High-precision mass measurements for nuclear structure and fundamental studies … … and more

Klaus Blaum: JoGu-University Mainz and GSI Darmstadt

Content

- **Motivation and history**
- **Experimental setup and measurement procedure**
- **High-precision mass measurements**
- **High-precision *g*-factor measurements**
- **Summary**

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In collaboration with:

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High-precision mass measurements

Requirements for mass spectrometry

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

K. B., Phys. Rep. 425, 1-78 (2006)	δm/m
General physics & chemistry	$\leq 10^{-5}$
Nuclear structure physics - separation of isobars	$\leq 10^{-6}$
Astrophysics - separation of isomers	$\leq 10^{-6}$
Weak interaction studies	$\leq 10^{-8}$
Metrology - fundamental constants	$\leq 10^{-9}$
CPT tests	$\leq 10^{-10}$
QED in highly-charged ions - separation of atomic states	$\leq 10^{-11}$

$B(Z,N$ ... $]\cdot c^2$

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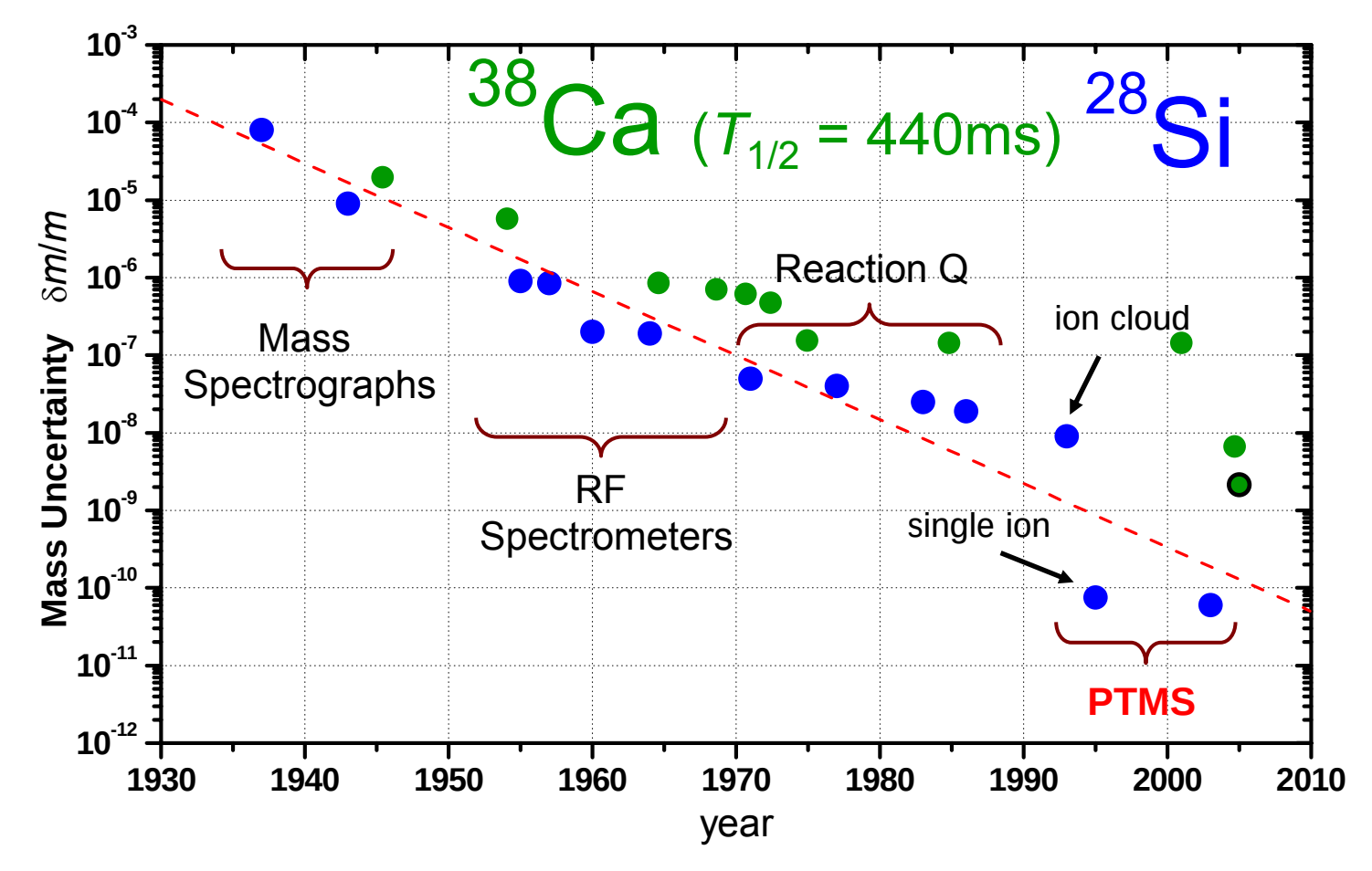
Precision: A brief history of mass spectrometry



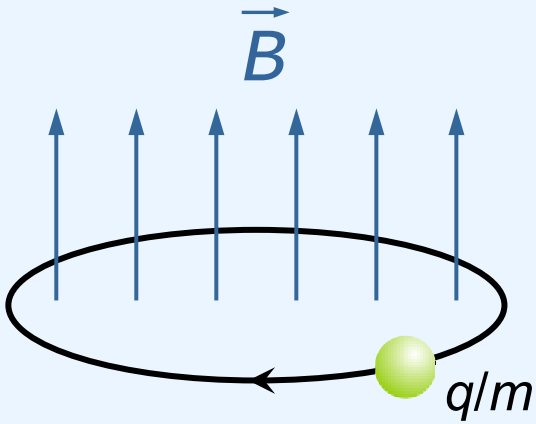
m(^{28}Si)= 27.976 926 532 6 u
δm = 0.000 000 001 9 u
Rel. Precision = 6x10^{-11}

Distance Mainz-Trento
800km ± 0.05mm

SMILETRAP, MIT-TRAP (now at FSU), Seattle-TRAP, Mainz-TRAP

CPT, ISOLTRAP, JYFLTRAP, LEBIT, SHIPTRAP

Principle of Penning trap mass spectrometry

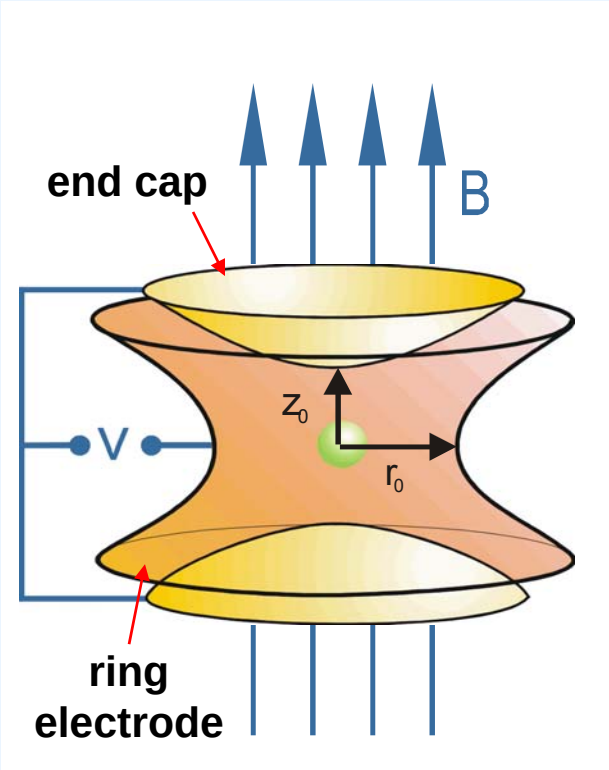


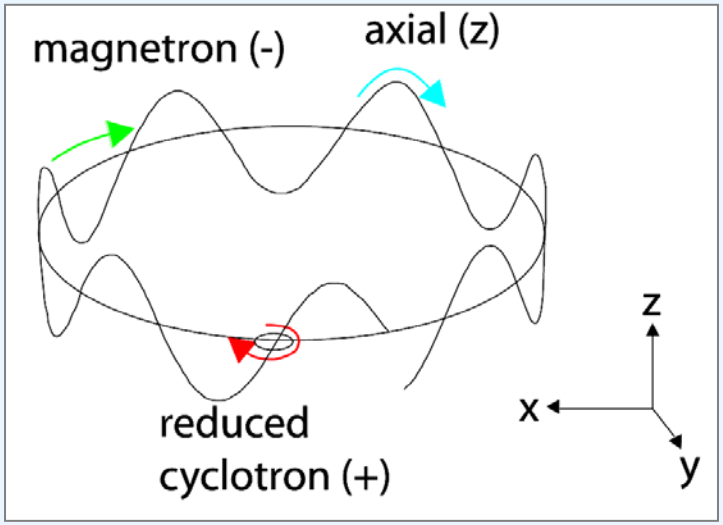
Cyclotron frequency:

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

PENNING trap

- Strong homogeneous magnetic field
- Weak electric 3D quadrupole field





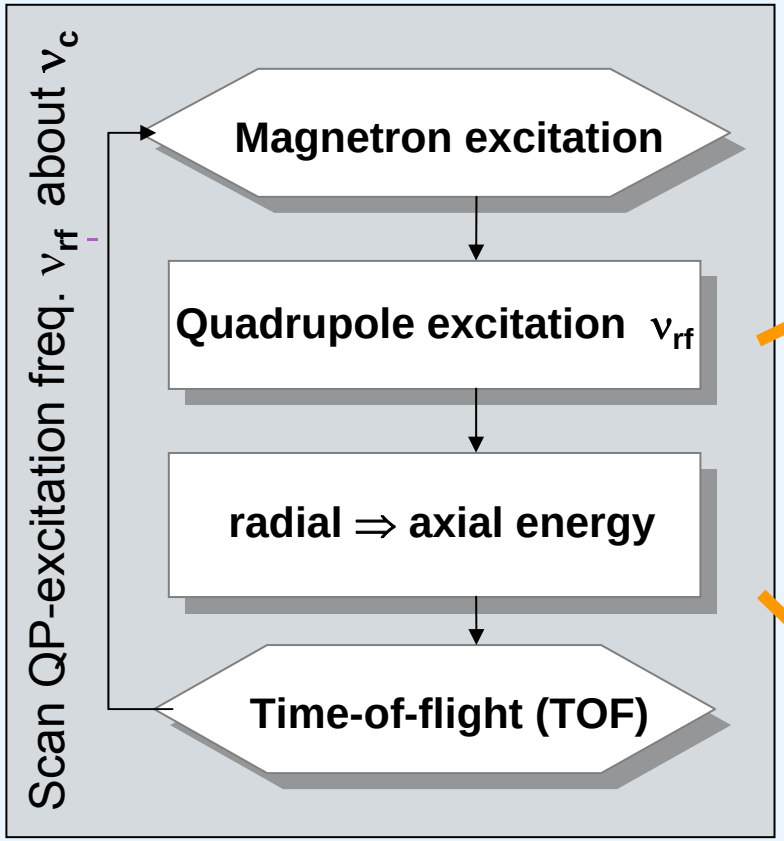
Typical frequencies
q = e, m = 100 u,
B = 6 T

$\Rightarrow$ $f_- \approx$ 1 kHz
$f_+ \approx$ 1 MHz

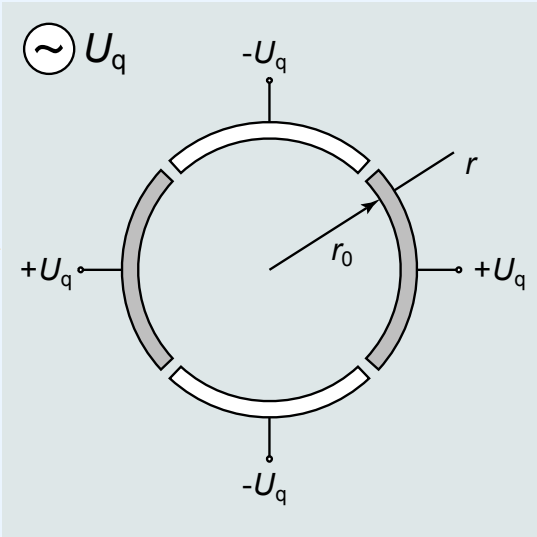
Brown & Gabrielse, Rev. Mod. Phys. 58, 233 (1986)

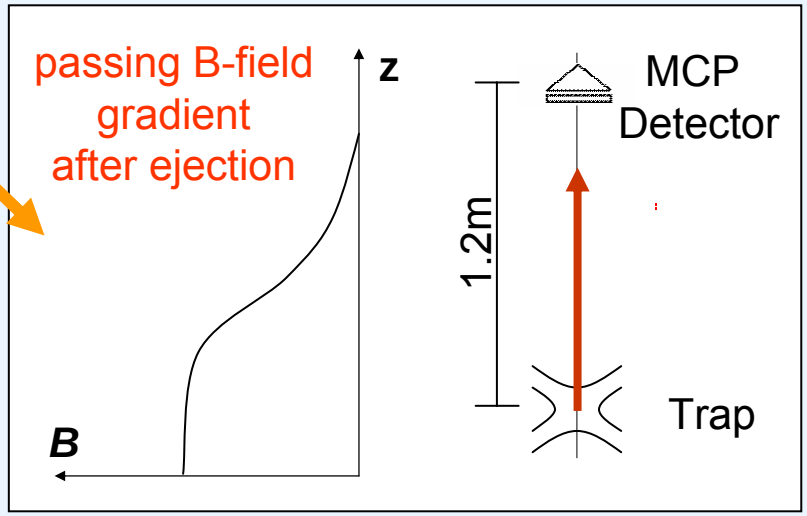
Time-of-flight mass spectrometry

Time-of-flight resonance technique



Conversion of magnetron into cyclotron motion

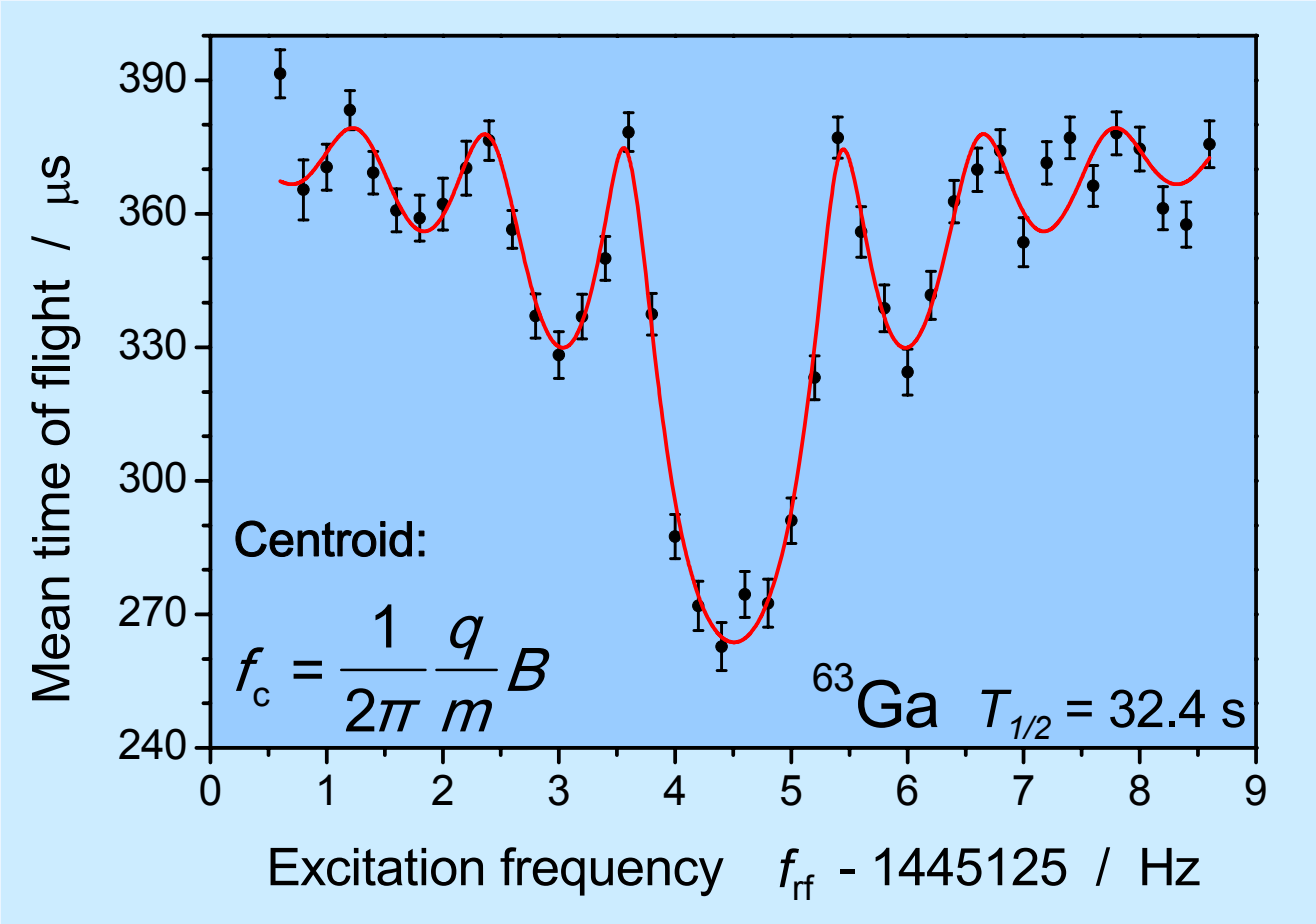




Resolving power: $R = f_{exc}\ T_{exc}$

TOF cyclotron resonance curve

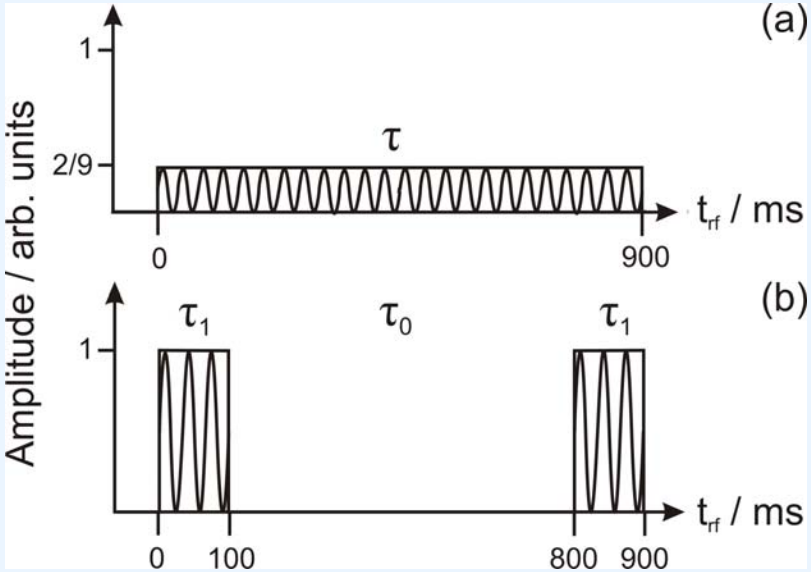
Measurement time: between 15 min and 4 h with ~50-100 ions/s

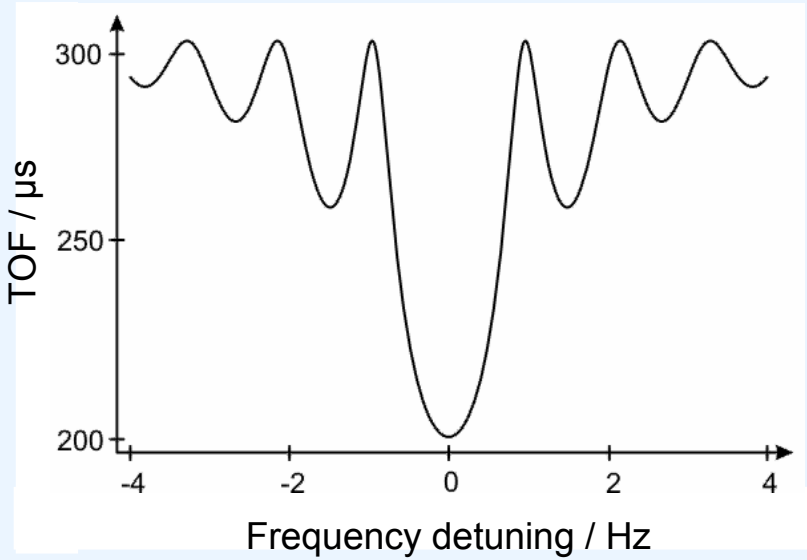


Determine atomic mass from frequency ratio with a well-known "reference mass".

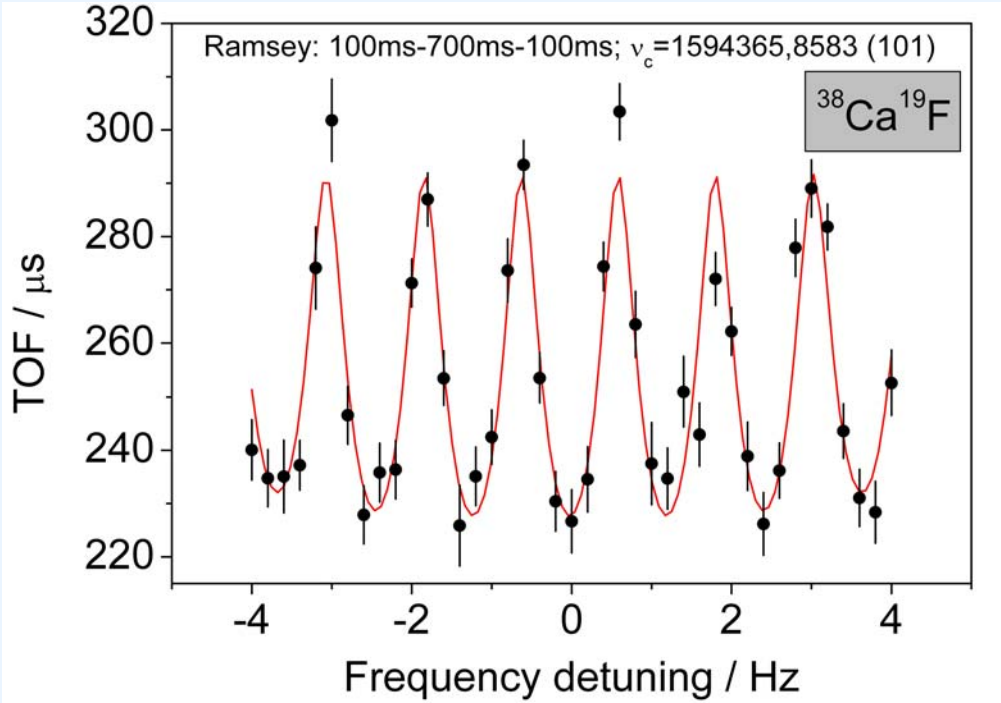
$$\frac{f_{c,ref}}{f_c} = \frac{m - m_e}{m_{ref} - m_e}$$

The Ramsey excitation technique





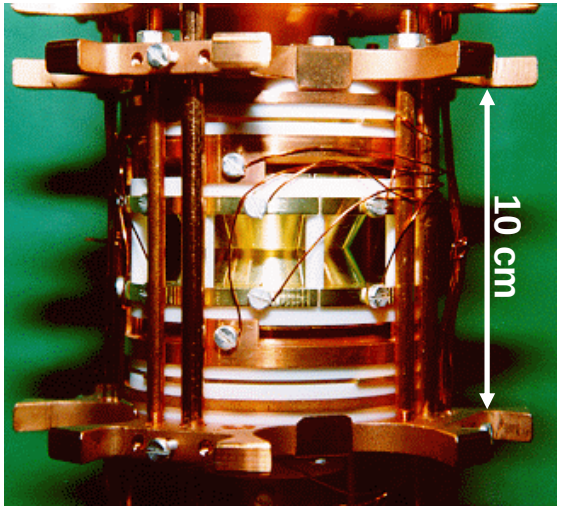
^{38}Ca ($T_{1/2}$ = 440 ms)

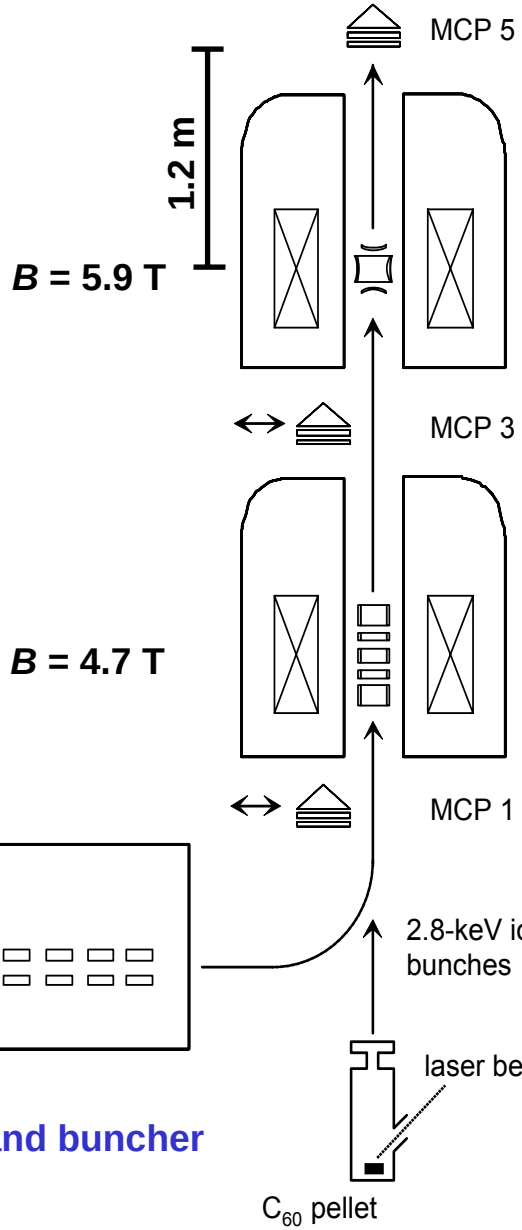


A precision gain of about a factor of 4 is obtained.

S. George *et al.*, Phys. Rev. Lett. 98, 162501(2007)

Triple-trap mass spectrometer ISOLTRAP





precision Penning trap

⇩

determination of cyclotron frequency ($R = 10^7$)

preparation Penning trap

⇩

removal of contaminant ions ($R = 10^5$)

8 m

8 m

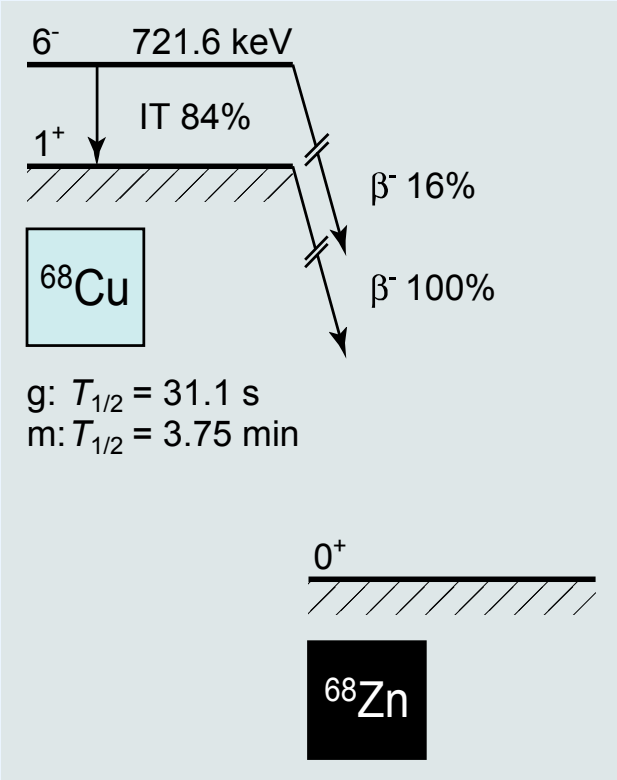
ion beam cooler and buncher

cluster ion source

F. Herfurth, et al., NIM A 469, 264 (2001)
K. Blaum et al., NIM B 204, 478 (2003)

Resolution and isolation of nuclear isomers

Isomerism in ^{68}Cu:

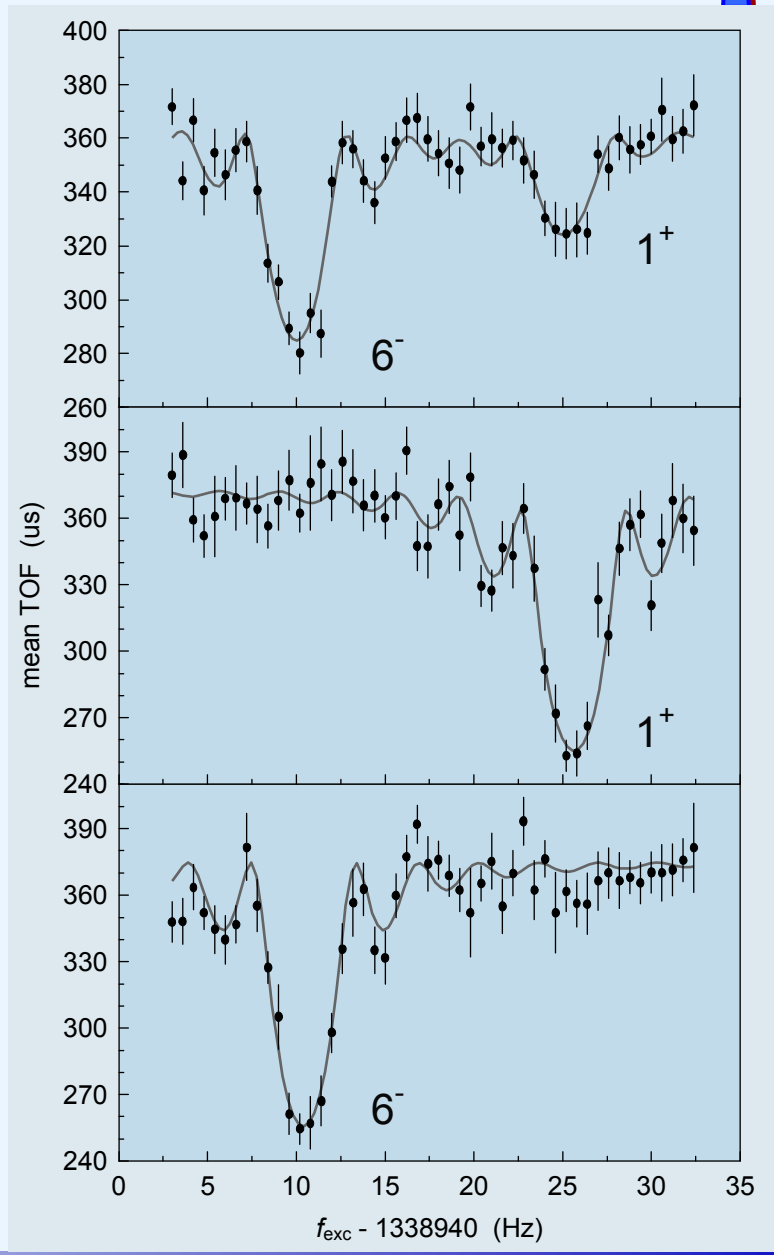


K. Blaum *et al.*, Europhys. Lett. 67, 586 (2004)

as produced by ISOLDE

isolation of the 1^+ ground state

isolation of the 6^- isomeric state



Applications

- Preparation of an isomerically pure beam
- Clear state-to-mass assignments
- Trap-assisted decay and laser spectroscopy

Isobaric Multiplet Mass Equation

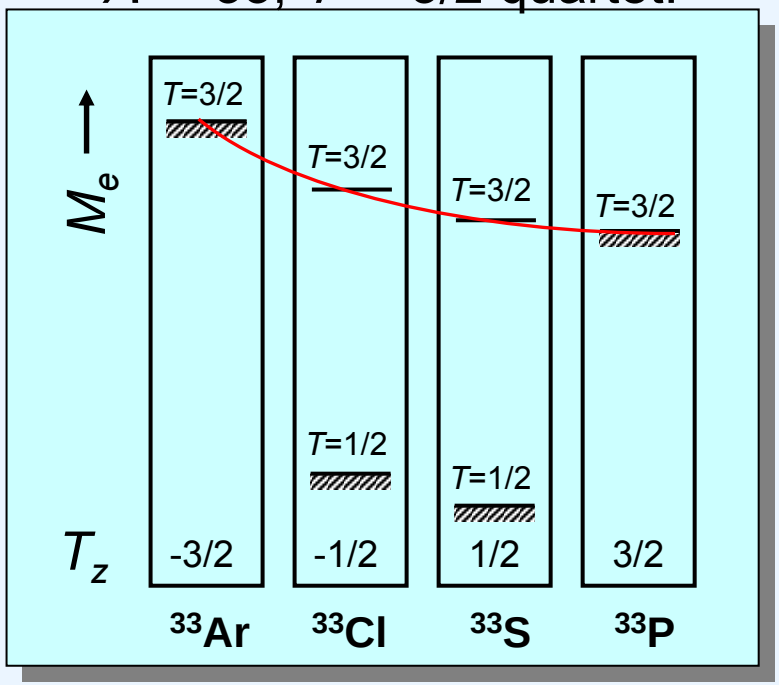
Mass formula for multiplets of nuclear states with same mass and isospin

$$M = a + bT_z + cT_z^2 + dT_z^3$$

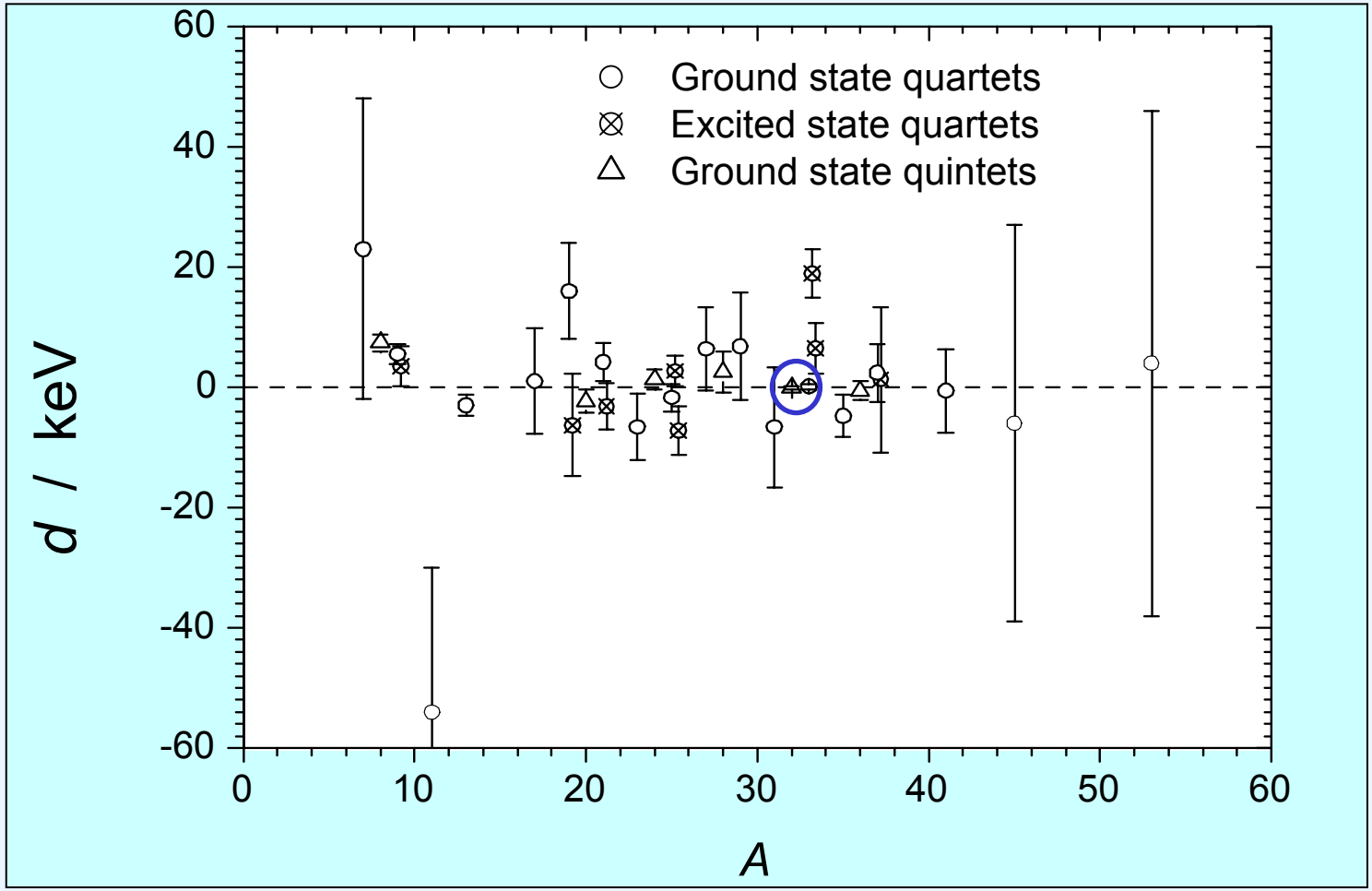
Commonly used quadratic form

?

A = 33, T = 3/2 quartet:



Most stringent test of IMME (with ^{32,33}Ar)



K. B. *et al.*, Phys. Rev. Lett. 91, 260801 (2003).

ISOLTRAP measurements 2002:

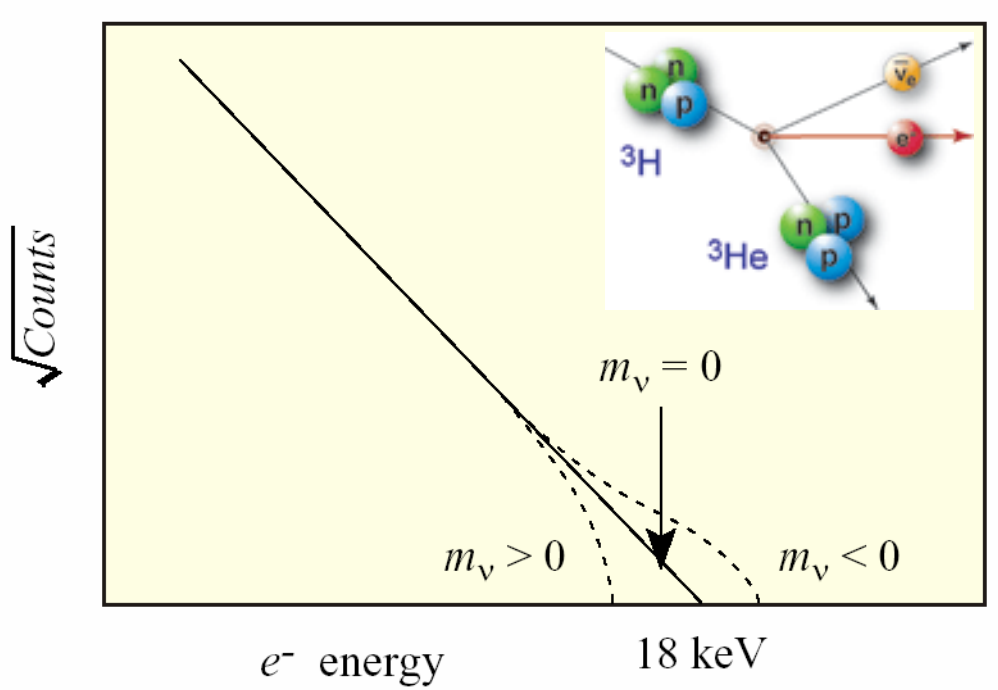
- ^{33}Ar with $u(m)$ = 0.44 keV
- ^{32}Ar with $u(m)$ = 1.8 keV

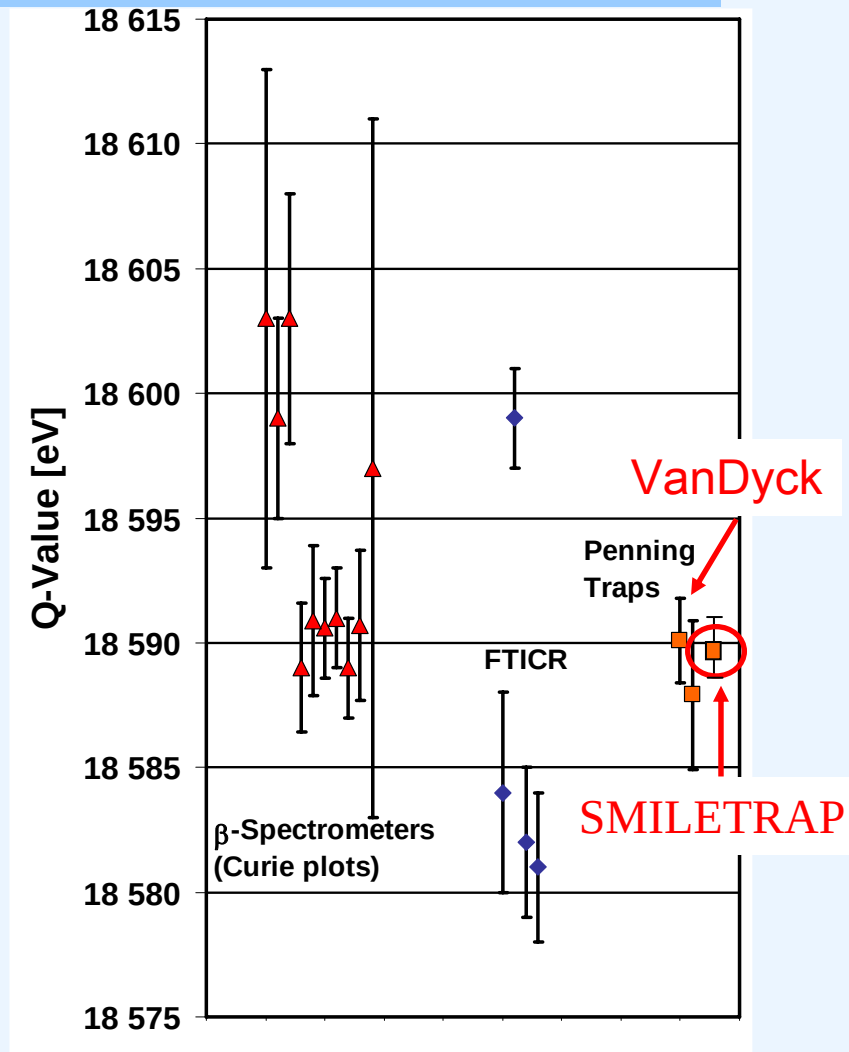
New status:

A = 33, T = 3/2	quartet:	d = -0.13(45) keV
A = 32, T = 2	quintet:	d = -0.11(30) keV

Determination of the $^3T \rightarrow {}^3He$ Q-Value

Important parameter for the determination of the electron neutrino rest mass.





- Q-value of Tritium beta decay

$$^3_1H \rightarrow {}^3_2He + e^- + \bar{\nu}$$

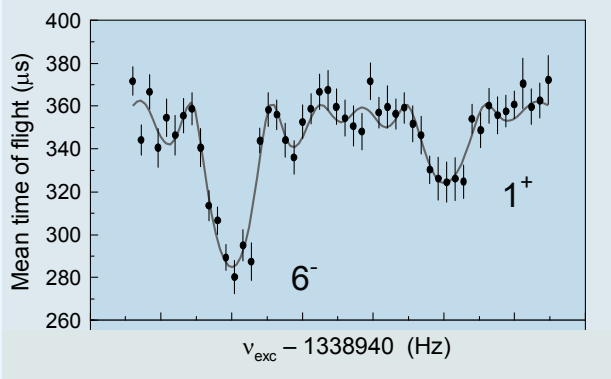
Q=18 589.8 (1.2) eV

Sz. Nagy *et al.*, Europhys.Lett. 74, 404 (2006)

m(^{4}He) = 4.002 603 254 153 (64) u R.S. Van Dyck *et al.*, Phys. Rev. Lett. 92 (2004) 220802

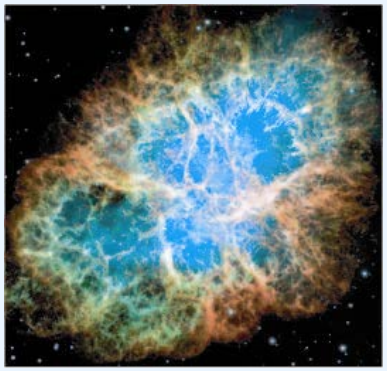
Recent results of fundamental studies

Population inversion of nuclear states and nuclear structure studies:



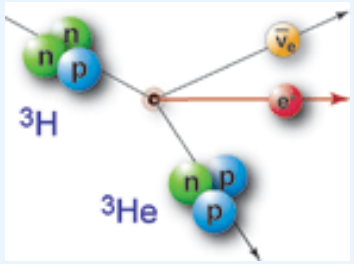
J. Van Roosbroeck *et al*., Phys. Rev. Lett. 92, 1112501 (2004)
K. Blaum *et al*., Europhys. Lett. 67, 586 (2004)
Sz. Nagy *et al*., Phys. Rev. Lett. 96, 163004 (2006)
C. Rauth *et al*., Phys. Rev. Lett., submitted (2007)

Why are there elements heavier than iron?



D. Rodríguez *et al*., Phys. Rev. Lett. 93, 161104 (2004)
M. Mukherjee *et al*., Phys. Rev. Lett. 93, 150801 (2004)

Are there scalar currents present in the Weak Interaction?



F. Herfurth *et al*., Phys. Rev. Lett. 87, 142501 (2001)
K. Blaum *et al*., Phys. Rev. Lett. 91, 260801 (2003)

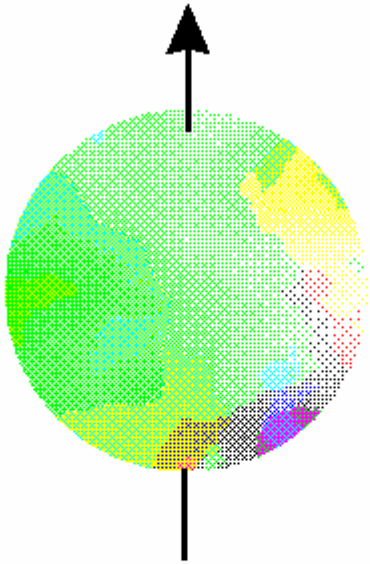
V_{ud} – is unitarity violated in quark mixing?

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

F. Herfurth *et al*., Eur. Phys. J. A 15, 17 (2002)
A. Kellerbauer *et al*., Phys. Rev. Lett. 93, 072502 (2004)
M. Mukherjee *et al*., Phys. Rev. Lett. 93, 150801 (2004)
S. George *et al*. Phys. Rev. Lett. 98, 162501 (2007)

High-precision *g*-factor measurements

The g – factor



relation between magnetic dipole moment and angular momentum

$$\vec{\mu} = g_J \frac{|q|}{2\,m} \hbar \vec{J}$$

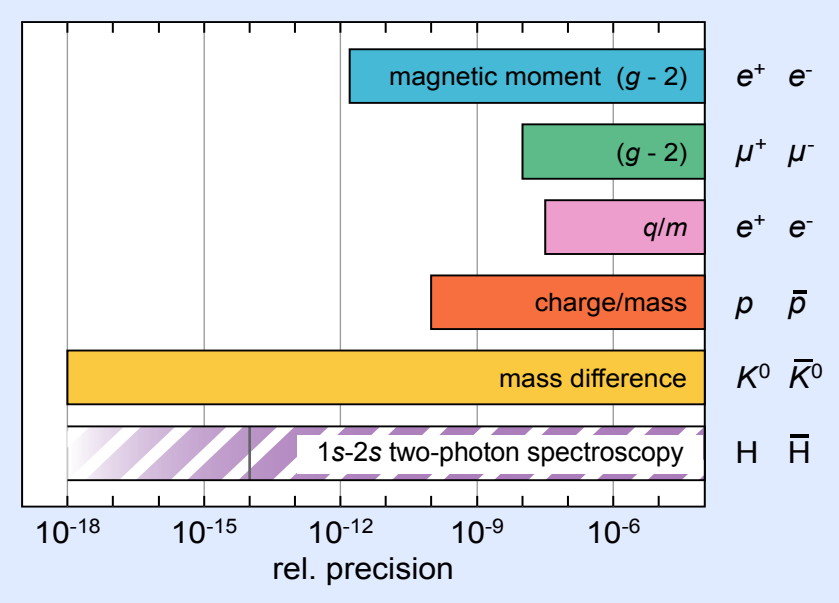
free lepton: g_s = g-factor of the spin

g-factor of the proton and the antiproton

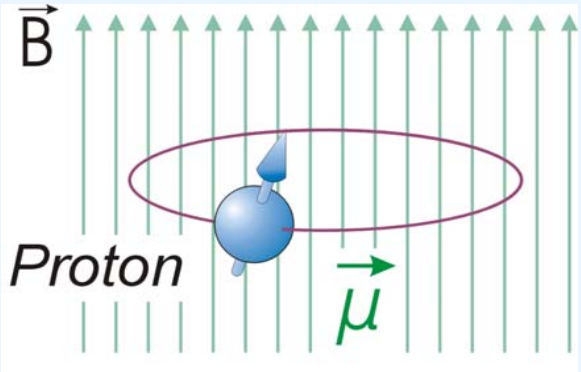
Test of CPT invariance

CPT $|\psi\rangle$: Reversal of space, charge, and time

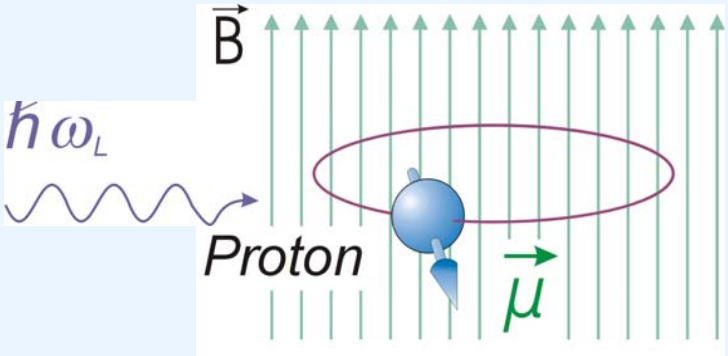
- Currently believed to hold
- CPT transforms particle into its antiparticle (P. Dirac 1928)



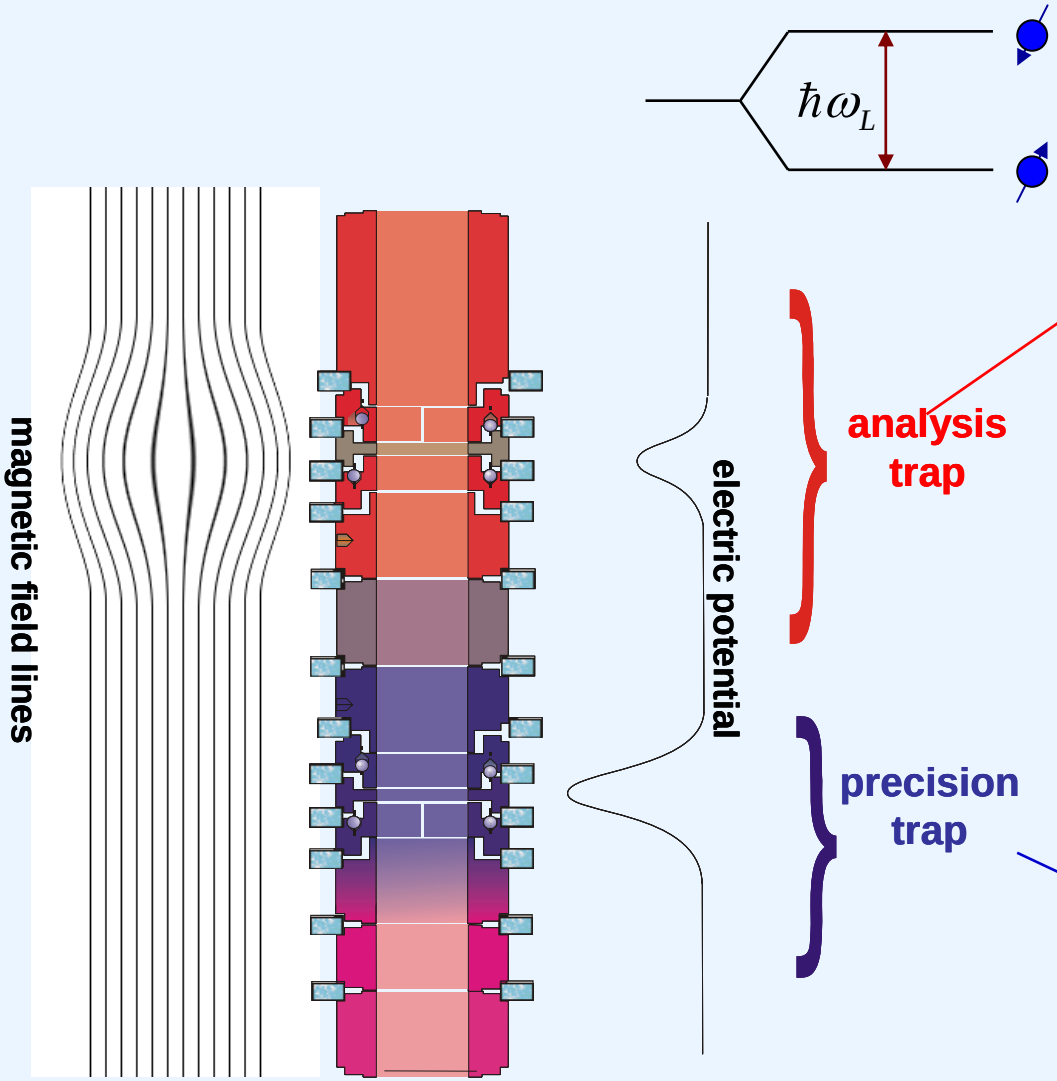
PDG: $g_p = 2\times 2.792847337(29)$ $g_p = 2\times 2.800(8)$



$$\frac{|\overline{\mu}_p|}{\mu_N} = g_p \cdot \frac{|\overline{s}|}{\hbar}$$



Measurement principle for a proton



Zeeman splitting in the spin eigenstates → Larmor frequency

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

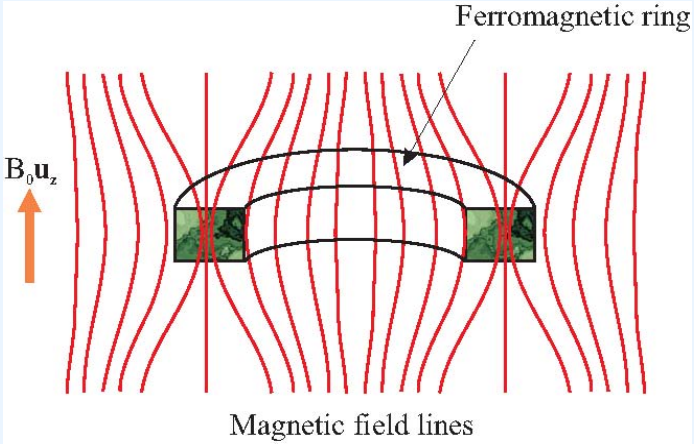
$$g_p = 2 \cdot \frac{\omega_L}{\omega_c}$$

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

Eigenmotions of the particle → cyclotron frequency

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

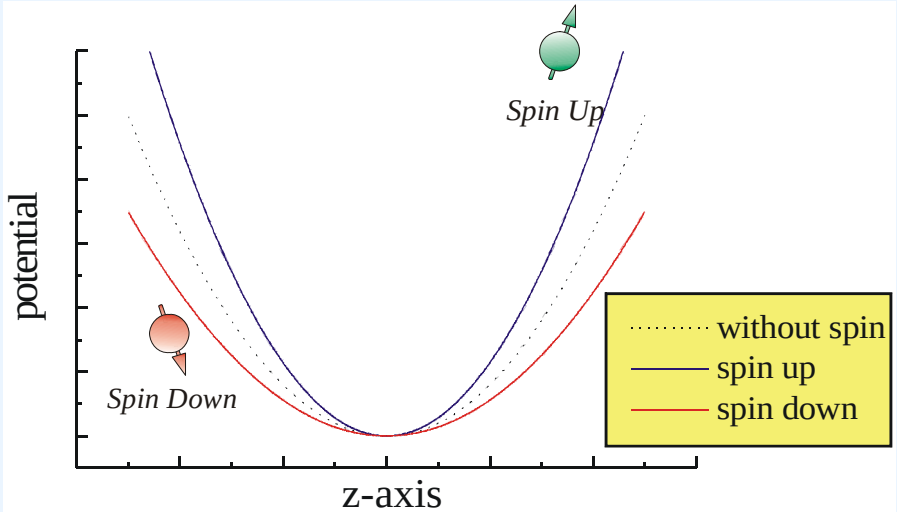
Measurement of the Lamor frequency



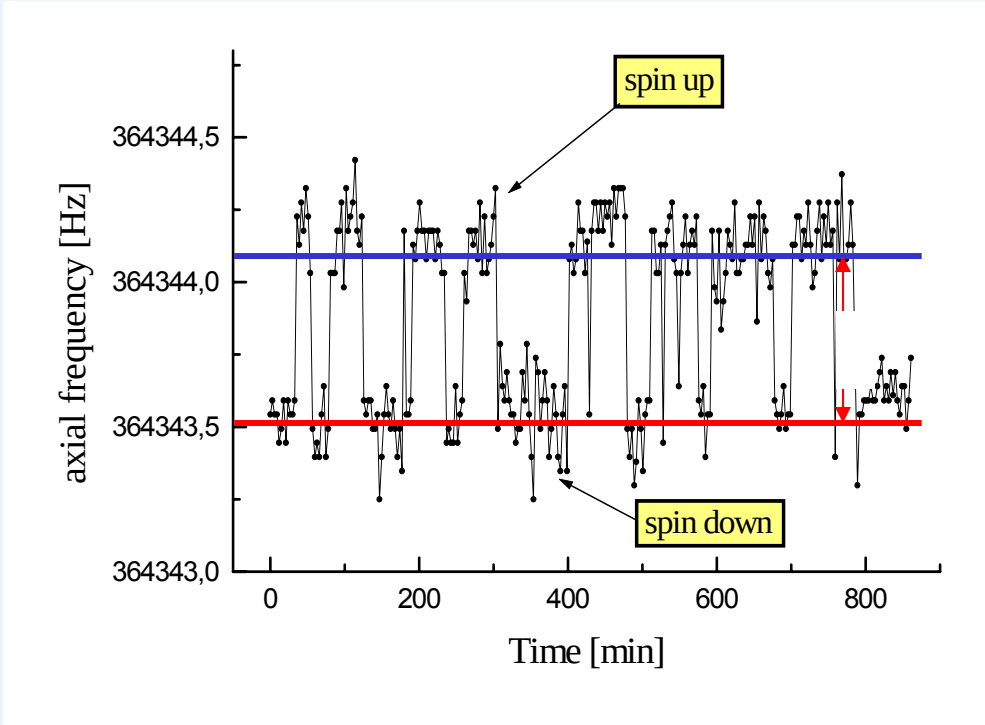
magnetic bottle

$$V_{mag} = -\vec{\mu}\cdot\vec{B} = \mp|\mu|(B_0 + B_2 z^2 + \ldots)$$

$$\Delta\omega_z = \frac{B_2}{m\cdot\omega_z}\cdot g\cdot\mu_B$$



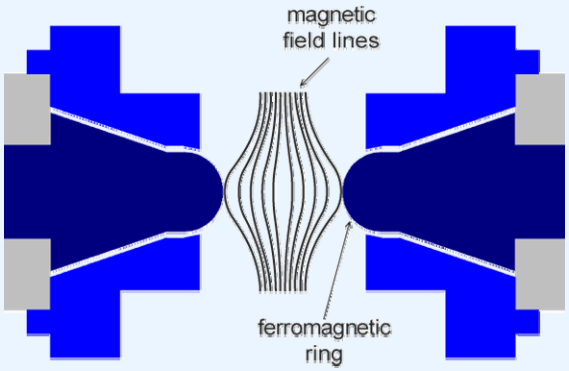
Potential as seen by the particle in different spin states.

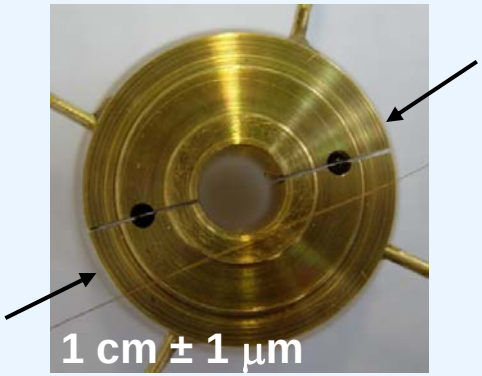


spin-flips result in measurable axial frequency jumps

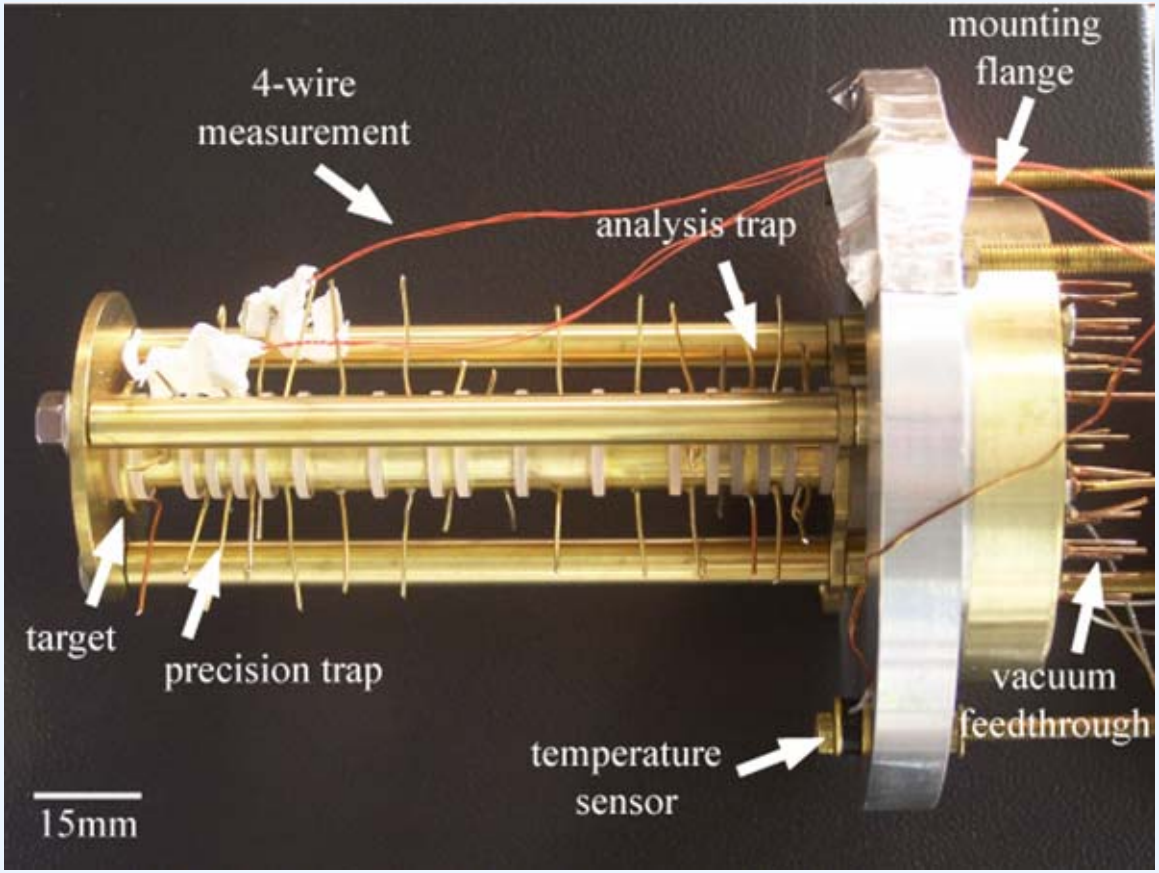
Status of the (anti)proton g-factor experiment

Hybrid analysis trap





Manufactured at the Institute for Microtechnique Mainz (IMM).



J. Verdú *et al*., AIP Conference Proceedings 796, 260-265 (2005)

Summary

High-accuracy experiments with stored ions in Penning traps have a broad range of applications!

- Fundamental tests:
  - Unitarity test of the CKM matrix: [Hardy & Towner, PRL 94, 092502 (2005)]
    $\delta m/m<10^{-8}$ for short-lived radionuclides ($T_{1/2}$<100 ms)
  - Test of $E=mc^2$: [S. Rainville et al., Nature 438, 1096 (2005)]
    $\delta m/m<10^{-10}$ for ^{32}S, ^{33}S
  - Test of CPT invariance: [G. Gabrielse et al., PRL 82, 3198 (1999)]
    $\delta g/g<10^{-9}$ for proton and antiproton
  - Test of bound-state QED [J. Verdú et al. PRL 92, 093002 (2004)]
    $\delta g/g<10^{-9}$ for hydrogen-like highly-charged ions
- Fundamental constants: m_e, m_p, α, $N_a h$, μ, … [G. Gabrielse et al., PRL 97, 030802 (2006)]

Thanks a lot for your attention.

Email: blaumk@uni-mainz.de **www.quantum.physik.uni-mainz.de/en/mats**