving power!

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 $\quad \Delta x \leq 0.1\ \mu$m

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

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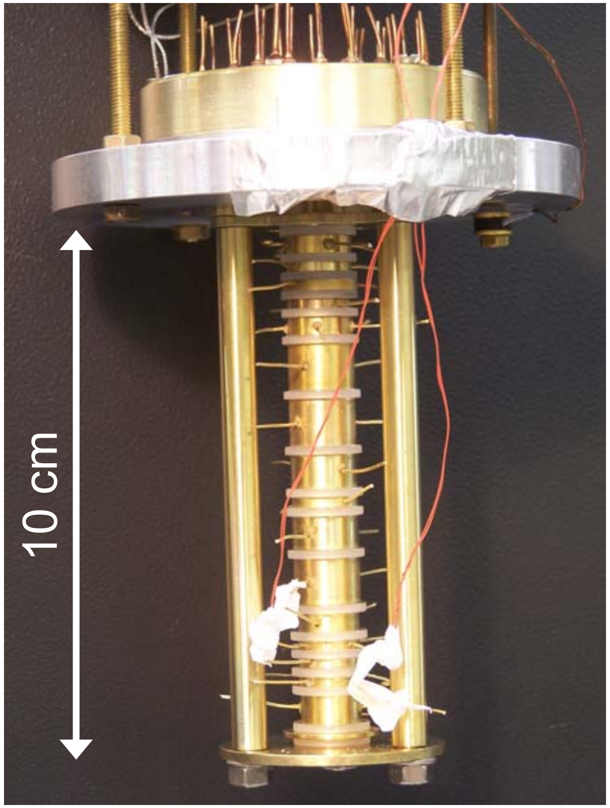
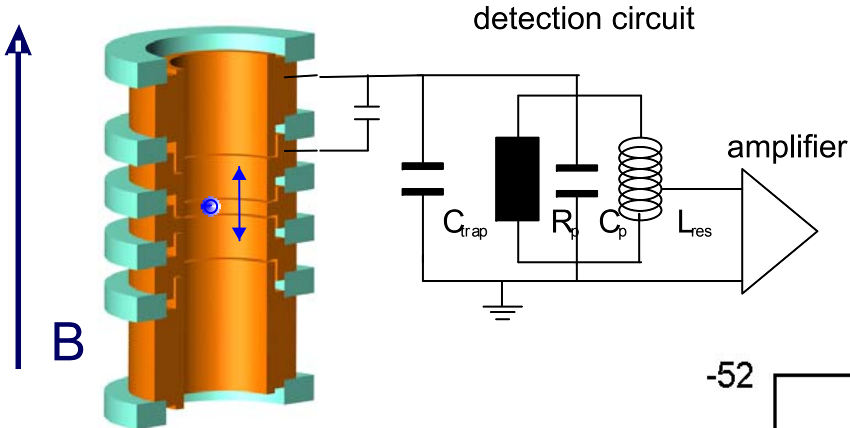
Part II

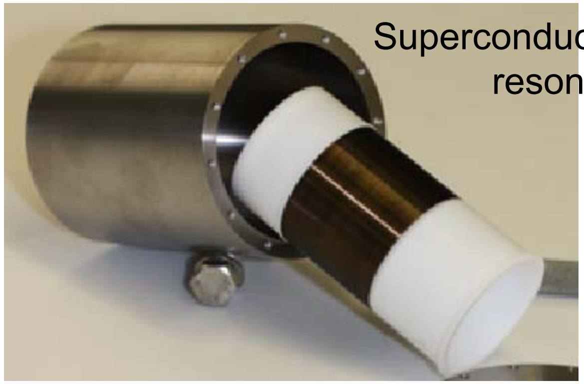
High-precision *g*-factor measurements



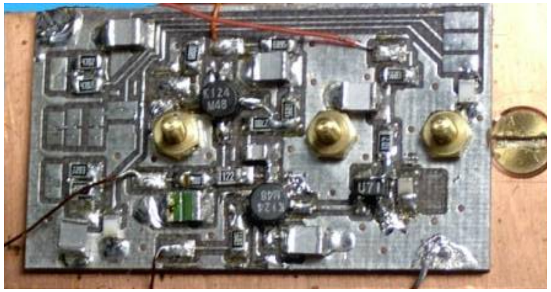
Single proton sensitivity



Penning trap

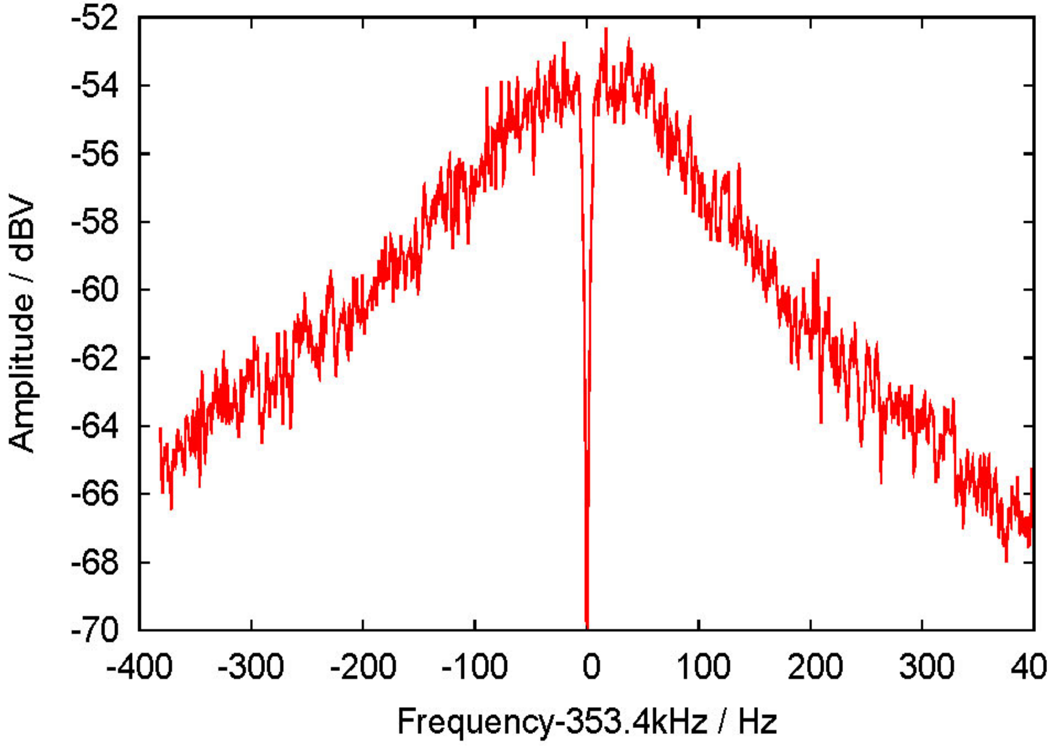


Superconducting helical resonator



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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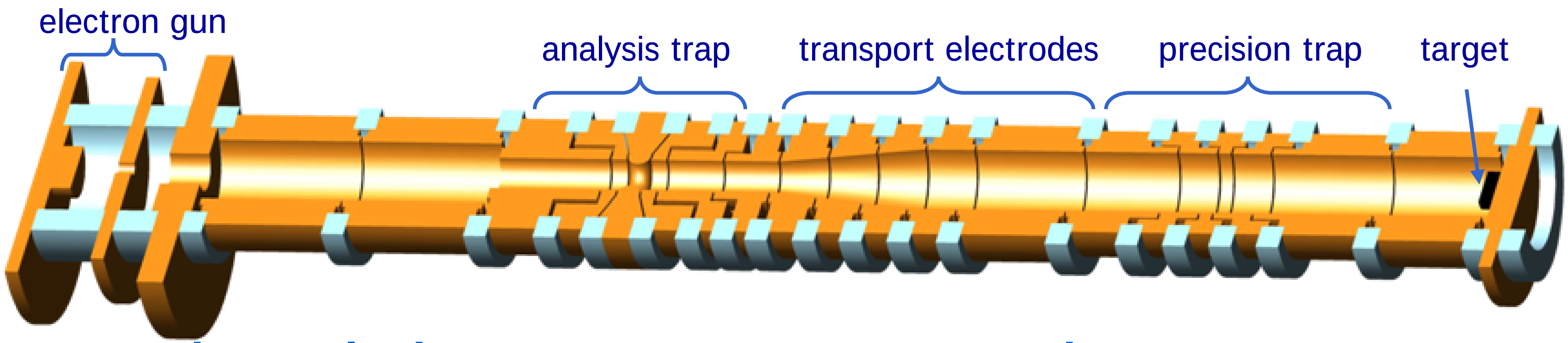
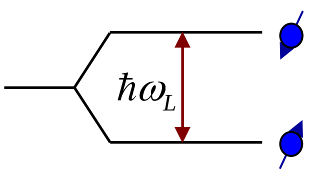
Status of the *g*-factor (anti)proton exp.



The analysis trap



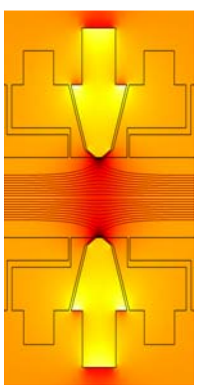
$$\omega_L = \frac{2\mu \cdot B}{\hbar} = g\frac{e}{2m_p}B$$

⇩

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

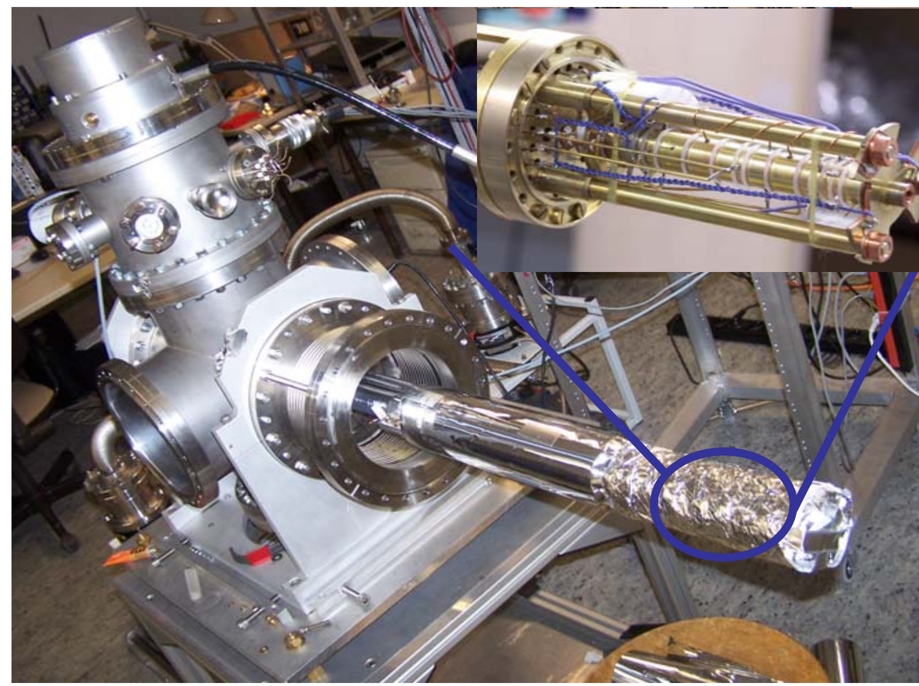
⇧

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



COMSOL simulation

The cryostat



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

g-factor resonance of a single proton

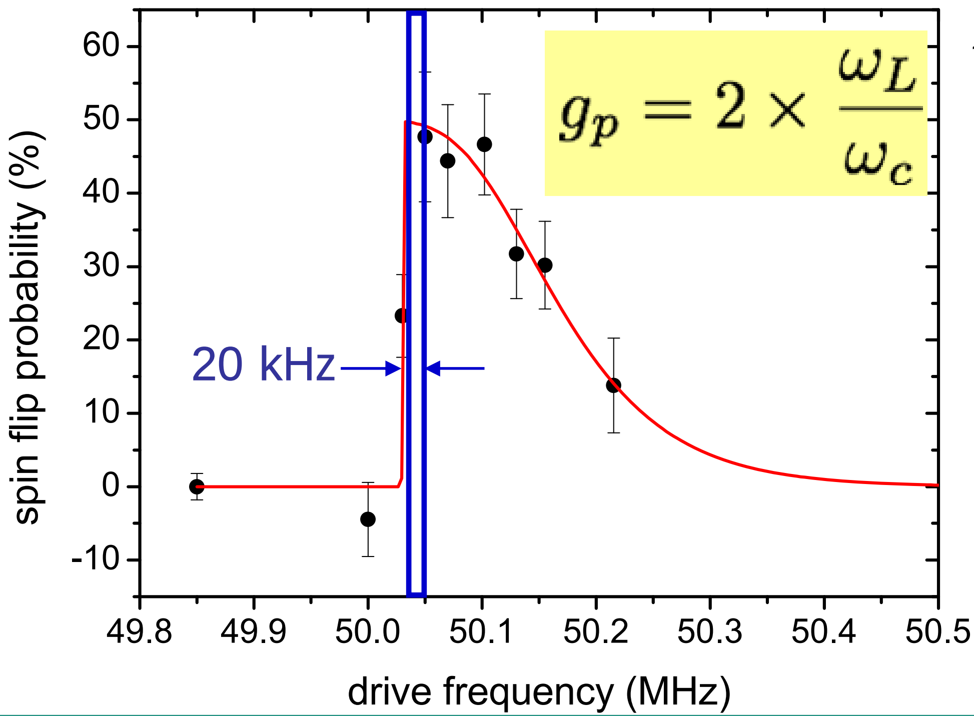
Compare *g*-factors of p and $\bar{p}$:

Test of matter-antimatter symmetry.

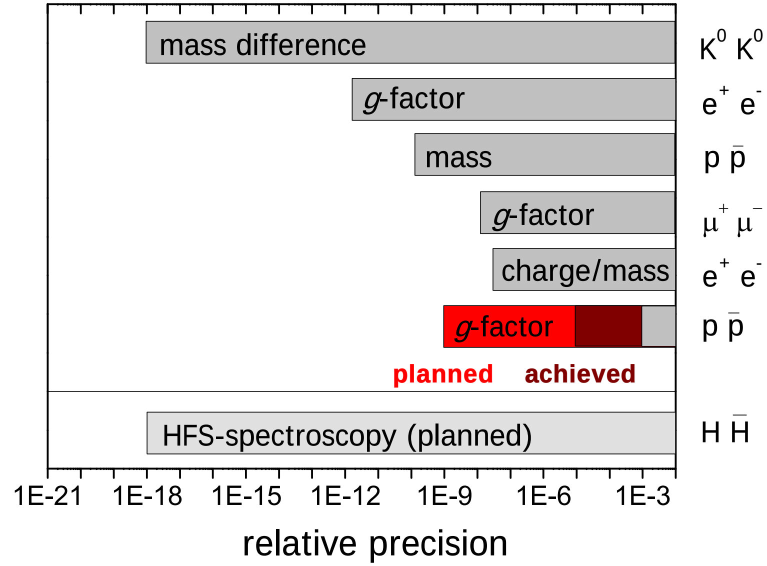
Highly challenging experiment since

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

one million times harder compared to e^-.



$$g_p = 2 \times \frac{\omega_L}{\omega_c}$$



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)

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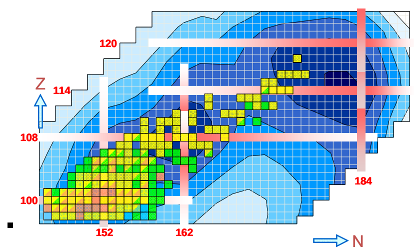
Summary

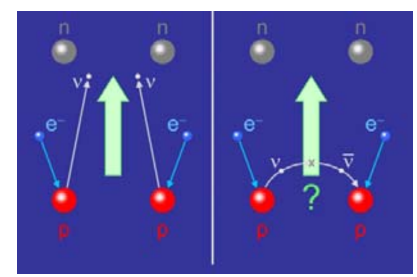
Breathtaking results in high-precision experiments with stored and cooled exotic ions have been achieved!

- Accurate masses have been obtained for reliable nucleosynthesis calculations.

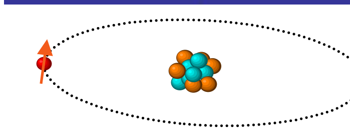
- High-precision mass measurements with strong impact on neutrino physics research.



- Discovery of a suitable candidate for 0ν2EC search.



- Most stringent test of bound-state QED and first direct *g*-factor measurement on a free proton.



- Development of novel and unique storage devices.
- … and many more!