High-Precision Experiments Using Radioactive Ions, Lasers and/or Storage Devices

-for nuclear physics and atomic physics
-for testing fundamental interactions and symmetries

H.-Jürgen Kluge
GSI Darmstadt and University of Heidelberg, Germany

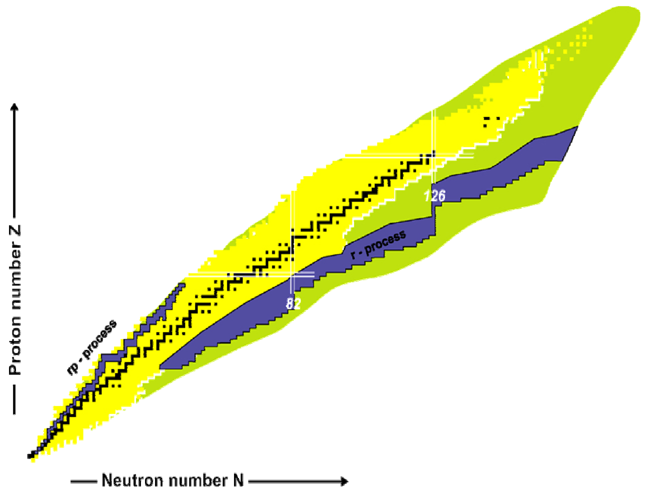
Handout

- Atomic physics techniques for studying nuclear ground state properties, fundamental interactions and symmetries: Status and perspectives
  H.-J. Kluge
  Hyperfine Interactions (to be published)
- Copies of transparencies

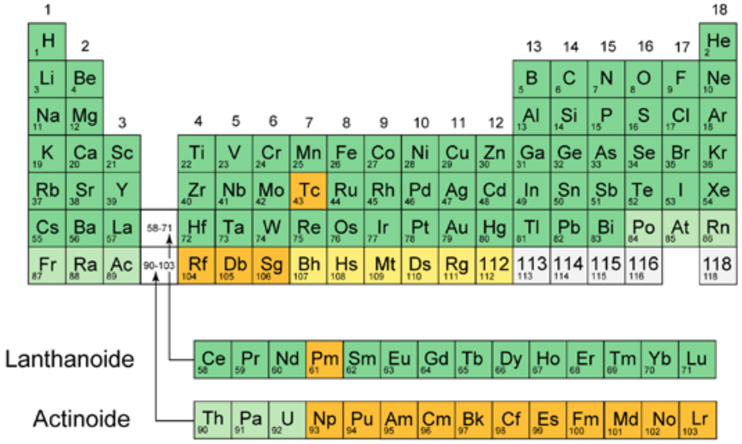
Outline

1. What can we learn on nuclear ground state properties from optical spectroscopy?
2. Laser spectroscopy far from stability
   - resonance ionization mass spectroscopy
   - collinear spectroscopy
   - magneto-optical trap
3. Mass spectrometry for fundamental studies
   - mass of the neutrino
   - storage ring mass spectrometry
   - Penning trap mass spectrometry
4. A brief look into the future
   - HITRAP
   - FAIR
5. Conclusion

The Playground of Nuclear Physics



The Playground of Atomic Physics



1	2	3		4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
H 1																		He 2
Li 3	Be 4												B 5	C 6	N 7	O 8	F 9	Ne 10
Na 11	Mg 12												Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
K 19	Ca 20	Sc 21		Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
Rb 37	Sr 38	Y 39		Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
Cs 55	Ba 56	La 57	58-71	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
Fr 87	Ra 88	Ac 89	90-103	Rf 104	Db 105	Sg 106	Bh 107	Hs 108	Mt 109	Ds 110	Rg 111	112 112	113 113	114 114	115 115	116 116		118 118

Lanthanoide	Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
Actinoide	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103

Nuclear ground state properties by atomic-physics techniques

* **MASS** — nuclear binding energy

* **NUCLEAR HALF LIFE**

This information is model-independent.

J + I = F — nuclear spin

This information is the most basic one and should be known for each nucleus.

${}^1\Delta^2=\{(A_1/g_1)/(A_2/g_2)\}-1$ — magnetism between two isotopes

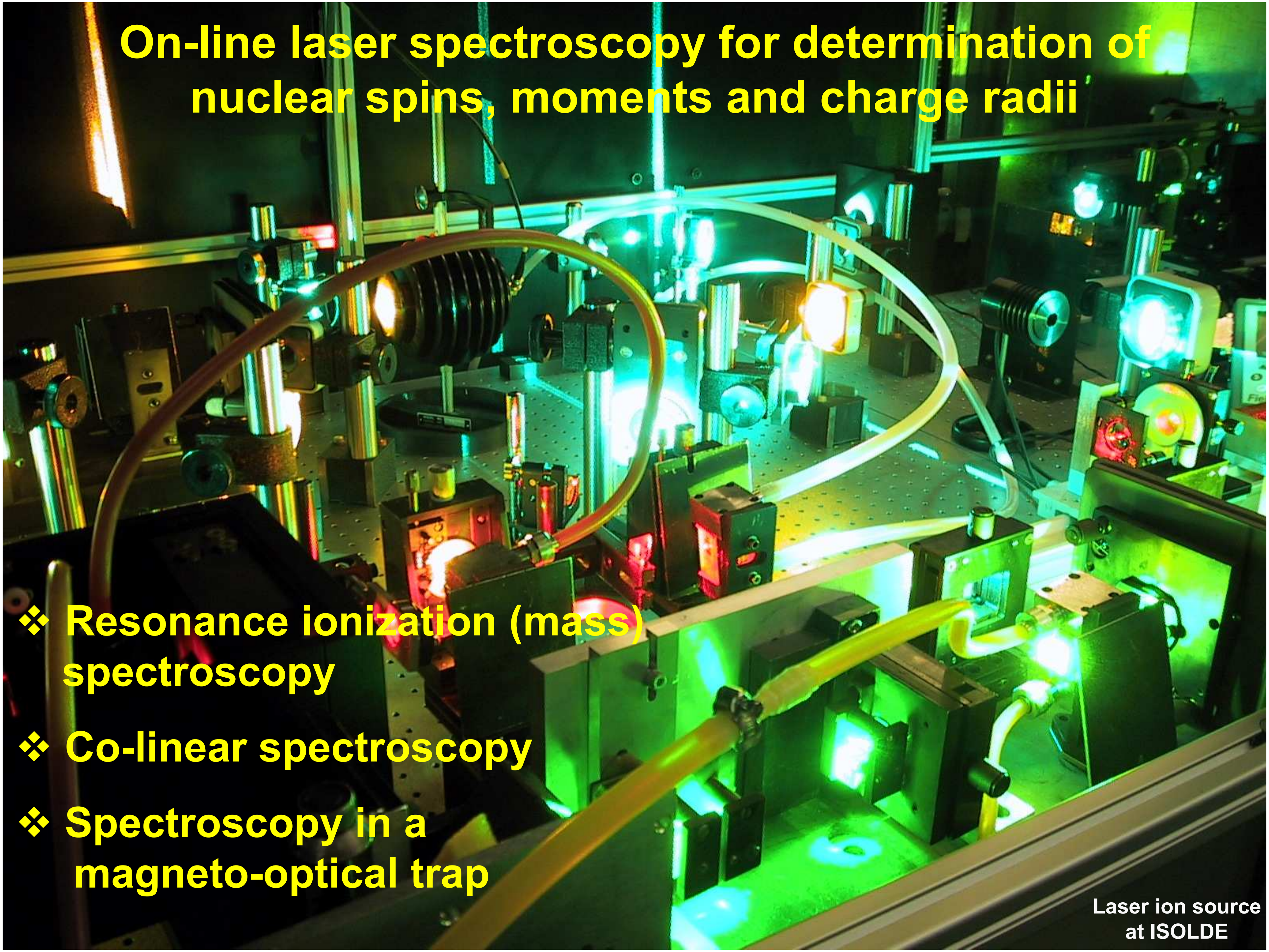
Presently, only optical isotope shift measurements give access to the charge radii of radionuclides.

* **ISOTOPE SHIFT**

Finite Size Effect

$\delta\langle r^2\rangle^{A,A'}$ — change of ms charge radius

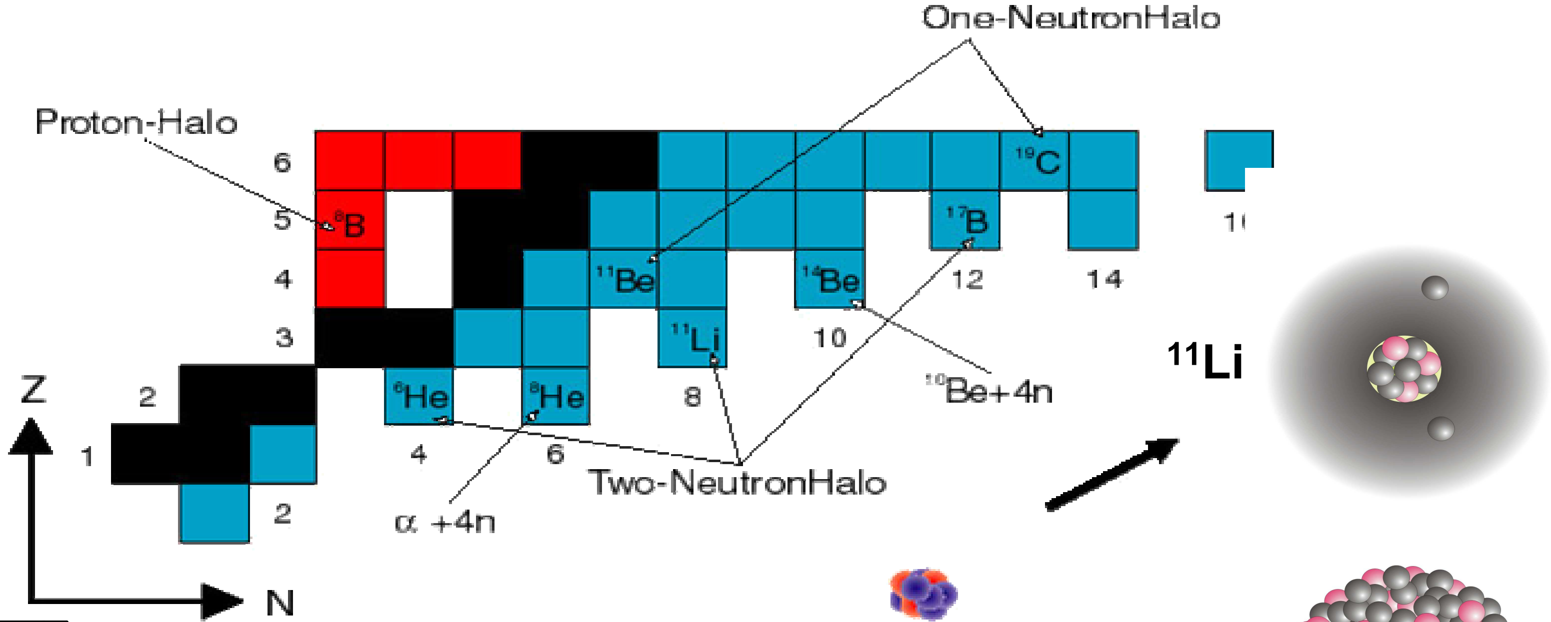
On-line laser spectroscopy for determination of nuclear spins, moments and charge radii

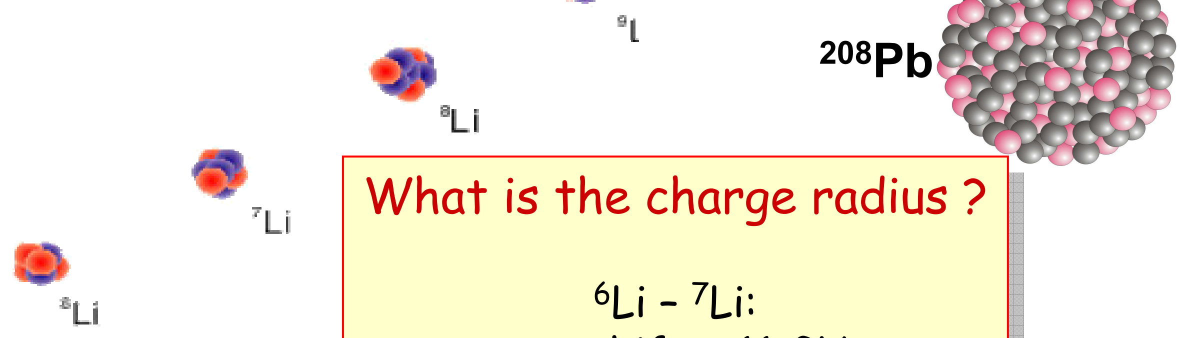


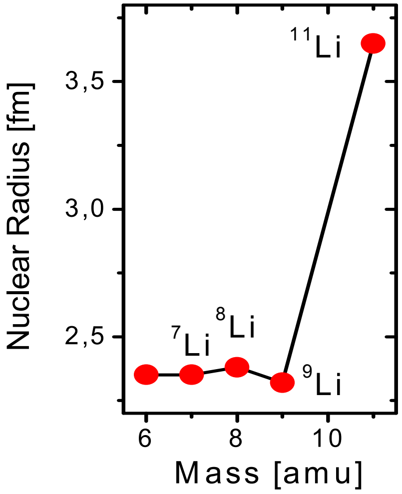
- Resonance ionization (mass) spectroscopy
- Co-linear spectroscopy
- Spectroscopy in a magneto-optical trap

Laser ion source at ISOLDE

Nuclear charge radii of halo nuclei







I. Tanihata et al.

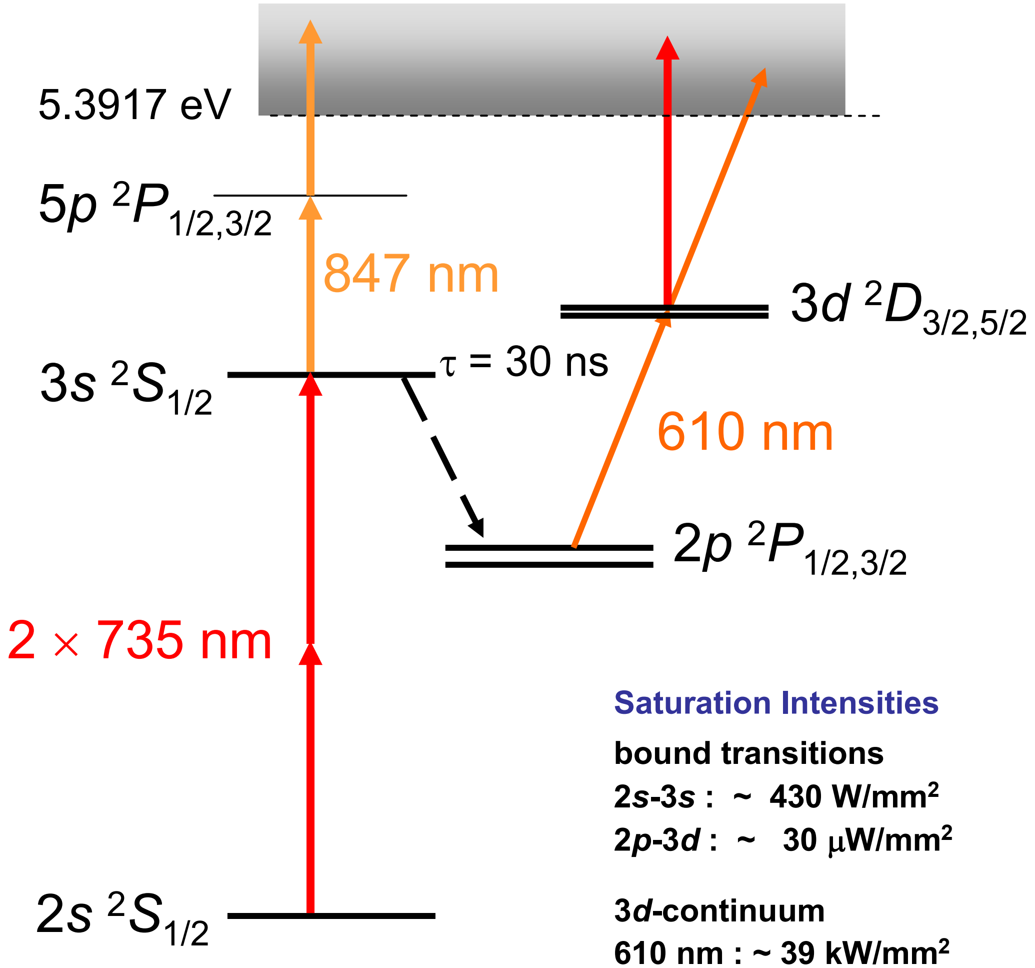
What is the charge radius ?

^{6}Li - ^{7}Li:
mass shift ≈ 11 GHz
volume shift ≈ 1 MHz

Yan, Z.-C. and G.W.F. Drake, PRA 66, 042504 (2002)

Excitation Scheme for RIMS of Lithium

"Doubly-Resonant-4-Photon Ionization"



Saturation Intensities

bound transitions

2*s*-3*s* : ~ 430 W/mm²

2*p*-3*d* : ~ 30 µW/mm²

3*d*-continuum

610 nm : ~ 39 kW/mm²

735 nm : ~ 16 kW/mm²

2s - 3s transition

→ narrow line

2-photon spectroscopy

→ Doppler cancellation

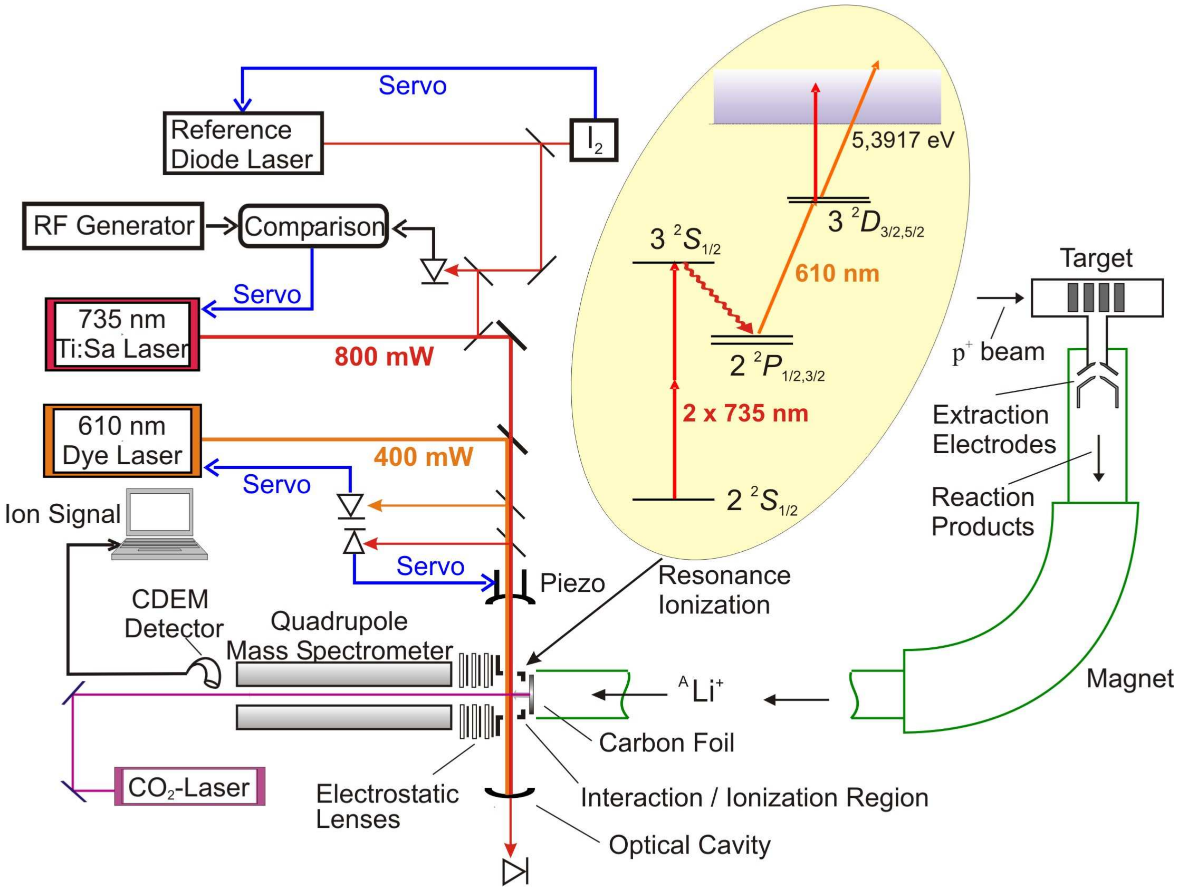
Spontaneous decay

→ decoupling of precise spectroscopy and efficient ionization

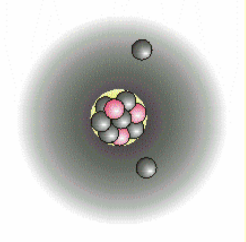
2p - *3d* transition

→ resonance enhancement for efficient ionization

Doppler-free resonance ionization mass spectroscopy of lithium isotopes at GSI and TRIUMF



^{11}Li



Lifetime ≈ 9 ms
30,000 Atoms/s

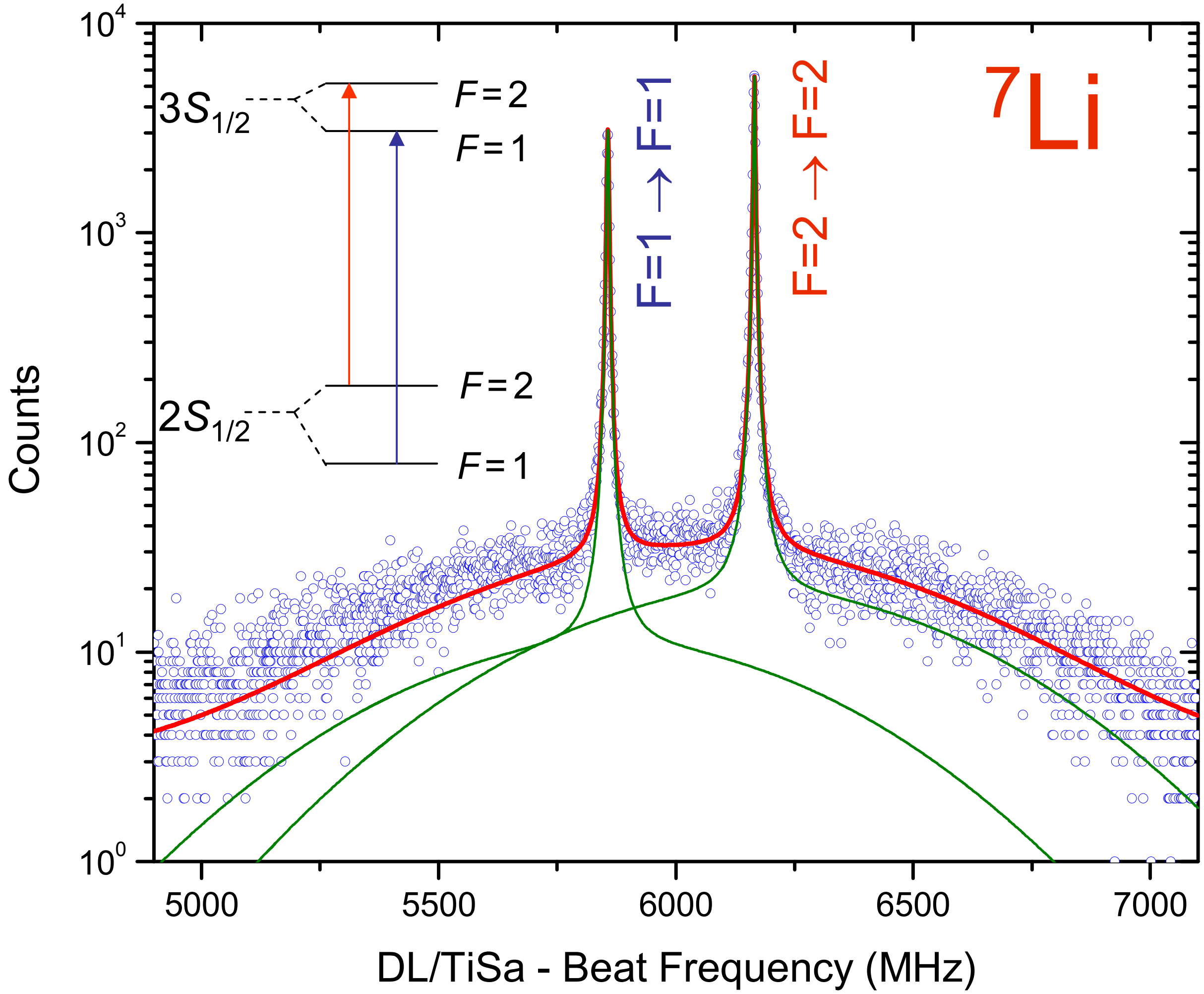
Novel technique developed at GSI by Wilfried Nörtershäuser, Andreas Dax et al.

^{8,9}Li at GSI
^{11}Li at TRIUMF

A relative accuracy of better than 10^{-5} is required for the IS measurement **and** for the calculation of the mass shift.

Mass shift calculation by G. Drake, Z.-C. Yan, K. Pachucki et al.

Line Shape of Two-Photon Resonance



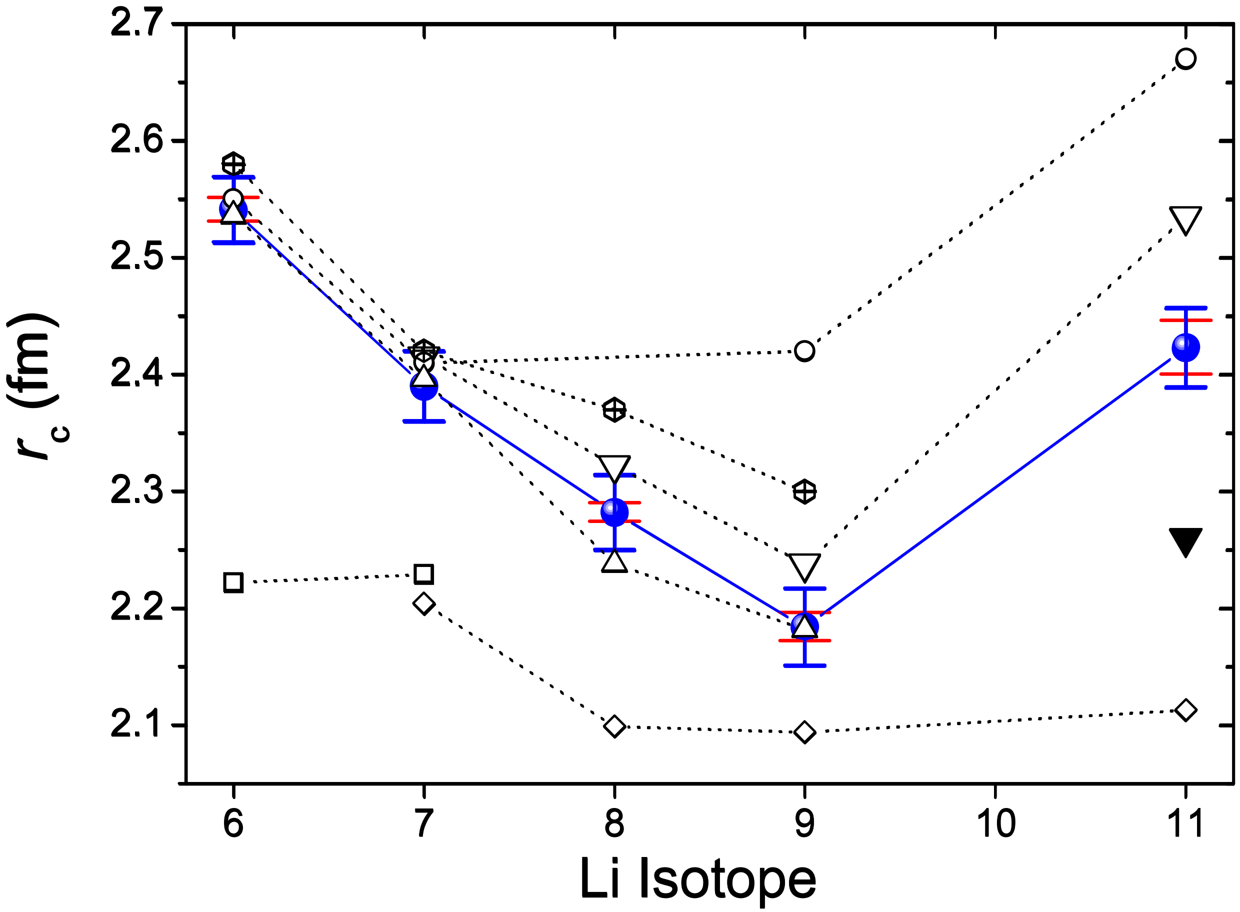
Linewidth Voigt
G_L= 4.6 (1) MHz (FWHM)
G_G= 1.8 (1) MHz (FW 1/e)

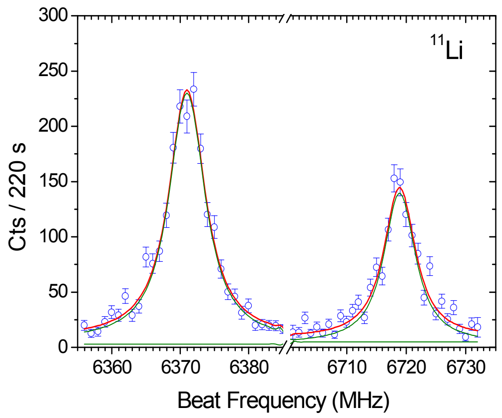
Expected Natural Width
G_L= 2.7 MHz (FWHM)

Background Gaussian
$G_G \approx$ 1.2 GHz
relative Amplitude
$\approx 3 \times 10^{-3}$

Amplitude Ratio
F=1 : F=2 2.85 : 5

Nuclear charge radii of lithium isotopes





Experiment

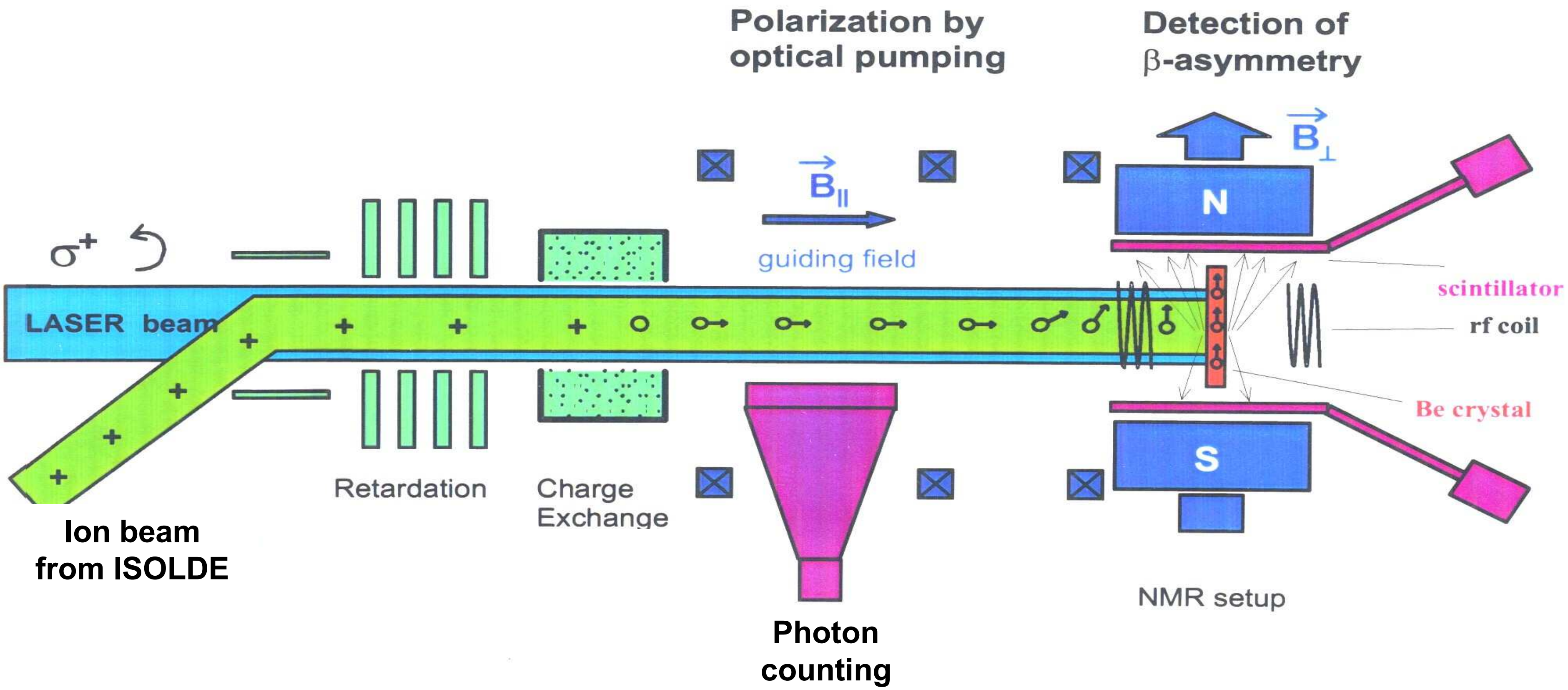
⋯●⋯ Isotope Shift
(this experiment, 2004)

Theory

⋯□⋯ *ab initio* No-Core Shell Model
⋯◇⋯ Large-Basis Shell Model
(P. Navrátil 2003, 1998)
⋯△⋯ Greens-Function Monte Carlo
(S. C. Pieper 2001/2002)
⋯▽⋯ Stochastic Variational Multi Cluster
(Y. Suzuki, 2002)
⋯⊕⋯ Fermionic Molecular Dynamics
(T. Neff, 2005)
⋯○⋯ Dynamic Correlation Model
(M. Tomaselli, 2002)

R. Sánchez *et al.*, PRL 96, 033002 (2006)
Nature Physics 2, 145 (2006)
M. Puchalski *et al.*, PRL 97, 133001 (2006)

Co-linear spectroscopy combined with nuclear-radiation-detected optical pumping of Li-11 at ISOLDE



Ion beam from ISOLDE

Photon counting

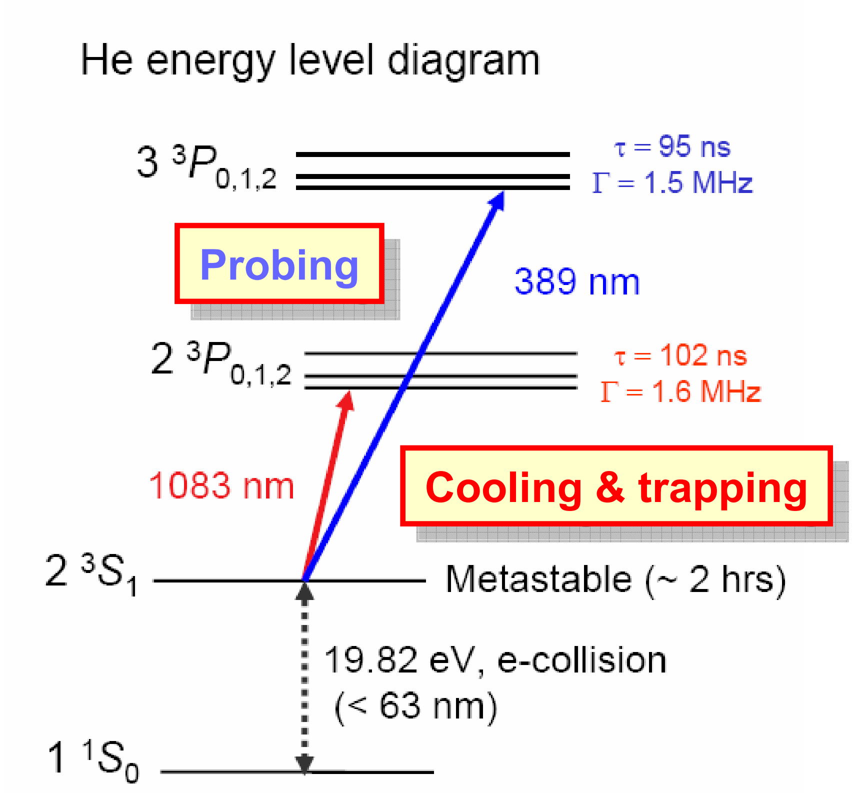
constant of motion: $\delta E_{\text{ion source}} = \delta(\frac{1}{2}mv^2) = \text{const} = mv \cdot \delta v$

Spin & magnetic moment : E. Arnold et al., PL B 197 (1987) 311

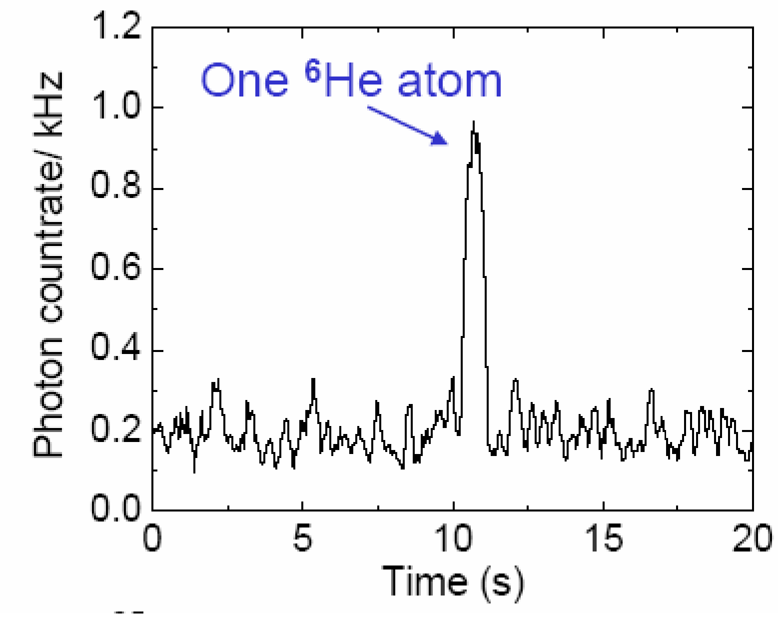
Spectroscopic quadrupole moment: First round: E. Arnold et al., PL B 281 (1992) 16

Second round: R. Neugart et al., PRL 101 (2008) 132502

Detection of a single ^{6}He atom at Argonne

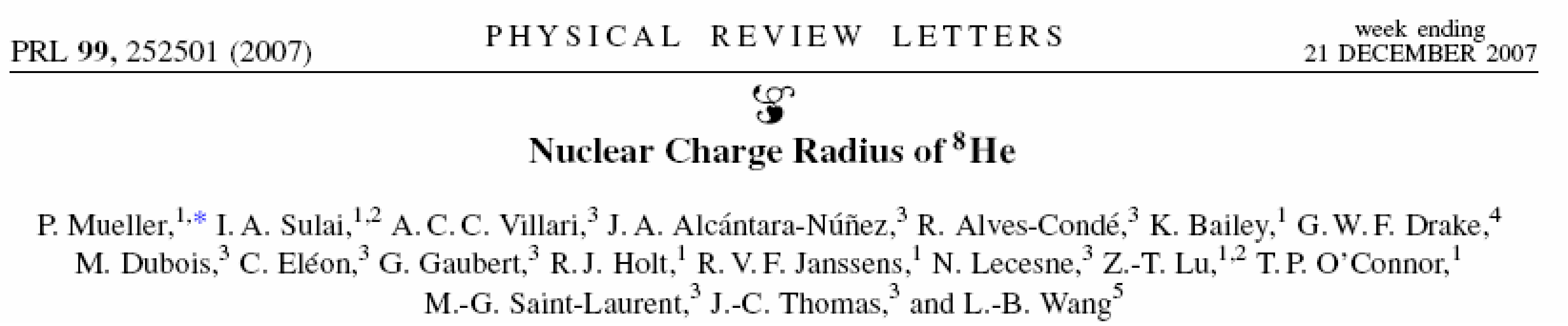


Shelving spectroscopy
quantum jumps



Efficiency: ~ 10^{-8} → single atom detection necessary!
Single-atom signal: ~ 1.0 kHz
Single-atom S/N: ~ 10 in 100 ms
^{6}He capture rate: ~ 150 per hour

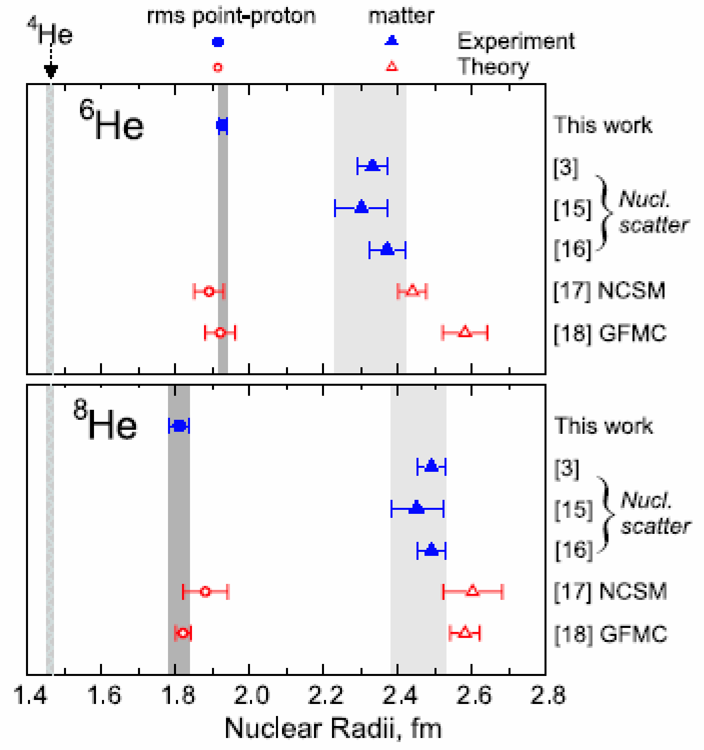
Nuclear charge radius of helium-8



PRL **99,** 252501 (2007) PHYSICAL REVIEW LETTERS week ending 21 DECEMBER 2007

Nuclear Charge Radius of ^{8}He

P. Mueller,[1,*] I. A. Sulai,[1,2] A. C. C. Villari,[3] J. A. Alcántara-Núñez,[3] R. Alves-Condé,[3] K. Bailey,[1] G. W. F. Drake,[4]
M. Dubois,[3] C. Eléon,[3] G. Gaubert,[3] R. J. Holt,[1] R. V. F. Janssens,[1] N. Lecesne,[3] Z.-T. Lu,[1,2] T. P. O'Connor,[1]
M.-G. Saint-Laurent,[3] J.-C. Thomas,[3] and L.-B. Wang[5]



Short summary of this part

Atomic physics techniques are

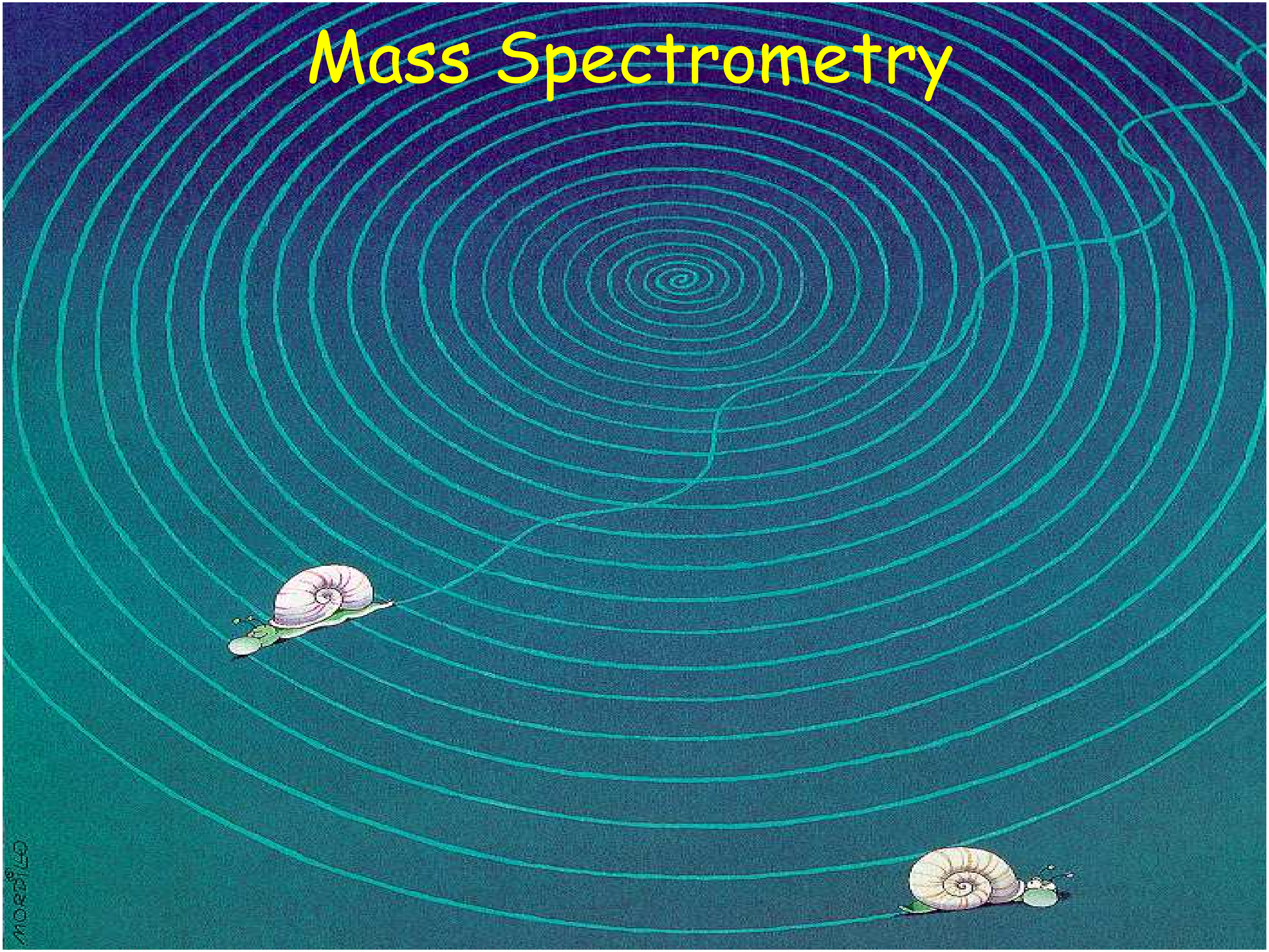
- accurate
- sensitive and
- deliver model-independent information on nuclear ground state properties.

Laser spectroscopy is (still) the only access to charge radii of short-lived isotopes.

Now, also the charge radii of very light nuclei are accessible. In this case, atomic theory is essential.

Resonance ionization (mass) spectroscopy and co-linear spectroscopy are the laser spectroscopic technique most often applied at radioactive beam facilities.

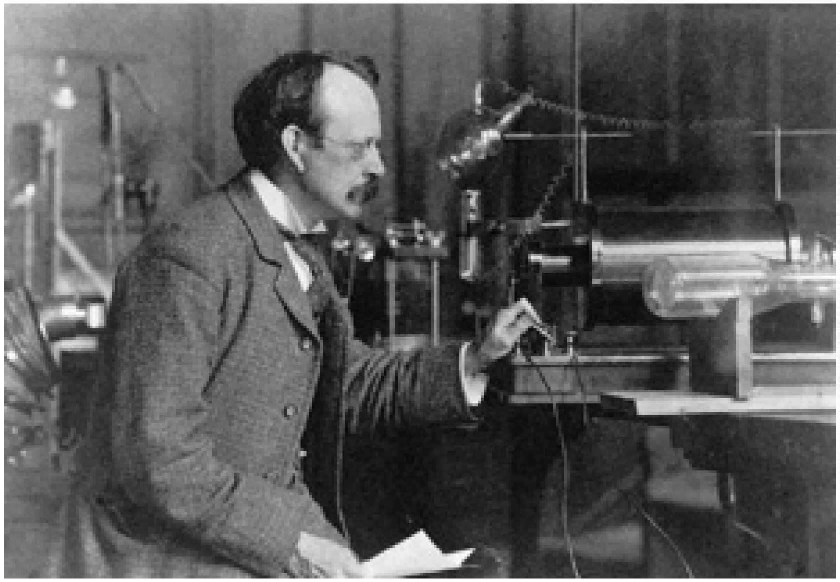
Mass Spectrometry

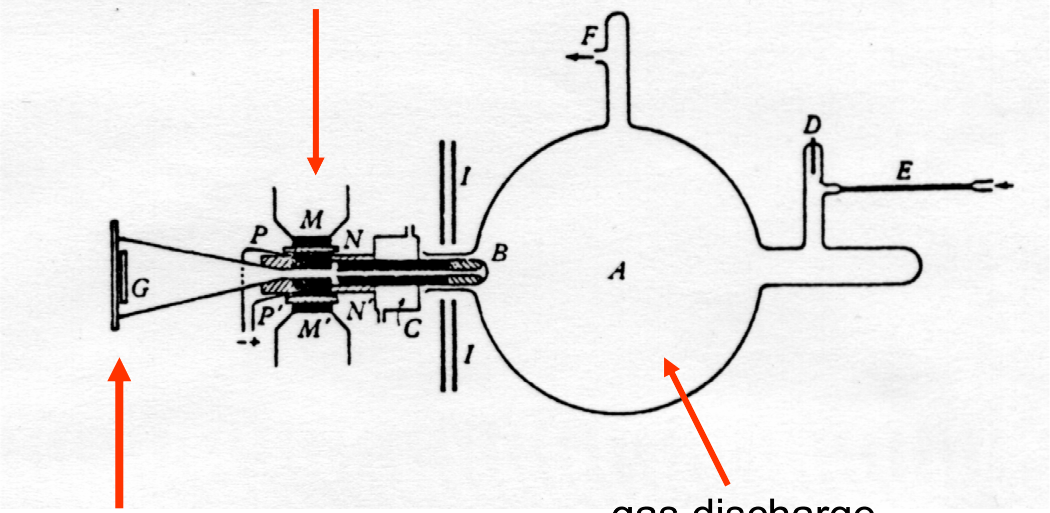


A short retrospect: Deflection of ions

J.J. Thompson 1907 deflection in e.m. fields 1912 isotopy in neon

The Nobel Prize in Physics 1906: „in recognition of the great merits of his theoretical and experimental investigations on the conduction of electricity by gases"





electric field
magnetic field

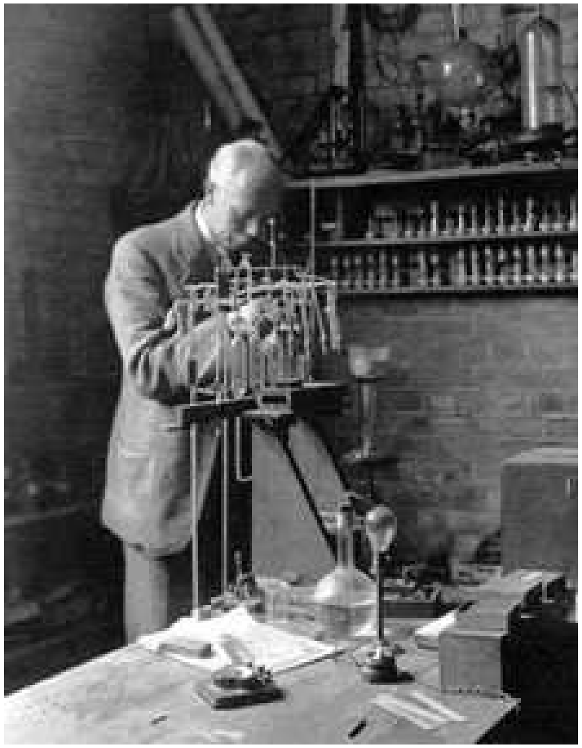
screen
photo plate

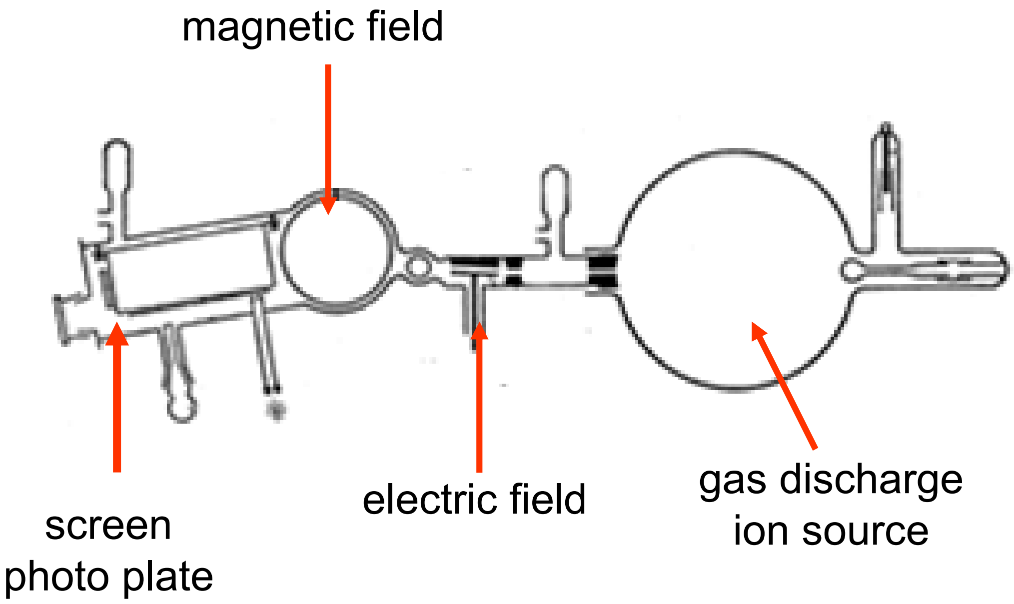
gas discharge
ion source

A short retrospect: First mass spectrograph

J.J. Thompson	1907 deflection in e.m. fields	1912 isotopy in neon
F.W. Aston	1919 mass spectrograph	1927 mass defect

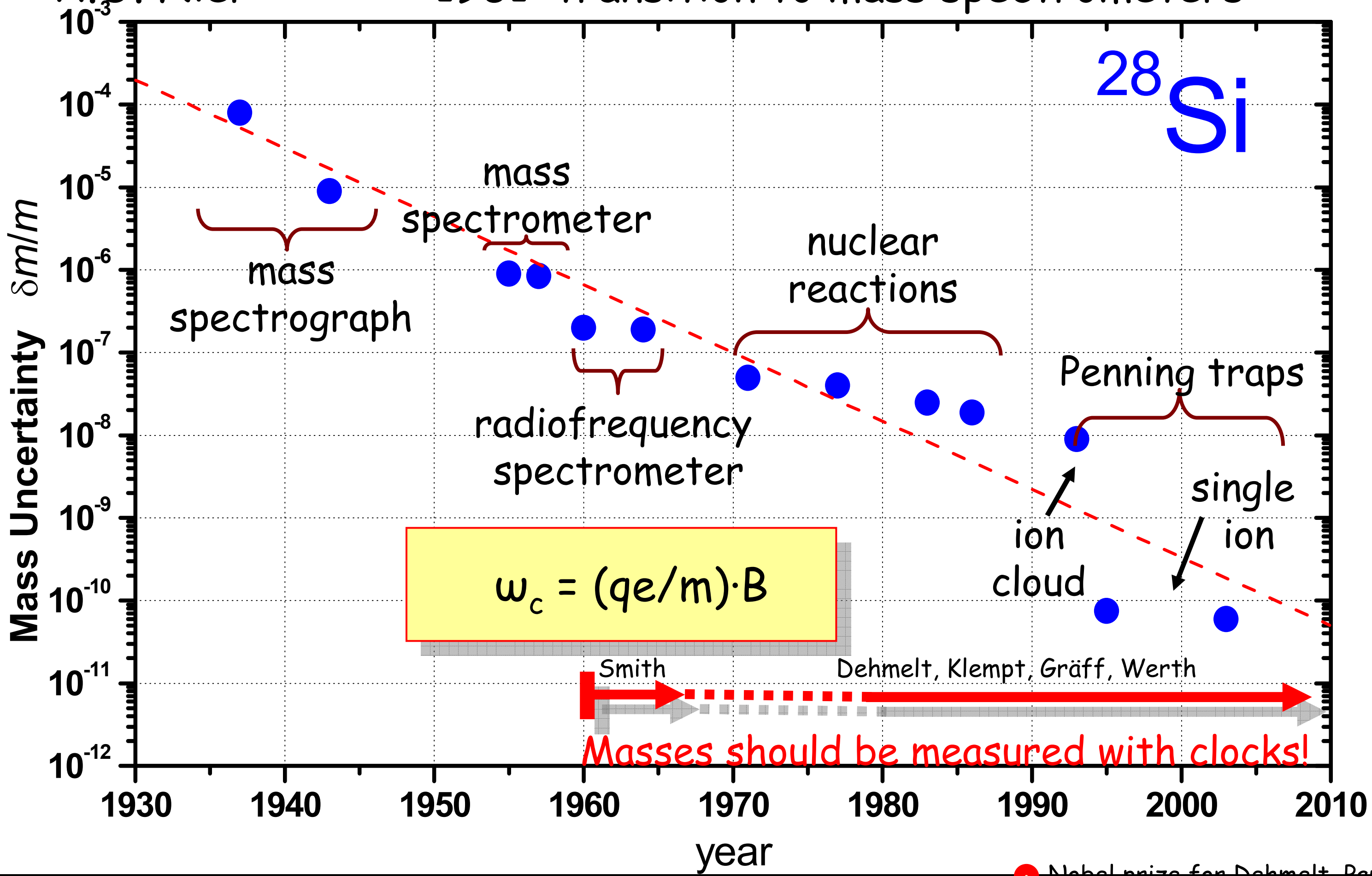
The Nobel Prize in Chemistry 1922: „for his discovery, by means of his mass spectrograph, of isotopes, in a large number of non-radioactive elements, and for his enunciation of the whole-number rule"





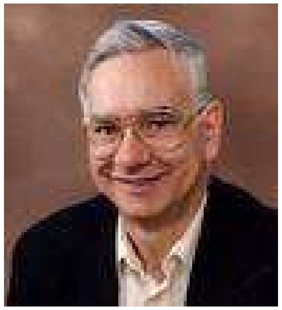
A short retrospect: Further developments

J.J. Thompson	1907 deflection in e.m. fields	1912 isotopy in neon
F.W. Aston	1919 mass spectrograph	1927 mass defect
J. Mattauch	1936 double-focusing mass spectrograph	
A.O. Nier	1951 transition to mass spectrometers	



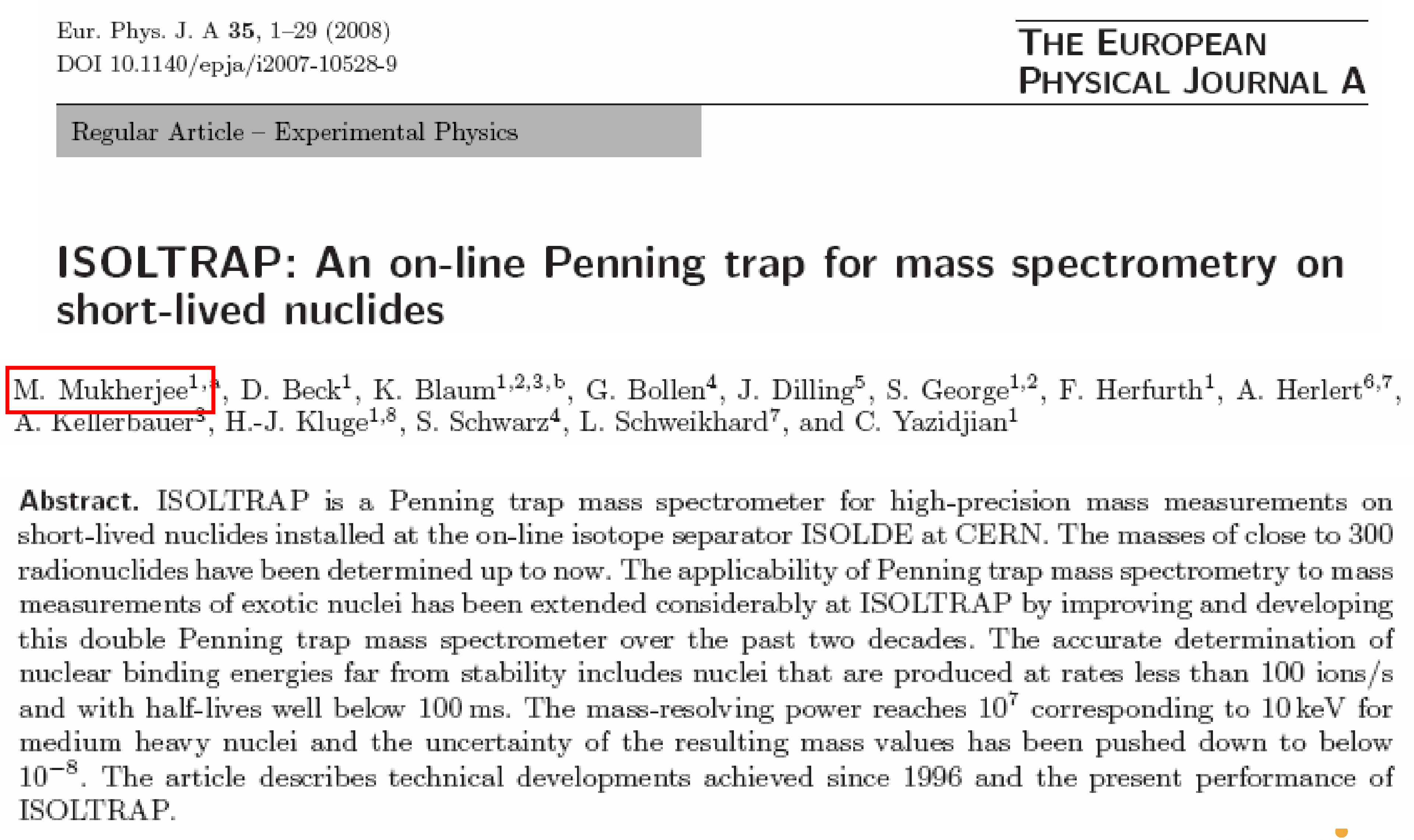
Masses should be measured with clocks!

● ~~Nobel prize for Dehmelt, Paul, Ramsey~~



Dave Pritchard

ISOLTRAP: The pioneering on-line Penning trap mass spectrometer installed at ISOLDE



Eur. Phys. J. A **35**, 1–29 (2008)
DOI 10.1140/epja/i2007-10528-9

THE EUROPEAN PHYSICAL JOURNAL A

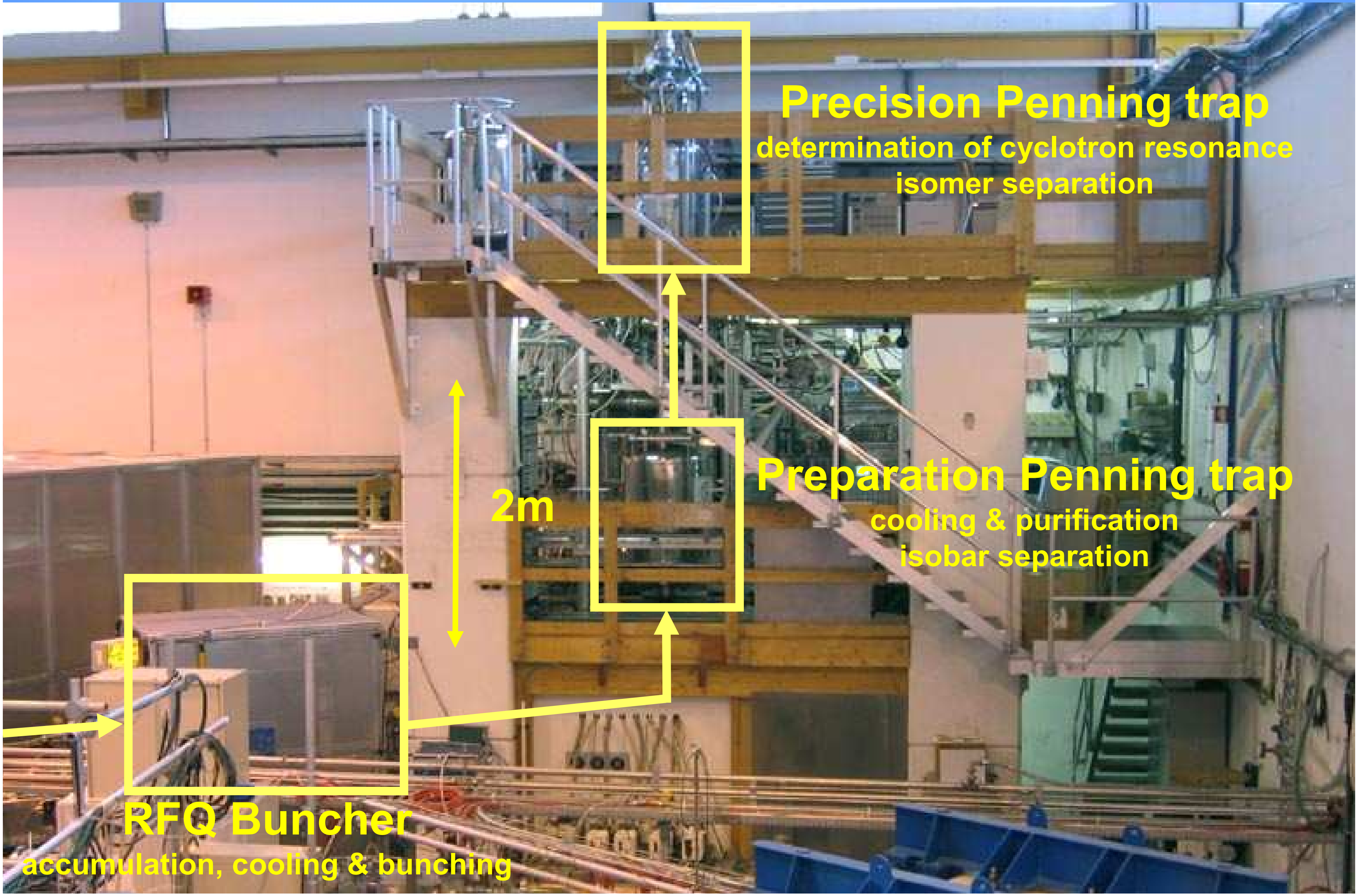
Regular Article – Experimental Physics

ISOLTRAP: An on-line Penning trap for mass spectrometry on short-lived nuclides

M. Mukherjee[1,a], D. Beck[1], K. Blaum[1,2,3,b], G. Bollen[4], J. Dilling[5], S. George[1,2], F. Herfurth[1], A. Herlert[6,7], A. Kellerbauer[3], H.-J. Kluge[1,8], S. Schwarz[4], L. Schweikhard[7], and C. Yazidjian[1]

Abstract. ISOLTRAP is a Penning trap mass spectrometer for high-precision mass measurements on short-lived nuclides installed at the on-line isotope separator ISOLDE at CERN. The masses of close to 300 radionuclides have been determined up to now. The applicability of Penning trap mass spectrometry to mass measurements of exotic nuclei has been extended considerably at ISOLTRAP by improving and developing this double Penning trap mass spectrometer over the past two decades. The accurate determination of nuclear binding energies far from stability includes nuclei that are produced at rates less than 100 ions/s and with half-lives well below 100 ms. The mass-resolving power reaches 10^7 corresponding to 10 keV for medium heavy nuclei and the uncertainty of the resulting mass values has been pushed down to below 10^{-8}. The article describes technical developments achieved since 1996 and the present performance of ISOLTRAP.

ISOLTRAP


Precision Penning trap
determination of cyclotron resonance
isomer separation
Preparation Penning trap
cooling & purification
isobar separation
2m
RFQ Buncher
accumulation, cooling & bunching

The importance of high-accuracy mass spectrometry for fundamental physics

The mass of a fundamental particle is a fundamental property in itself.

In a composite quantum mechanical system the mass is the sum of the masses of all building blocks minus the binding energy.

Thus, binding energies can be determined via measuring the mass of the composite system and those of its building blocks.

For an atom, for example:

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

High-accuracy mass spectrometry can therefore be used to test

all fundamental physical interactions

(electromagnetic, weak, strong interaction) except gravitation.

Recipe for

highest resolving power
extreme accuracy
ultimate sensitivity
:

- store particles for a period of time as long as possible

(Heisenberg principle)

- cool particles to temperatures as low as possible

(relativistic effects)

- if possible use only one single cooled & stored ion

(Coulomb interaction)

The recipe works out:
Pioneers of cooling and storing

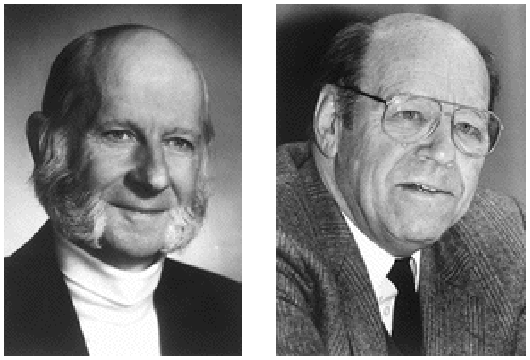
Principle of Penning Traps

Frans Michel
Penning

Storage and Cooling of Antiprotons

Nobel Prize 1984

J. van der Meer
C. Rubbia



Storage and Cooling of Ions

Nobel Prize 1989

H. Dehmelt
W. Paul

Storage and Cooling of Atoms

Nobel Prize 1997

S. Chu   C. Cohen-Tannoudji   W. D. Phillips

Bose-Einstein Condensation

Nobel Prize 2001

E. Cornell   W. Ketterle   C. Wieman

Application of storage devices and mass spectrometry for fundamental physics

Test of symmetries

- CPT (charge conjugation, parity, time reversal)
- electric dipole moment
- non-conservation of parity & anapole moment

Test of fundamental interactions and relations

- quantum electrodynamics in extreme fields
- relativity: $E = mc^2$
- test of the Standard Model: unitarity of the quark mixing matrix

Neutrino physics

- double beta decay
- mass of the electron antineutrino
- neutrino oscillations

Fundamental constants and metrology

- fine structure constant
- mass of the electron
- re-definition of Avogadro constant the kilogram

Application of storage devices and mass spectrometry for fundamental physics

Test of symmetries

- CPT (charge conjugation, parity, time reversal)
- electric dipole moment
- non-conservation of parity & anapole moment

Test of fundamental interactions and relations

- quantum electrodynamics in extreme fields
- relativity: $E = mc^2$
- test of the Standard Model: unitarity of the quark mixing matrix

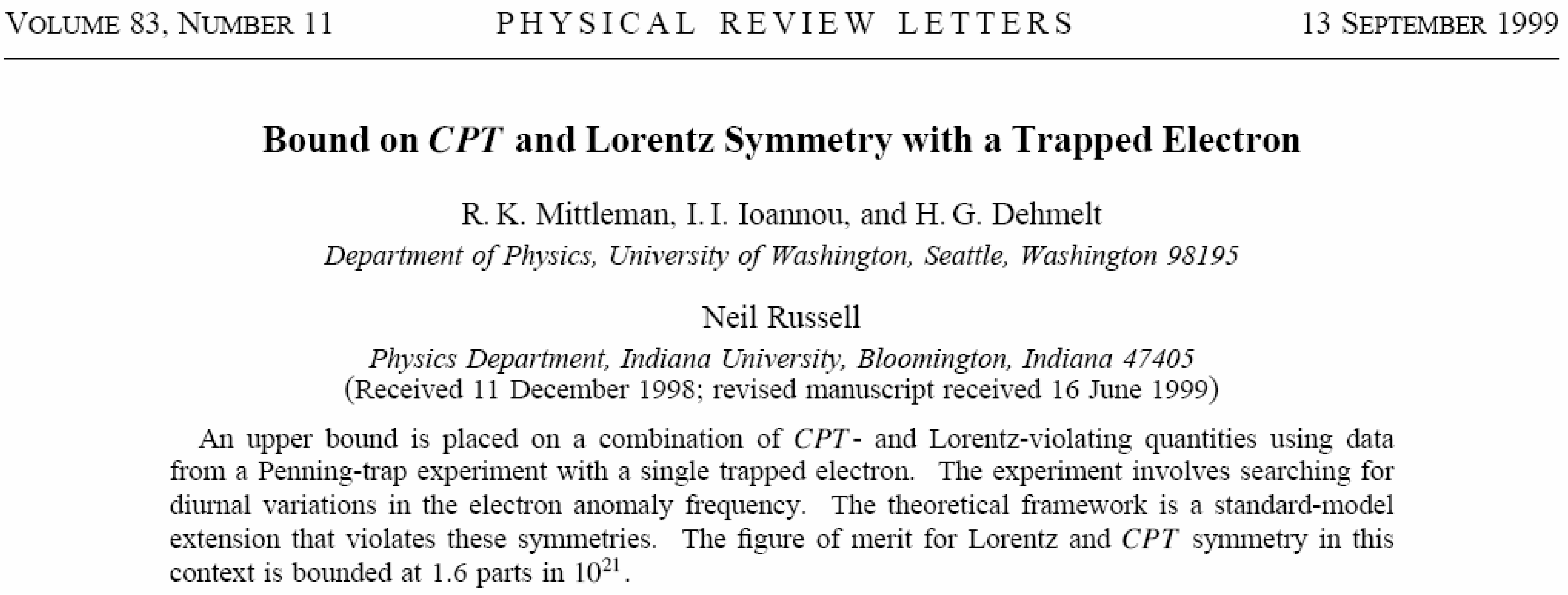
Neutrino physics

- double beta decay
- mass of the electron antineutrino
- neutrino oscillations

Fundamental constants and metrology

- fine structure constant
- mass of the electron
- re-definition of Avogadro constant the kilogram

Example for test of symmetries: CPT electron - positron



VOLUME 83, NUMBER 11 PHYSICAL REVIEW LETTERS 13 SEPTEMBER 1999

Bound on *CPT* and Lorentz Symmetry with a Trapped Electron

R. K. Mittleman, I. I. Ioannou, and H. G. Dehmelt
Department of Physics, University of Washington, Seattle, Washington 98195

Neil Russell
Physics Department, Indiana University, Bloomington, Indiana 47405

(Received 11 December 1998; revised manuscript received 16 June 1999)

An upper bound is placed on a combination of *CPT*- and Lorentz-violating quantities using data from a Penning-trap experiment with a single trapped electron. The experiment involves searching for diurnal variations in the electron anomaly frequency. The theoretical framework is a standard-model extension that violates these symmetries. The figure of merit for Lorentz and *CPT* symmetry in this context is bounded at 1.6 parts in 10^{21}.

Application of storage devices and mass spectrometry for fundamental physics

Test of symmetries

- CPT (charge conjugation, parity, time reversal)
- electric dipole moment
- non-conservation of parity & anapole moment

Test of fundamental interactions and relations

- quantum electrodynamics in extreme fields
- relativity: $E = mc^2$
- test of the Standard Model: unitarity of the quark mixing matrix

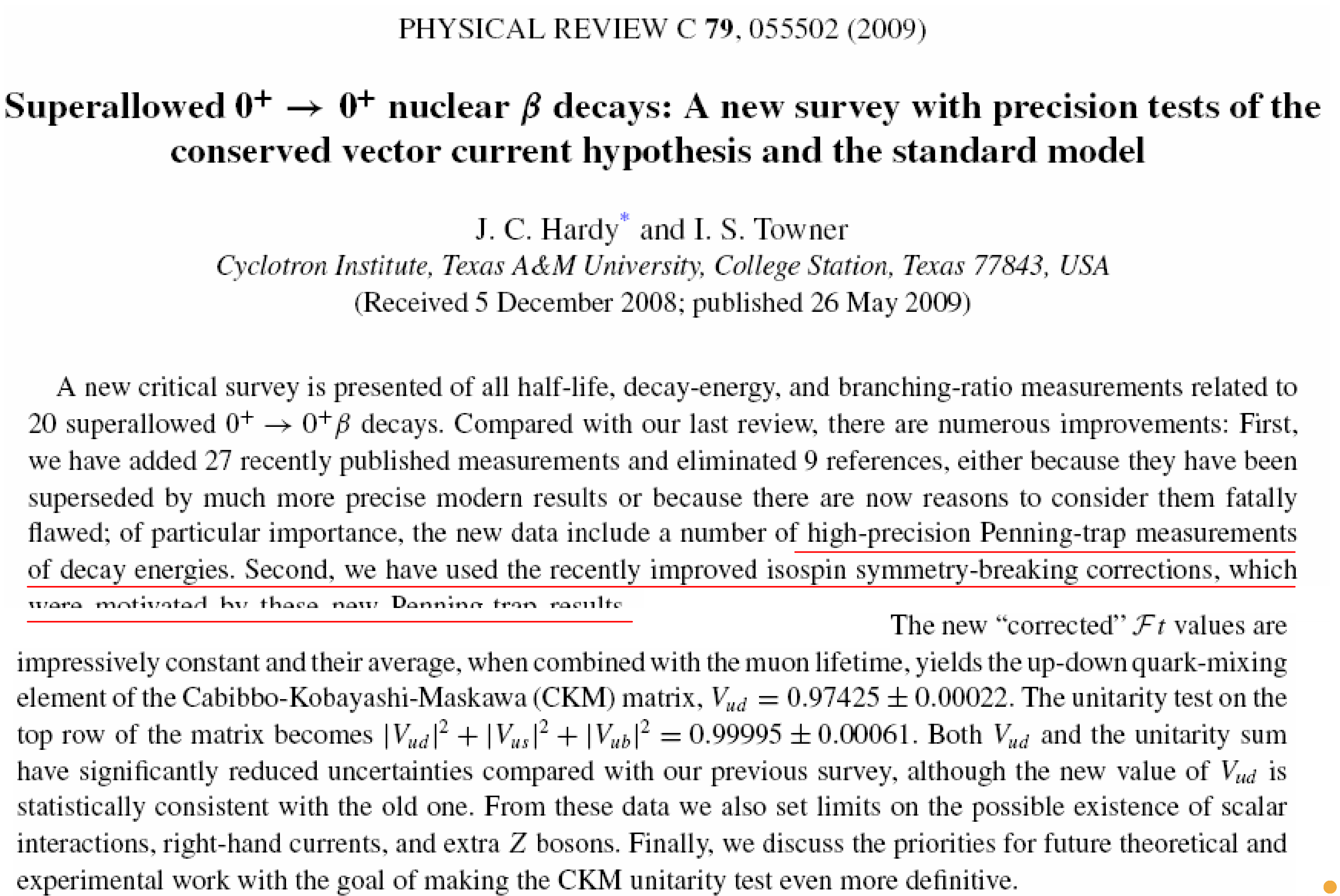
Neutrino physics

- double beta decay
- mass of the electron antineutrino
- neutrino oscillations

Fundamental constants and metrology

- fine structure constant
- mass of the electron
- re-definition of Avogadro constant the kilogram

Example for test of fundamental interactions: Test of the Standard Model



PHYSICAL REVIEW C **79**, 055502 (2009)

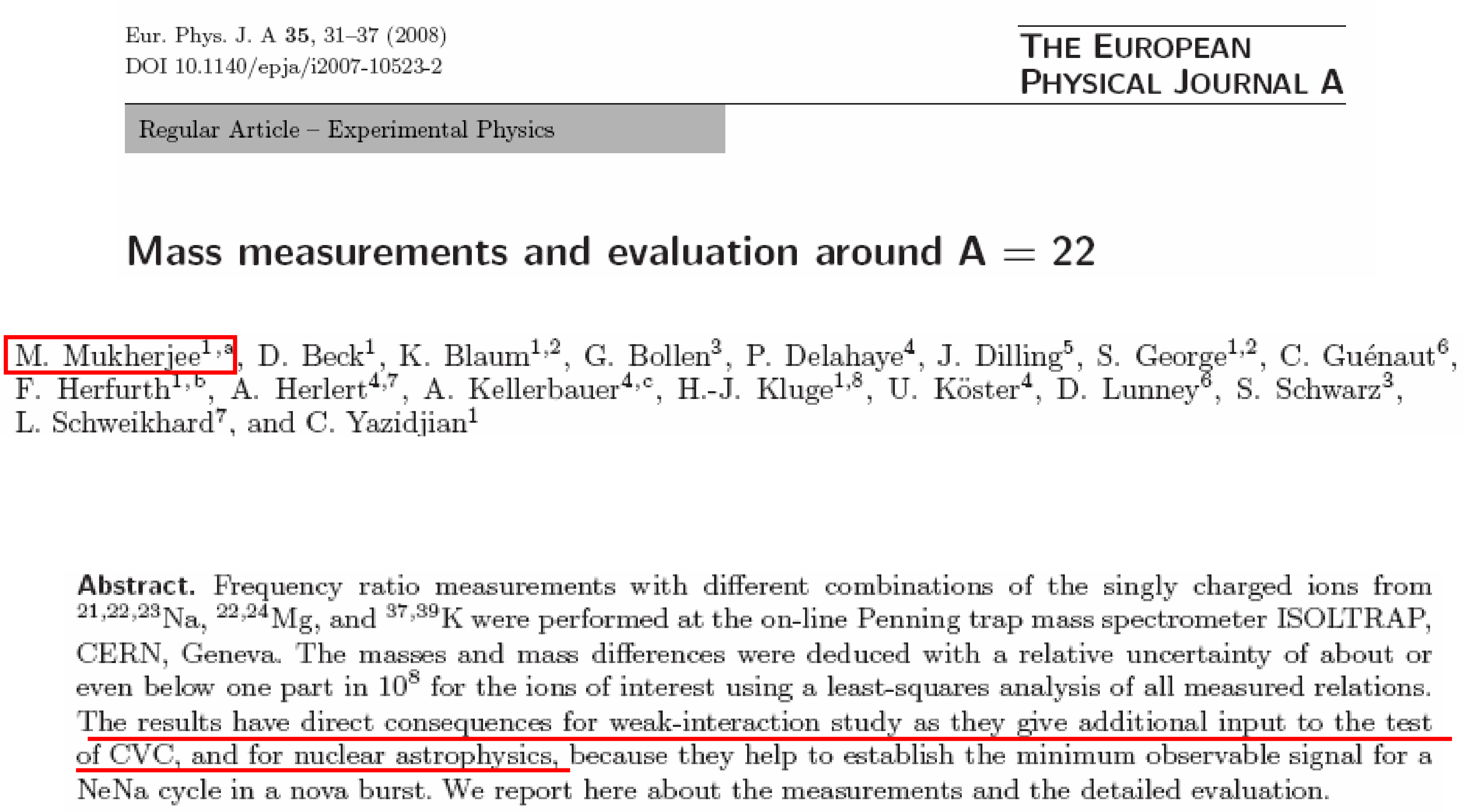
Superallowed $0^+ \rightarrow 0^+$ nuclear β decays: A new survey with precision tests of the conserved vector current hypothesis and the standard model

J. C. Hardy* and I. S. Towner
Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA

(Received 5 December 2008; published 26 May 2009)

A new critical survey is presented of all half-life, decay-energy, and branching-ratio measurements related to 20 superallowed $0^+ \rightarrow 0^+ \beta$ decays. Compared with our last review, there are numerous improvements: First, we have added 27 recently published measurements and eliminated 9 references, either because they have been superseded by much more precise modern results or because there are now reasons to consider them fatally flawed; of particular importance, the new data include a number of high-precision Penning-trap measurements of decay energies. Second, we have used the recently improved isospin symmetry-breaking corrections, which were motivated by these new Penning-trap results.

The new "corrected" $\mathcal{F}t$ values are impressively constant and their average, when combined with the muon lifetime, yields the up-down quark-mixing element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, $V_{ud} = 0.97425 \pm 0.00022$. The unitarity test on the top row of the matrix becomes $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99995 \pm 0.00061$. Both V_{ud} and the unitarity sum have significantly reduced uncertainties compared with our previous survey, although the new value of V_{ud} is statistically consistent with the old one. From these data we also set limits on the possible existence of scalar interactions, right-hand currents, and extra Z bosons. Finally, we discuss the priorities for future theoretical and experimental work with the goal of making the CKM unitarity test even more definitive.



Eur. Phys. J. A **35**, 31–37 (2008)
DOI 10.1140/epja/i2007-10523-2

THE EUROPEAN
PHYSICAL JOURNAL A

Regular Article – Experimental Physics

Mass measurements and evaluation around A = 22

M. Mukherjee[1,a], D. Beck[1], K. Blaum[1,2], G. Bollen[3], P. Delahaye[4], J. Dilling[5], S. George[1,2], C. Guénaut[6], F. Herfurth[1,b], A. Herlert[4,7], A. Kellerbauer[4,c], H.-J. Kluge[1,8], U. Köster[4], D. Lunney[6], S. Schwarz[3], L. Schweikhard[7], and C. Yazidjian[1]

Abstract. Frequency ratio measurements with different combinations of the singly charged ions from ^{21,22,23}Na, ^{22,24}Mg, and ^{37,39}K were performed at the on-line Penning trap mass spectrometer ISOLTRAP, CERN, Geneva. The masses and mass differences were deduced with a relative uncertainty of about or even below one part in 10^8 for the ions of interest using a least-squares analysis of all measured relations. The results have direct consequences for weak-interaction study as they give additional input to the test of CVC, and for nuclear astrophysics, because they help to establish the minimum observable signal for a NeNa cycle in a nova burst. We report here about the measurements and the detailed evaluation.

Application of storage devices and mass spectrometry for fundamental physics

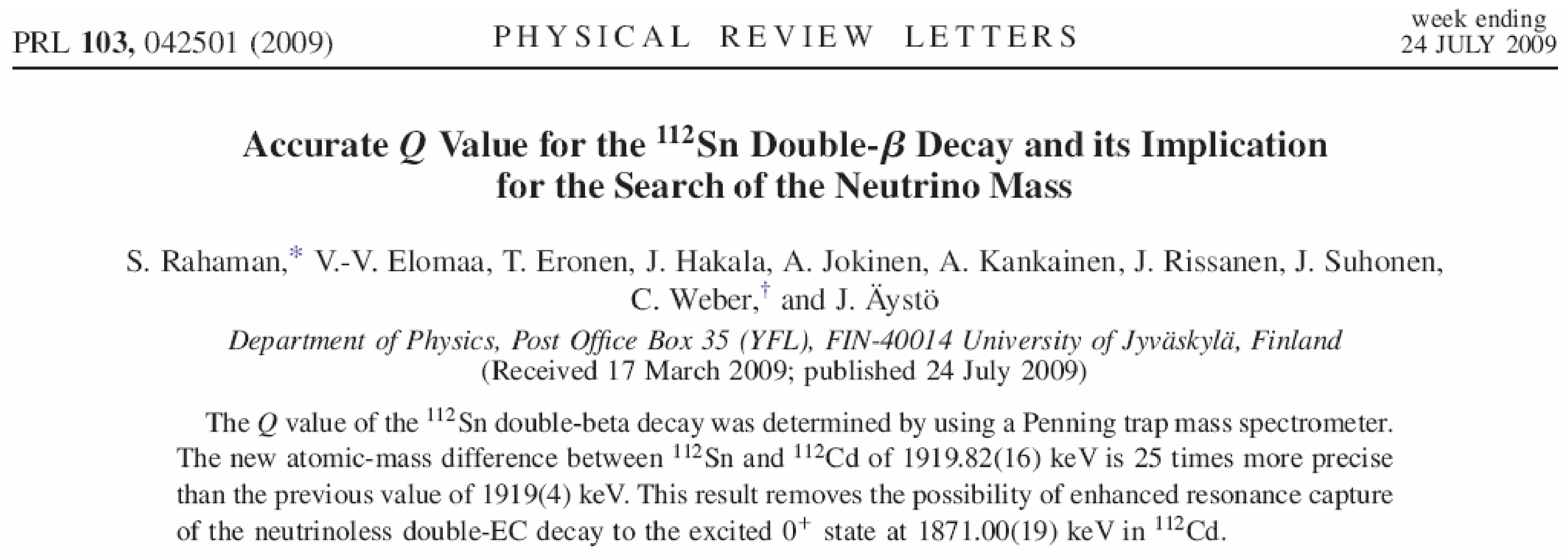
Test of symmetries
- CPT (charge conjugation, parity, time reversal)
- electric dipole moment
- non-conservation of parity & anapole moment

Test of fundamental interactions and relations
- quantum electrodynamics in extreme fields
- relativity: $E = mc^2$
- test of the Standard Model: unitarity of the quark mixing matrix

Neutrino physics
- double beta decay
- mass of the electron antineutrino
- neutrino oscillations

Fundamental constants and metrology
- fine structure constant
- mass of the electron
- re-definition of Avogadro constant the kilogram

Examples for neutrino physics: Double ß-decay



PRL **103,** 042501 (2009) PHYSICAL REVIEW LETTERS week ending 24 JULY 2009

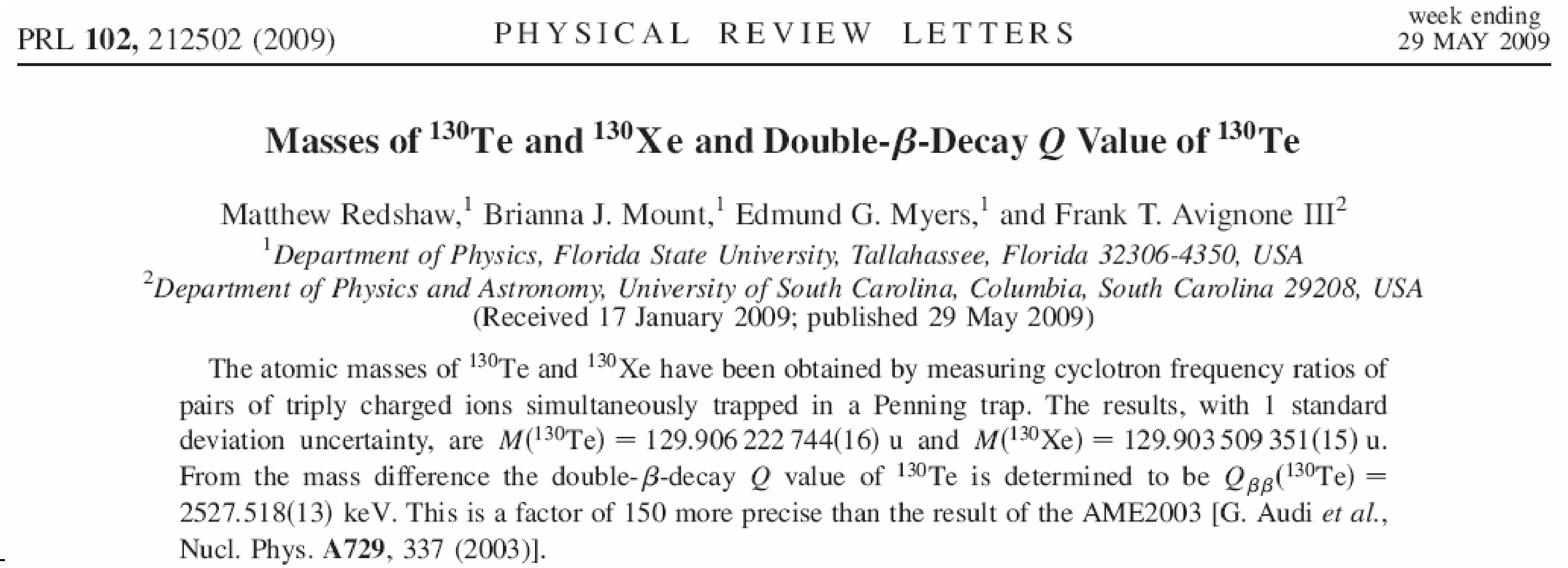
Accurate Q Value for the ^{112}Sn Double-β Decay and its Implication for the Search of the Neutrino Mass

S. Rahaman,* V.-V. Elomaa, T. Eronen, J. Hakala, A. Jokinen, A. Kankainen, J. Rissanen, J. Suhonen, C. Weber,† and J. Äystö

Department of Physics, Post Office Box 35 (YFL), FIN-40014 University of Jyväskylä, Finland

(Received 17 March 2009; published 24 July 2009)

The Q value of the ^{112}Sn double-beta decay was determined by using a Penning trap mass spectrometer. The new atomic-mass difference between ^{112}Sn and ^{112}Cd of 1919.82(16) keV is 25 times more precise than the previous value of 1919(4) keV. This result removes the possibility of enhanced resonance capture of the neutrinoless double-EC decay to the excited 0^+ state at 1871.00(19) keV in ^{112}Cd.



PRL **102,** 212502 (2009) PHYSICAL REVIEW LETTERS week ending 29 MAY 2009

Masses of ^{130}Te and ^{130}Xe and Double-β-Decay Q Value of ^{130}Te

Matthew Redshaw,[1] Brianna J. Mount,[1] Edmund G. Myers,[1] and Frank T. Avignone III[2]

[1] *Department of Physics, Florida State University, Tallahassee, Florida 32306-4350, USA*

[2] *Department of Physics and Astronomy, University of South Carolina, Columbia, South Carolina 29208, USA*

(Received 17 January 2009; published 29 May 2009)

The atomic masses of ^{130}Te and ^{130}Xe have been obtained by measuring cyclotron frequency ratios of pairs of triply charged ions simultaneously trapped in a Penning trap. The results, with 1 standard deviation uncertainty, are $M(^{130}\text{Te}) = 129.906\,222\,744(16)$ u and $M(^{130}\text{Xe}) = 129.903\,509\,351(15)$ u. From the mass difference the double-β-decay Q value of ^{130}Te is determined to be $Q_{\beta\beta}(^{130}\text{Te}) = 2527.518(13)$ keV. This is a factor of 150 more precise than the result of the AME2003 [G. Audi *et al.*, Nucl. Phys. **A729**, 337 (2003)].

Application of storage devices and mass spectrometry for fundamental physics

Test of symmetries

- CPT (charge conjugation, parity, time reversal)
- electric dipole moment
- non-conservation of parity & anapole moment

Test of fundamental interactions and relations

- quantum electrodynamics in extreme fields
- relativity: $E = mc^2$
- test of the Standard Model: unitarity of the quark mixing matrix

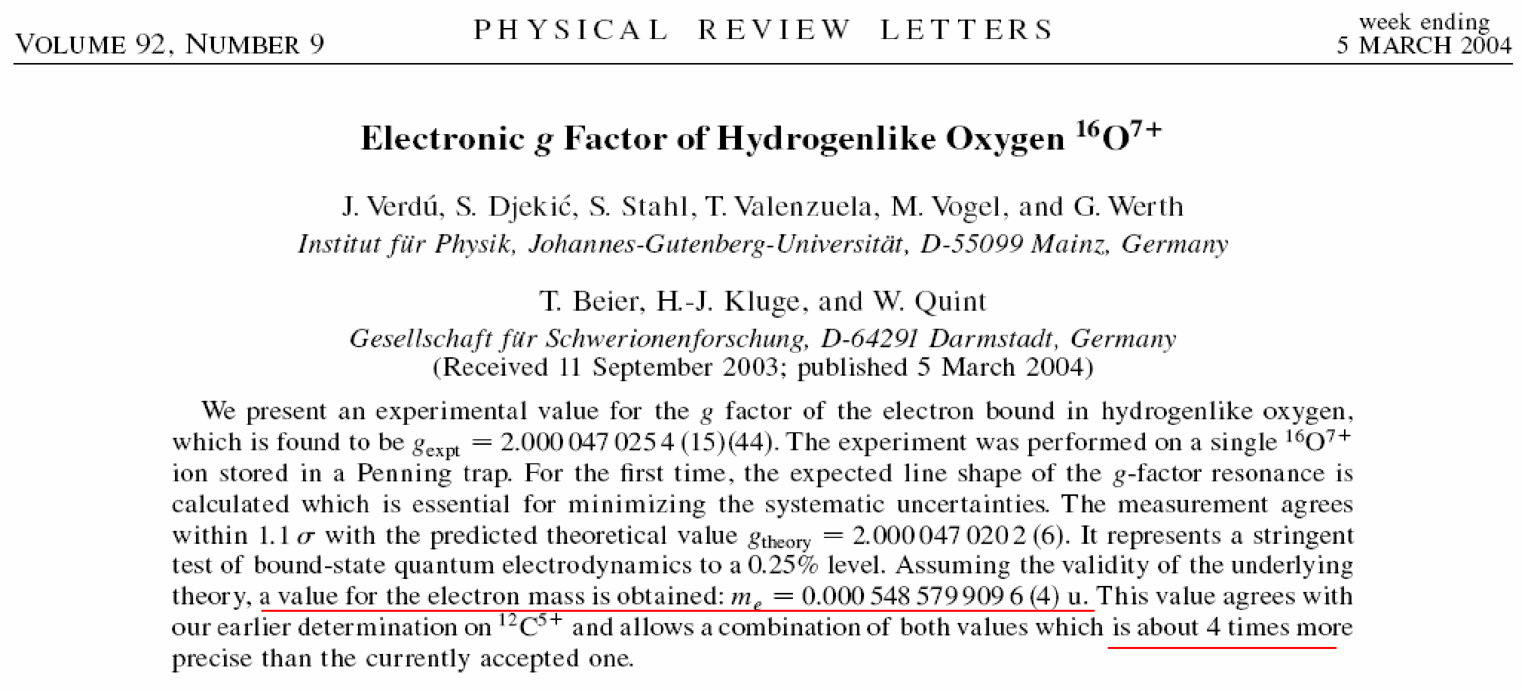
Neutrino physics

- double beta decay
- mass of the electron antineutrino
- neutrino oscillations

Fundamental constants and metrology

- fine structure constant
- mass of the electron
- Avogadro constant and re-definition of the kilogram

Examples for fundamental constants:
Mass of the electron & fine structure constant



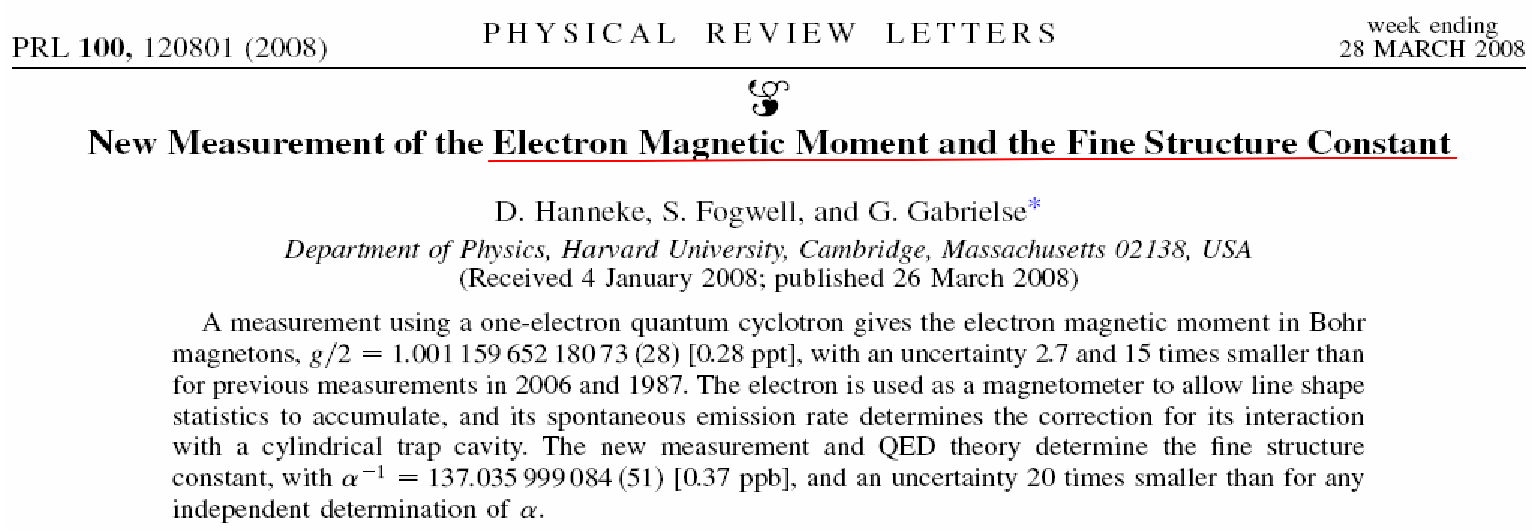
VOLUME 92, NUMBER 9 PHYSICAL REVIEW LETTERS week ending 5 MARCH 2004

Electronic g Factor of Hydrogenlike Oxygen $^{16}O^{7+}$

J. Verdú, S. Djekić, S. Stahl, T. Valenzuela, M. Vogel, and G. Werth
Institut für Physik, Johannes-Gutenberg-Universität, D-55099 Mainz, Germany

T. Beier, H.-J. Kluge, and W. Quint
Gesellschaft für Schwerionenforschung, D-64291 Darmstadt, Germany
(Received 11 September 2003; published 5 March 2004)

We present an experimental value for the g factor of the electron bound in hydrogenlike oxygen, which is found to be $g_{\mathrm{expt}} = 2.000\,047\,025\,4\,(15)(44)$. The experiment was performed on a single $^{16}O^{7+}$ ion stored in a Penning trap. For the first time, the expected line shape of the g-factor resonance is calculated which is essential for minimizing the systematic uncertainties. The measurement agrees within $1.1\,\sigma$ with the predicted theoretical value $g_{\mathrm{theory}} = 2.000\,047\,020\,2\,(6)$. It represents a stringent test of bound-state quantum electrodynamics to a 0.25% level. Assuming the validity of the underlying theory, a value for the electron mass is obtained: $m_e = 0.000\,548\,579\,909\,6\,(4)$ u. This value agrees with our earlier determination on $^{12}C^{5+}$ and allows a combination of both values which is about 4 times more precise than the currently accepted one.



PRL **100,** 120801 (2008) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2008

New Measurement of the Electron Magnetic Moment and the Fine Structure Constant

D. Hanneke, S. Fogwell, and G. Gabrielse*
Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
(Received 4 January 2008; published 26 March 2008)

A measurement using a one-electron quantum cyclotron gives the electron magnetic moment in Bohr magnetons, $g/2 = 1.001\,159\,652\,180\,73\,(28)$ [0.28 ppt], with an uncertainty 2.7 and 15 times smaller than for previous measurements in 2006 and 1987. The electron is used as a magnetometer to allow line shape statistics to accumulate, and its spontaneous emission rate determines the correction for its interaction with a cylindrical trap cavity. The new measurement and QED theory determine the fine structure constant, with $\alpha^{-1} = 137.035\,999\,084\,(51)$ [0.37 ppb], and an uncertainty 20 times smaller than for any independent determination of α.

Three examples for modern mass spectrometers

First example

- the biggest mass spectrometer for the smallest mass
- a medium-sized mass spectrometer for medium-heavy masses
- the smallest mass spectrometer for heaviest masses

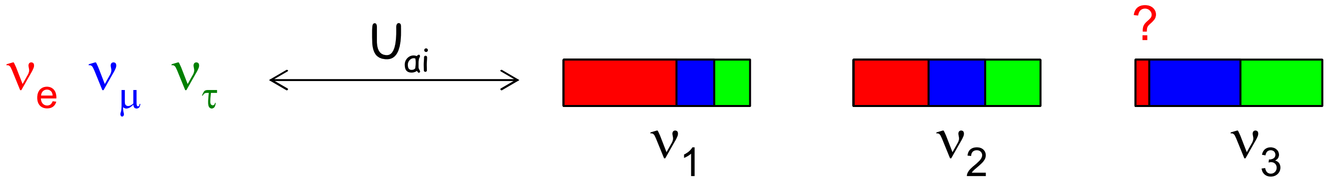
Karlsruhe Tritium Neutrino Experiment KATRIN:
a spectrometer for
determining the mass of the antineutrino

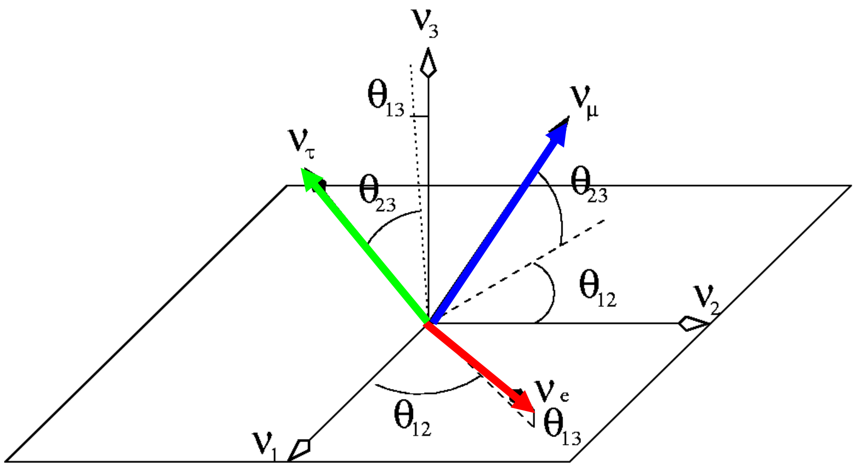
Results of the new neutrino oscillation experiments

three neutrino mass eigenstates: $\nu_i = \nu_1, \nu_2, \nu_3$ mass eigenstates with finite masses $m_i = m_1, m_2, m_3$

three flavour eigenstates: $\nu_\alpha = \nu_e, \nu_\mu, \nu_\tau$ produced in a weak reaction

mixed by a 3x3 unitary matrix: $\nu_\alpha = \sum_i U_{\alpha i} \nu_i$





known by recent neutrino oscillation experiments: $\Theta_{23}, \Theta_{12}, \Delta m^2_{23}, \Delta m^2_{12}$

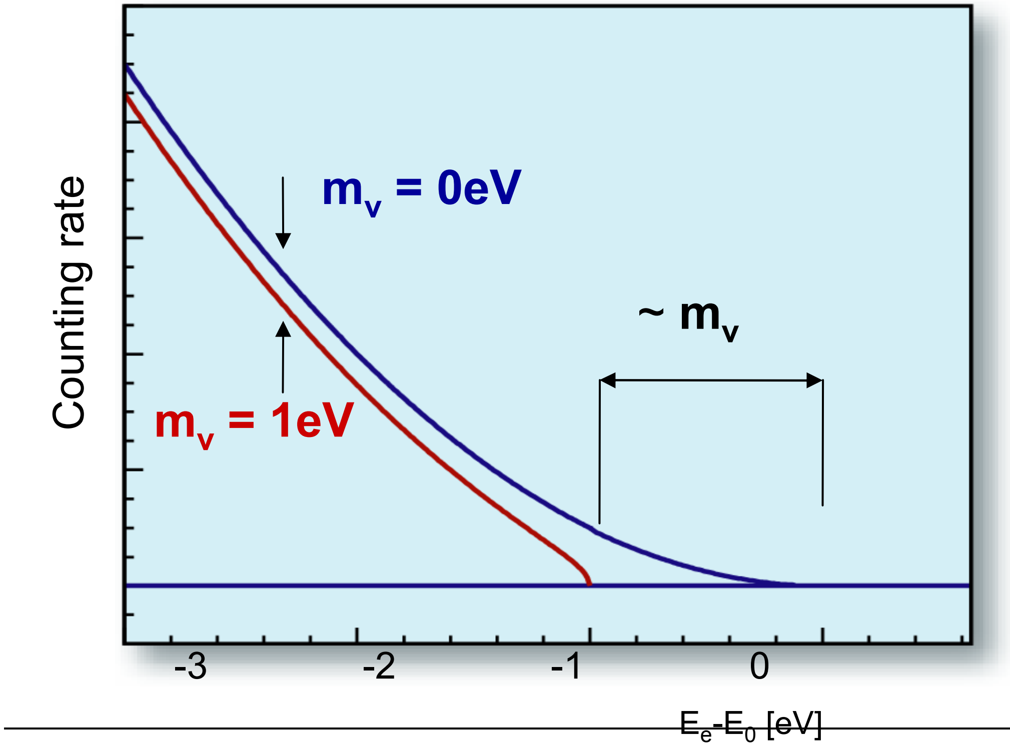
but the absolute masses have still to be determined !

How to measure the mass of the electron antineutrino?

Enrico Fermi (1934):

$$dN/dE = K \times F(E,Z) \times p \times E_{tot} \times (E_0-E_e) \times [\,(E_0-E_e)^2 - m_\nu^2\,]^{1/2}$$

Theoretical β-spectrum near the end point E_0



→ no dependence of the β-decay of tritium on nuclear structure

→ no absolute calibration of intensity required

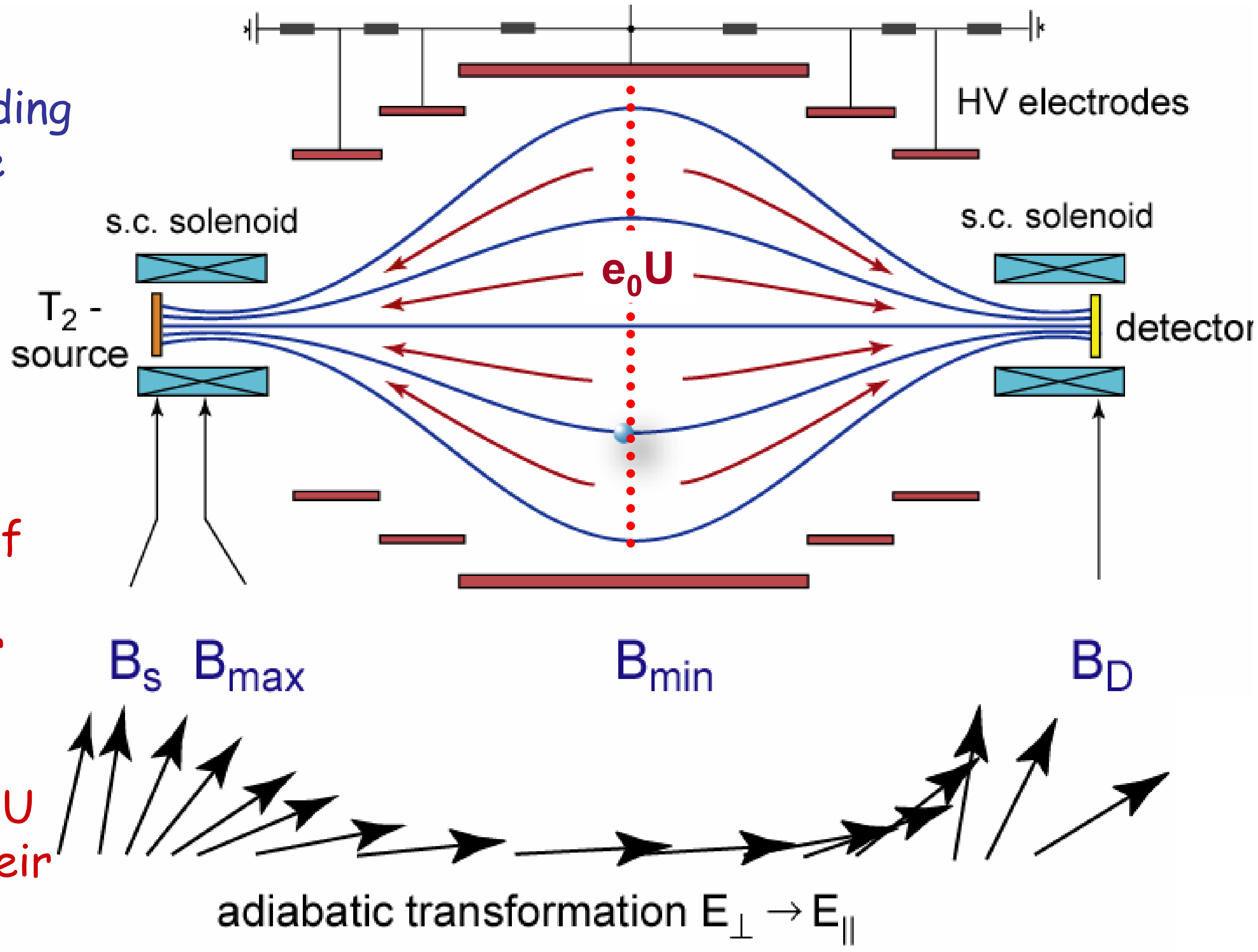
E.W. Otten and C. Weinheimer, Rep. Prog. Phys. **71**, 086201 (2008)

Principle of an electrostatic filter with magnetic-adiabatic collimation

Magnetic-adiabatic guiding of β-particles along the magnetic-field lines:

$B_{max} = 6$ T

$B_{min} = 3\times10^{-4}$ T



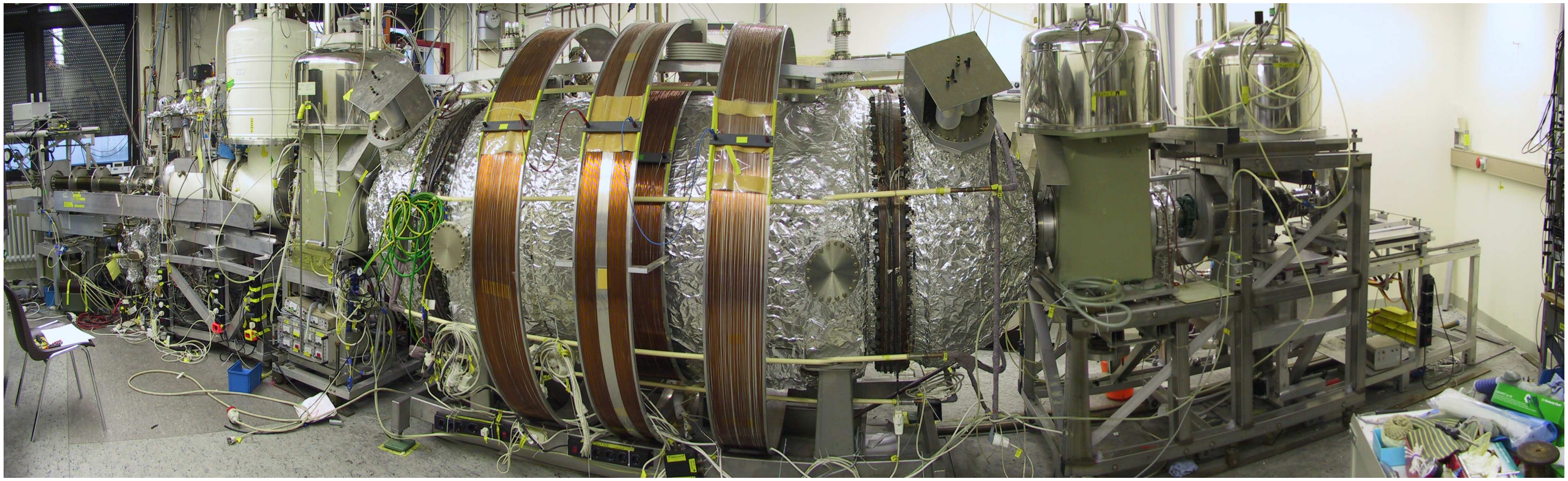
Energy determination of the ß-particles with static electric field for retardation that is varied:

β-particles with $E_\beta > e_0 \cdot U$ are transmitted and their is intensity integrated.

A. Picard et al., Nucl. Instr. Meth. 63 (1992) 345

The antineutrino mass experiment at the University of Mainz

20 mCi molecular tritium, frozen at T = 1.86 K
on a graphite backing of A = 2cm², d ~ 130 monolayers (~ 45nm)



Frog-eye photograph of the Mainz spectrometer: 4 m length, 0.9 m diameter

$$m_\nu^2 = -0.7 \pm 2.2 \pm 2.1 \text{ eV}^2 \rightarrow m_\nu < 2.2 \text{ eV @ } 95\% \text{ C.L.}$$

How to reduce the upper limit for the mass of the electron antineutrino
by a factor of 10?

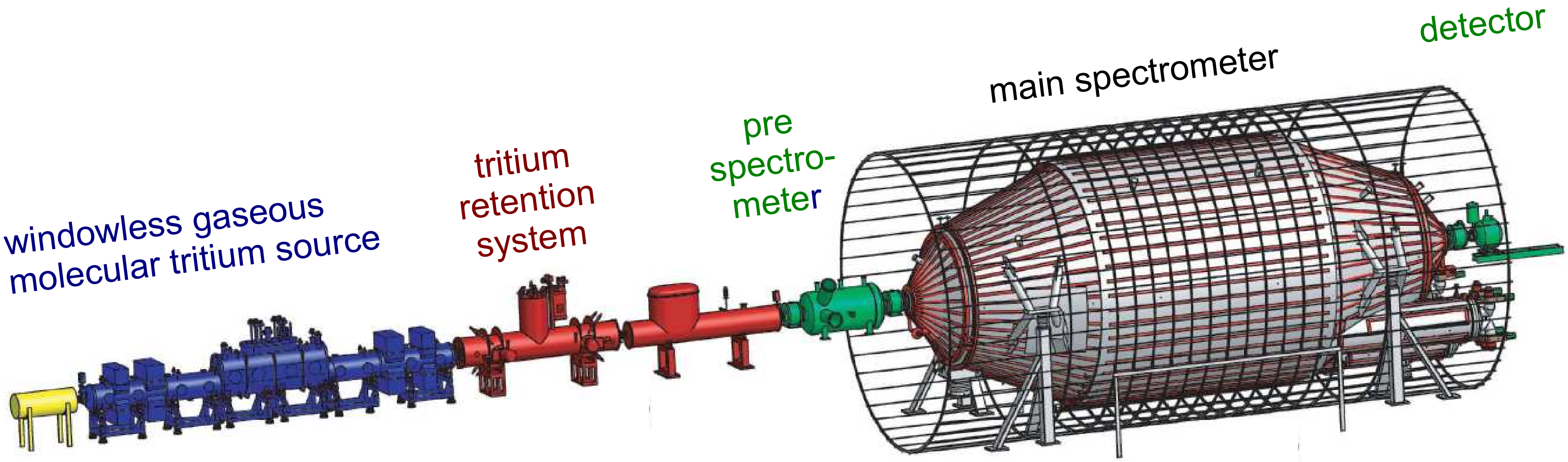
How to reach an upper limit of 0.2 eV?
The Karlsruhe Tritium Neutrino Experiment KATRIN

Goal:

10 times lower energy limit: 2.2 eV → 0.2 eV

To be reached by:

- higher energy resolving power: 4 eV → 1 eV
- higher statistics 100 days → 1000 days
- bigger spectrometer 1 m → 10 m diameter



Scientific Report FZKA 7090

From Deggendorf to Karlsruhe: The 8500 km detour

KATRIN in Leopoldshafen – 25 November 2006

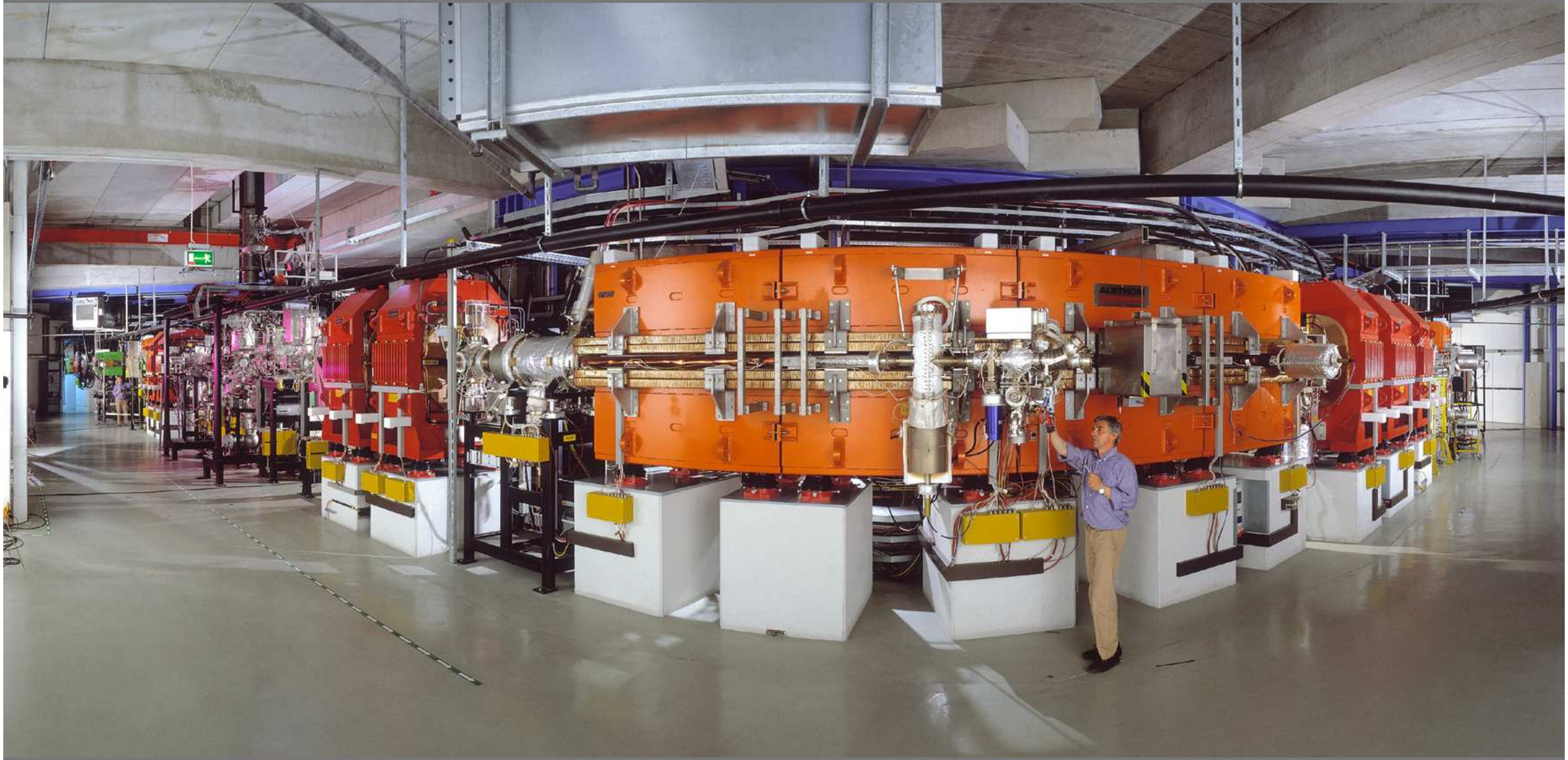
Three examples for modern mass spectrometers

Second example

- the biggest mass spectrometer for the smallest mass
- a medium-sized mass spectrometer for medium-heavy masses
- the smallest mass spectrometer for heaviest masses

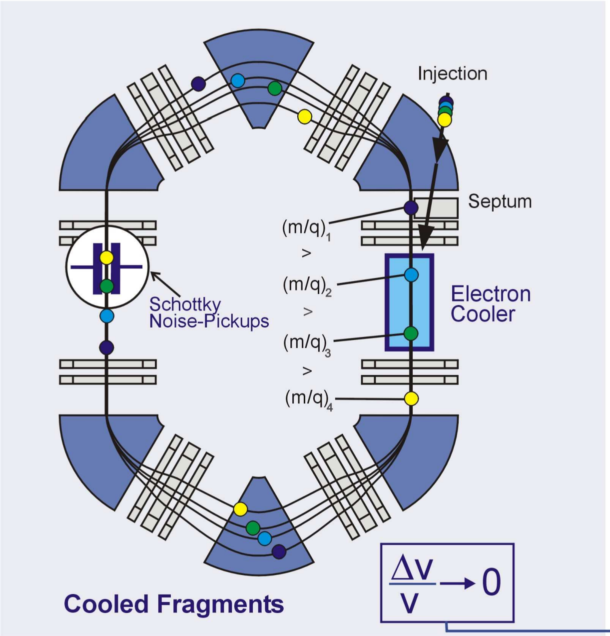
Experimental Storage Ring ESR at
GSI/Darmstadt:
a high-precision spectrometer
for highly charged ions

The Experimental Storage Ring ESR at GSI/Darmstadt

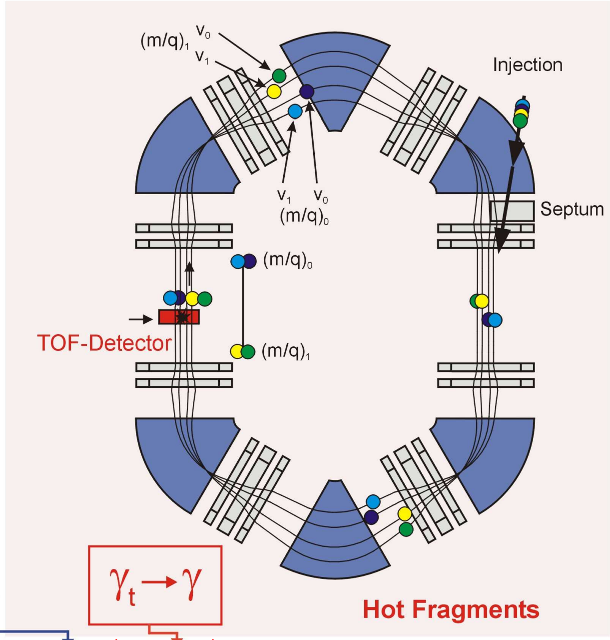


Principle of mass determination in a storage ring

Schottky mass spectrometry



Isochronous mass spectrometry

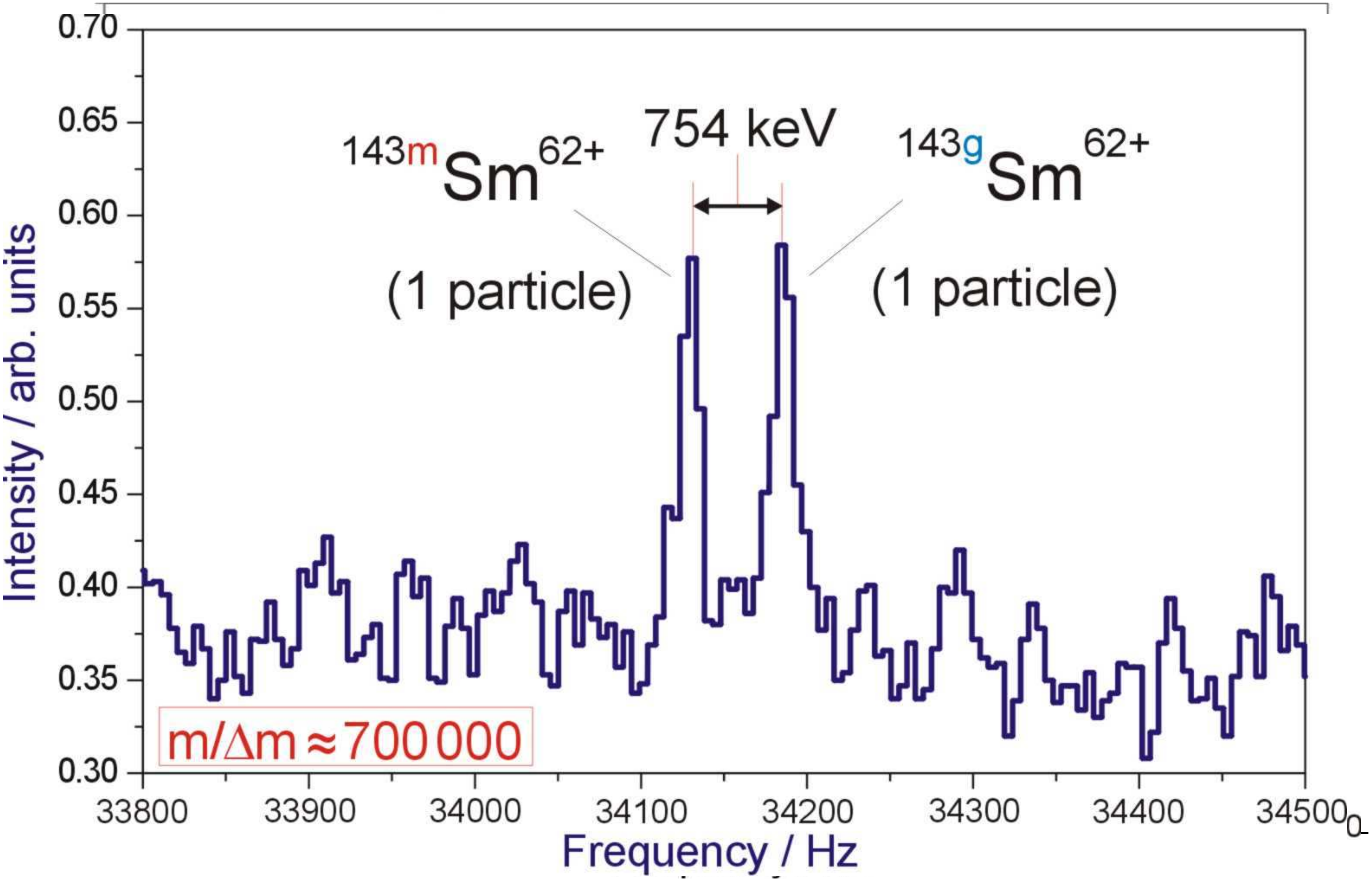


$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \cancel{\frac{\Delta v}{v}}\left(1-\cancel{\frac{\gamma^2}{\gamma_t^2}}\right)$$

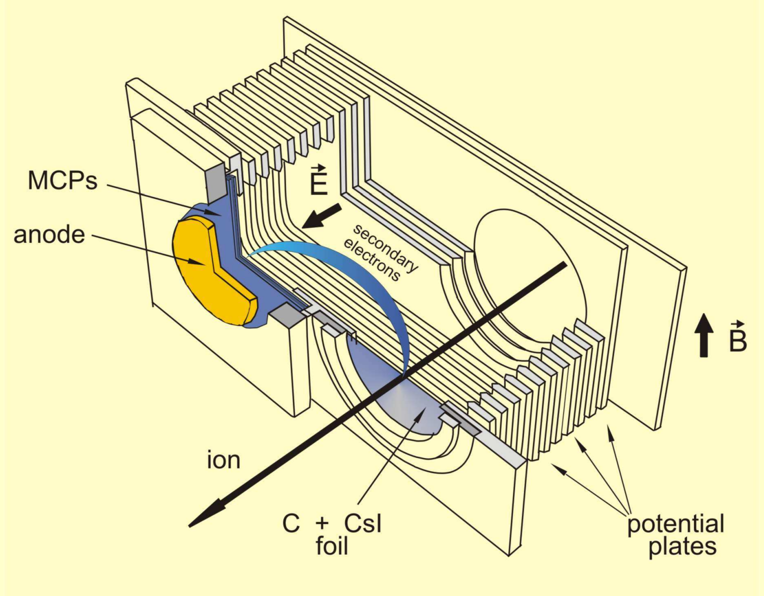
Electron cooling is required.
All ions have identical velocity equal to that of the electrons in the electron cooler.
High resolving power & high accuracy.
Longer half-lives: $T_{1/2} \geq 10$ s
Measurement of revolution frequency.

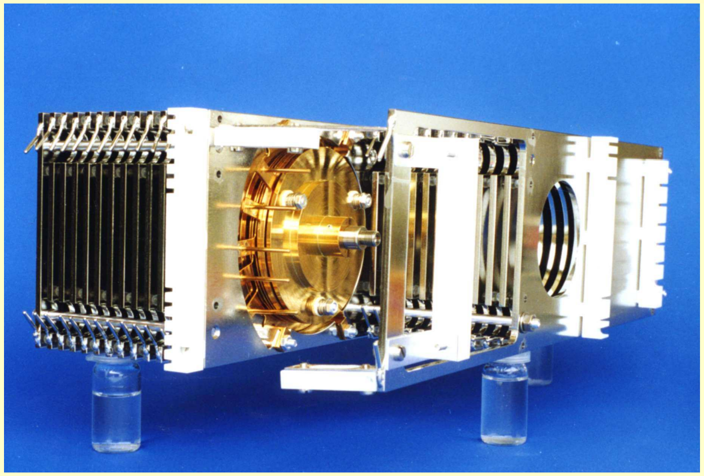
Electron cooling is not required.
All ions with identical q/m have equal time of revolution in the ring.
Complex ion-optical operation parameters of ring.
Short nuclear half-lives: $T_{1/2} \geq 100$ µs
Measurement of time of flight.

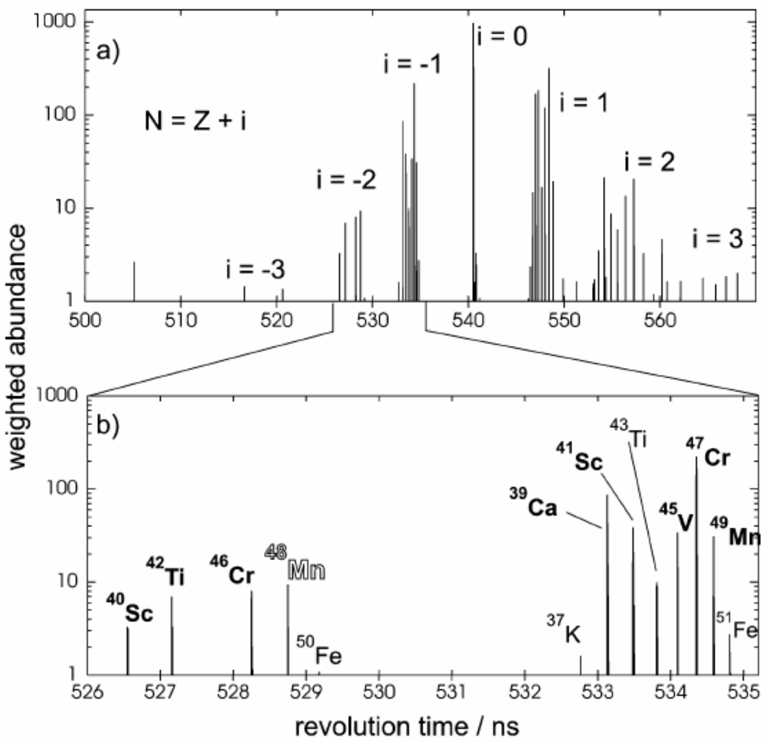
Schottky mass spectrometry in the storage ring ESR



Isochronous mass spectrometry using the ESR







PERFORMANCE:

$\delta m/m \approx 10^{-5} - 10^{-6}$

very short half-lives

up to ~ 10^4 turns in the storage ring

1000 km flight path

Up to now determined masses at the ESR

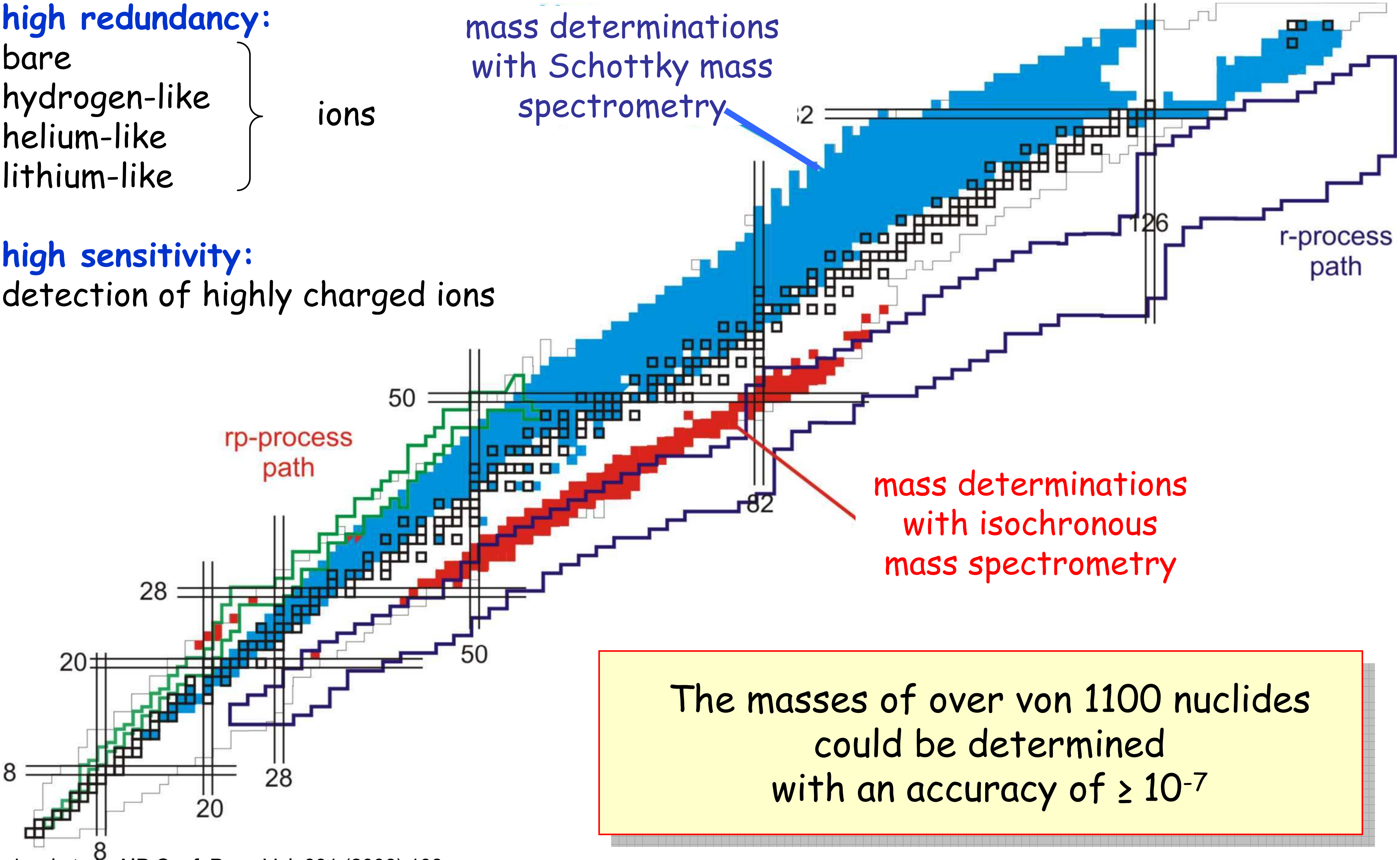
high redundancy:

bare
hydrogen-like
helium-like
lithium-like

} ions

high sensitivity:

detection of highly charged ions



mass determinations with Schottky mass spectrometry

mass determinations with isochronous mass spectrometry

The masses of over von 1100 nuclides could be determined with an accuracy of $\geq 10^{-7}$

H. Geissel et al., AIP Conf. Proc. Vol. 831 (2006) 108

Three examples for modern mass spectrometers

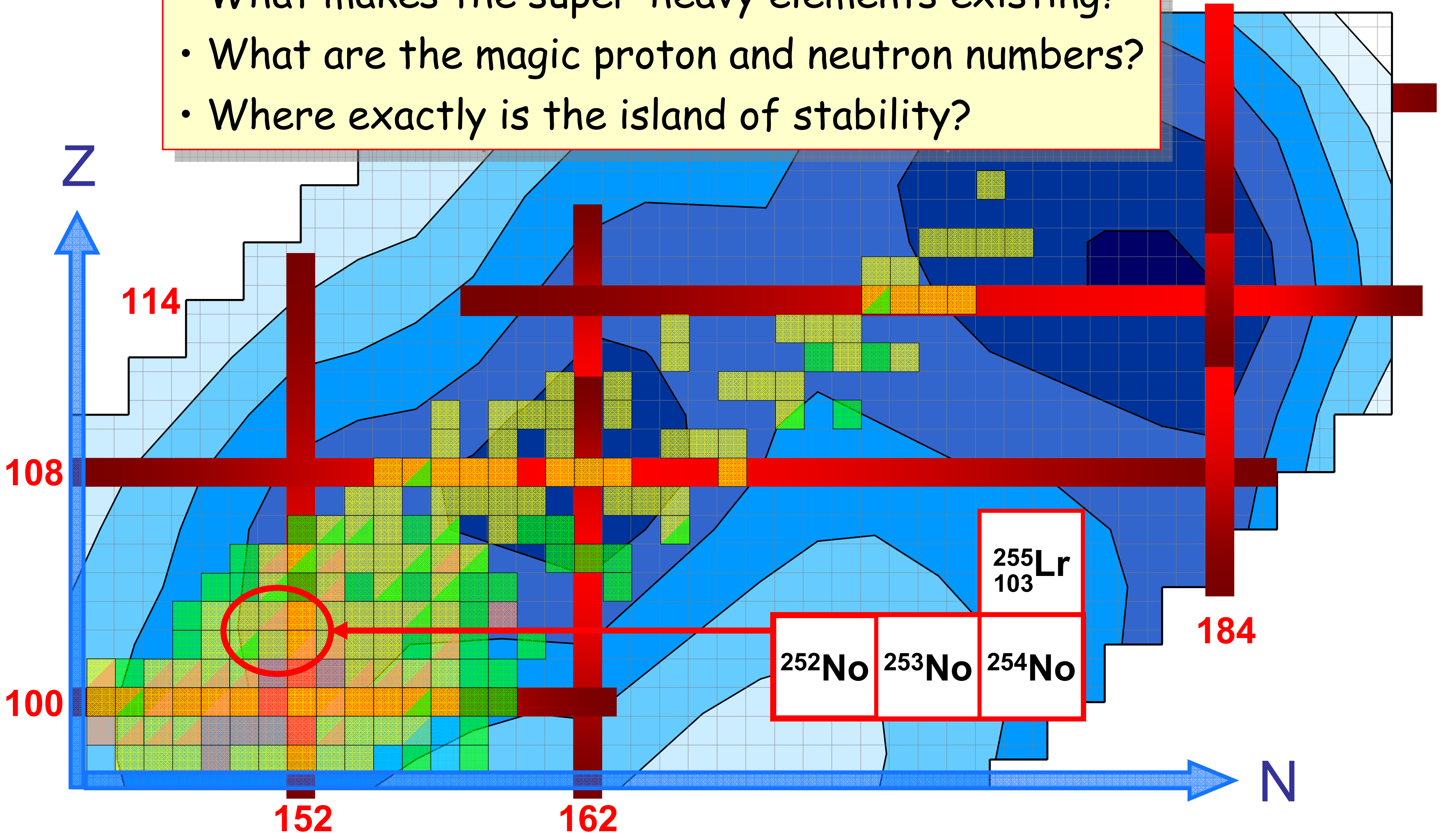
Third example

- the biggest mass spectrometer for the smallest mass
- a medium-sized mass spectrometer for medium-heavy masses
- the smallest mass spectrometer for heaviest masses

SHIPTRAP:
a Penning trap at GSI/Darmstadt
for mass spectrometry of isotopes
of superheavy elements

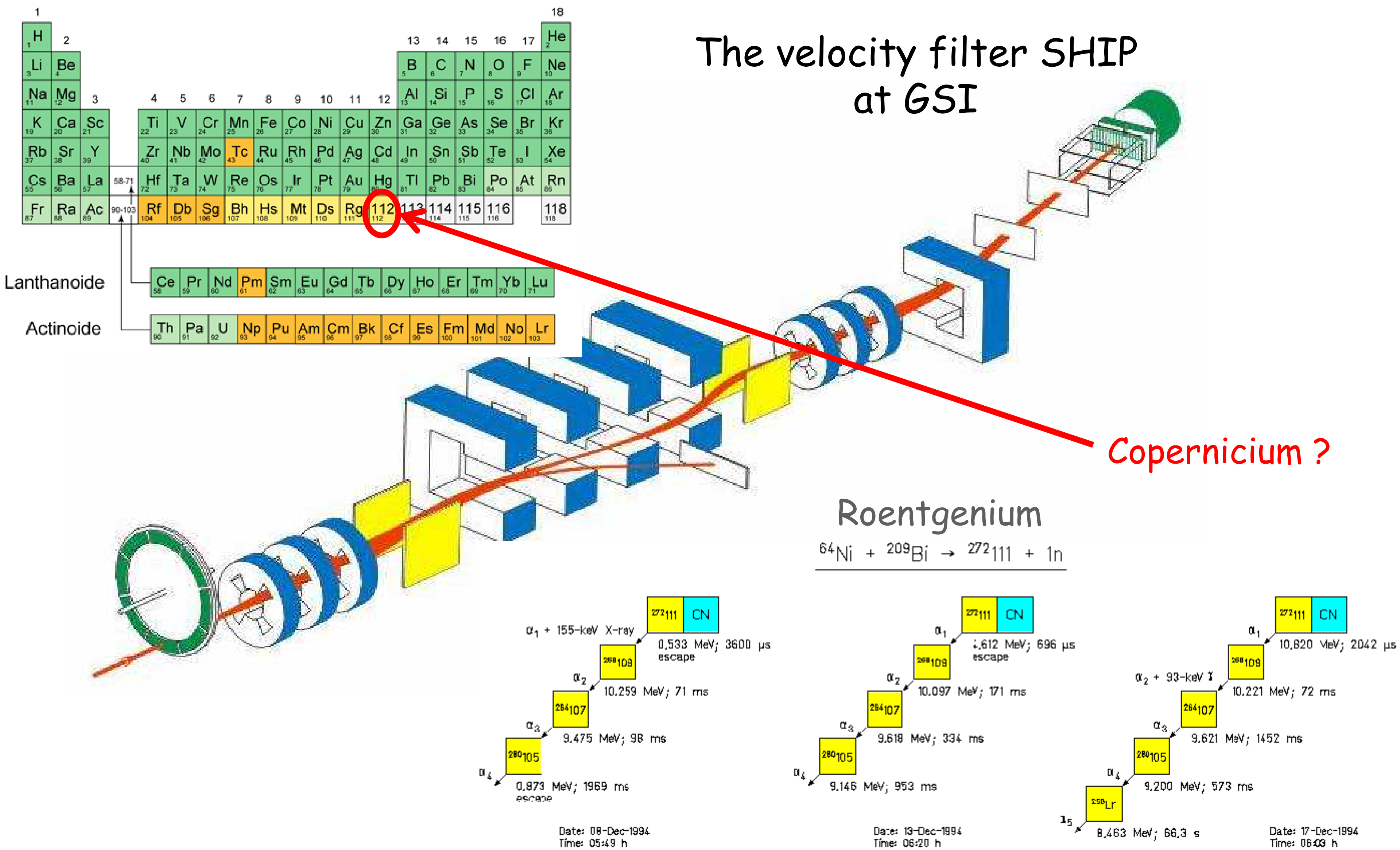
Chart of nuclei in the region of super-heavy elements

- What makes the super-heavy elements existing?
- What are the magic proton and neutron numbers?
- Where exactly is the island of stability?



Calculations of R. Smolanczuk and A. Sobiczewski, published in: S. Hofmann, G. Münzenberg, Rev. Mod. Phys. 72, 733 (2000)

Production and separation of super-heavy elements



The velocity filter SHIP
at GSI

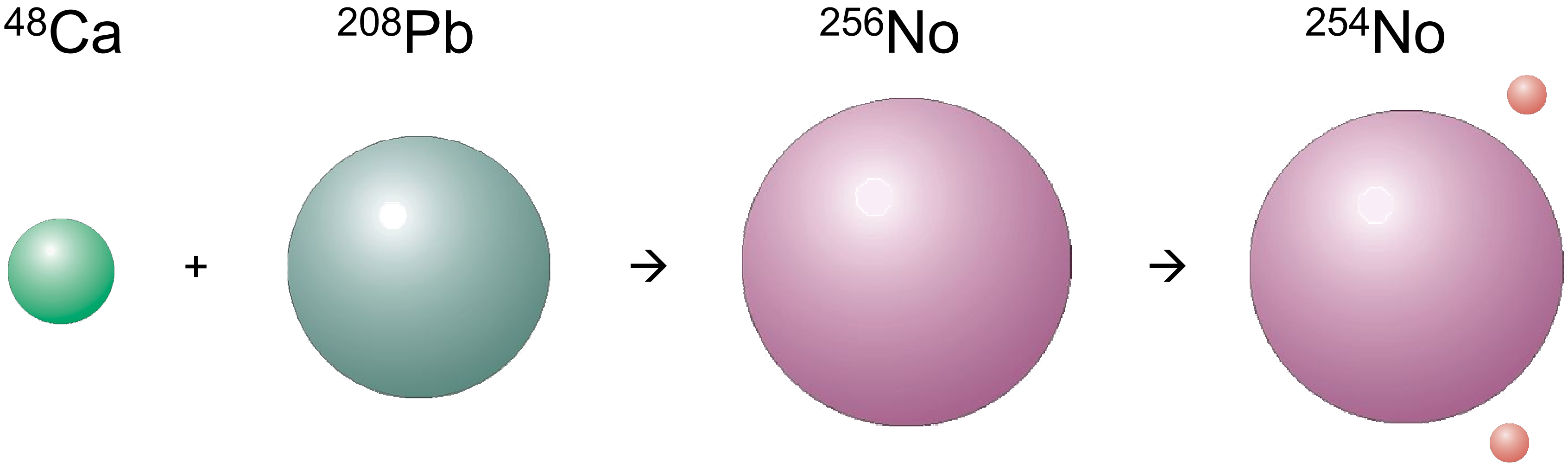
Copernicium ?

Roentgenium

$^{64}Ni + ^{209}Bi \rightarrow ^{272}111 + 1n$

Production of nobelium (Z = 102)

cold fusion: $^{208}\mathrm{Pb}(^{48}\mathrm{Ca},2n)^{254}\mathrm{No}$



$^{48}\mathrm{Ca}$ + $^{208}\mathrm{Pb}$ → $^{256}\mathrm{No}$ → $^{254}\mathrm{No}$

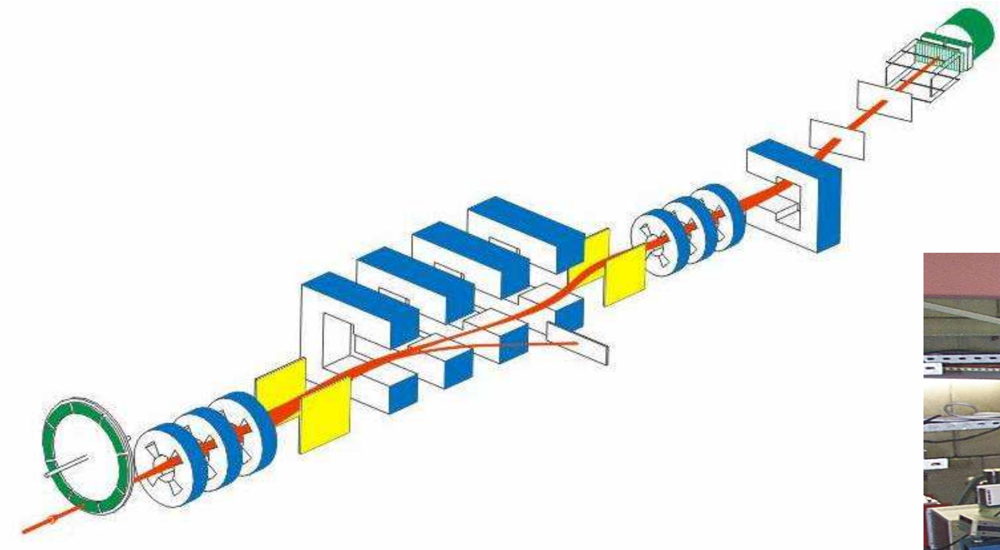
4.5 MeV/u

200 keV/u

~ 10^{13} particles/s

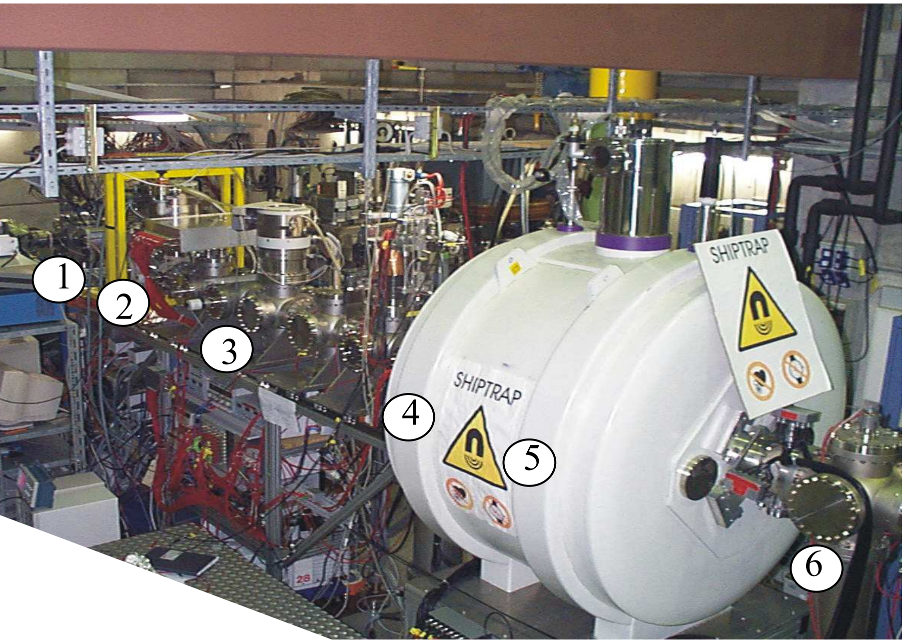
~ 1 particle/s

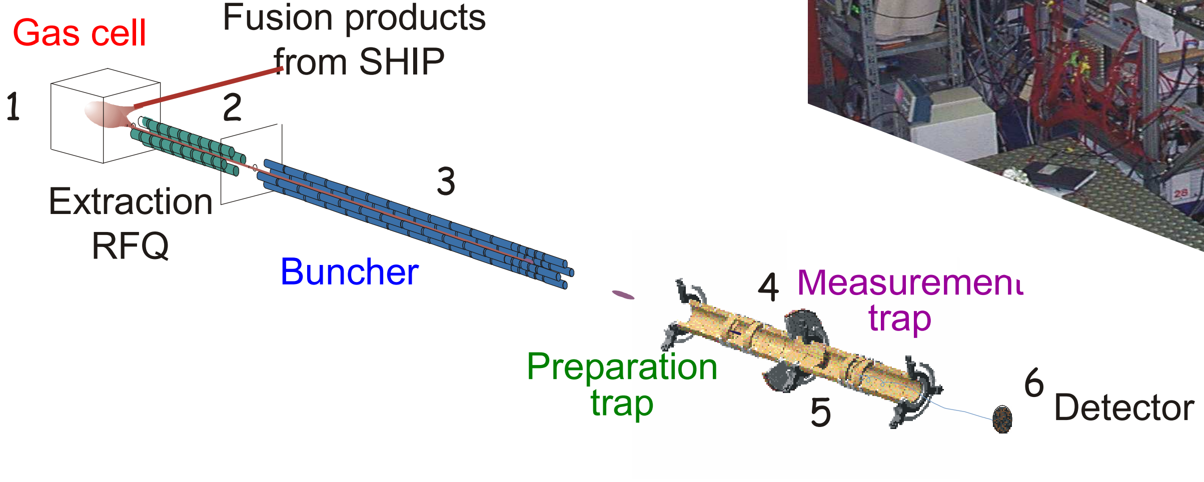
SHIPTRAP at GSI



Laser spectroscopy
Mass spectrometry
Nuclear spectroscopy
Chemistry

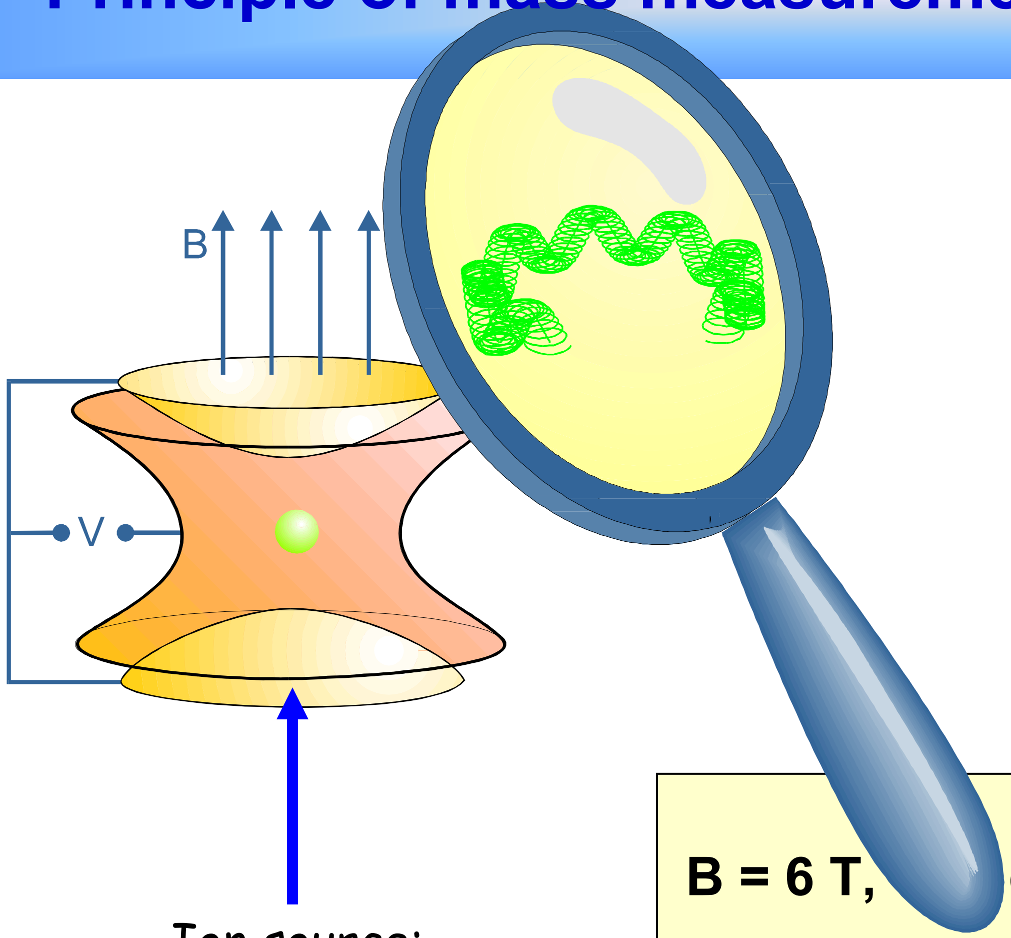
} of isotopes of the elements heavier than uranium





M. Block, K. Blaum, F. Herfurth,
L. Schweikhard et al.

Principle of mass measurements in Penning traps



Ion source:
stable isotopes
radionuclides
highly charged ions
electrons
antiprotons

Ion storage in a strong and homogenous magnetic field of strength B

Mass determination by measurement of the cyclotron frequency

$$\nu_c = (q\cdot e/m)\cdot(B/2\pi)$$

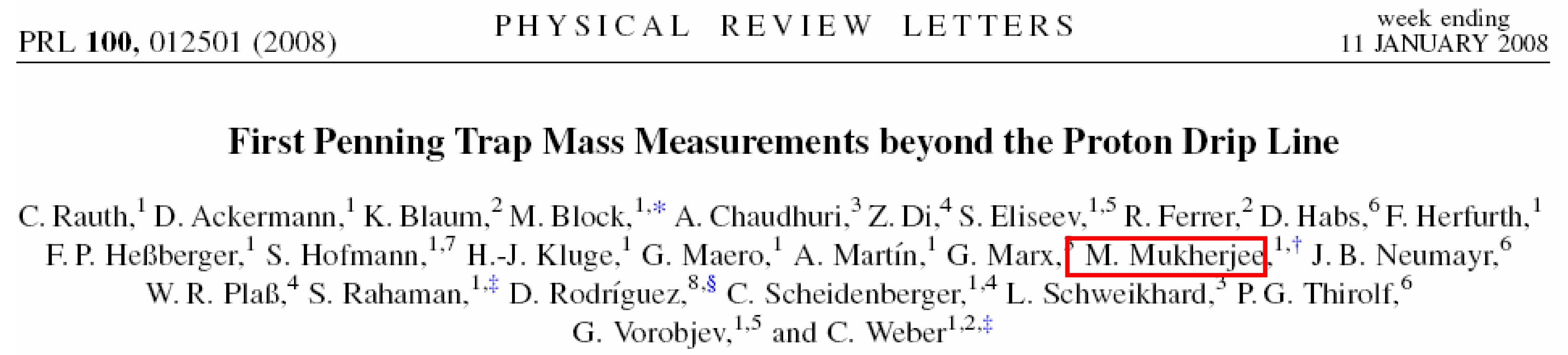
Example:

$B = 6$ T, $q = 1$, $m = 100$ u → $\nu_c = 1$ MHz

$T_{obs} = 1$ s → $\Delta\nu_c = 1$ Hz

→ $R = 10^6$ and $\delta m/m = 10^{-8}$

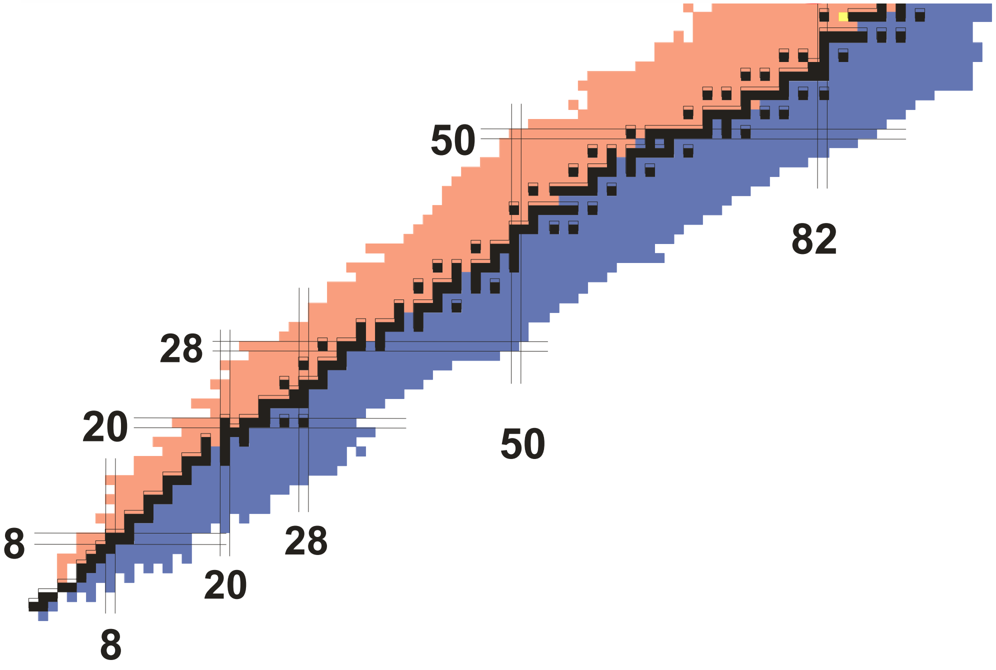
SHIPTRAP masses



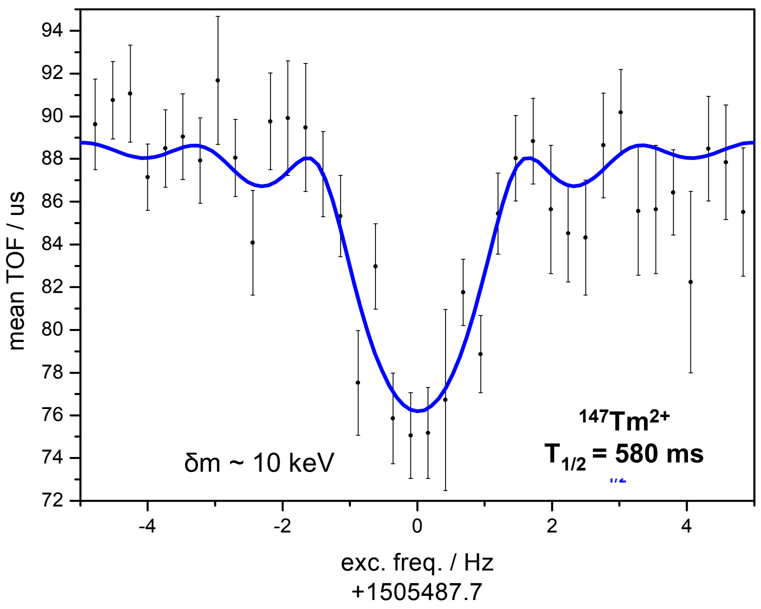
PRL **100,** 012501 (2008) PHYSICAL REVIEW LETTERS week ending 11 JANUARY 2008

First Penning Trap Mass Measurements beyond the Proton Drip Line

C. Rauth,[1] D. Ackermann,[1] K. Blaum,[2] M. Block,[1,*] A. Chaudhuri,[3] Z. Di,[4] S. Eliseev,[1,5] R. Ferrer,[2] D. Habs,[6] F. Herfurth,[1] F. P. Heßberger,[1] S. Hofmann,[1,7] H.-J. Kluge,[1] G. Maero,[1] A. Martín,[1] G. Marx,[3] M. Mukherjee,[1,†] J. B. Neumayr,[6] W. R. Plaß,[4] S. Rahaman,[1,‡] D. Rodríguez,[8,§] C. Scheidenberger,[1,4] L. Schweikhard,[3] P. G. Thirolf,[6] G. Vorobjev,[1,5] and C. Weber[1,2,‡]



in the precision trap



δm ~ 10 keV

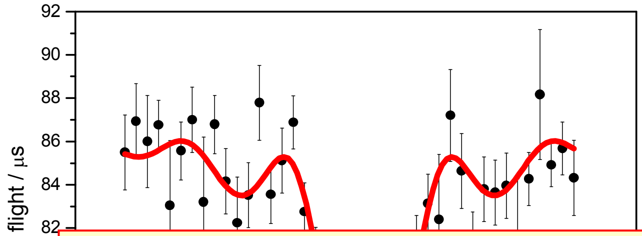
$^{147}Tm^{2+}$

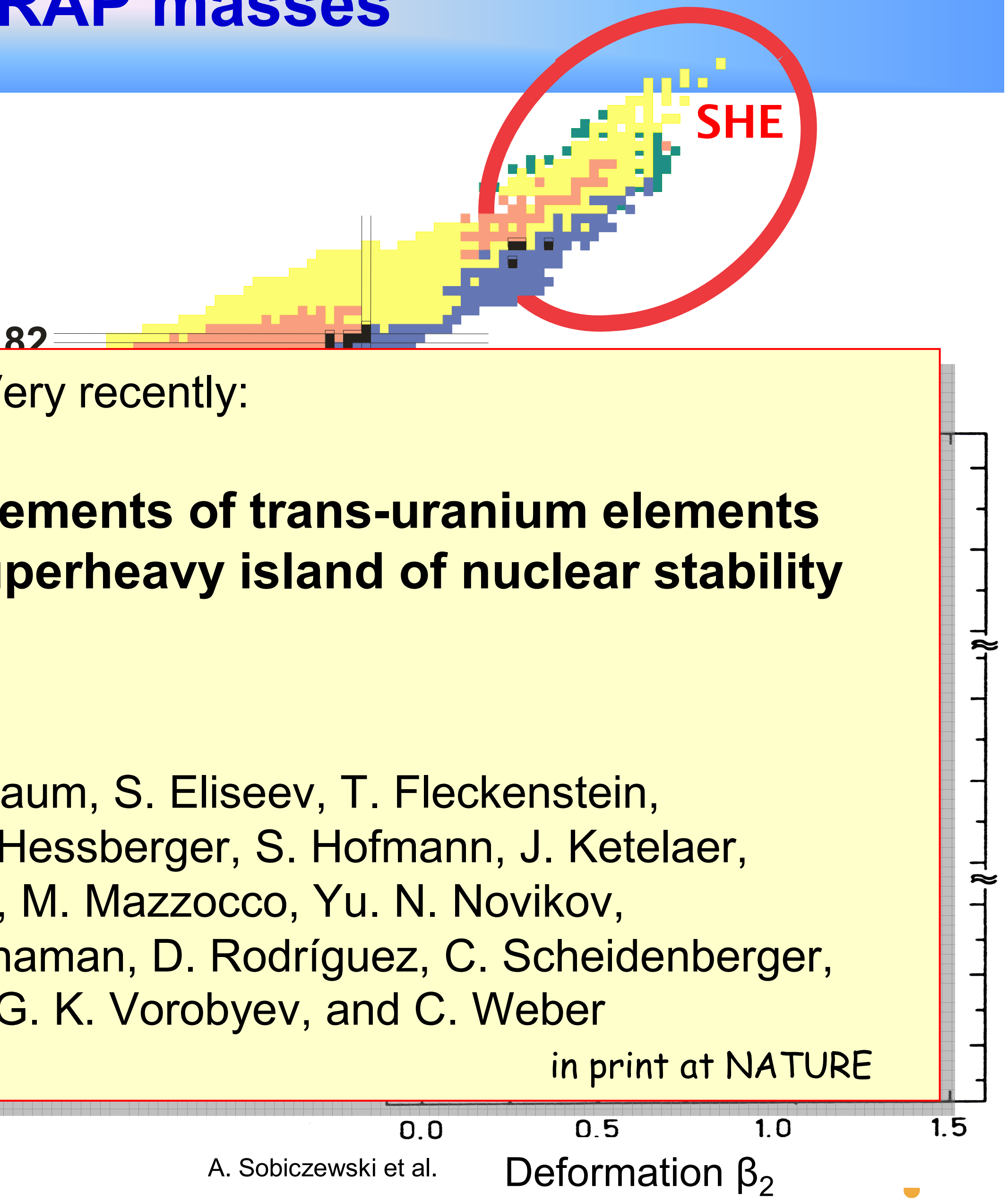
$T_{1/2}$ = 580 ms

C. Rauth et al., PRL 100, 012501 (2008)

A. Sobiczewski et al.

SHIPTRAP masses





A. Sobiczewski et al.

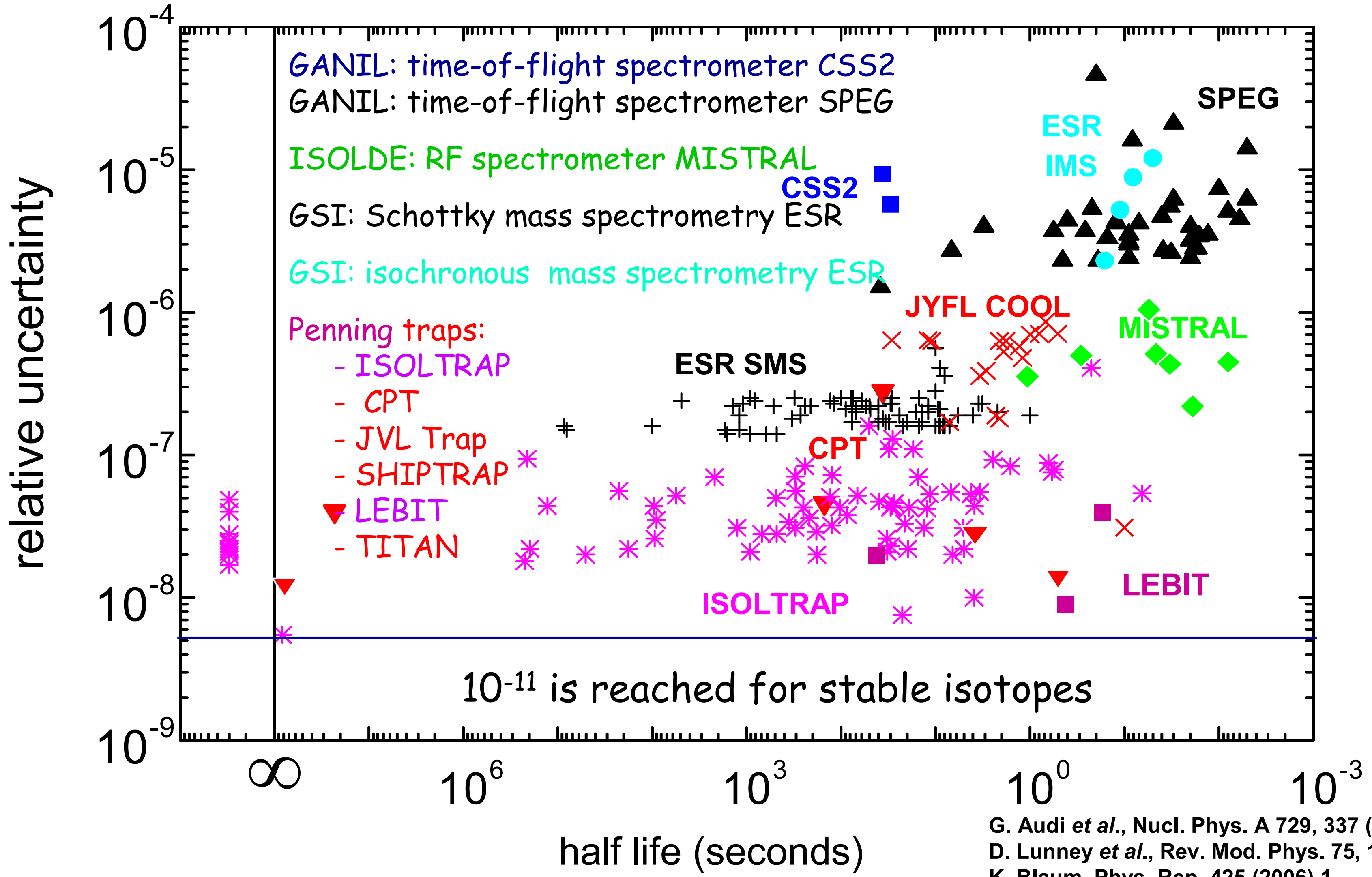
Very recently:

First direct mass measurements of trans-uranium elements
Bridging the gap to the superheavy island of nuclear stability

M. Block, D. Ackermann, K. Blaum, S. Eliseev, T. Fleckenstein,
E. Haettner, F. Herfurth, F. P. Hessberger, S. Hofmann, J. Ketelaer,
J. Ketter, H.-J. Kluge, G. Marx, M. Mazzocco, Yu. N. Novikov,
W. R. Plass, A. Popeko S. Rahaman, D. Rodríguez, C. Scheidenberger,
L. Schweikhard, P. G. Thirolf, G. K. Vorobyev, and C. Weber

in print at NATURE

Accuracy of mass determinations of radionuclides (published since 2003)

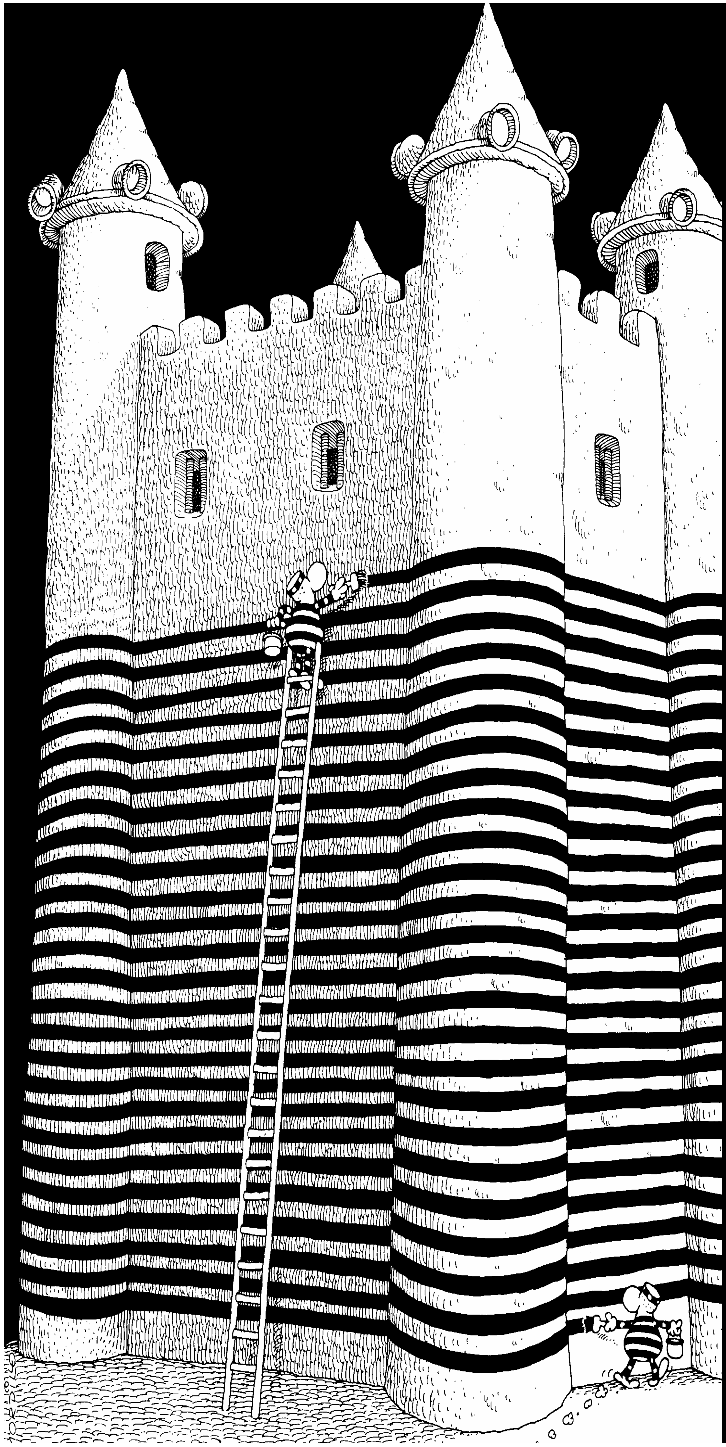


G. Audi *et al.*, Nucl. Phys. A 729, 337 (2003)
D. Lunney *et al.*, Rev. Mod. Phys. 75, 1021 (2003)
K. Blaum, Phys. Rep. 425 (2006) 1

55

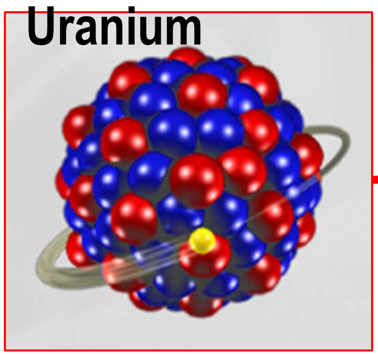
Short summary of this part

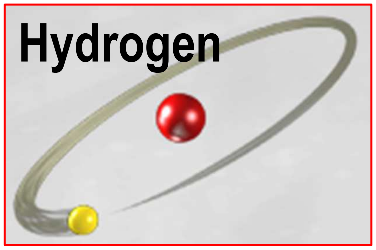
- Open questions of fundamental physics can be addressed by mass spectrometry
- Extreme accuracy, resolving power and sensitivity are required and can be realized
- Three very different examples of state-of-the-art mass spectrometers
  - the retardation spectrometer KATRIN for determination of the neutrino mass
  - the storage ring mass spectrometer for Schottky and time-of-flight mass spectrometry of radionuclides
  - the Penning trap mass spectrometer SHIPTRAP for determining the masses of the superheavy elements

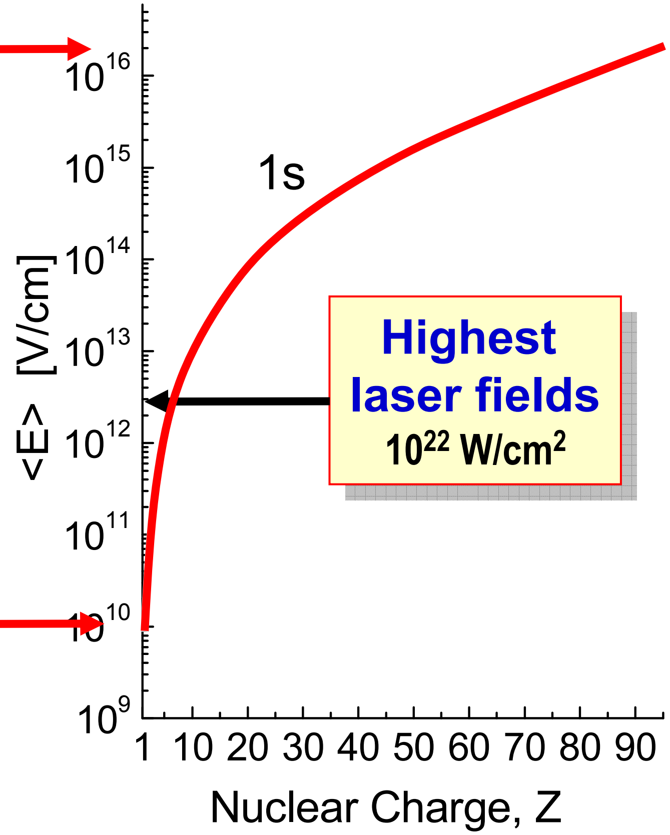


A brief look into the mid-term and long-term future

Test of Quantum Electrodynamics in Extreme Electromagnetic Fields and Spectroscopy of Simple Systems







Highest laser fields

10^{22} W/cm^2

H-like Uranium

$\langle E \rangle = 1.8 \times 10^{16}$ V/cm

$E_K = -132 \times 10^3$ eV

$\Delta E_{Lamb} \approx 500$ eV

$Z \cdot \alpha \approx 1$

Quantum **E**lectro- **D**ynamics

Hydrogen

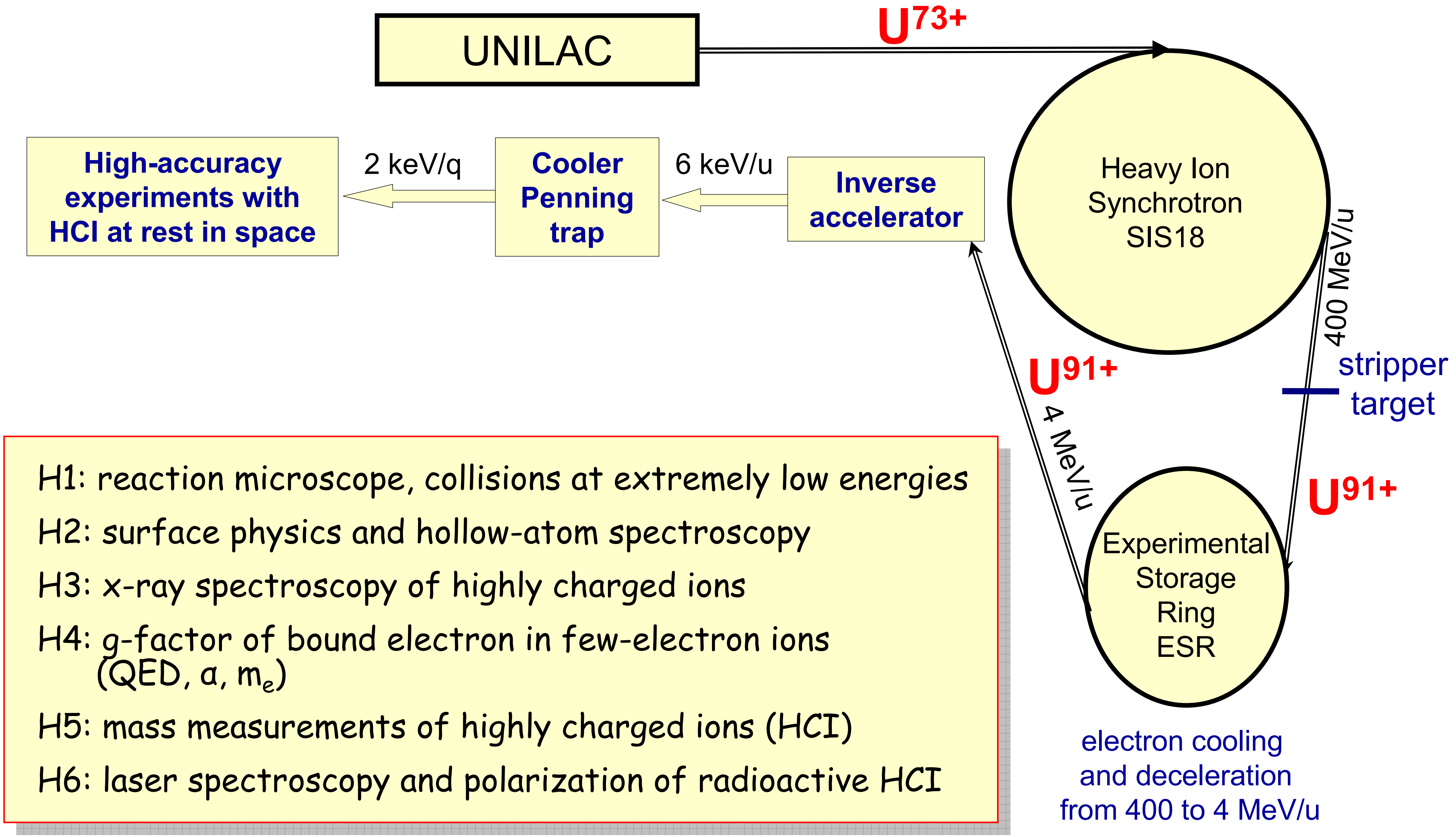
$\langle E \rangle = 1 \times 10^{10}$ V/cm

$Ek = -13.6$ eV

$\Delta E_{Lamb} \approx 10^{-5}$ eV

$Z \cdot \alpha \approx 10^{-2}$

A ^brief look into the future:
The mid-term project HITRAP at GSI



UNILAC

U^{73+}

Heavy Ion Synchrotron SIS18

400 MeV/u

stripper target

U^{91+}

Experimental Storage Ring ESR

electron cooling and deceleration from 400 to 4 MeV/u

U^{91+}

4 MeV/u

Inverse accelerator

6 keV/u

Cooler Penning trap

2 keV/q

High-accuracy experiments with HCI at rest in space

H1: reaction microscope, collisions at extremely low energies

H2: surface physics and hollow-atom spectroscopy

H3: x-ray spectroscopy of highly charged ions

H4: g-factor of bound electron in few-electron ions
(QED, α, m_e)

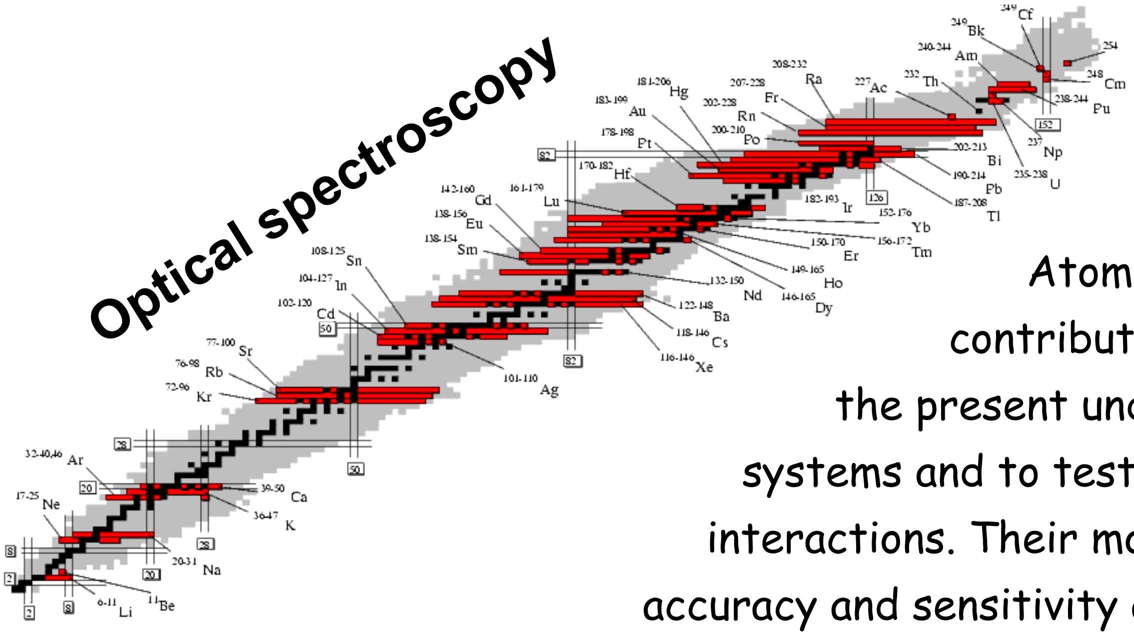
H5: mass measurements of highly charged ions (HCI)

H6: laser spectroscopy and polarization of radioactive HCI

A brief look into the long-term future: FAIR at Darmstadt
- antiprotons and highly charged ions -

Conclusion

Optical spectroscopy



Atomic physics techniques have contributed in the past very vitally to the present understanding of nuclear systems and to tests of symmetries and interactions. Their model independence, accuracy and sensitivity as well as new techniques for the study and manipulation of radioactive ion beams will also be essential in the future at radioactive-beam facilities.

Mass spectrometry