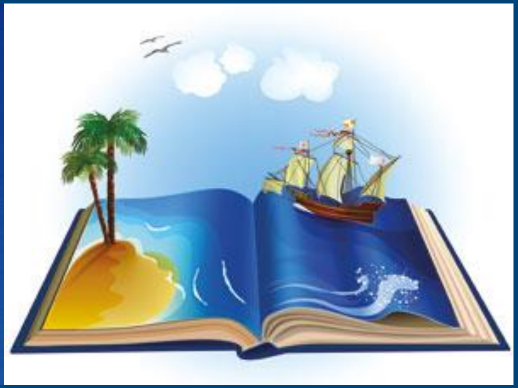
GSI Colloquium 19.05.2015

Investigating the Atomic and Nuclear Properties of the Heaviest Elements



Michael Block

GSI Darmstadt

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Institut für Kernchemie der Universität Mainz

Outline

- Status of superheavy element (SHE) research
- Basics of Penning trap mass spectrometry (PTMS)
- Direct mass measurements of nobelium and lawrencium isotopes
- New developments and selected results related to neutrino physics
- Basics of resonance ionization laser spectroscopy (RIS)
- Experimental efforts towards RIS of ^{254}No at GSI
- Summary and conclusions

SHIPTRAP Collaborators

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D. Nesterenko, Yu. Novikov, W. R. Plaß, S. Raeder, D. Rodríguez,
D. Rudolph, C. Scheidenberger, S. Schmidt, L. Schweikhard,
P. Thirolf, G. Vorobjev, C. Weber, …

Laser Spectroscopy Collaborators

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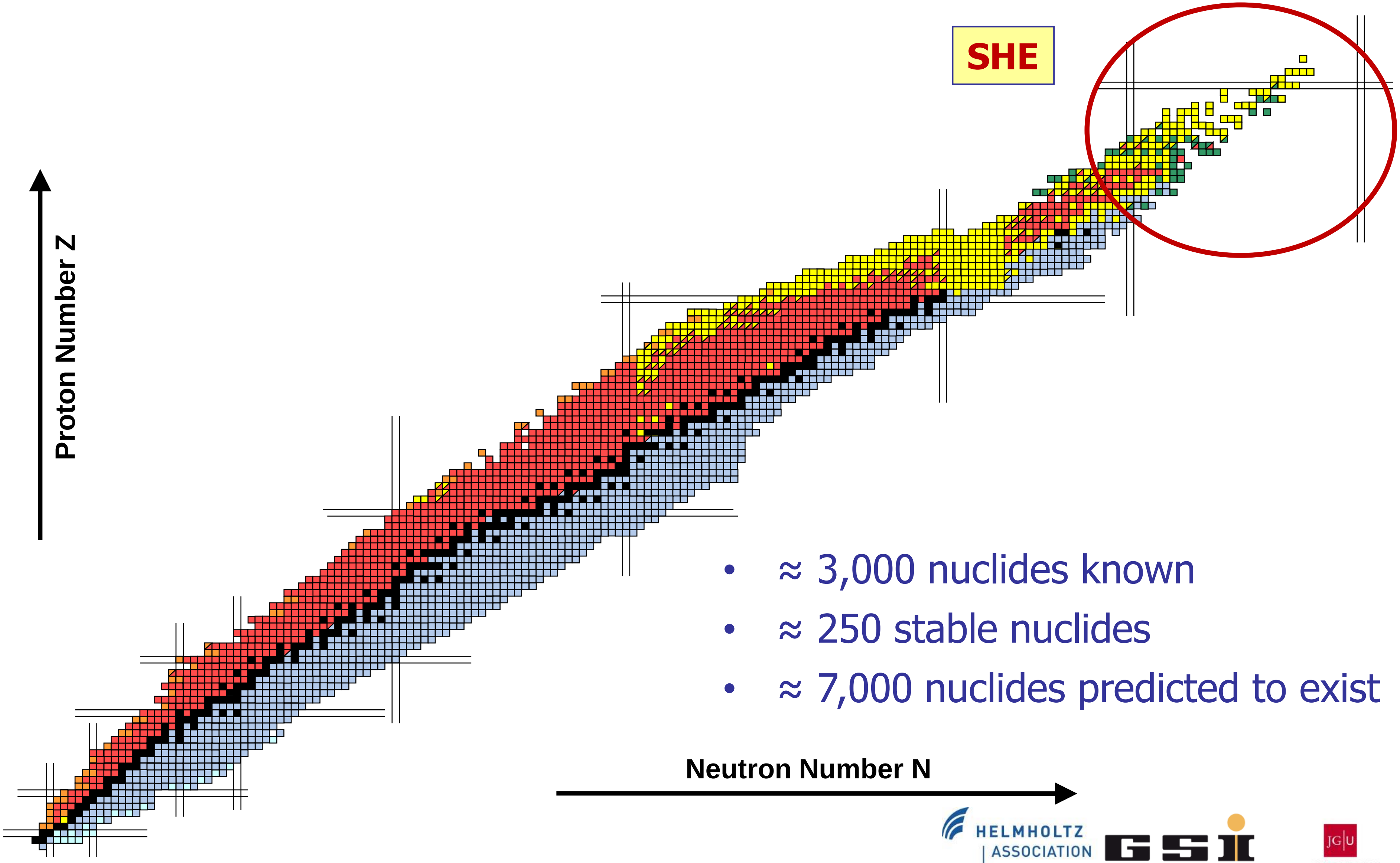
B. Cheal, C. Wraith

Former members:

E. Minaya Ramirez, J. Even, Ch. Droese

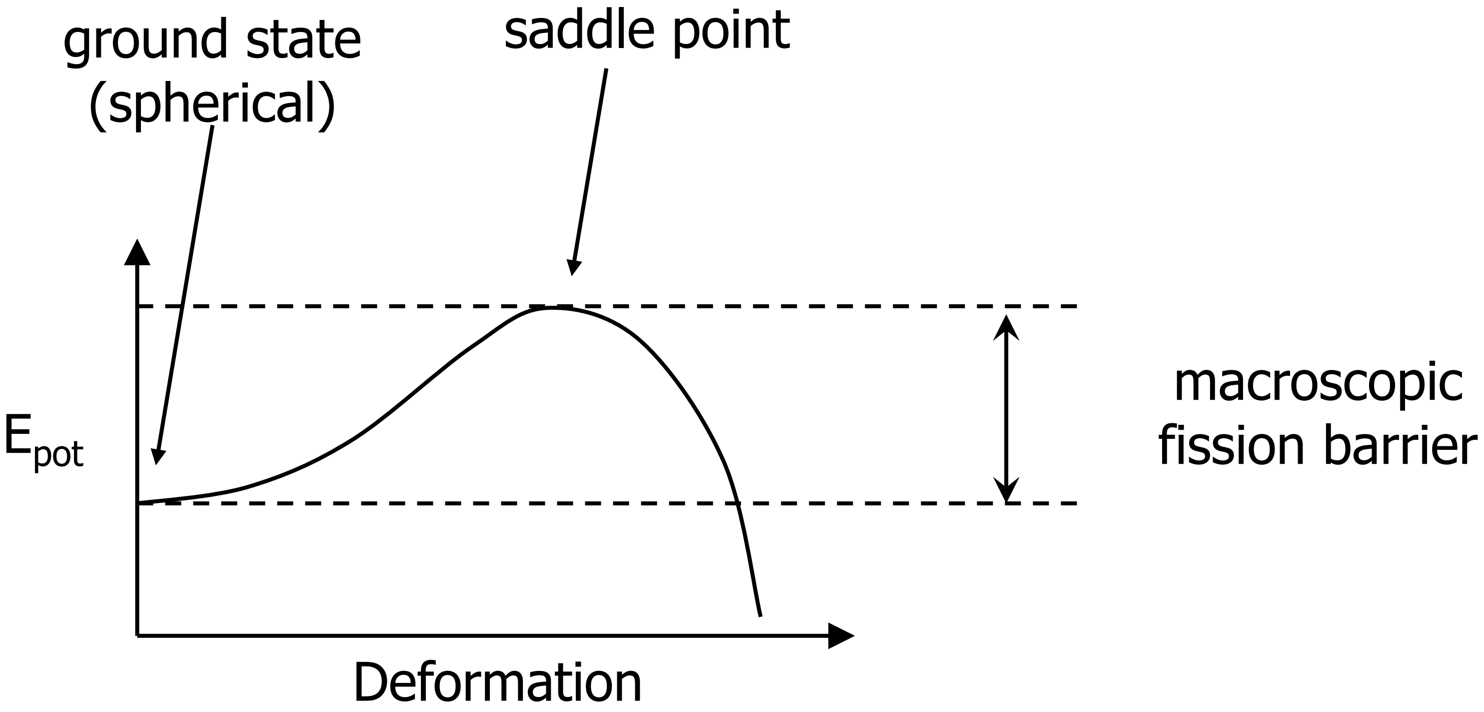
Superheavy Elements – Present Status and Key Questions

Nuclear Chart



- ≈ 3,000 nuclides known
- ≈ 250 stable nuclides
- ≈ 7,000 nuclides predicted to exist

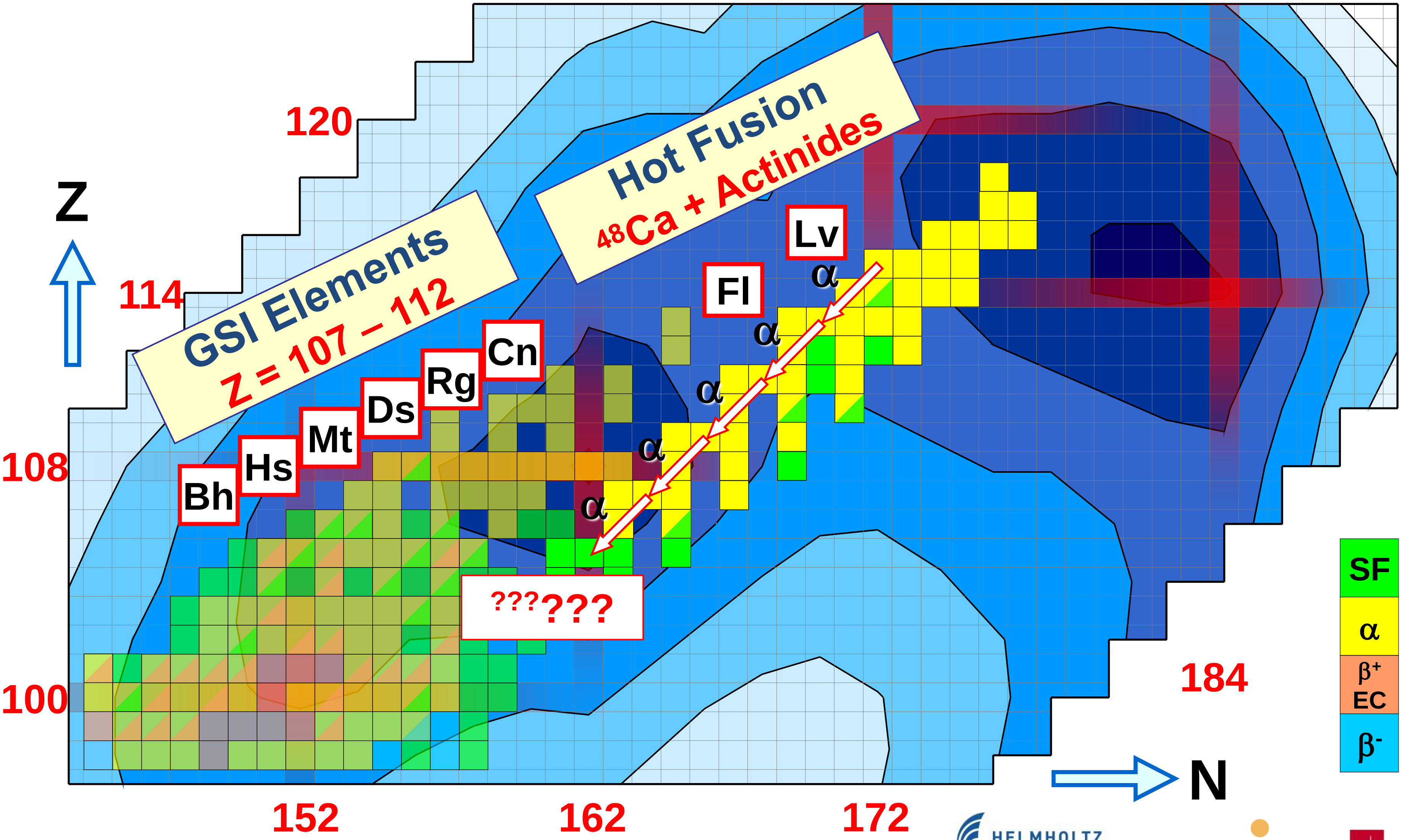
Superheavy Nuclei (SHN)



- fission barrier in liquid drop model vanishes for $Z \approx 106$
- stabilization against spontaneous fission by nuclear shell effects

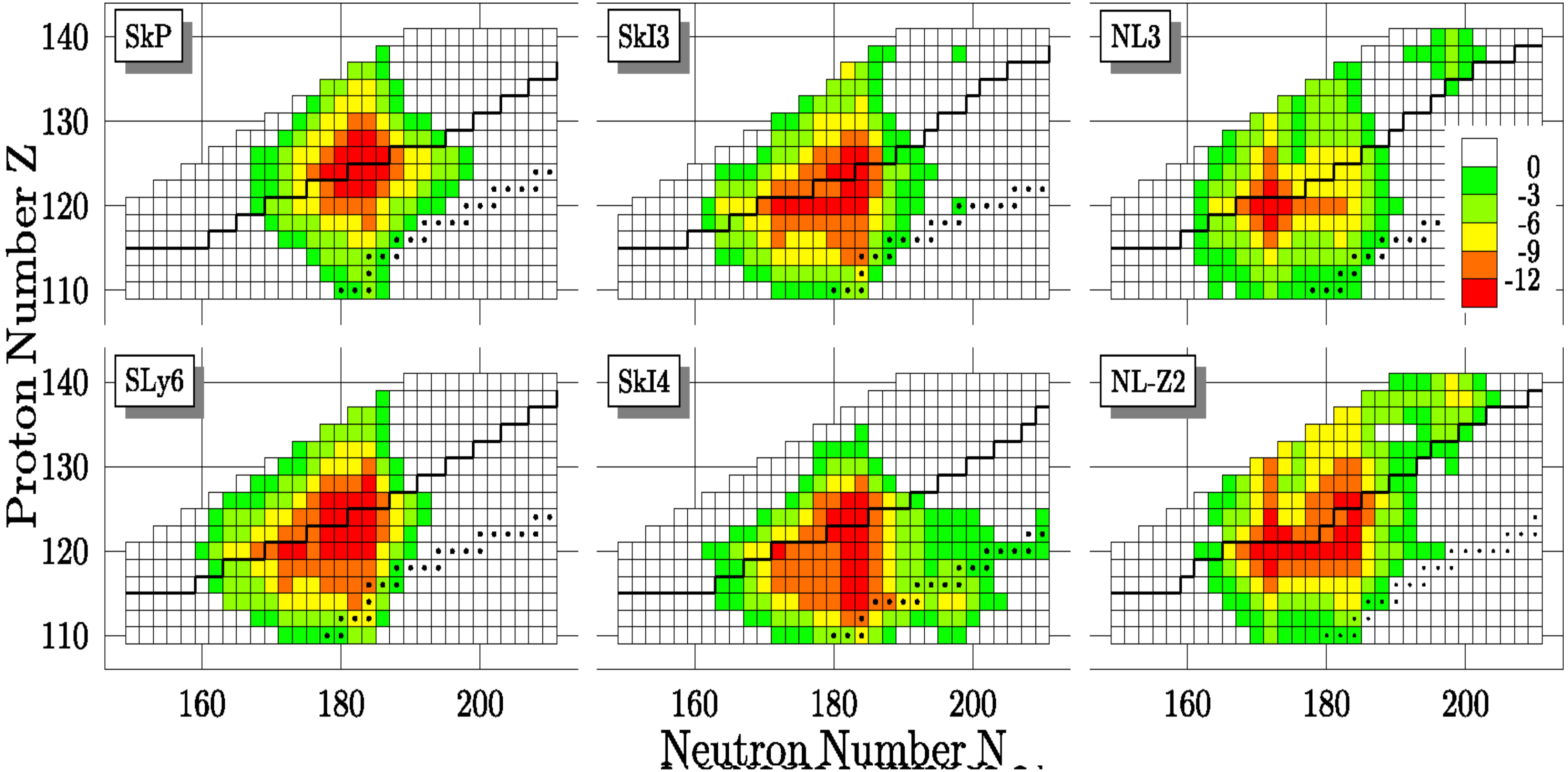
superheavy nuclei owe their very existence to shell effects

Superheavy Nuclides – Current Landscape



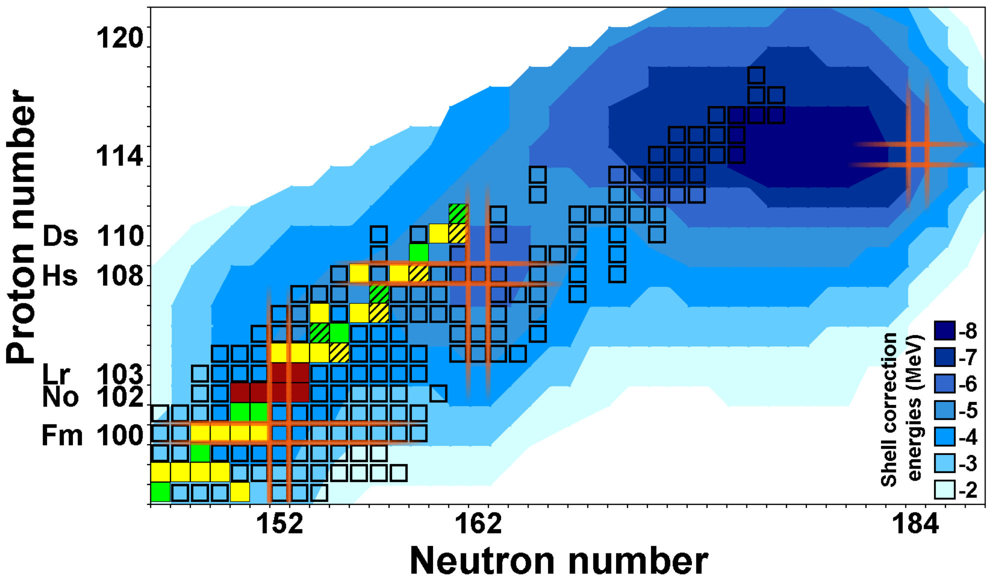
Courtesy Ch.E. Düllmann

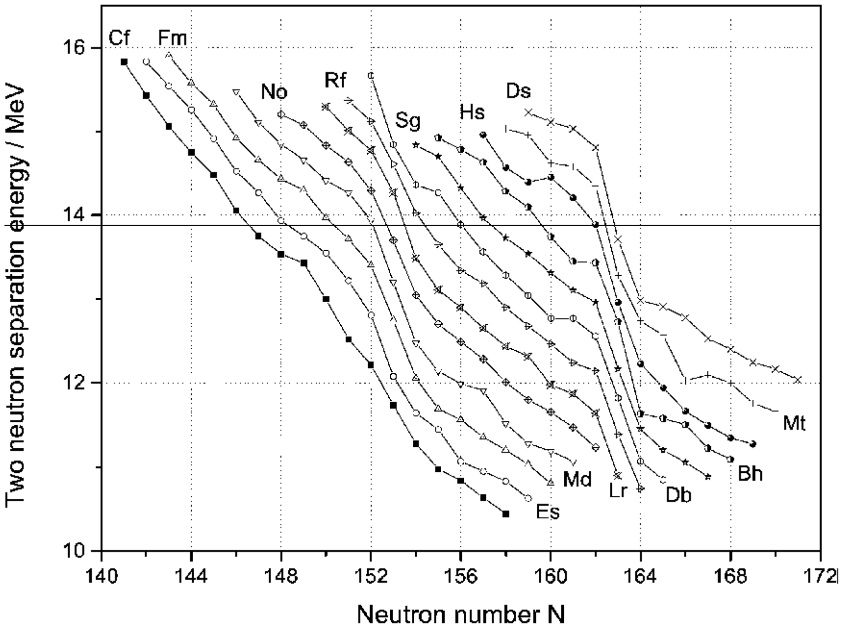
Nuclear Shells: Magic Numbers in SHE?



M. Bender et al., Phys. Lett. B 515 (2001) 42

Importance of Masses for Z > 100



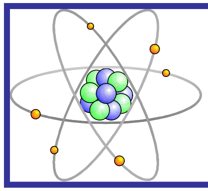


high-precision mass measurements provide

- accurate absolute binding energies to map nuclear shell effects
- anchor points to fix decay chains

➡ Studies the nuclear structure evolution

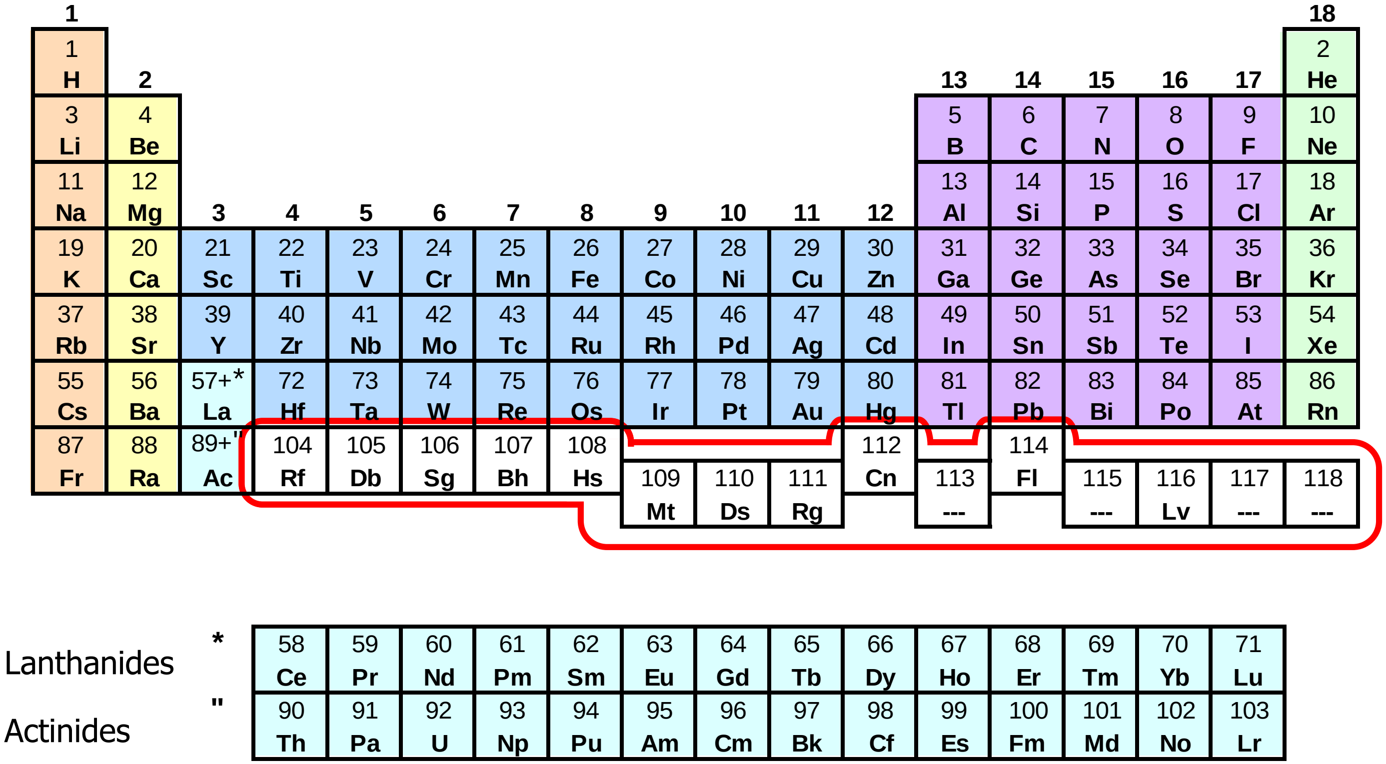
➡ Benchmark theoretical nuclear models



= N · ● + Z · ● + Z · ●

\- binding energy

Atomic Physics Studies of the Heaviest Elements



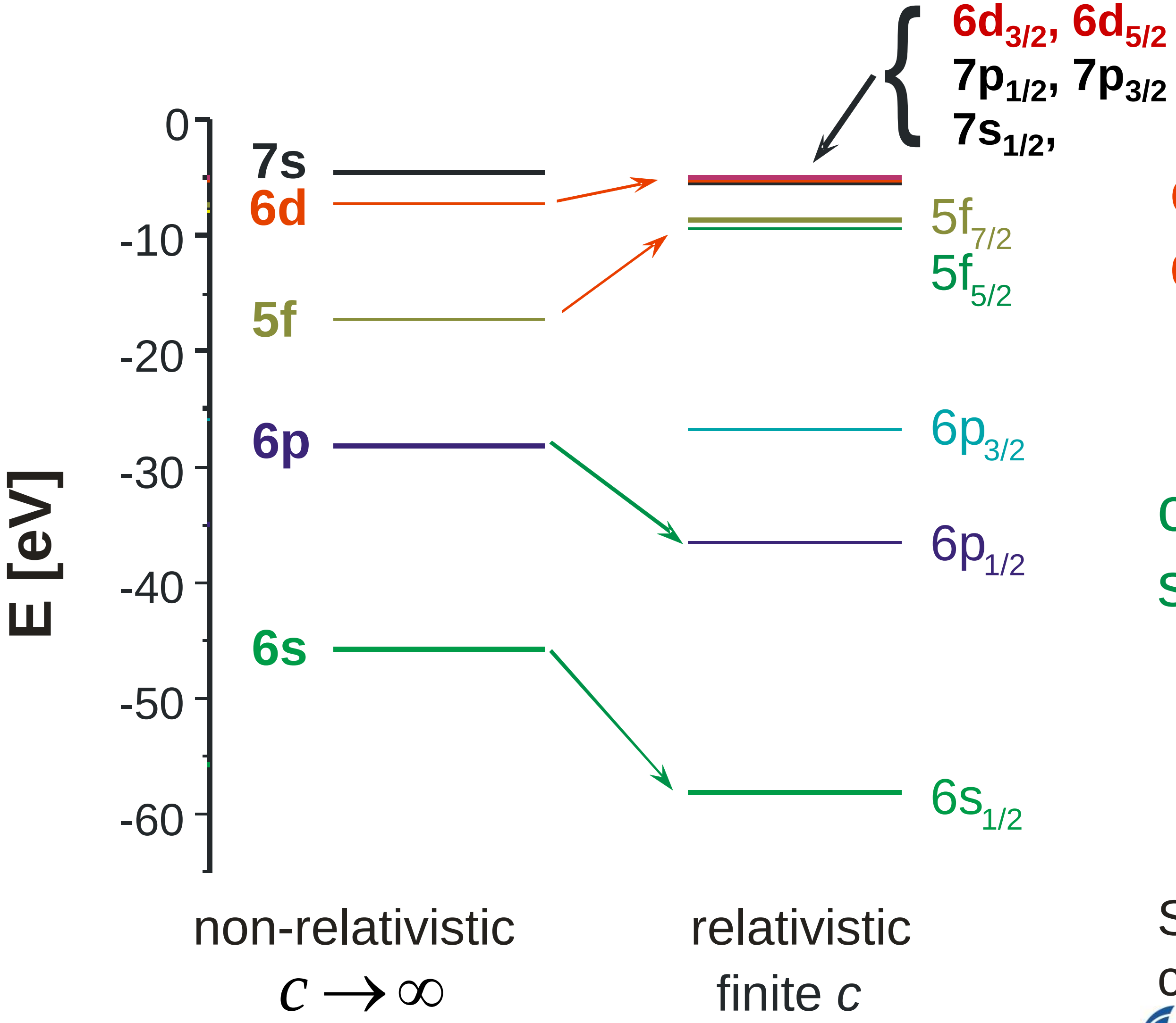
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 **H**																	2 **He**
3 **Li**	4 **Be**											5 **B**	6 **C**	7 **N**	8 **O**	9 **F**	10 **Ne**
11 **Na**	12 **Mg**											13 **Al**	14 **Si**	15 **P**	16 **S**	17 **Cl**	18 **Ar**
19 **K**	20 **Ca**	21 **Sc**	22 **Ti**	23 **V**	24 **Cr**	25 **Mn**	26 **Fe**	27 **Co**	28 **Ni**	29 **Cu**	30 **Zn**	31 **Ga**	32 **Ge**	33 **As**	34 **Se**	35 **Br**	36 **Kr**
37 **Rb**	38 **Sr**	39 **Y**	40 **Zr**	41 **Nb**	42 **Mo**	43 **Tc**	44 **Ru**	45 **Rh**	46 **Pd**	47 **Ag**	48 **Cd**	49 **In**	50 **Sn**	51 **Sb**	52 **Te**	53 **I**	54 **Xe**
55 **Cs**	56 **Ba**	57+* **La**	72 **Hf**	73 **Ta**	74 **W**	75 **Re**	76 **Os**	77 **Ir**	78 **Pt**	79 **Au**	80 **Hg**	81 **Tl**	82 **Pb**	83 **Bi**	84 **Po**	85 **At**	86 **Rn**
87 **Fr**	88 **Ra**	89+" **Ac**	104 **Rf**	105 **Db**	106 **Sg**	107 **Bh**	108 **Hs**	109 **Mt**	110 **Ds**	111 **Rg**	112 **Cn**	113 **---**	114 **Fl**	115 **---**	116 **Lv**	117 **---**	118 **---**

chemistry with single atoms

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

- study atomic structure and architecture of periodic table
- affected by strong relativistic effects and QED
- benchmark theoretical calculations

Relativistic Effects in Uranium



expansion of d, f orbitals

contraction of $s_{1/2}$, $p_{1/2}$ orbitals

Spin-orbit coupling

J. P. Desclaux, At. Data Nucl. Data Tables 12 (1973) 311

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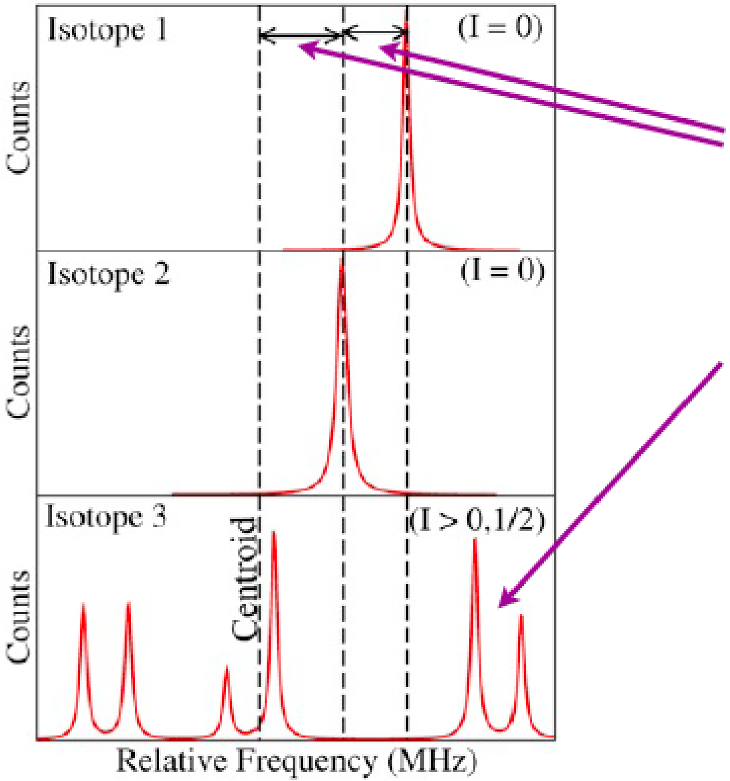
Laser Spectroscopy of the Heaviest Elements

Methods:	Search for atomic levels	hyperfine spectroscopy	Measurement of isotopic shifts
Motivation:	**relativistic and QED effects**	**Nuclear moments & spins**	**changes in mean square charge radii**



Isotope Shifts

→ $\delta\langle r^2\rangle$

Hyperfine Structure

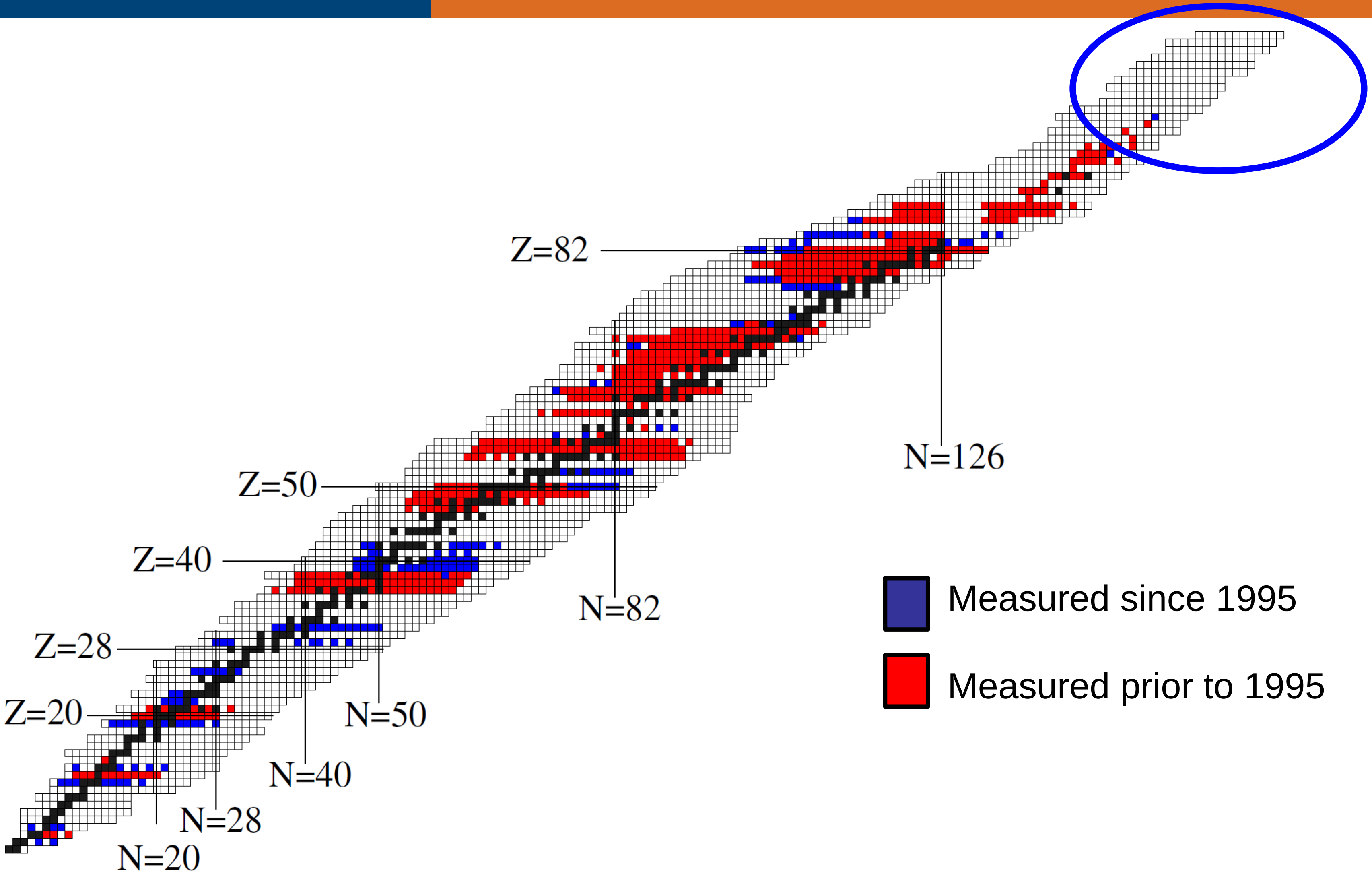
→ μ

→ Q_s → $\langle\beta_2\rangle$

→ Nuclear spin

adapted from B. Cheal

Laser spectroscopy – Status of Measurements



🟦 Measured since 1995

🟥 Measured prior to 1995

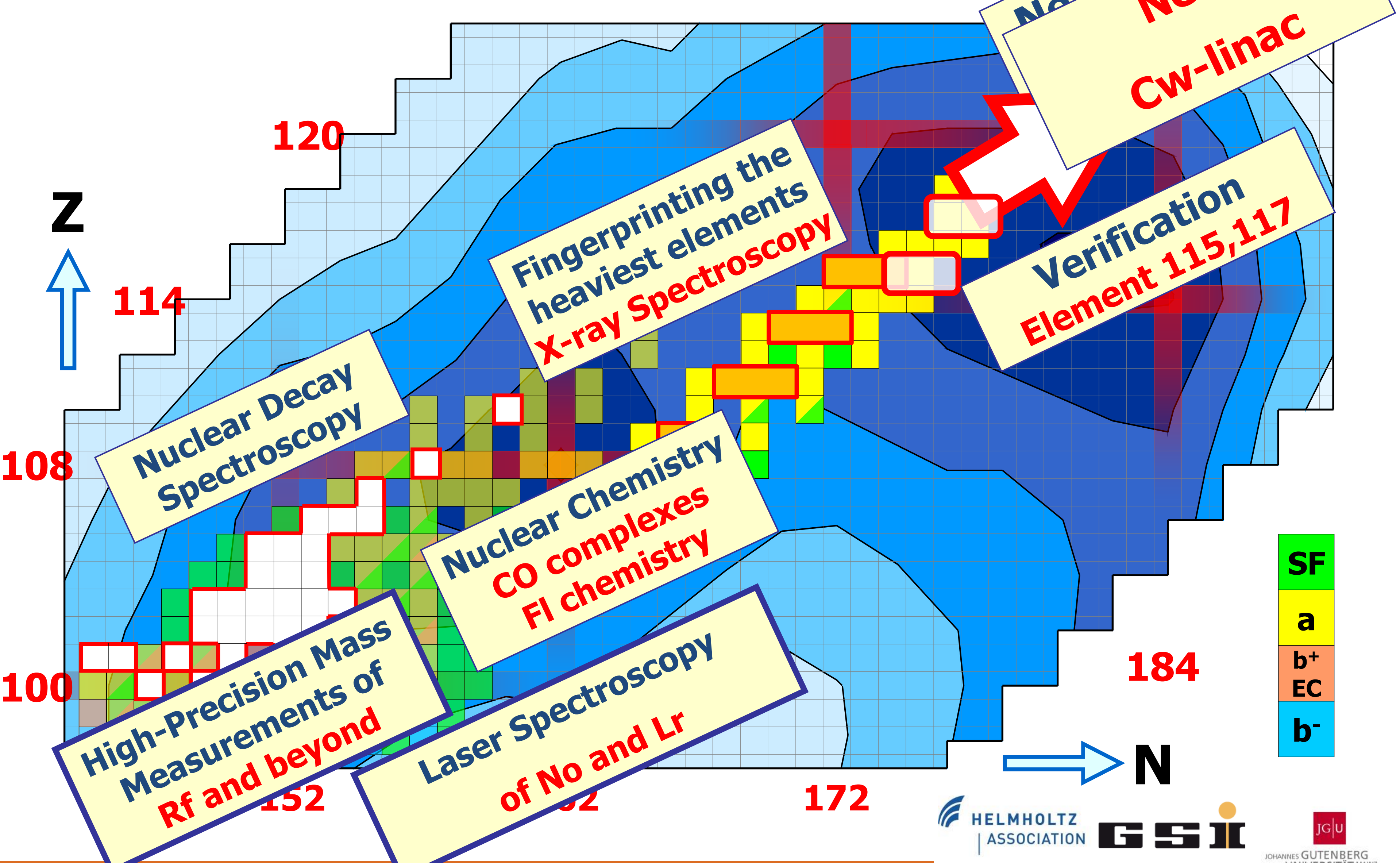
Figure from B. Cheal and K.T. Flanagan, J. Phys. G. **37** (2010) 113101

Superheavy Elements – Key Questions

- Where is the end of the periodic table in atomic number and mass?
- What is the heaviest element that we can synthesize?
- What are the properties and boundaries of the predicted ”island of stability” of superheavy elements?
- What are the details of the fission process and competing decay modes?
- Are there remnants of long-lived superheavy elements on earth?
- How do relativistic effects affect the architecture of the periodic table?

SHE research at GSI/HIM follows a comprehensive approach investigating atomic, chemical, and nuclear properties of SHE

Future Directions in SHE Research at GSI



New Elements

New Cw-linac

Fingerprinting the heaviest elements
X-ray Spectroscopy

Verification
Element 115,117

Nuclear Decay Spectroscopy

Nuclear Chemistry
CO complexes
Fl chemistry

High-Precision Mass Measurements of
Rf and beyond

Laser Spectroscopy
of No and Lr

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Courtesy Ch.E. Düllmann

Production of the Heaviest Elements

Requirements – Some Facts and Figures

Beam intensity:

- present: 6 x 10^{12} pps (1μA_p) for typical beams ^{48}Ca, ^{50}Ti, …
- future: ≥6 x 10^{13} pps (10μA_p) feasible

➢ need for high-power targets

Targets:

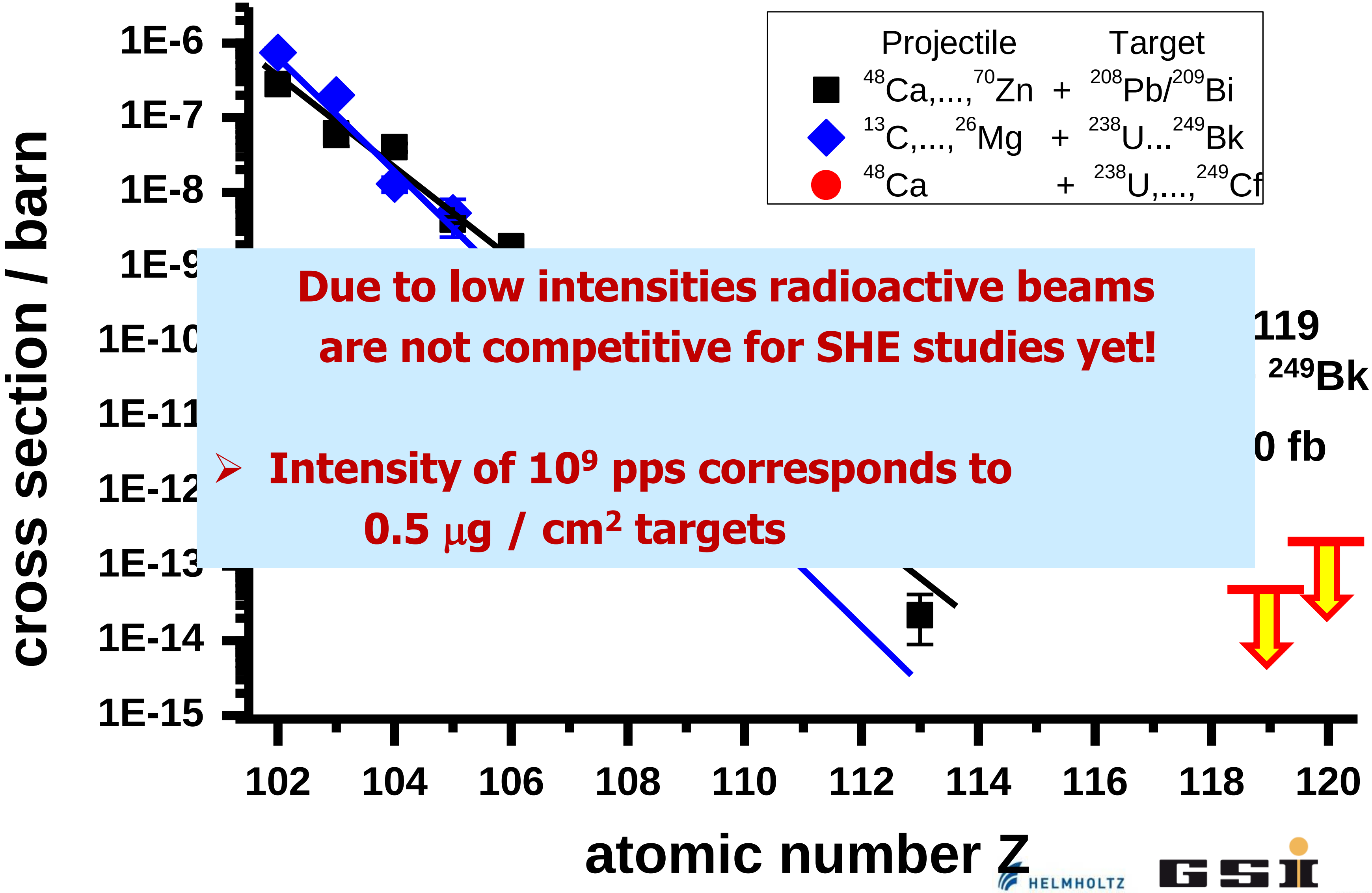
- 0.5-1.0 mg/cm^2 thickness
- about 10 mg of material needed for typical target wheel geometries

➢ limited availability of actinide material

Recoil separator

- High transmission, short separation time
- low background (beam suppression, low n, γ background)

Cross Sections for SHE Production

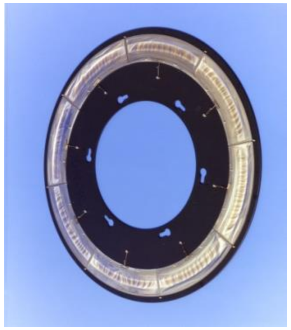


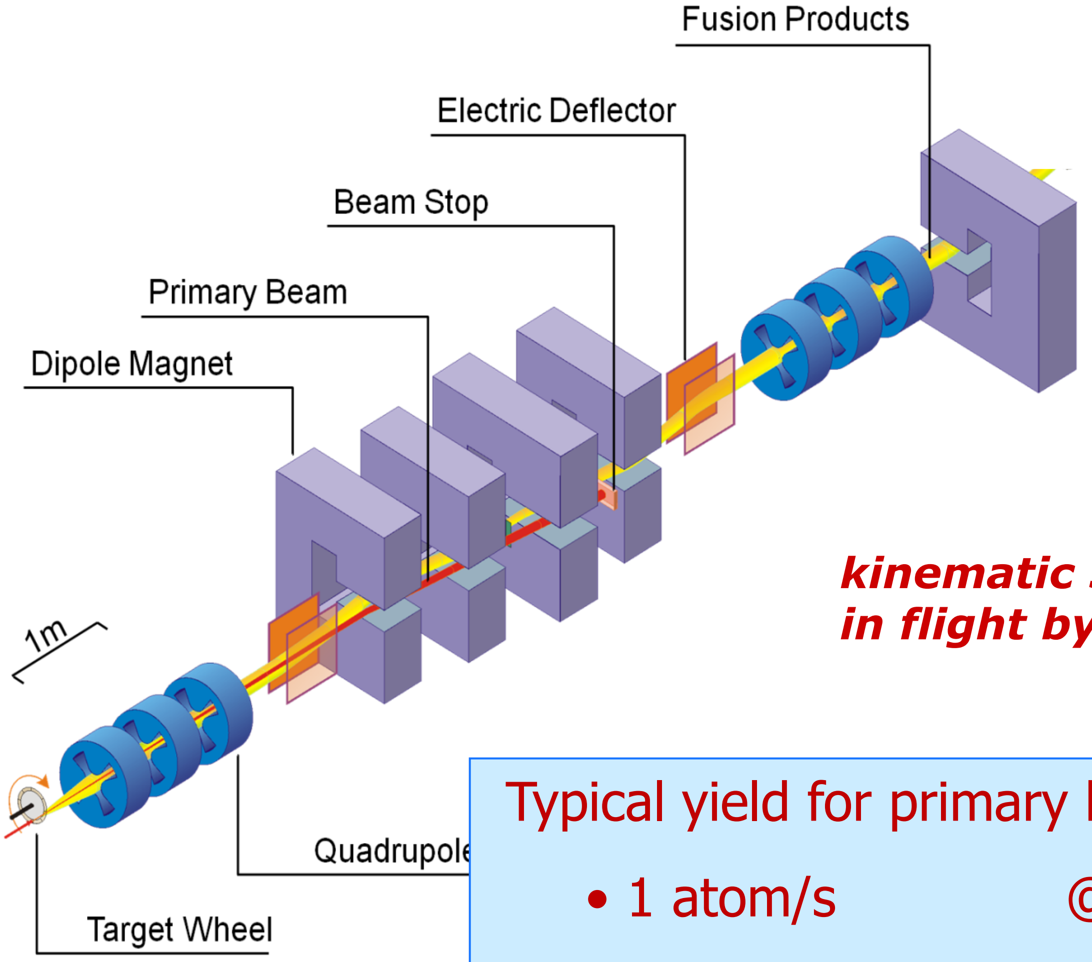
Due to low intensities radioactive beams are not competitive for SHE studies yet!

- ➢ **Intensity of 10^9 pps corresponds to $0.5\ \mu g\ /\ cm^2$ targets**

Courtesy Ch.E. Düllmann

Synthesis and Separation by SHIP





kinematic separation
in flight by velocity filter

Typical yield for primary beam ≈ 6 x 10^{12} / s

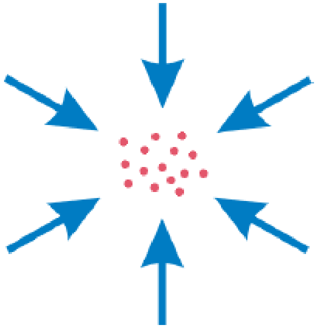
- 1 atom/s @ Z ≈ 102 ($\sigma \approx 1$ μb)
- 1 atom/week @ Z= 112 ($\sigma \approx 1$ pb)

Basics of Penning Trap Mass Spectrometry

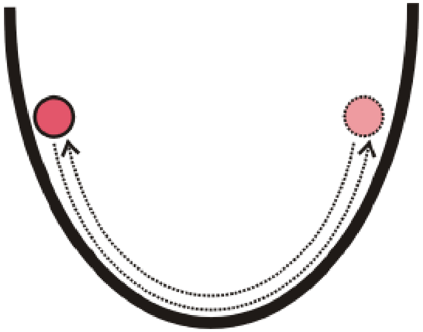
Basic Idea of a Particle Trap

restoring force 3D

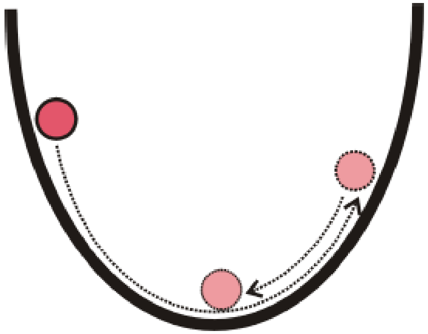
$$\vec{F} \propto -\vec{r}$$



harmonic oscillation



reducing the kinetic energy by cooling

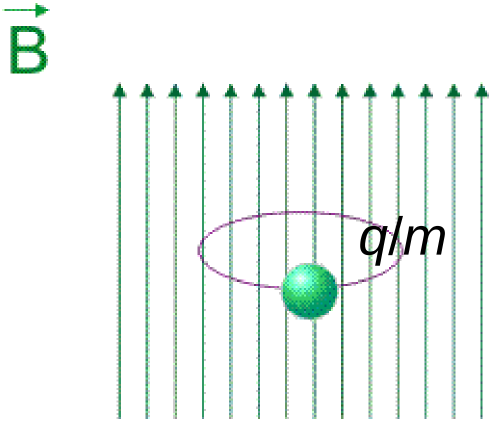


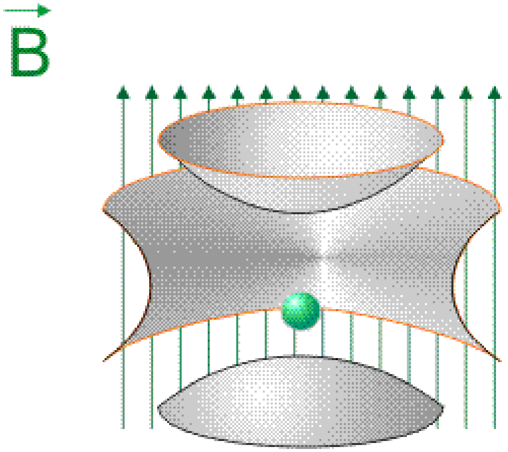
- confine single particles (nearly) at rest
- minimize perturbations (collisions, field imperfections, ...)
- long observation / measurement times

Courtesy H.-J.. Kluge

Principle of Penning Traps

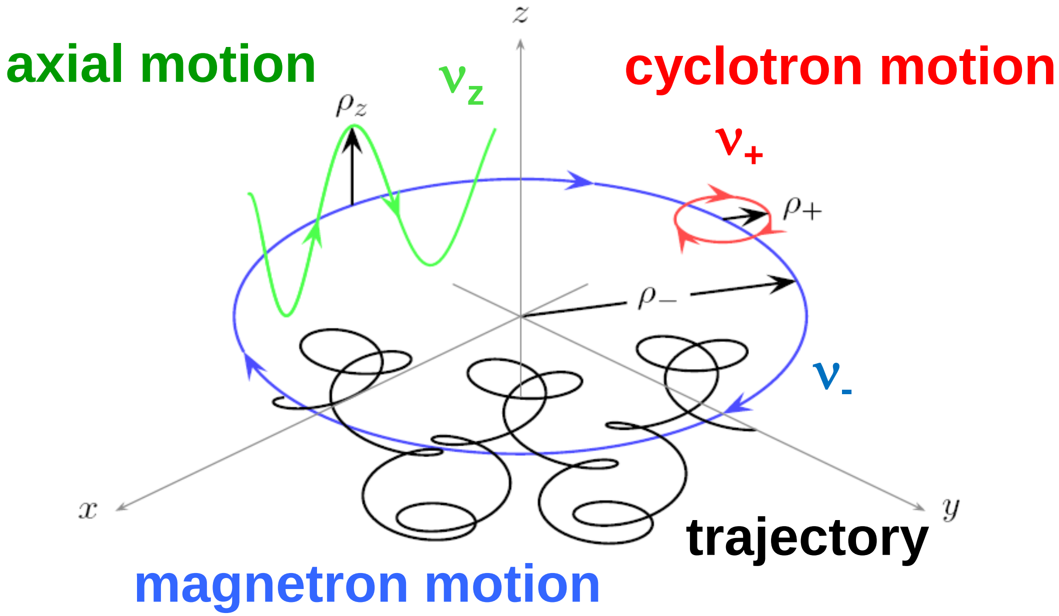
PENNING trap





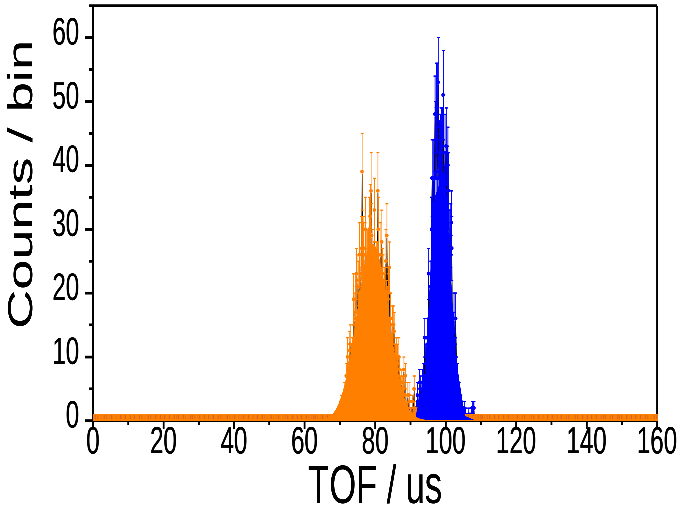
- Strong homogeneous magnetic field
- Weak electric 3D quadrupolar field

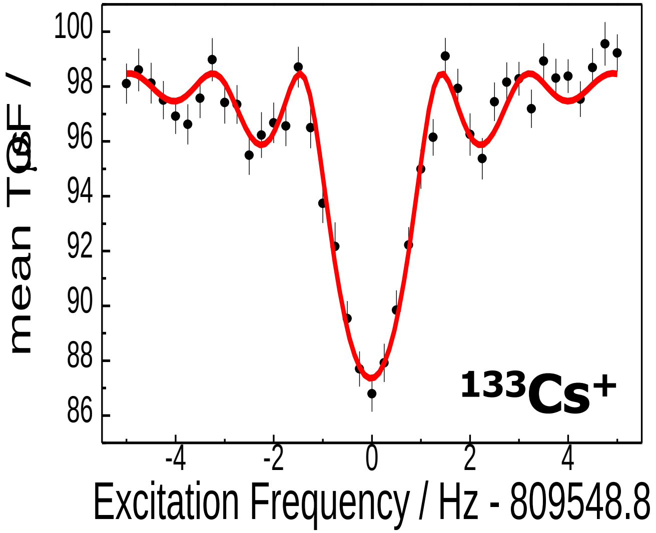
Cyclotron frequency: $$f_c = \frac{1}{2\pi}\cdot\frac{q}{m}\cdot B$$

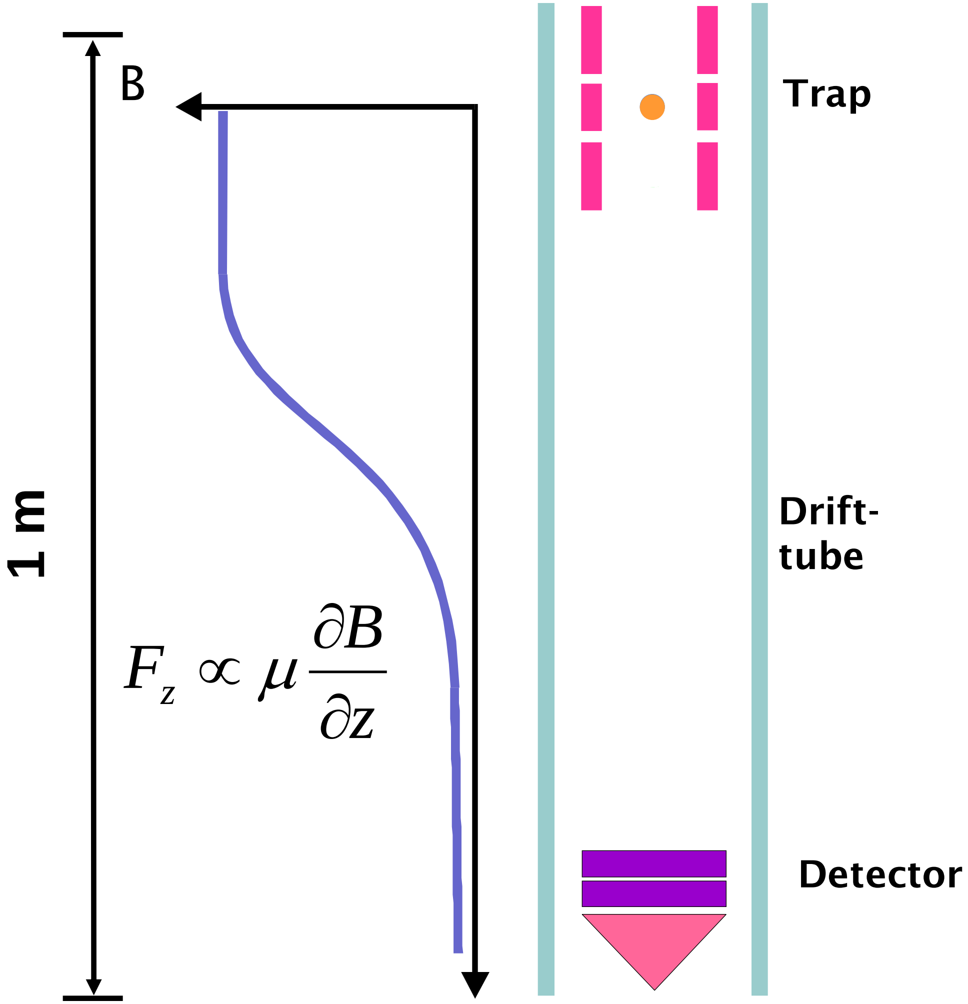


L. S. Brown and G. Gabrielse, Rev. Mod. Phys. 58 (1986) 233
G. Gabrielse, Int. J. Mass Spectr. 279, (2009) 107

Cyclotron frequency measurement







$$F_z \propto \mu \frac{\partial B}{\partial z}$$

Time-of-flight resonance technique

M. König et al., Int. J. Mass Spec. Ion Process. 142 (1995) 95

Penning Trap Mass Spectrometry

determine mass via cyclotron frequency measurement

$$\nu_C = \frac{1}{2\pi}\frac{qB}{\boxed{m}}$$

magnetic field calibration

$$\nu_{ref} = \frac{1}{2\pi}\frac{q_{ref}\cdot B}{m_{ref}}$$

$$\left.\begin{array}{l} \\ \\ \end{array}\right\} \boxed{r = \frac{\nu_{\mathrm{Re}\,f}}{\nu_C} = \frac{m}{m_{ref}}}$$

$\Rightarrow$ atomic mass

$$\boxed{m = \frac{q}{q_{ref}}\left(m_{ref} - q_{ref}\cdot m_e\right)\frac{\nu_{ref}}{\nu_c} + q\cdot m_e}$$

statistical uncertainty

$$s(\nu) \propto \frac{1}{\nu_c}\frac{1}{T_{RF}\sqrt{N_{tot}}}$$

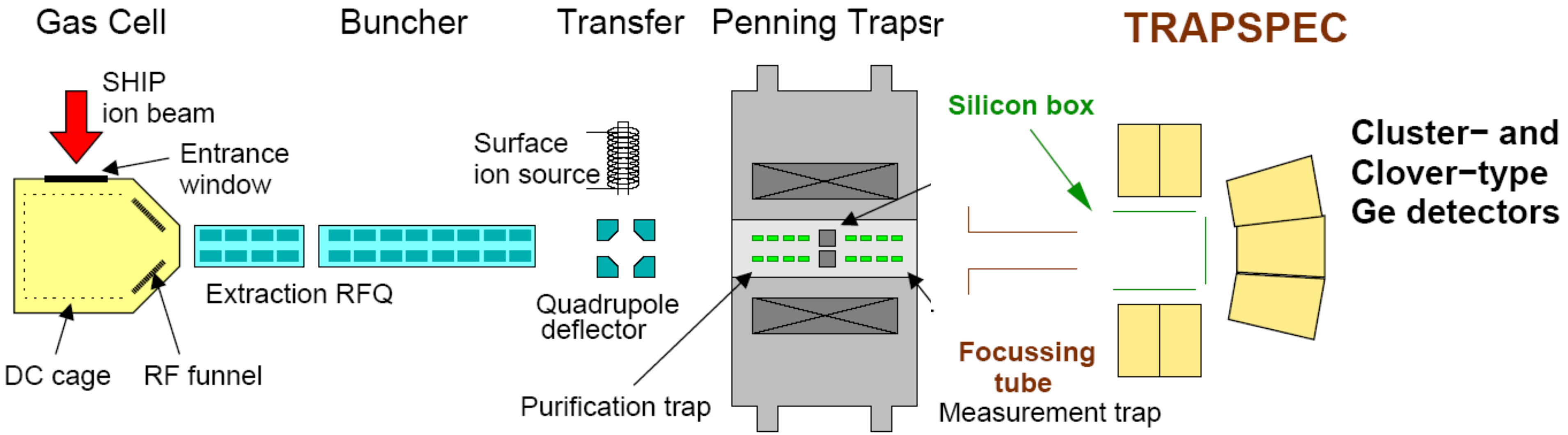
T_{RF} observation time

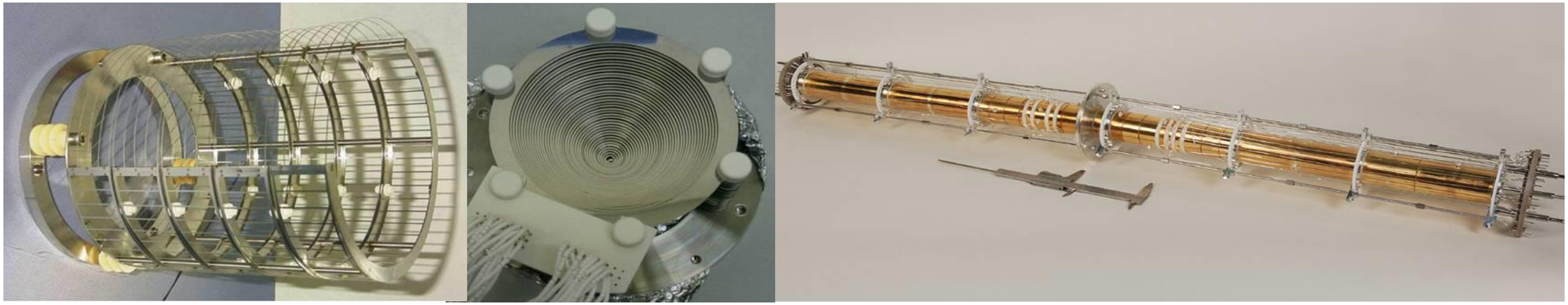
Ntot number of det. ions

Direct Mass Measurements of Nobelium and Lawrencium Isotopes with SHIPTRAP

SHIPTRAP Setup

≈ 50 MeV → ≈ 1 eV → ≈ 1 keV





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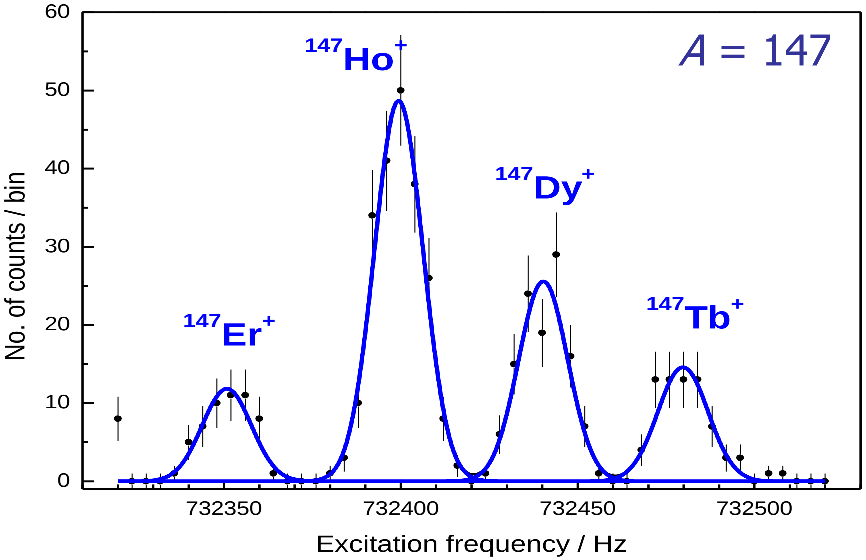
SHIPTRAP Performance

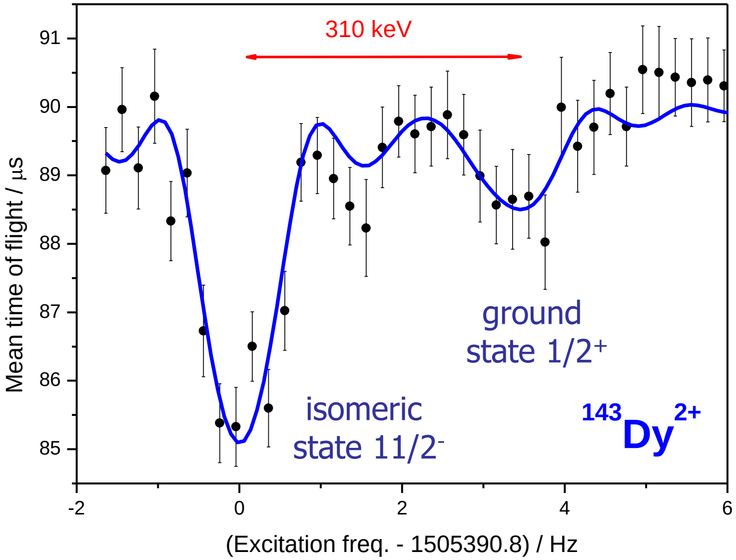


Mass resolving power of

m/δm ≈ 100,000

in purification trap:

⇒ separation of isobars



Mass resolving power of

m/δm ≈ 1,000,000

in measurement trap:

⇒ separation of isomers

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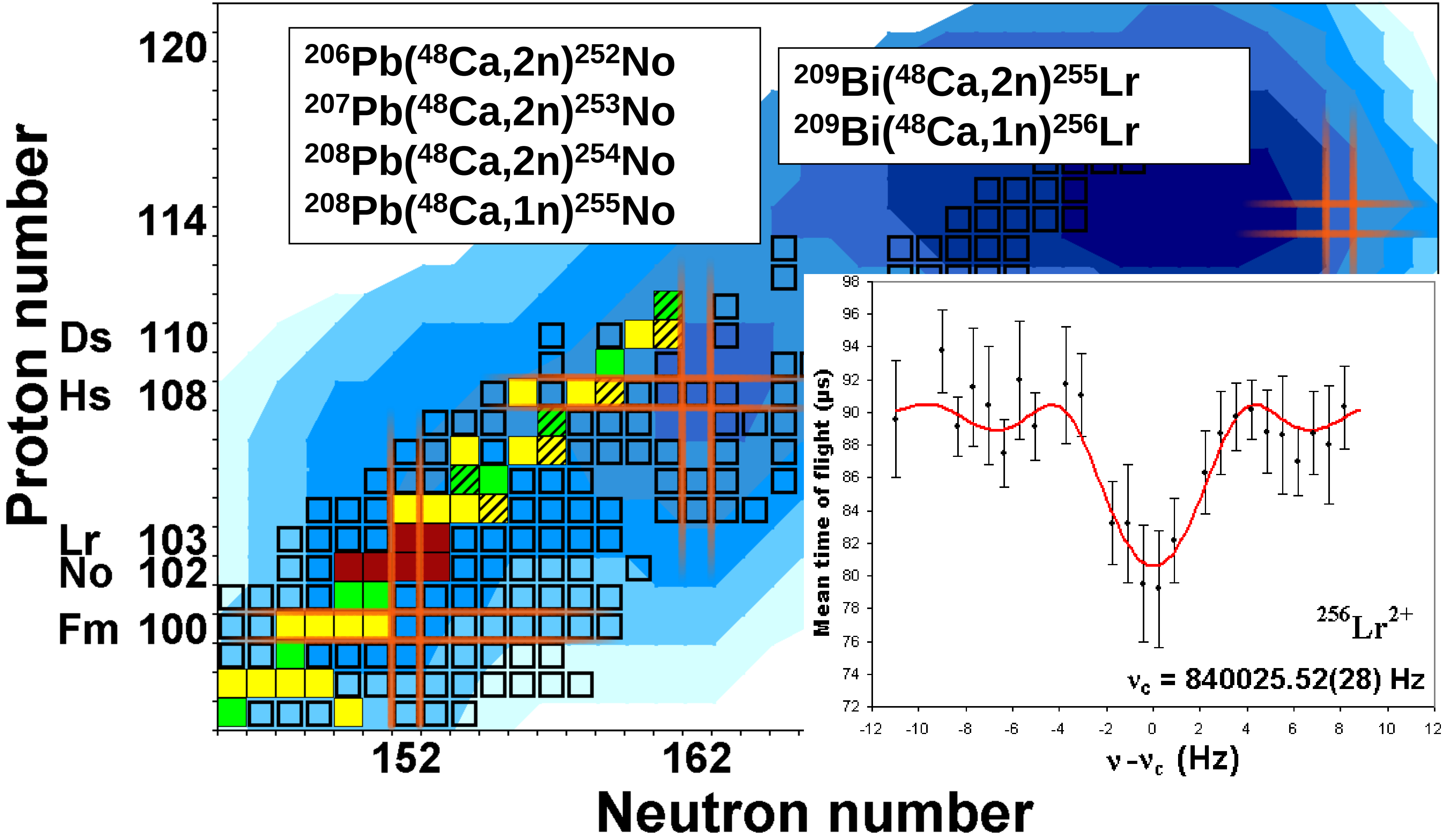
Direct mass measurements with SHIPTRAP

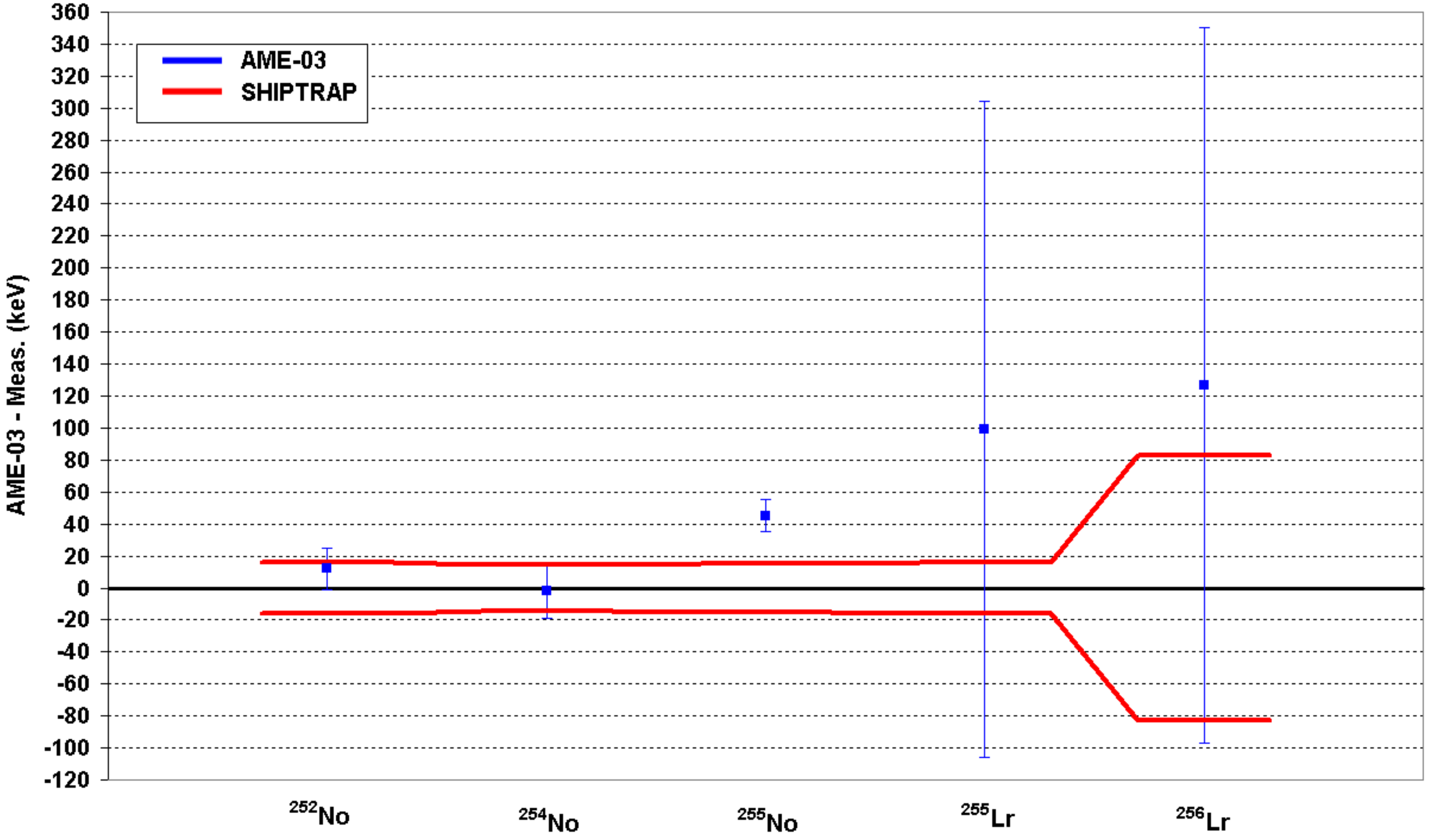


^{206}Pb(^{48}Ca,2n)^{252}No
^{207}Pb(^{48}Ca,2n)^{253}No
^{208}Pb(^{48}Ca,2n)^{254}No
^{208}Pb(^{48}Ca,1n)^{255}No

^{209}Bi(^{48}Ca,2n)^{255}Lr
^{209}Bi(^{48}Ca,1n)^{256}Lr

M. Block et al., Nature 463, 785 (2010), M. Dworschak et al., Phys. Rev. C 81, 064312 (2010)
E. Minaya Ramirez et al., Science 337, 1183 (2012)

SHIPTRAP Results vs. Atomic Mass Evaluation



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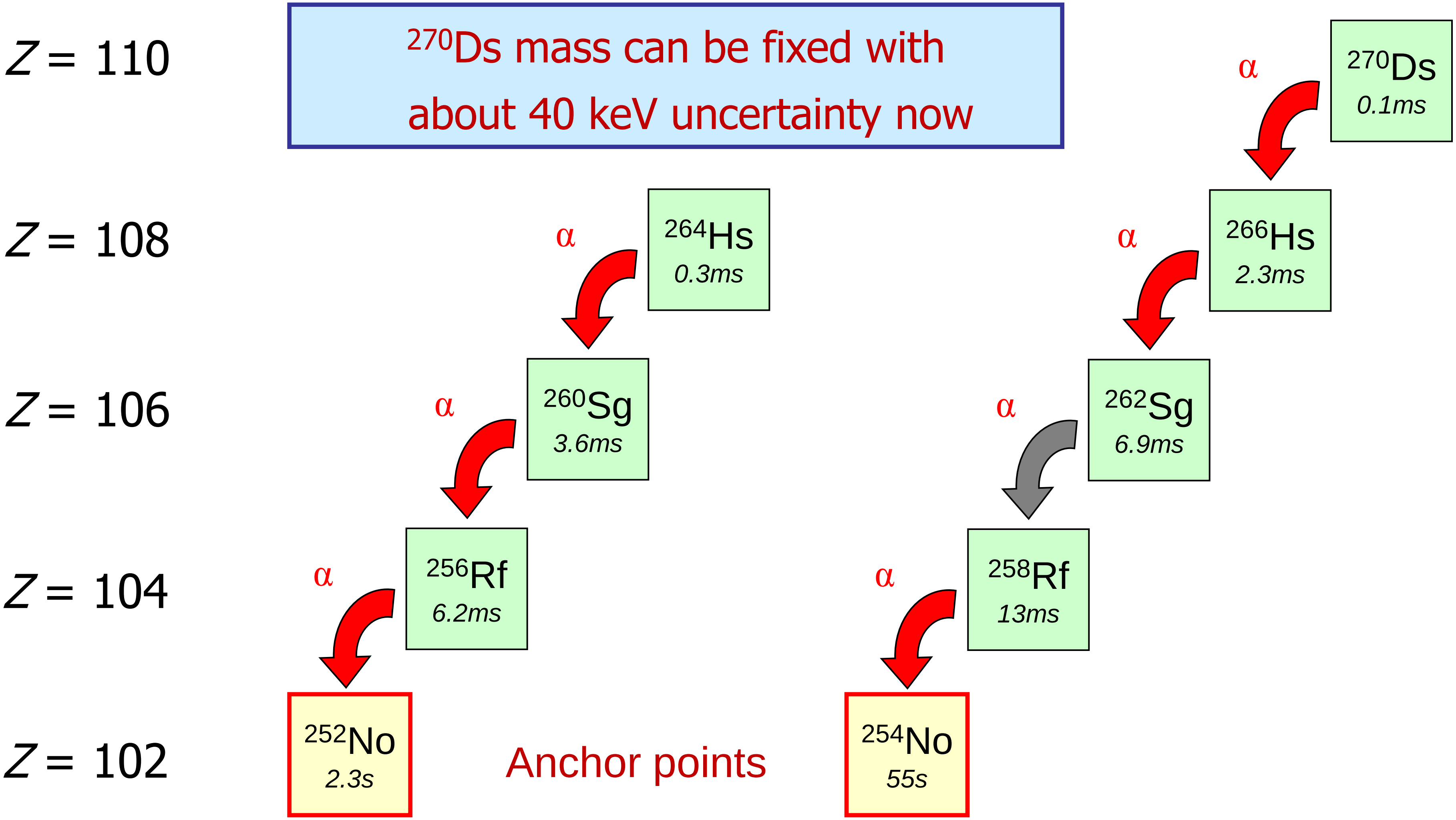
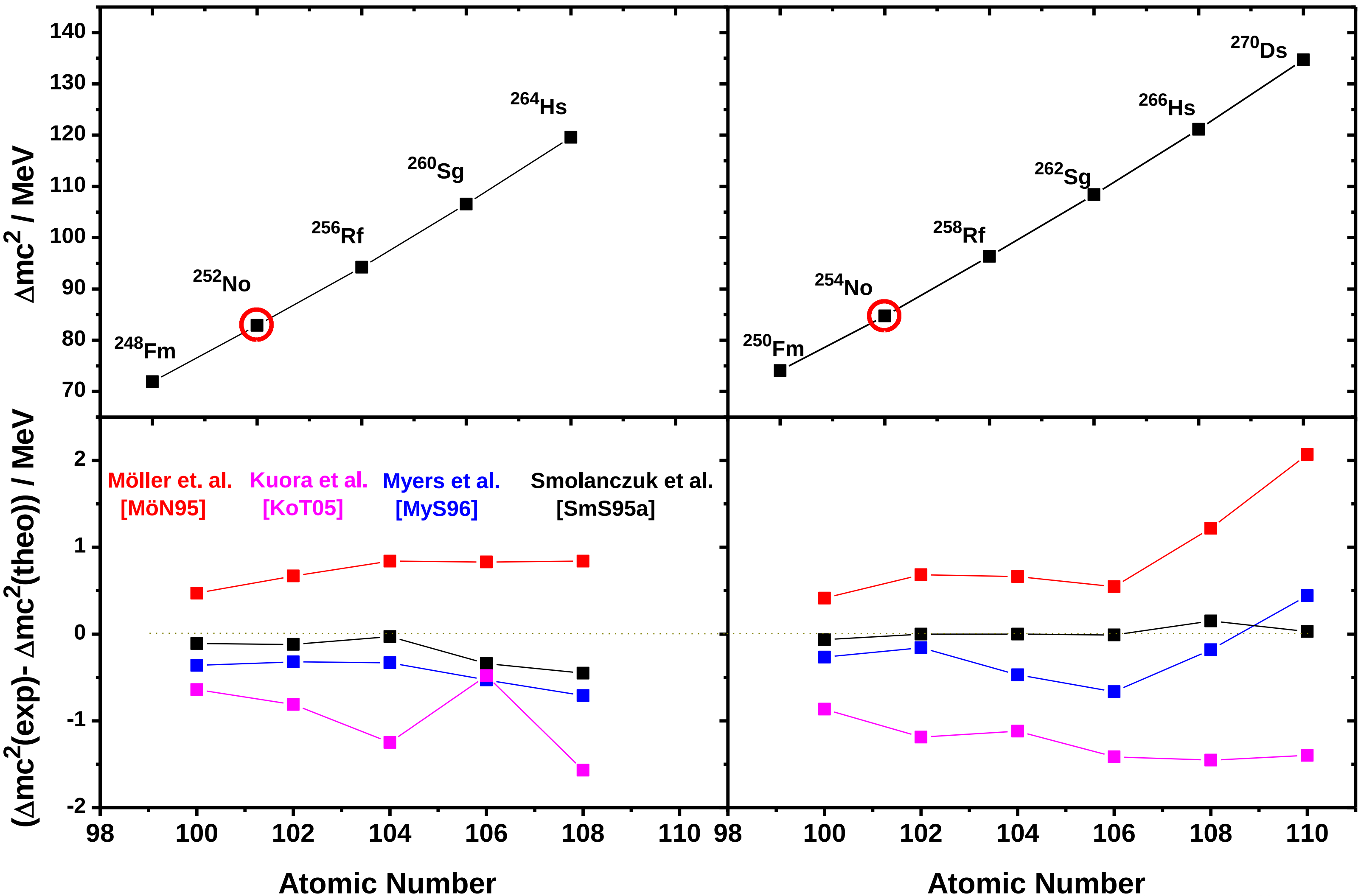
Pinning Down α-Decay Chains



^{270}Ds mass can be fixed with about 40 keV uncertainty now

Anchor points

Masses of even-even $N-Z = 48$ and $N-Z = 50$ Nuclei



/StrukturSWK/Abbildungen/Massen,
F.P. Heßberger, 3.9.2013

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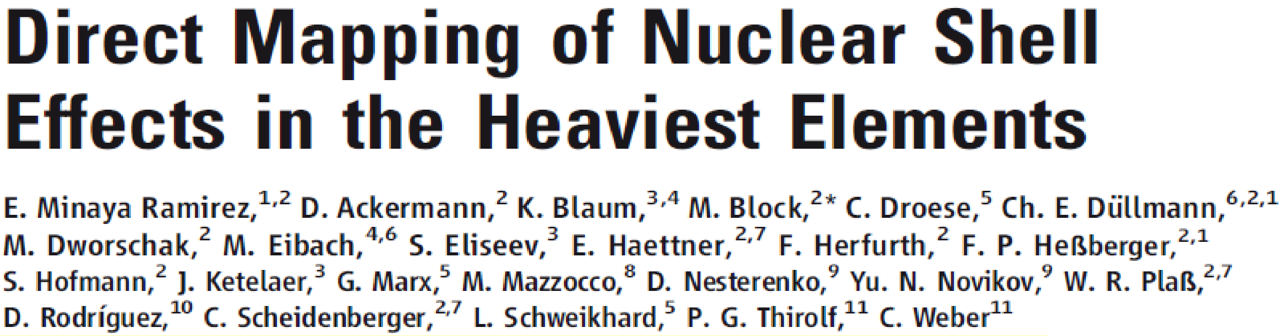
courtesy F. P. Hessberger

SHIPTRAP: Probing the Strength of Shell Effects



Direct Mapping of Nuclear Shell Effects in the Heaviest Elements

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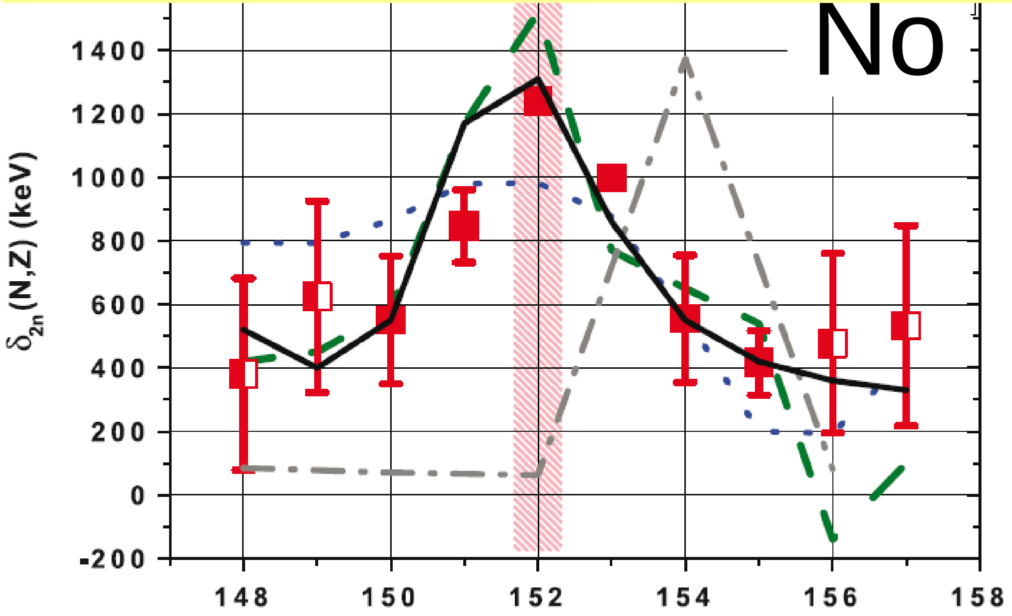
$$\delta_{2n}(N,Z) = 2B(N,Z) - B(N-2,Z) - B(N+2,Z)$$



🟥 Experimental

Muntian (mic-mac)
Z=114 N=184

Möller FRDM
Z=114 N=184

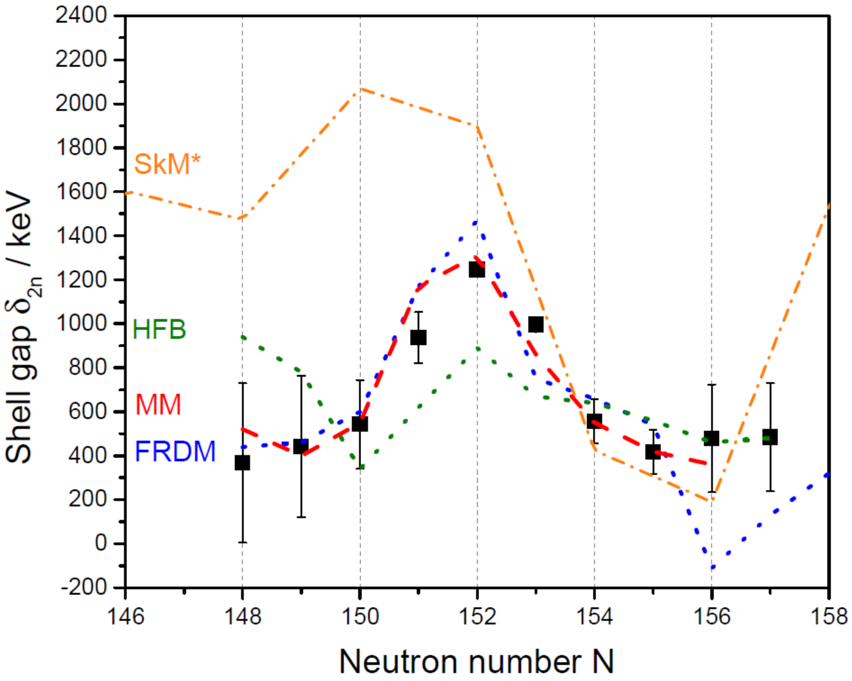
TW-99
Z=120 N=172

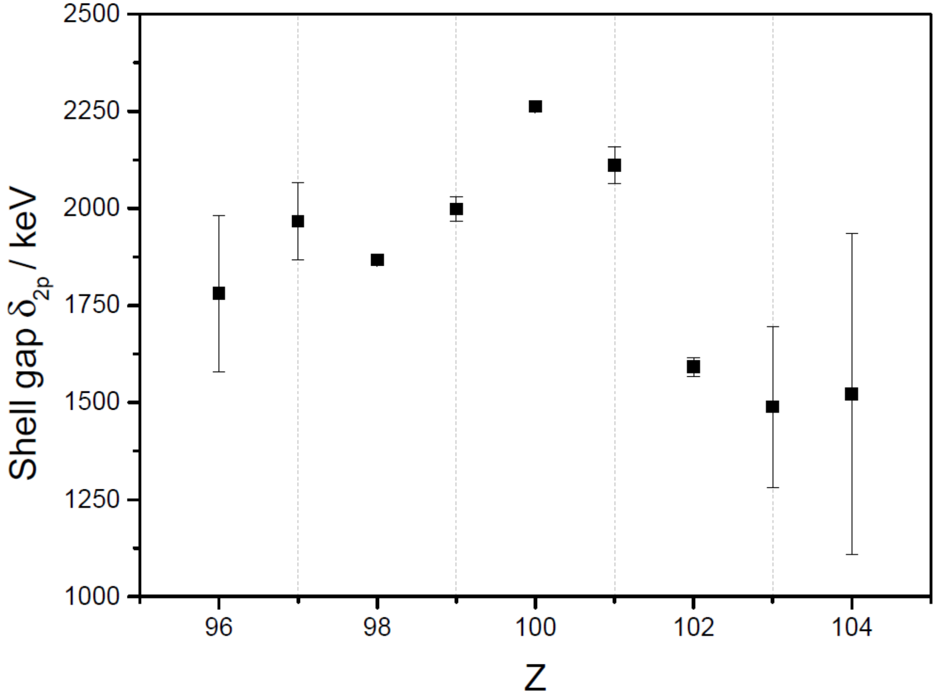
SkM*
Z=126 N=184

Science **337** (2012) 1207

SHIPTRAP: Probing the Strength of Shell Effects

$\delta_{2n}(N,Z) = 2B(N,Z) – B(N\text{-}2,Z) – B(N+2,Z)$



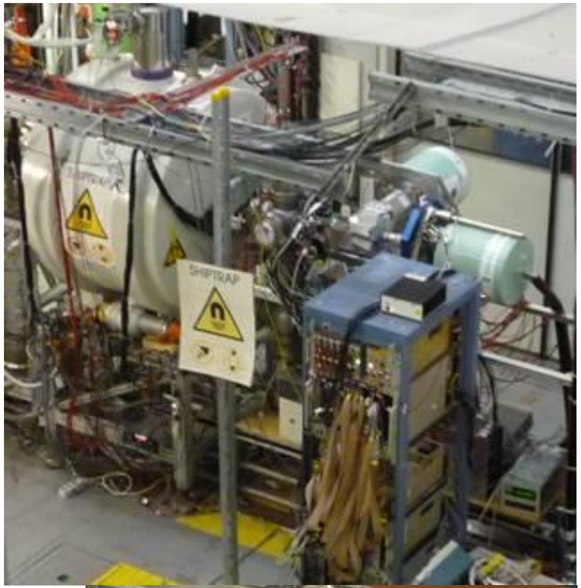


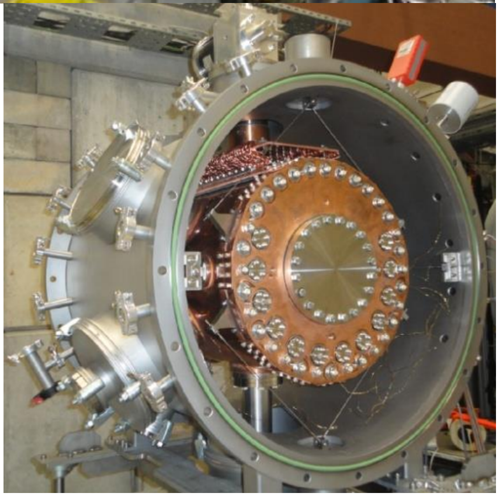
Upgrades and Improvements

Upgrades and Combinations

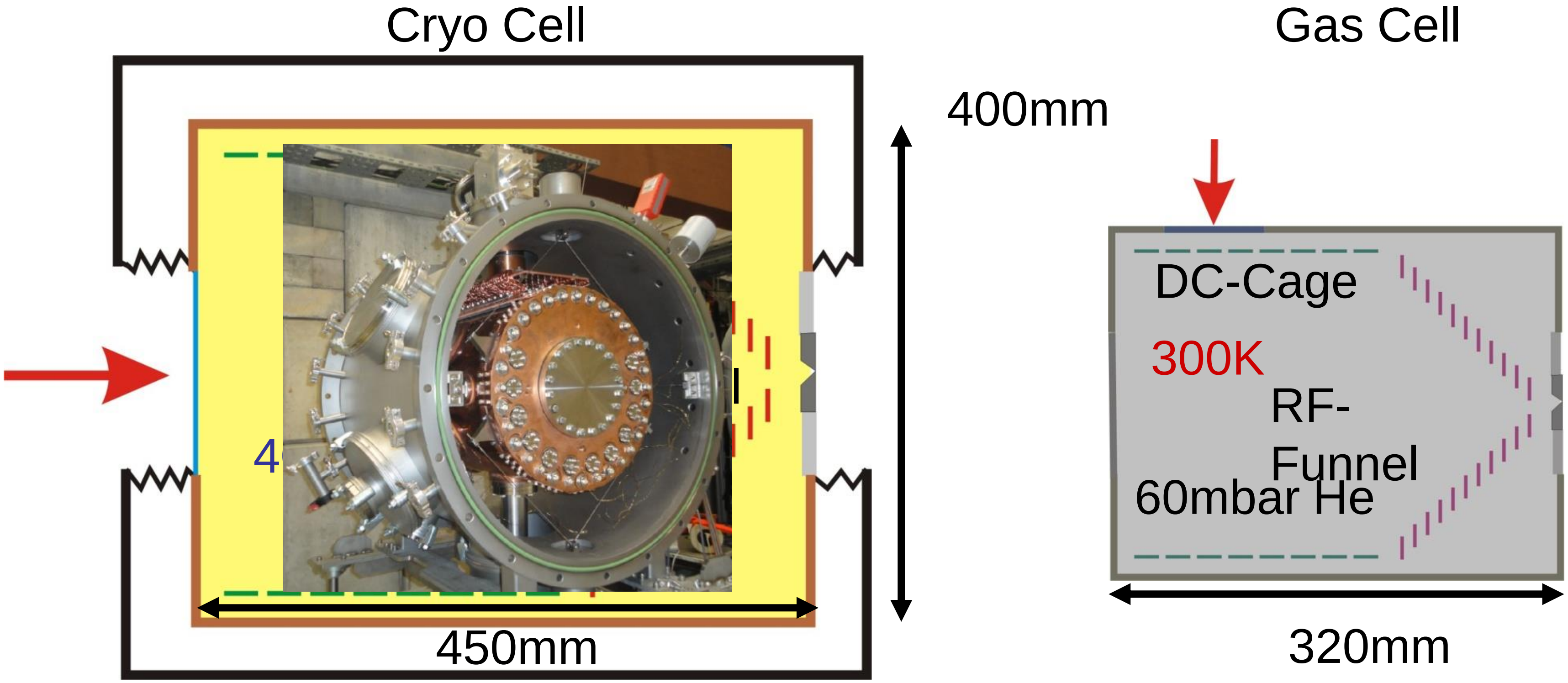
- Novel experiments
  - trap-assisted nuclear decay spectroscopy
  - laser spectroscopy (in gas cell / gas jet)
  - gas-phase chemistry (in gas cell / ion trap)

- Increase efficiency and sensitivity
  - cryogenic gas cell
  - novel measurement schemes (PI-ICR)
  - single-ion mass measurements (FT-ICR)
    (→ TRIGA-TRAP, TRAPSENSOR)





Cryogenic Gas Stopping Cell



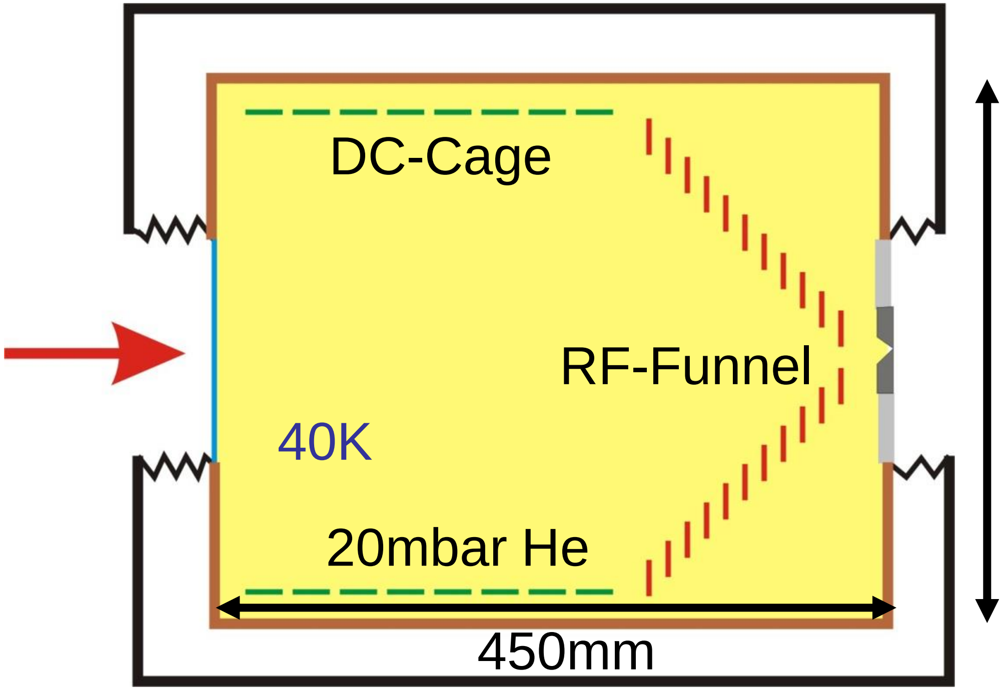
Advantages compared to 1st generation gas cell:

- Larger stopping volume and Coaxial injection of reaction products
- Higher cleanliness due to cryogenic operation
- Larger gas density at a lower absolute pressure

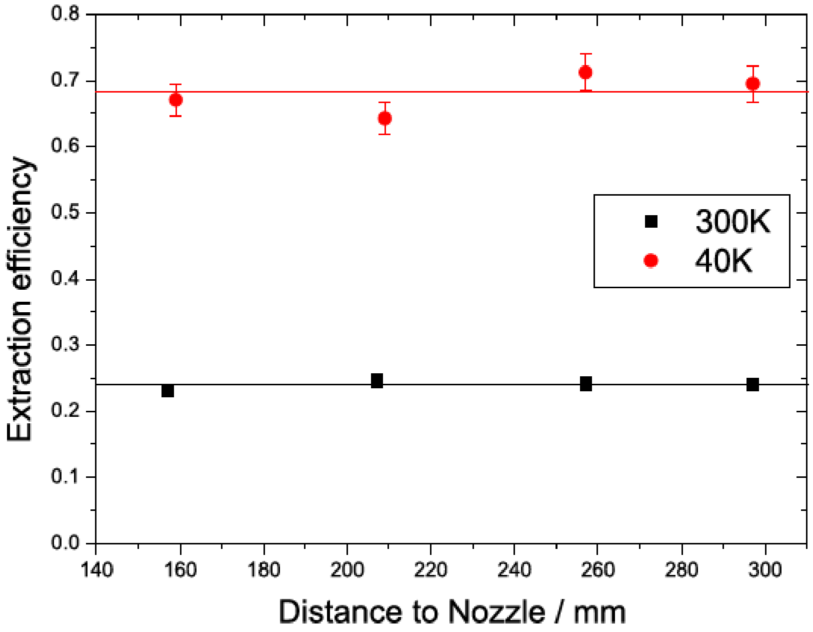
C. Droese et al. NIM B 338, 126 (2014)

Cryogenic Gas Stopping Cell

Cryo Cell



Gas Cell



Advantages compared to 1st generation gas cell:

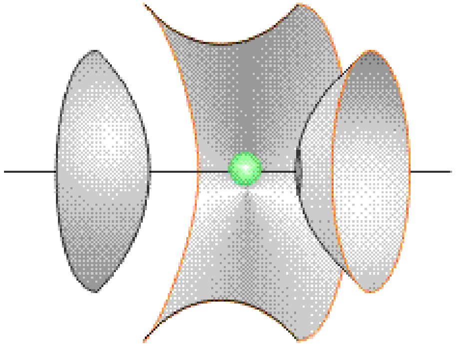
- Larger stopping volume and Coaxial injection of reaction products
- Higher cleanliness due to cryogenic operation
- Larger gas density at a lower absolute pressure

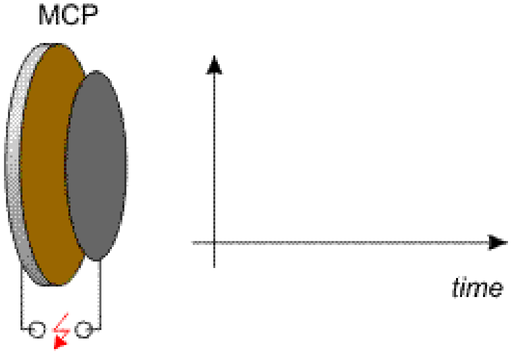
C. Droese et al. NIM B 338, 126 (2014)

Phase-Imaging Ion-Cyclotron-Resonance Technique

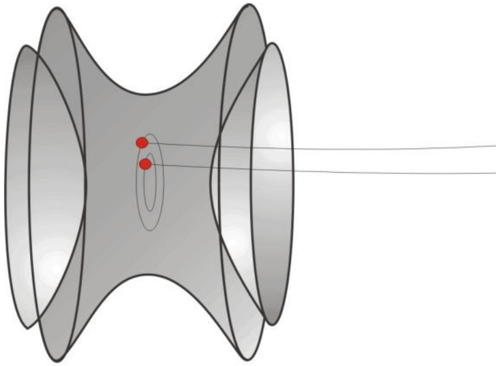
Recent Breakthrough

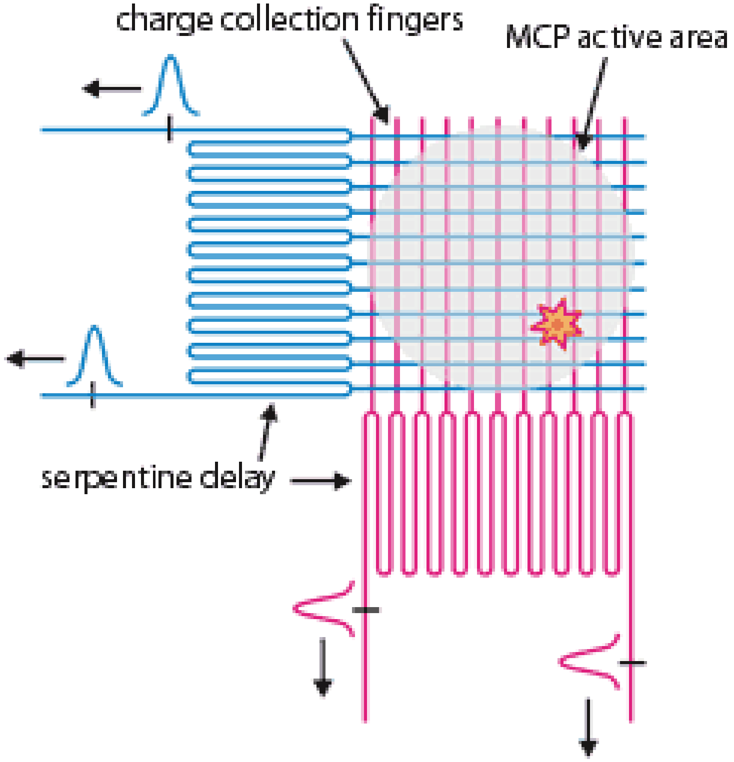
Destructive time-of-flight detection



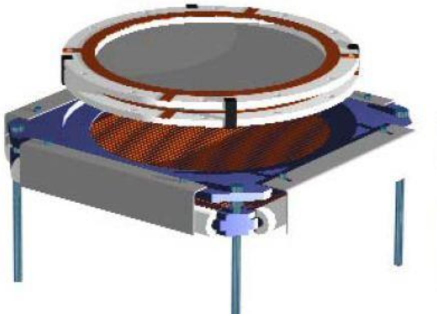


Spatially resolved detection



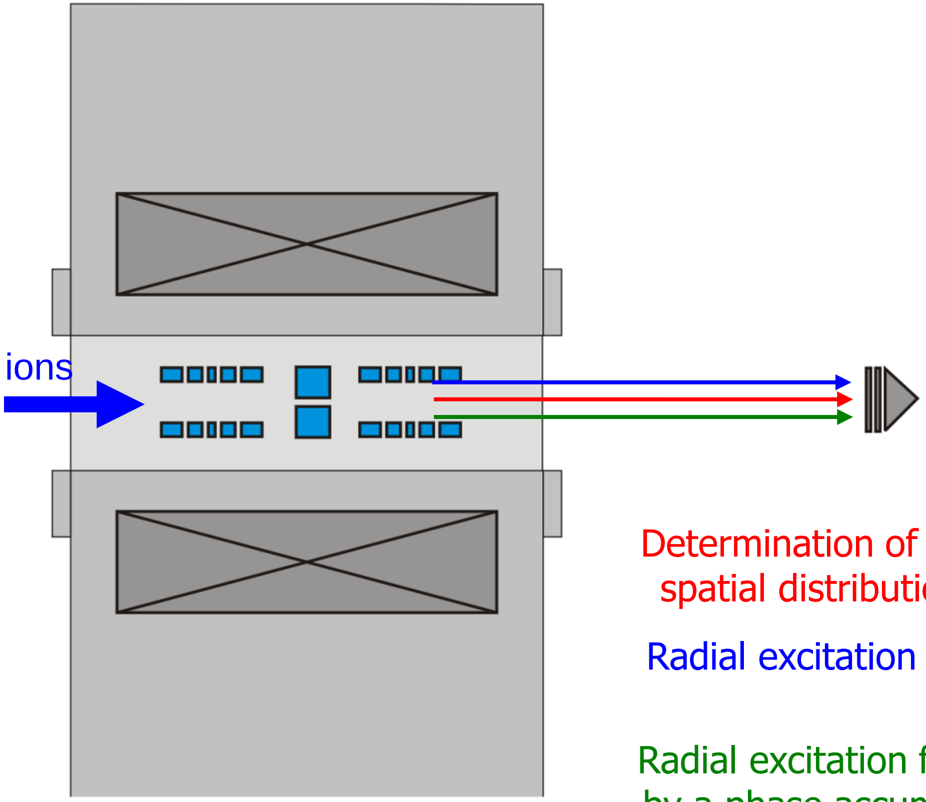


Delay-line detector



S. Eliseev et al., Appl. Phys. B114, 107 (2014)

Phase-Imaging Ion-Cyclotron-Resonance Method

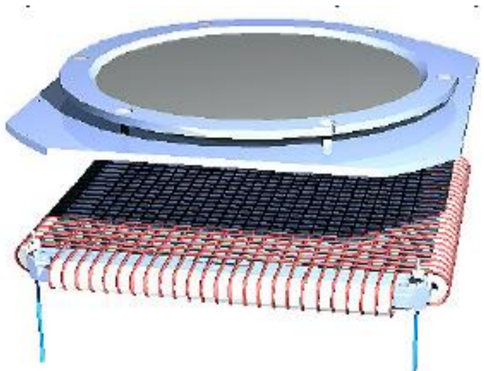


Determination of the spatial distribution

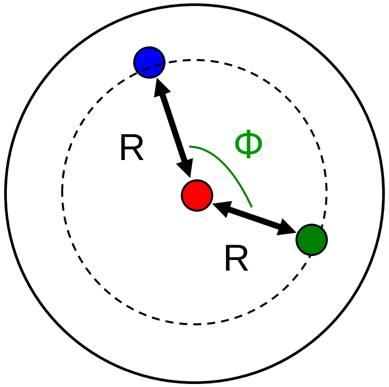
Radial excitation

Radial excitation followed by a phase accumulation time

Delay-Line Detector by Roentdek



Independent Measurements of Eigenfrequencies ν_+ and ν_-

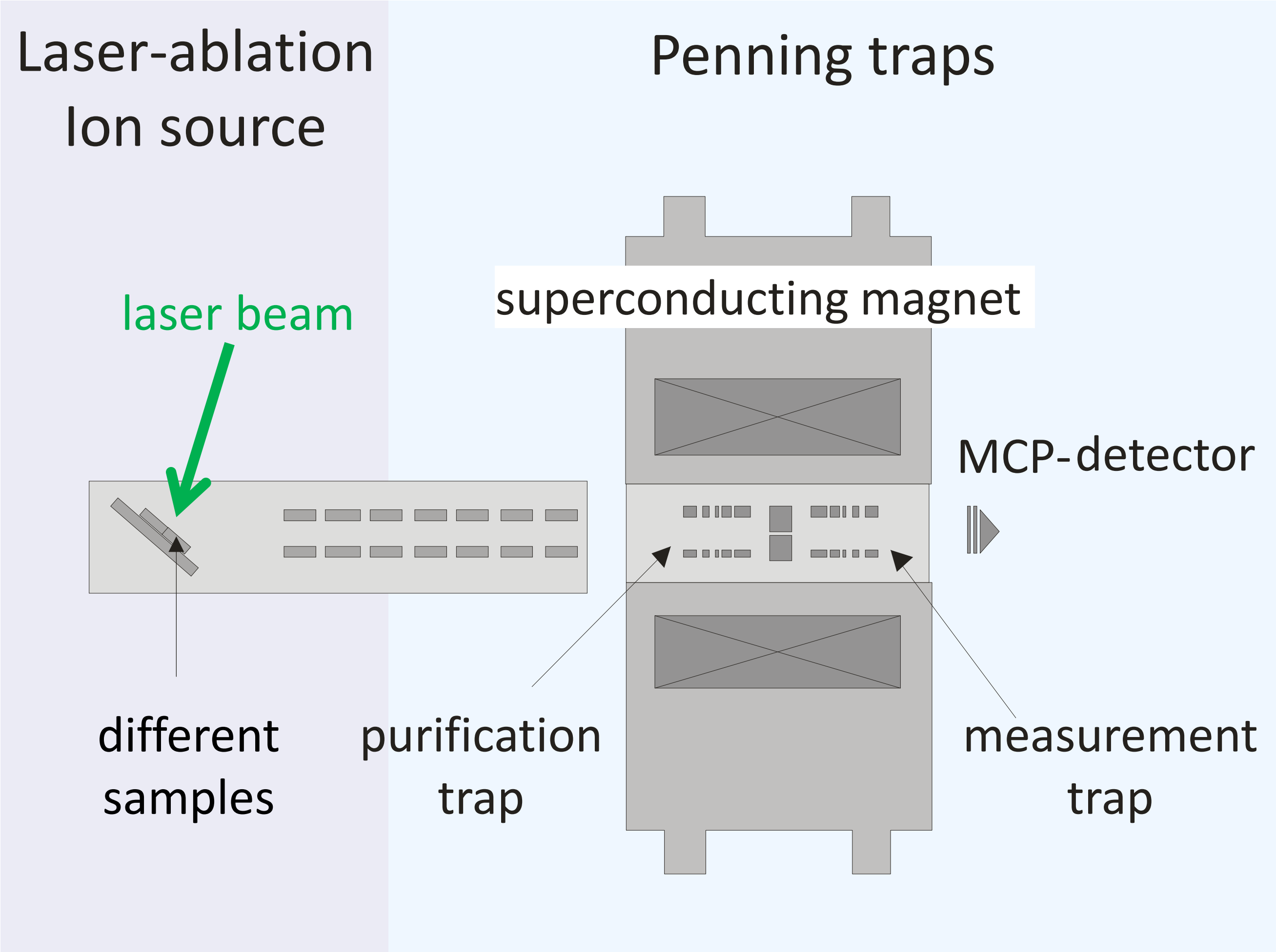


$$\phi + 2\pi n = 2\pi \nu t$$

$$\Delta \nu = \frac{\Delta \phi}{2\pi t} = \frac{\Delta R}{\pi t R}$$

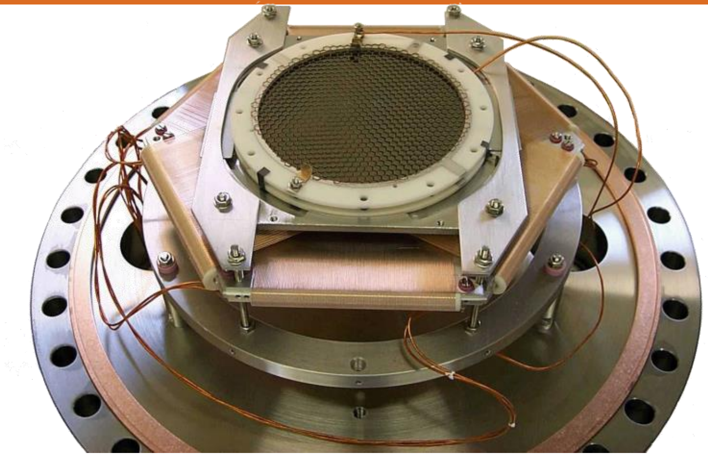
S. Eliseev et al., Phys. Rev. Lett. 110, 082501 (2013)

SHIPTRAP Off-line Setup



Position-sensitive Delayline Detector

Active diameter	42 mm
Channel diameter	25 µm
Open area ratio	>50 %
Position resolution	**70 µm**
Max. B-field	**a few mT**
Time resolution	~ 10 ns



(RoentDek GmbH DLD40)

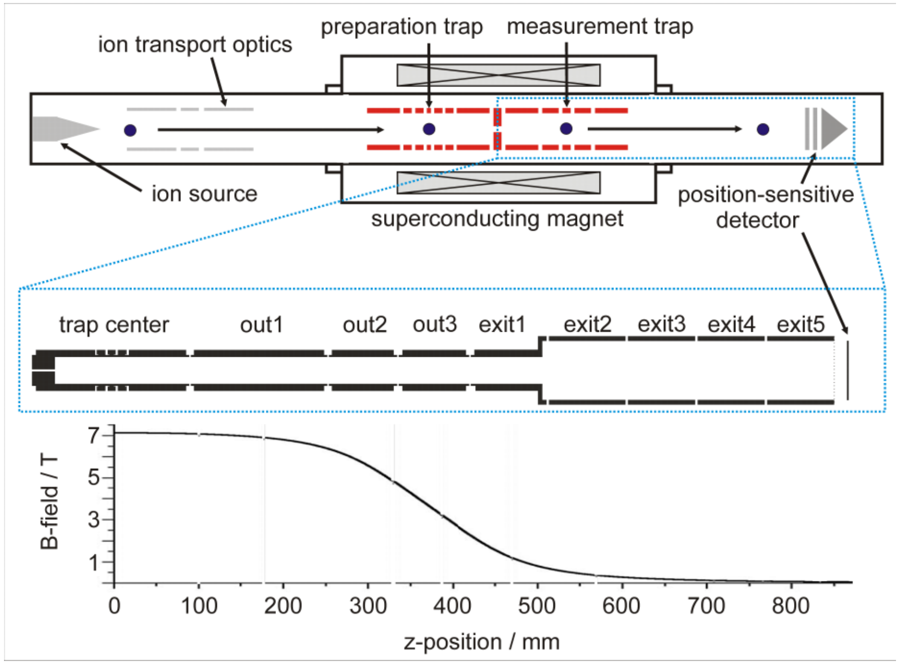
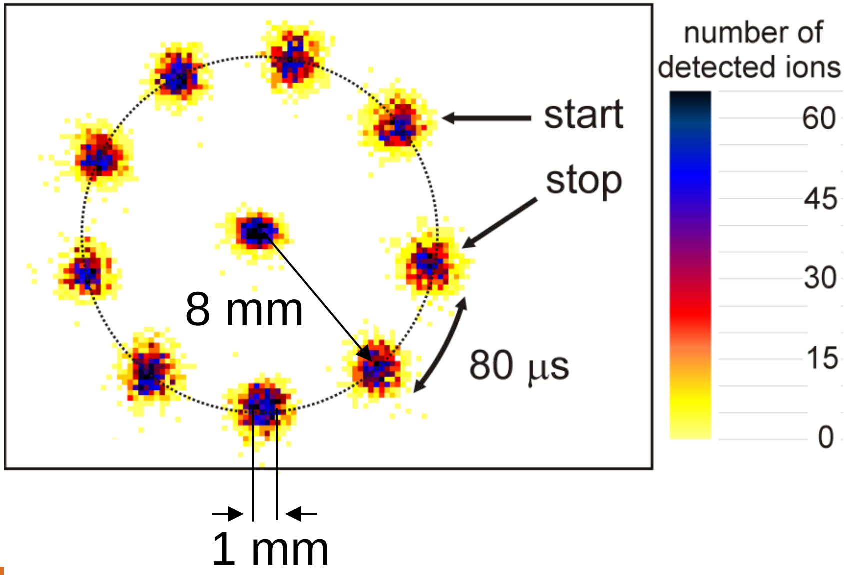
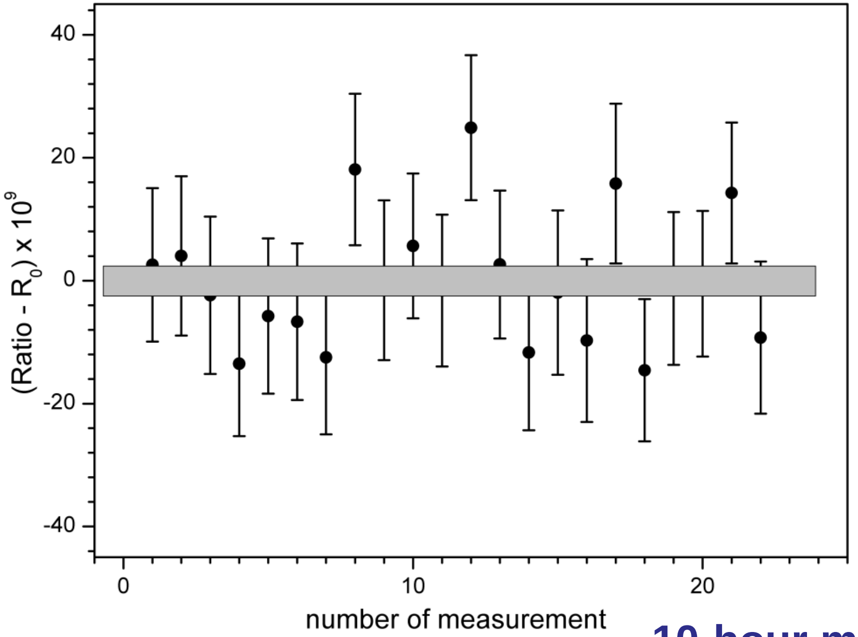


image of magnetron motion ($G \approx 20$)

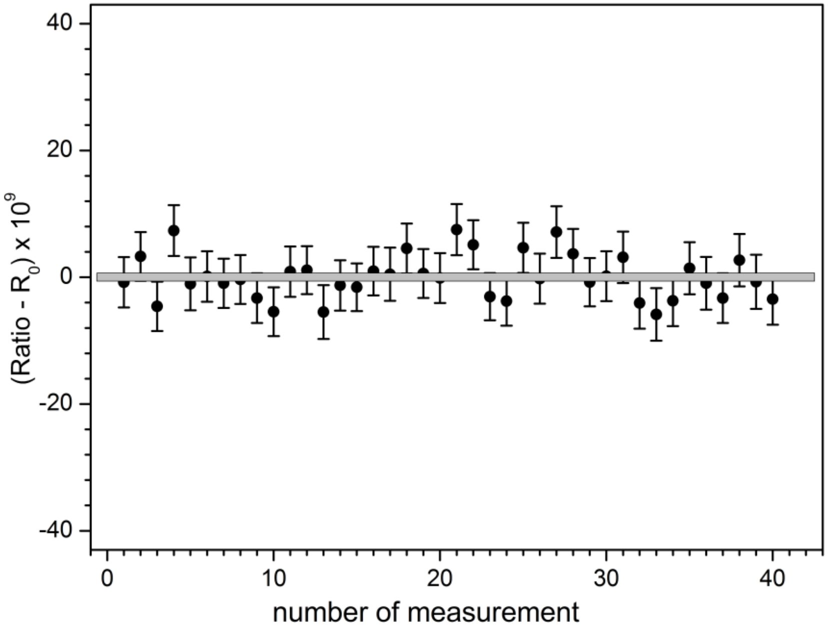


Increased Precision with Phase Method

ToF-ICR (Ramsey)



PI-ICR



10-hour measurements

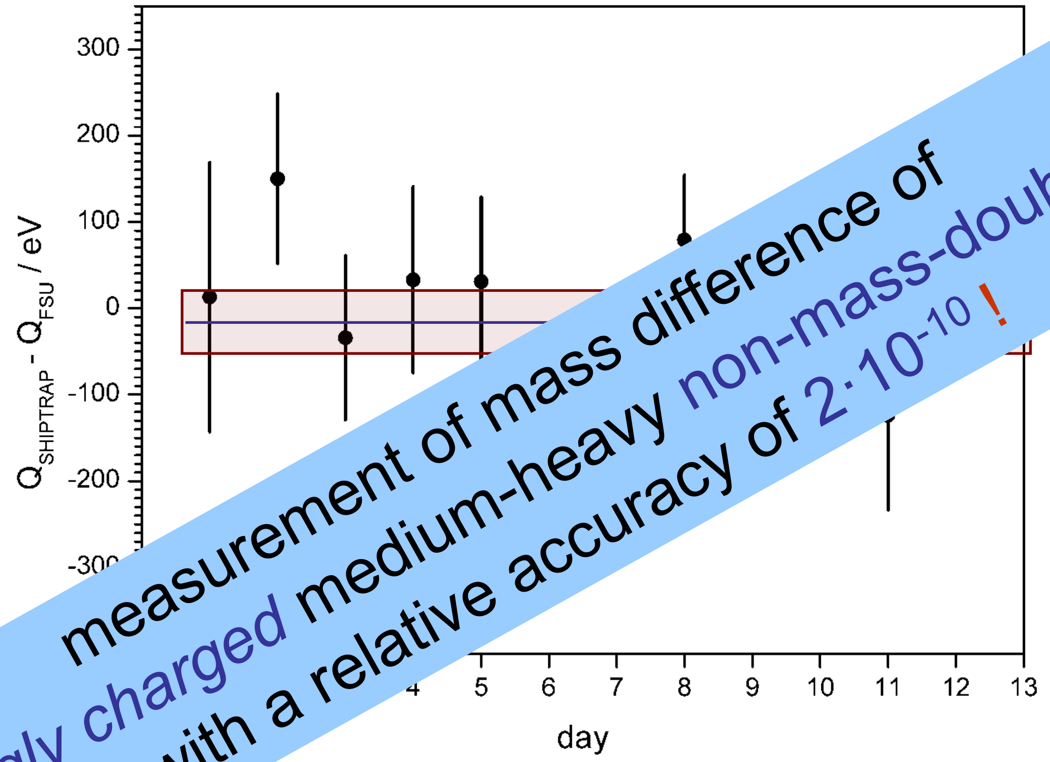
$\delta[M(^{124}Xe) - M(^{124}Te)] \sim 300$ eV

$\delta[M(^{132}Xe) - M(^{131}Xe)] \sim 70$ eV !!!

Gain in Precision ≈ 4.5 !!!

Veryfying the Accuracy of PI-ICR

$$\Delta M = M(^{132}Xe) - M(^{131}Xe)$$



measurement of mass difference of singly charged medium-heavy non-mass-doublets with a relative accuracy of $2{\cdot}10^{-10}$!

$$\delta(\Delta M)_{SHIPTRAP} = (30_{stat})(12_{sys})\ \mathrm{eV}$$

$$\Delta M_{SHIPTRAP} - \Delta M_{FSU} = (8 \pm 35)\ \mathrm{eV}$$

Selected SHIPTRAP Results with the PI-ICR Technique

Neutrino Mass Determination

- absolute mass and mass hierarchy of neutrinos still an open question
- present limits: m($\overline{\nu}_e$) < 2 eV / m(ν_e) < 225 eV

K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C, **38**, 090001 (2014).

Different experimental approaches:

- search for neutrinoless double beta transformation processes
- cosmology
- direct (anti)neutrino mass determination aiming at sub-eV uncertainty
  - spectrometry (KATRIN: ^{3}H β decay)
  - calorimetry (MARE: ^{187}Re β decay; ECHo ,HOLMES: ^{163}Ho EC)

required: independent measurement of *Q* - value (mass difference) with accuracy on the order of eV

β^- decay Spectrum Measurement

β^--decay of ^{3}H; Q-value ≈ 18.6 keV

β^--decay of ^{187}Re; Q-value ≈ 2.47 keV

KATRIN

MARE

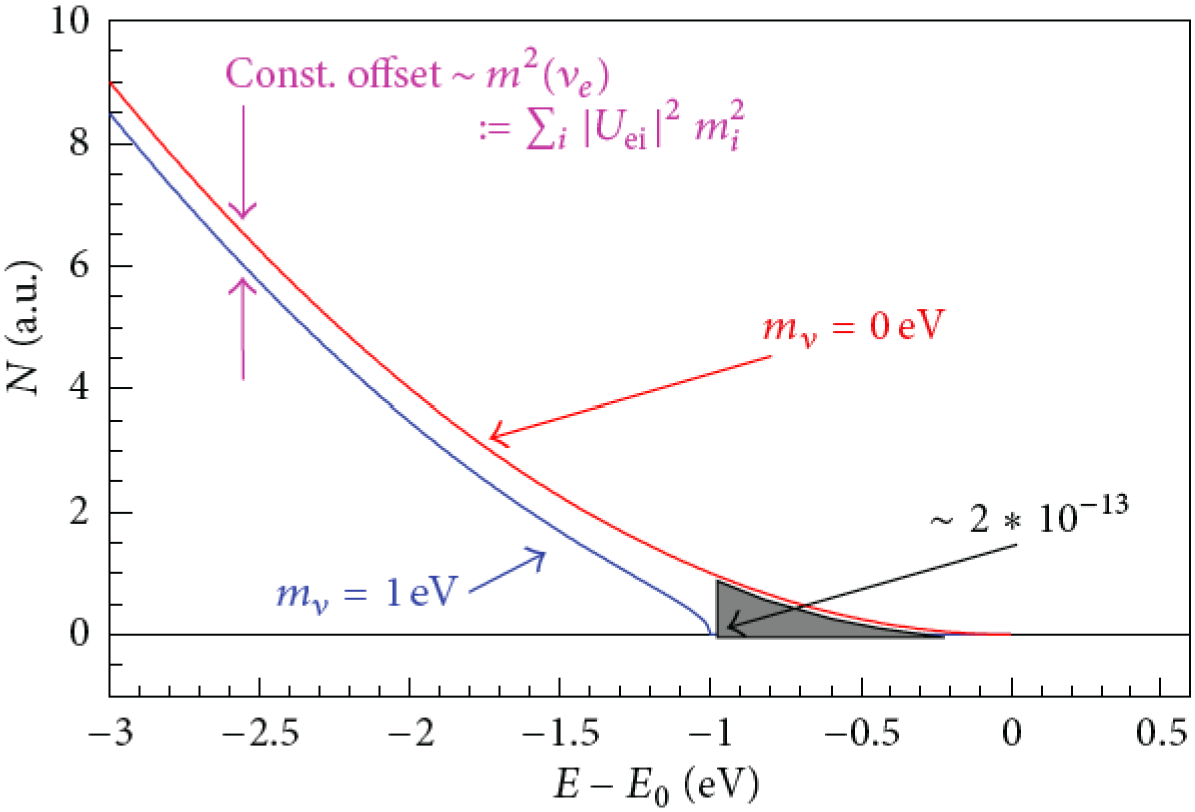
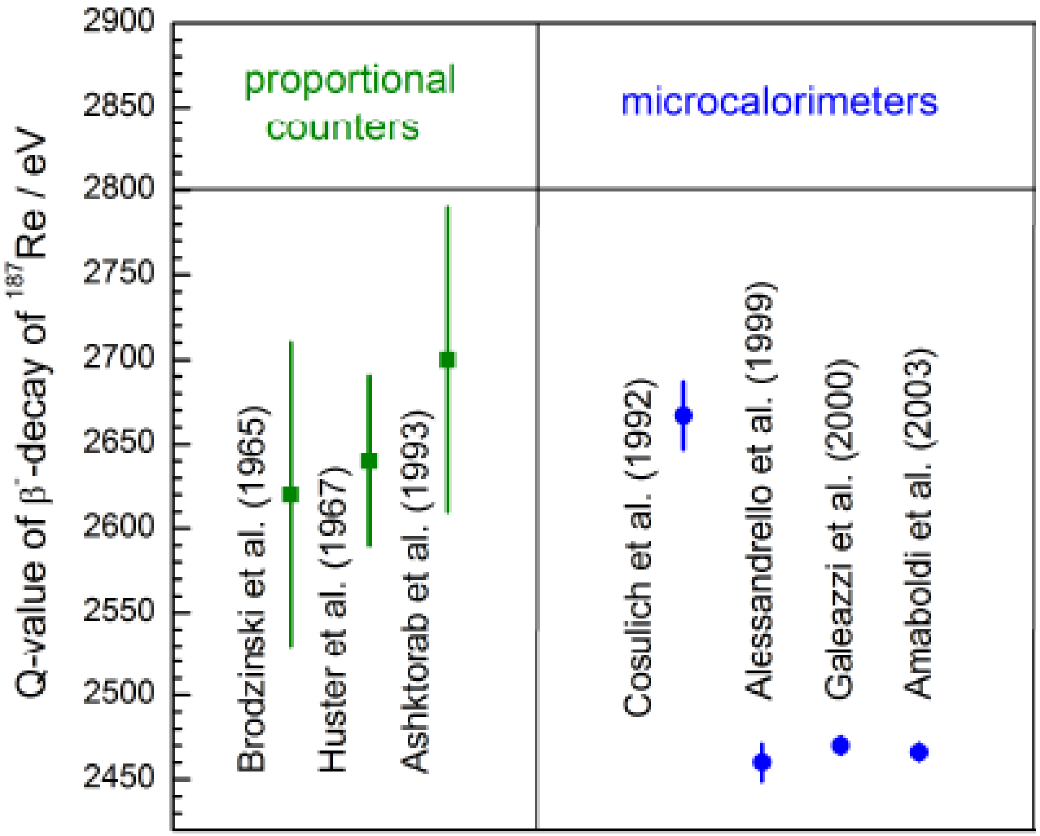


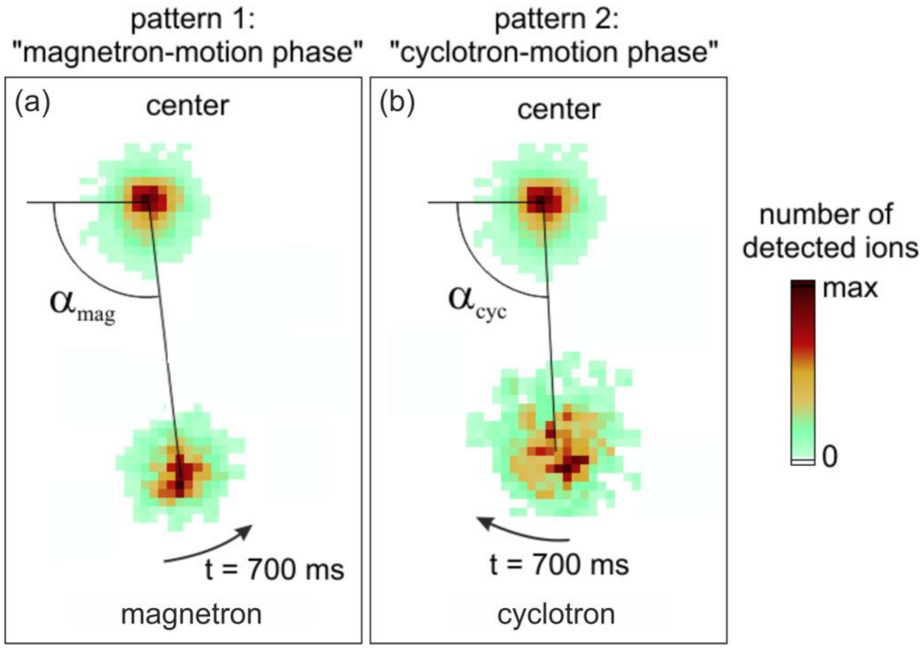
Fig. from G. Drexlin, V. Hannen, S. Mertens, and C. Weinheimer
Advances in High Energy Physics Volume 2013 (2013)

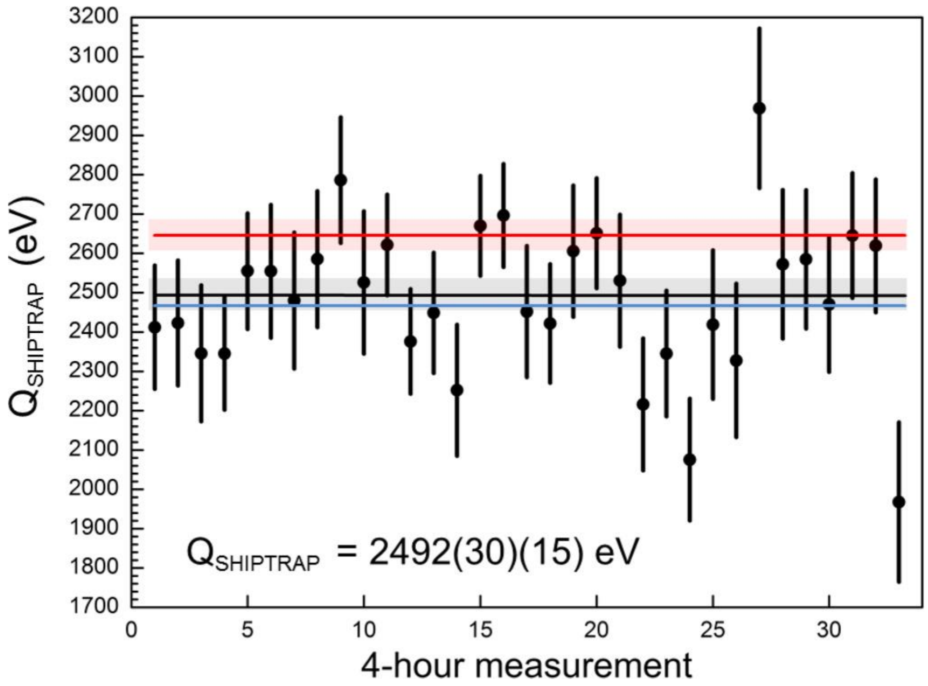
^{187}Re β Decay *Q* - Value



β^{-}-decay of ^{187}Re; Q-value ≈ 2.47 keV

SHIPTRAP results ^{187}Re/^{187}Os mass difference



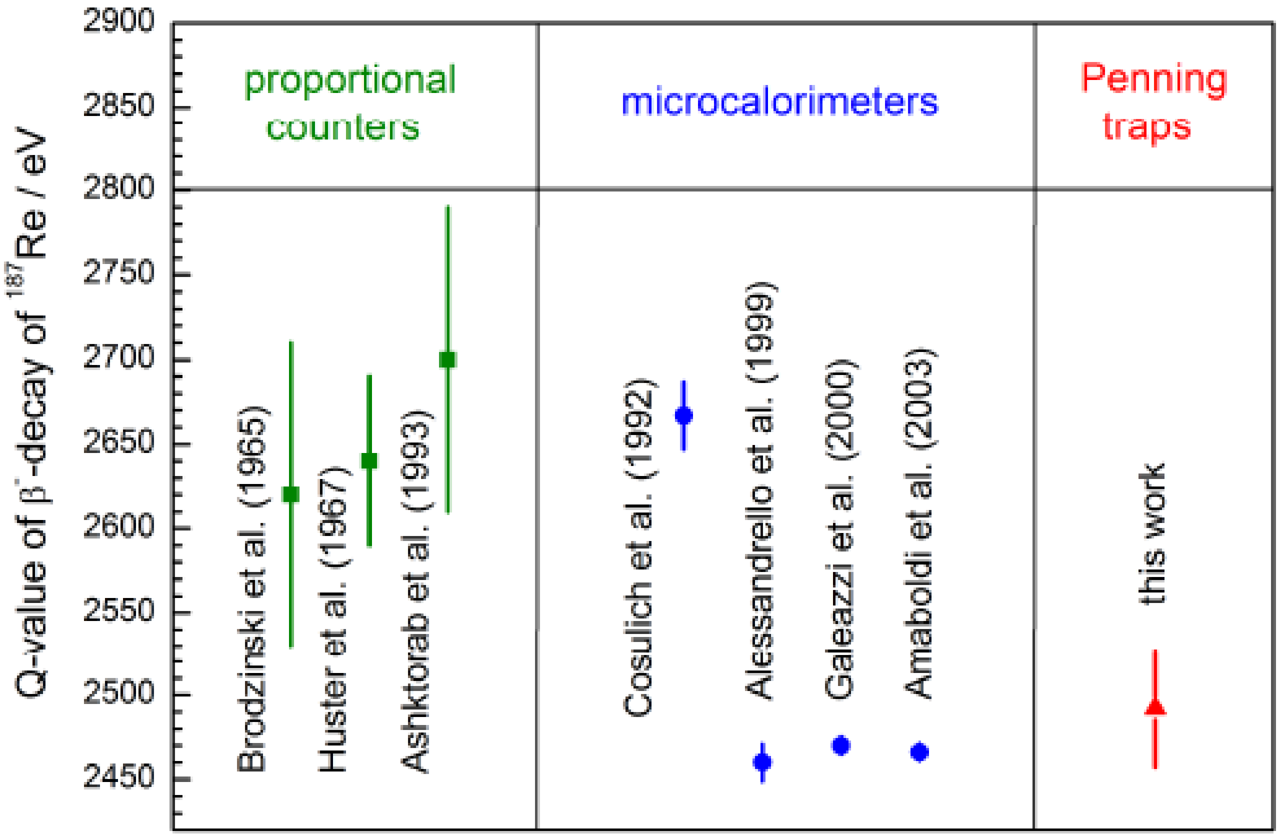


SHIPTRAP: ^{187}Re β^{-}decay

Q **- value=2492(30)(15) eV**

D. Nesterenko et al., Phys. Rev. C 90, 042501(R) (2014)

^{187}Re β Decay *Q* - Value



SHIPTRAP result confirms latest micro-calorimeter results

D. Nesterenko et al., Phys. Rev. C 90, 042501(R) (2014)

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Helmholtz Institute Mainz

GSI

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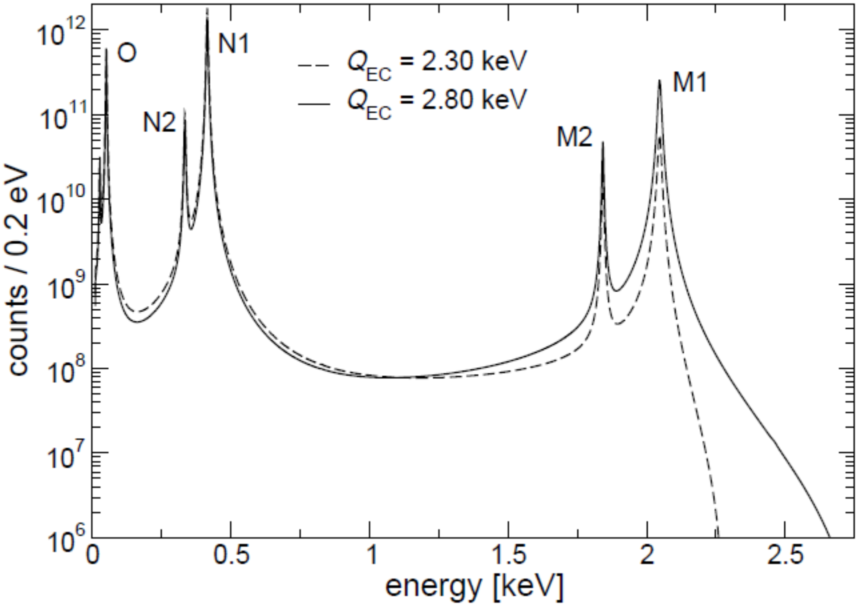
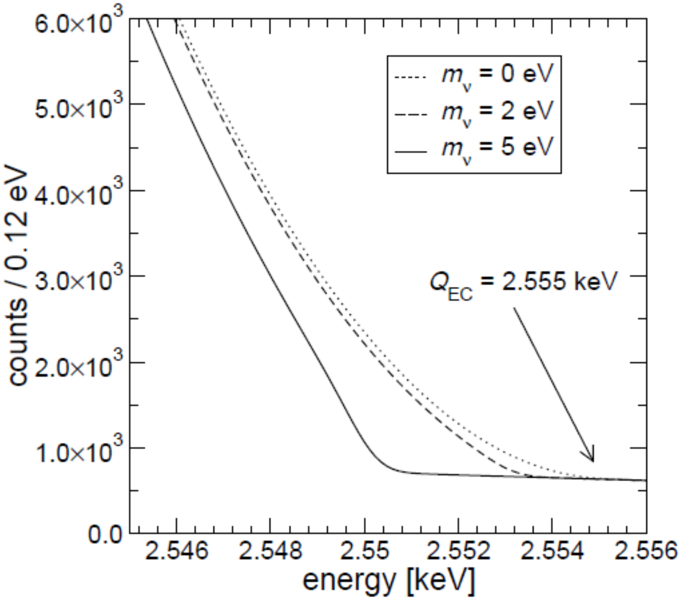
Electron Capture in ^{163}Ho

EC in ^{163}Ho; Q-value ≈ 2.55 keV (AME 2012)

$$^{163}\mathrm{Ho} \xrightarrow[\mathrm{EC}]{} {}^{163}\mathrm{Dy} + E_c + \nu_e\,(E_\nu) \xrightarrow[\text{ANALYSIS of DE-EXCITATION SPECTRUM}]{} m_\nu$$

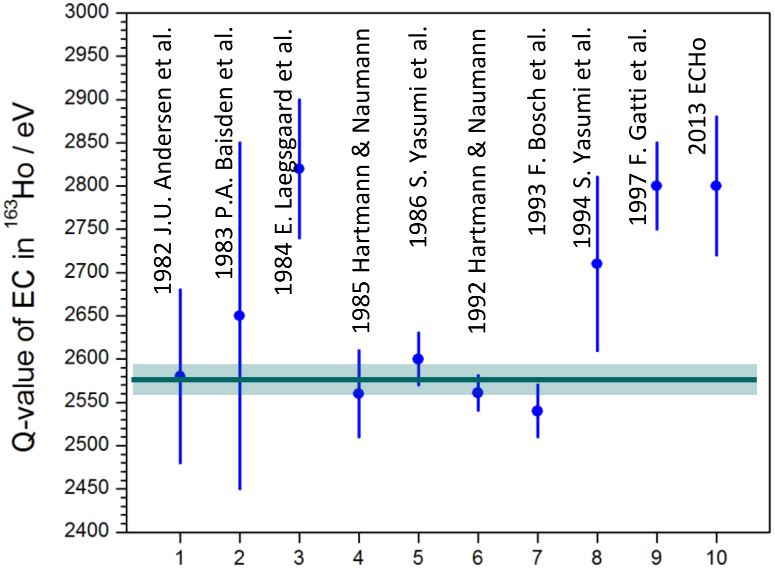




Holmes: B. Alpert et al., Eur. Phys. J. C 75 (2015) 112
ECHo: L. Gastaldo et al., J. Low Temp. Phys. 176 (2014) 876

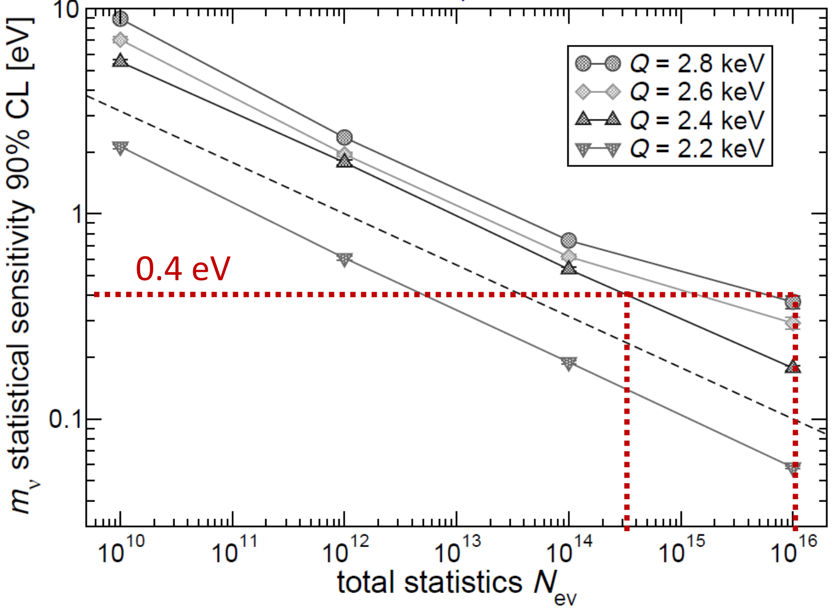
^{163}Ho EC Decay *Q* - Value

Q-value of EC in ^{163}Ho



Statistical sensitivity to m_n

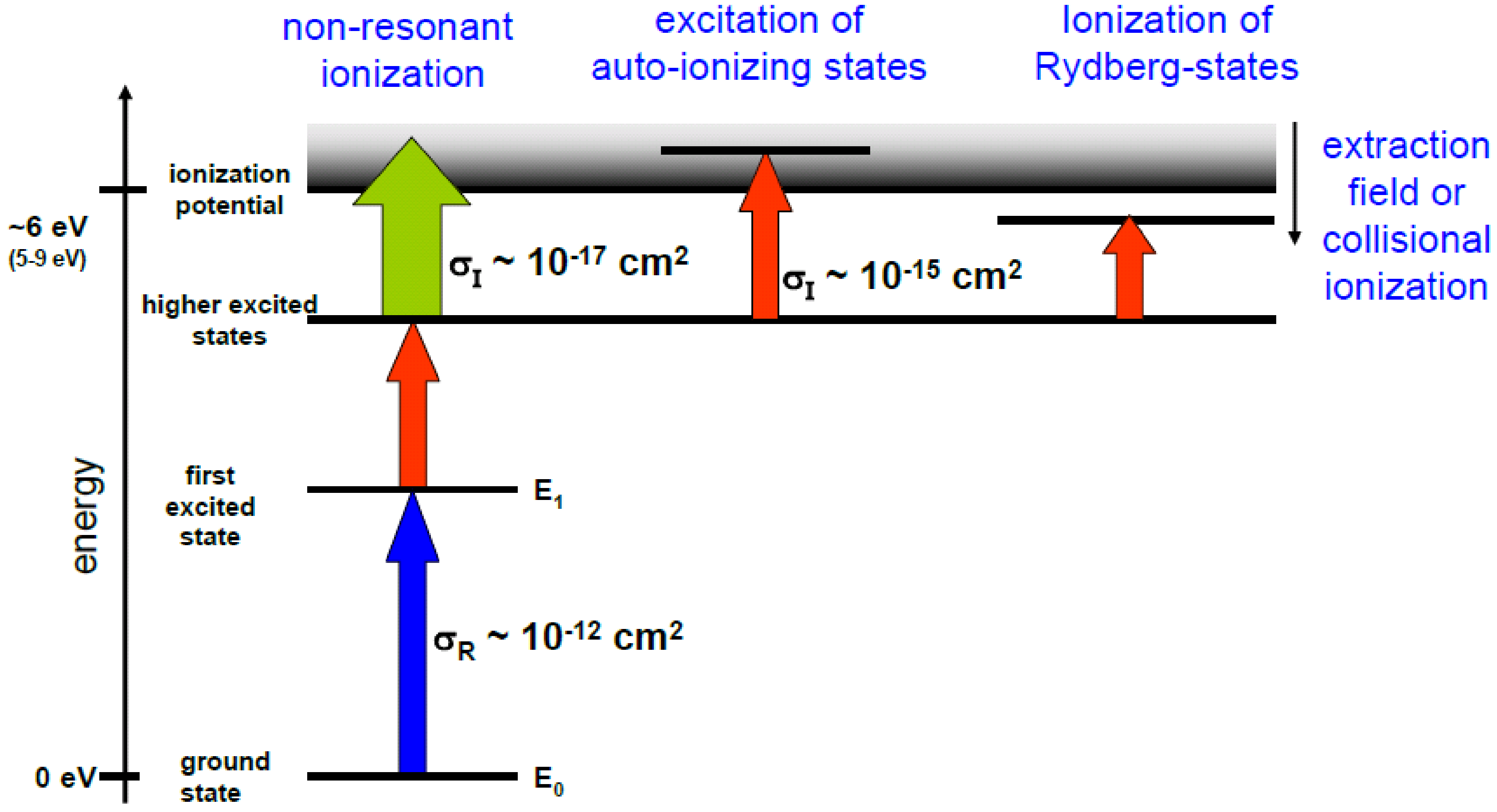
taken from A. Nucciotti, arXiv: 1405.5060v2



direct measurement of mass difference
^{163}Ho-^{163}Dy can clarify situation

Laser Spectroscopy of the Heaviest Elements

Principles of Resonant Laser Ionization



non-resonant ionization

excitation of auto-ionizing states

Ionization of Rydberg-states

extraction field or collisional ionization

ionization potential

~6 eV (5-9 eV)

higher excited states

$\sigma_I \sim 10^{-17}$ cm^2

$\sigma_I \sim 10^{-15}$ cm^2

first excited state

E_1

$\sigma_R \sim 10^{-12}$ cm^2

energy

0 eV

ground state

E_0

Efficiency × Selectivity

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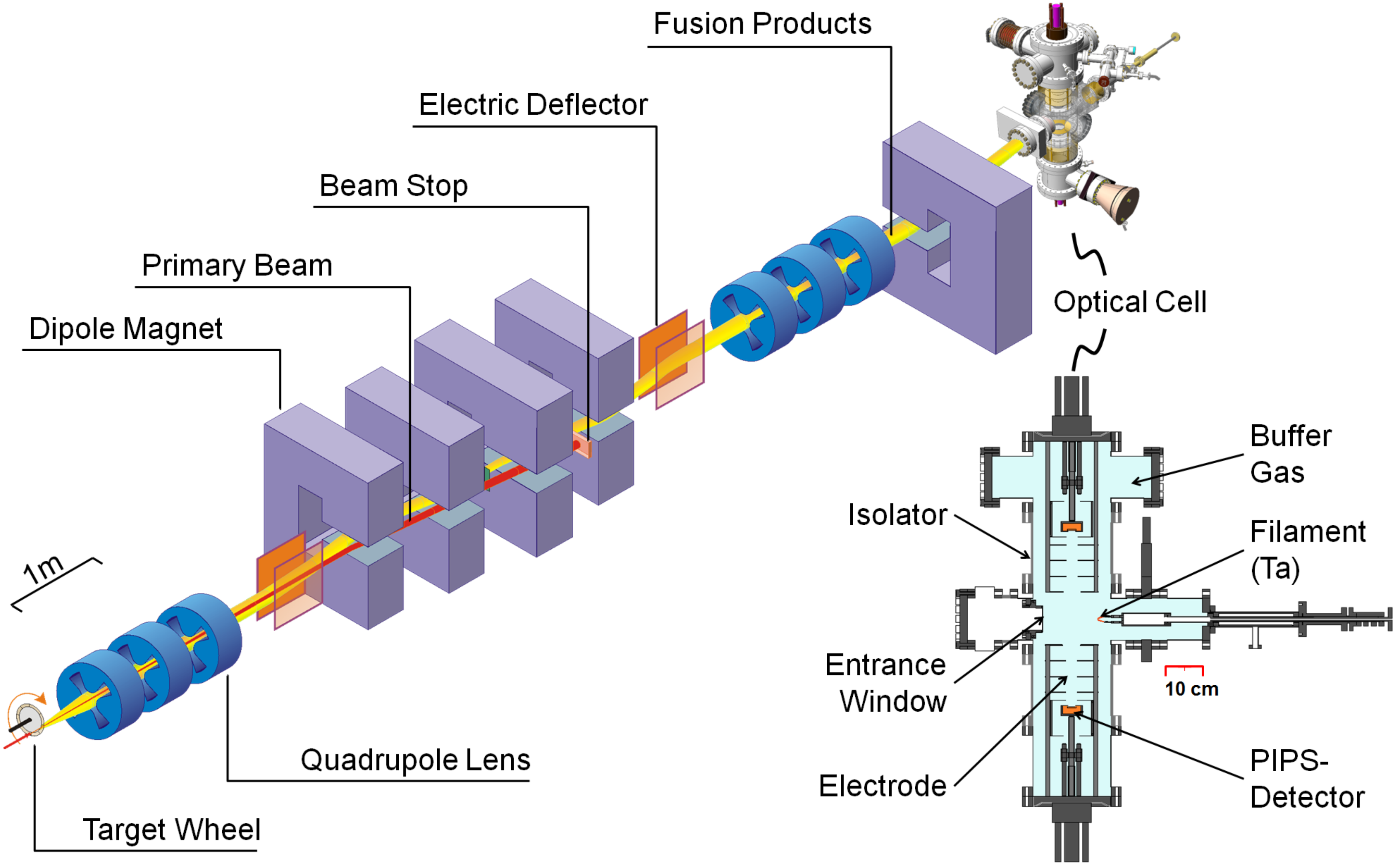
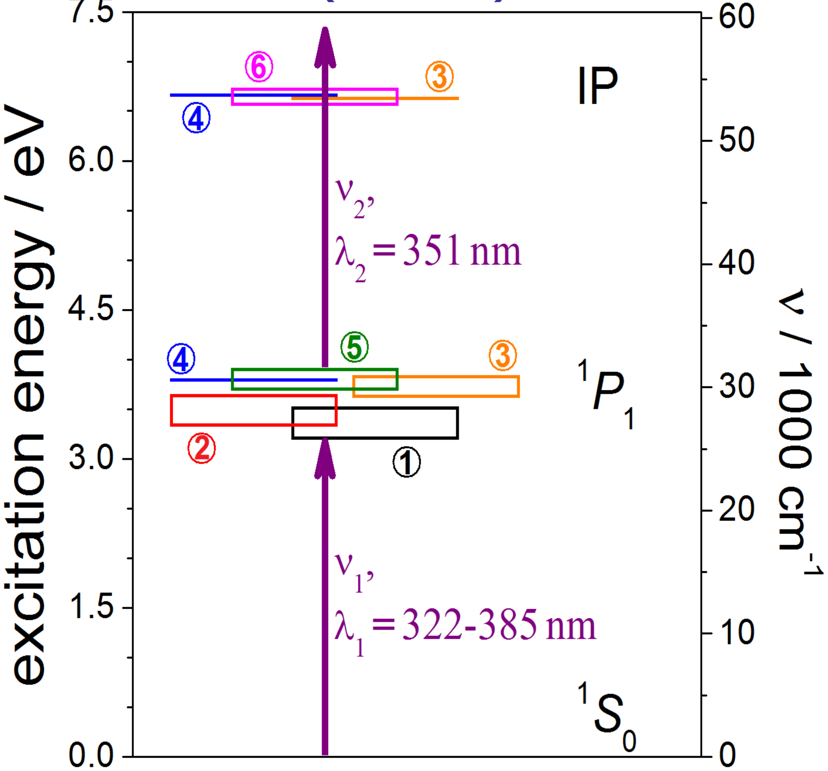
Adapted from K. Wendt / C. Geppert

Radiation Detected Resonance Ionization Spectroscopy



Search for Atomic Transitions in Nobelium

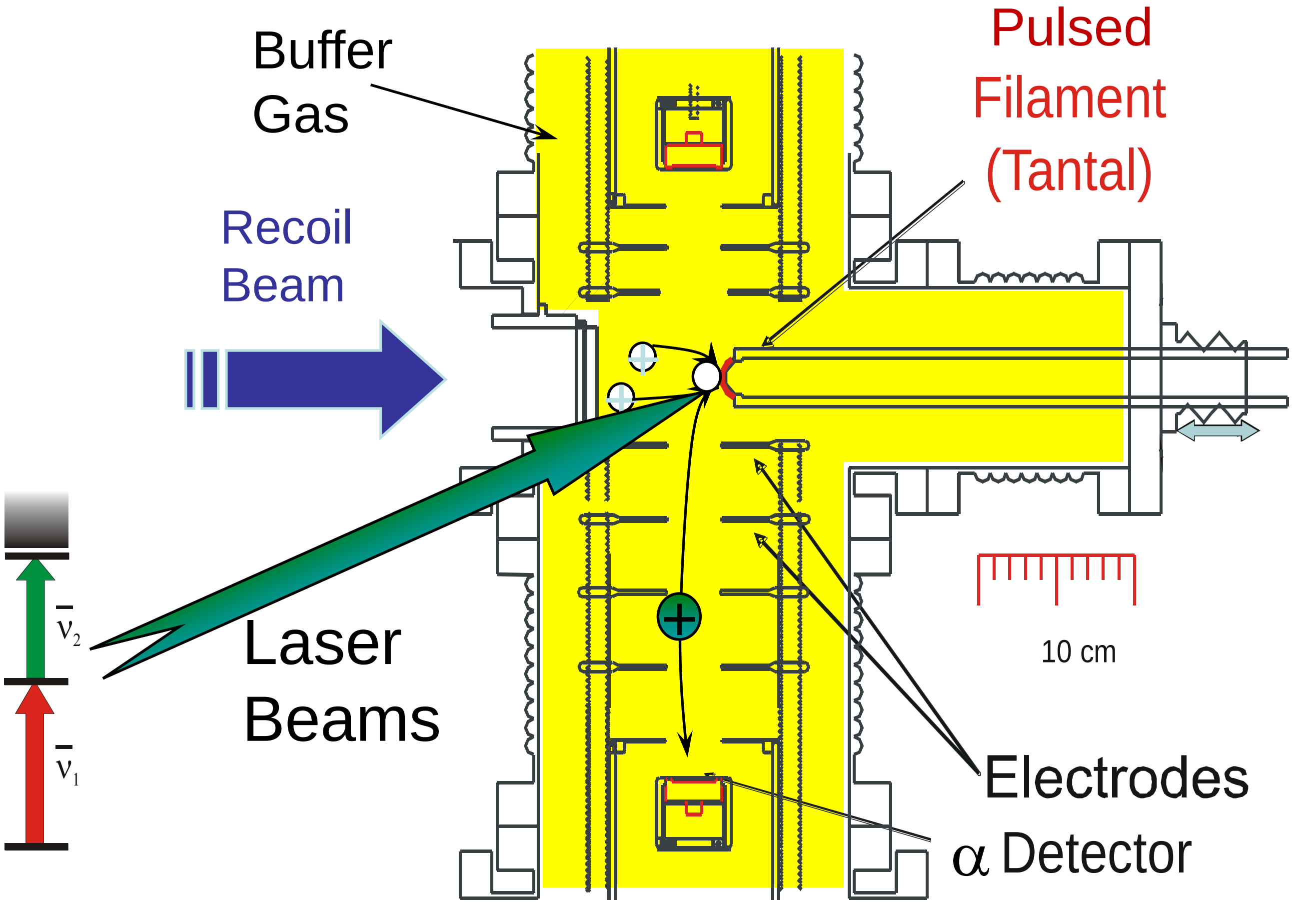
Theoretical predictions for the $^1S_0$-$^1P_1$- transition in the element nobelium (Z=102)

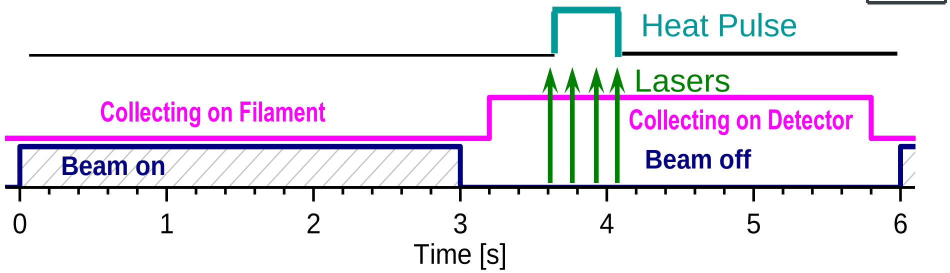


- RIS with two step excitation and non-resonant second step
- search for $^1P_1$ level in range predicted by different theories
- determine IP via Rydberg series
- Measure isotope shift of $^1P_1$-$^1S_0$ transition

[1],[2]: S. Fritzsche, Eur. Phys. J. D 33 (2005) 15
[3]: A. Borschevsky et al., Phys. Rev. A 75 (2007) 042514
[4]: Y. Liu et al., Phys. Rev. A 76 (2007) 062503
[5]: P. Indelicato et al., Eur. Phys. J. D 45 (2007) 155
[6]: J. Sugar, J. Chem. Phys. 60 (1974) 4103

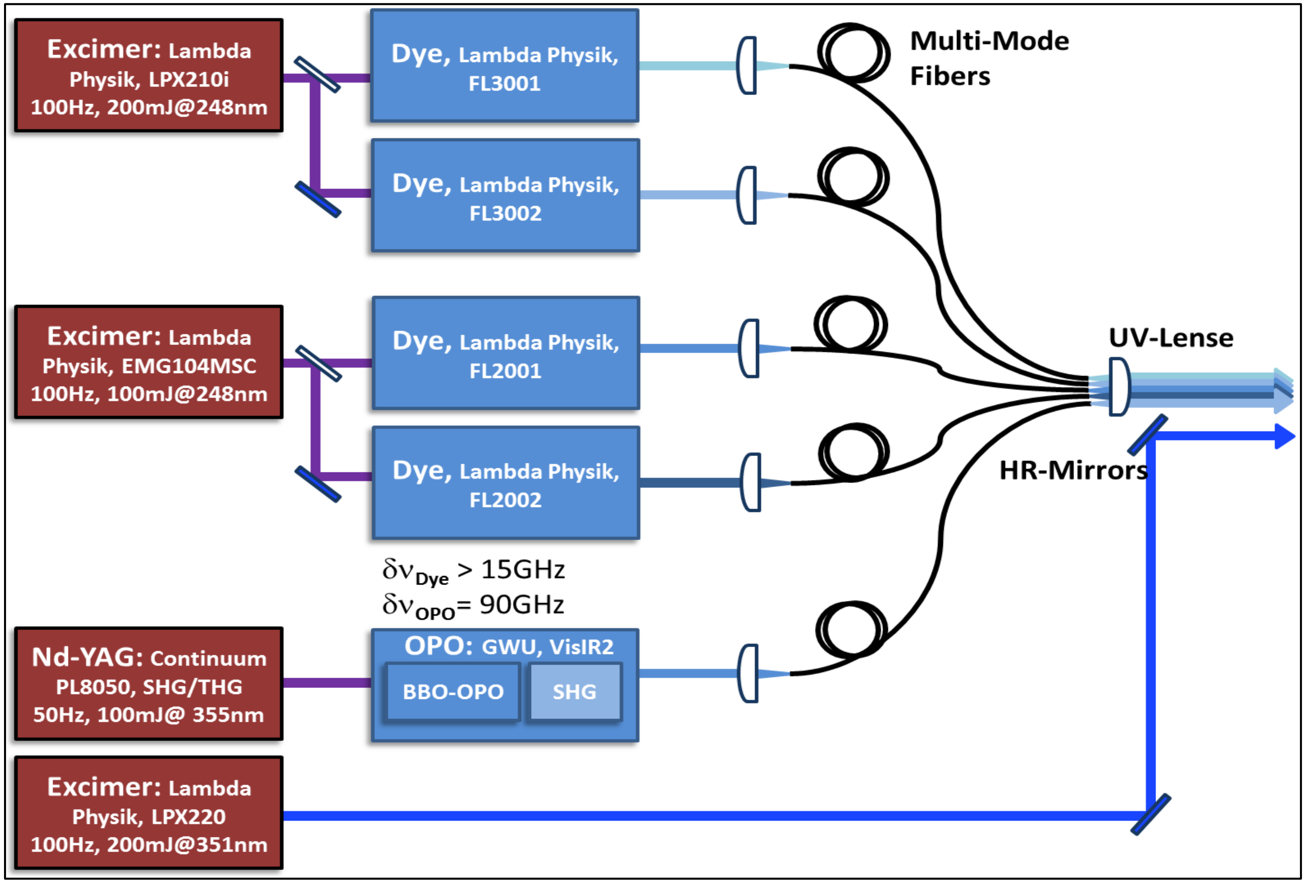
Resonant Ionization Laser Spectroscopy of Nobelium





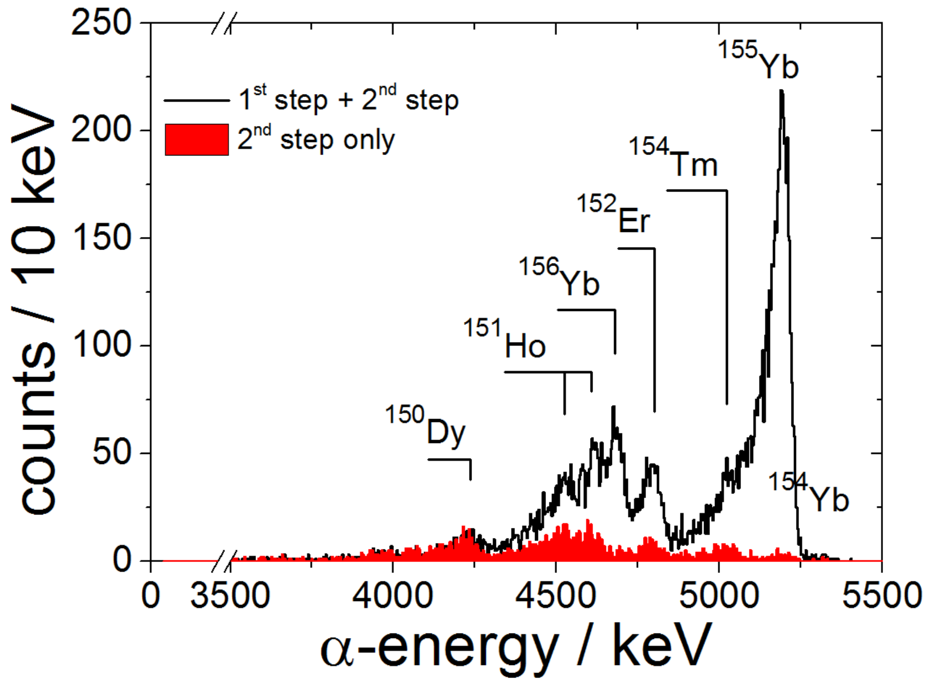
Laser System

Laser Systems

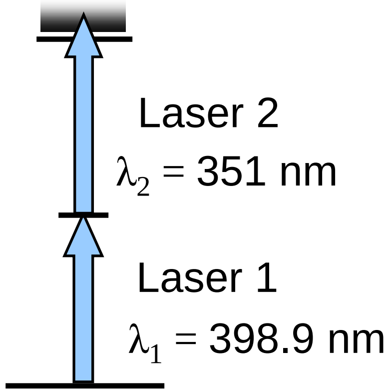


M.Laatiaoui et al., Hyp. Int. (2013)
DOI: 10.1007/s10751-013-0971-x

RADRIS-optimization: on-line experiments (^{155}Yb)



2-step excitation ^{155}Yb


Laser 2

λ_2 = 351 nm

Laser 1

λ_1 = 398.9 nm

overall efficiency 1% achieved

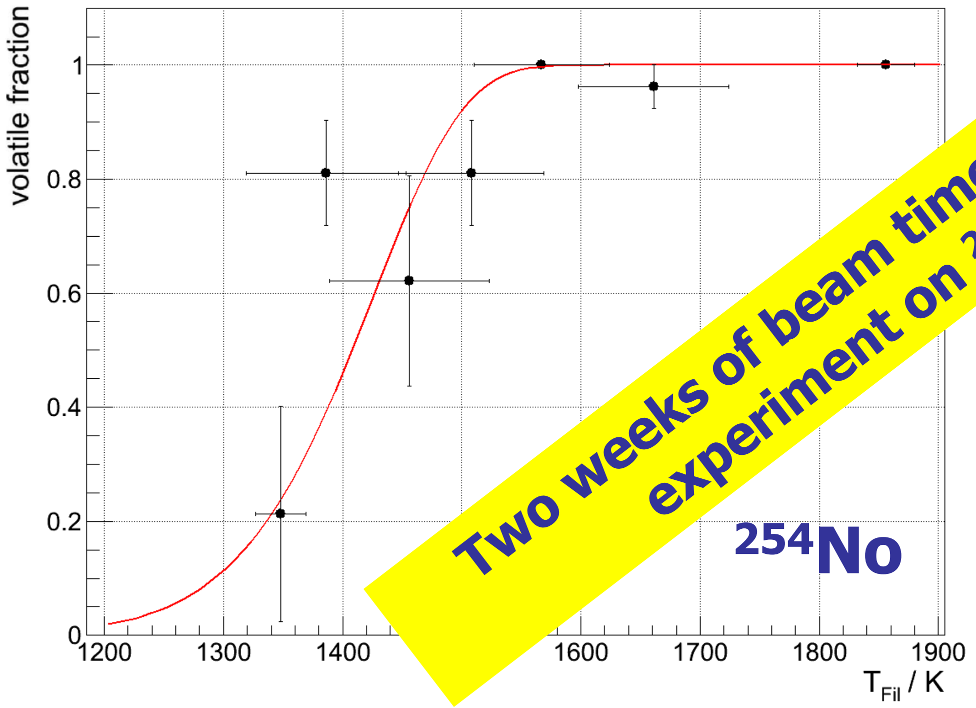
experiments on the chemical homolog Yb allow:

- optimization of full setup
- localizing the atom cloud
- monitoring of overall efficiency during level-search in nobelium

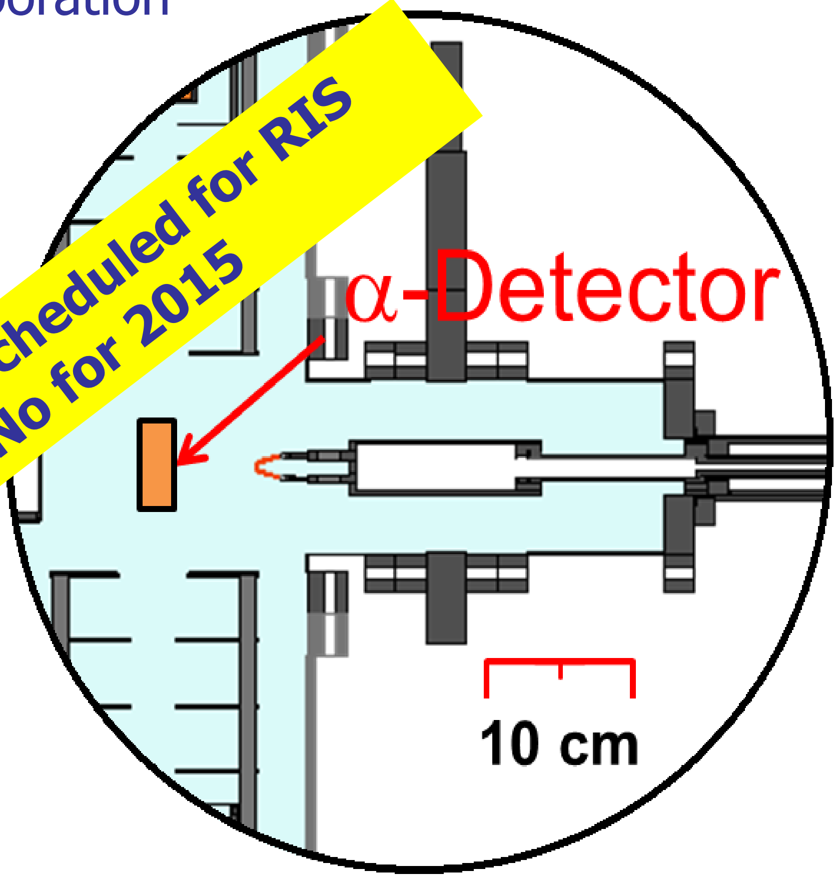
Evaporation of ^{254}No from Ta Filament

- measure residual activity on filament
- determine filament temperature for evaporation
- Desorption enthalpy of No from Ta:

246±24 kJ/mol



Two weeks of beam time scheduled for RIS experiment on ^{254}No for 2015



M.Laatiaoui et al., Eur. Phys. J. D 68 (2014) 71

Future Perspectives


It's not
FAIR!

Superheavy Elements Subcollaboration of NUSTAR @ FAIR

Proposal to integrate new "Superheavy Element" subcollaboration in NUSTAR @ FAIR submitted to Board of Representatives (Summer '14)

Focus: synthesis, nuclear structure, atomic physics, nuclear chemistry experiments in region Z ≥ 100

Existing facilties: SHIP, TASCA, SHIPTRAP, Chemistry beamline
Developments for high-intensity cw-Linac ongoing (HIM, GSI, U Frankfurt)

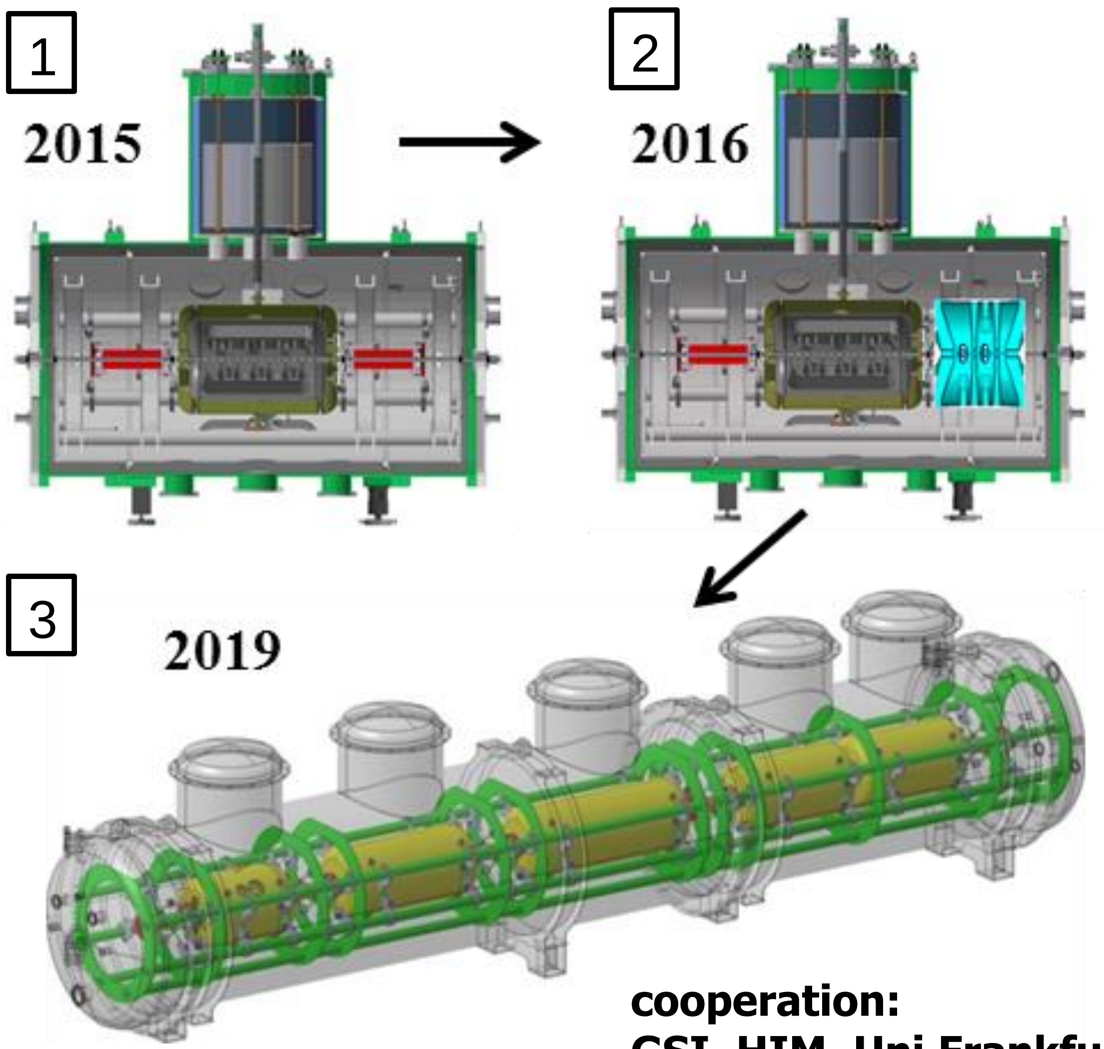
Complementary to existing NUSTAR activities at Super-FRS

Organizational Structure:
Spokesperson: R.-D. Herzberg (Univ. Liverpool)
Deputy: M. Block (GSI/HIM/JGU)
Technical Director: A. Yakushev (GSI)

Currently includes 9 German and 17 international institutes

Endorsed by NUSTAR Collaboration Committee: Sept. 25, 2014
submission to FAIR management: summer 2015

Staged Approach towards cw linac for SHE



1. **Full performance test of sc cw LINAC Demonstrator**
   - @GSI HLI
   - proof of principle

2. Full performance test of a shorter sc cavity

- energy variation (by Ampl & Phase)
- 8 gaps
- simpler design
- easier to fabricate

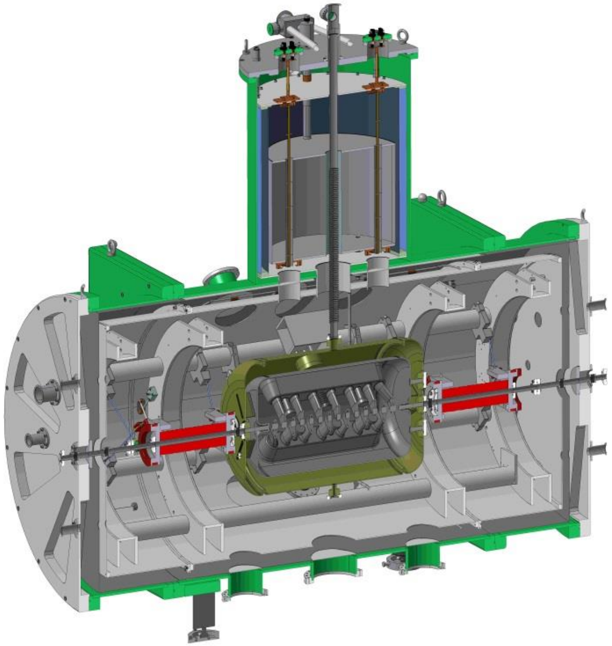
3. Advanced Demonstrator

- up to 4.61 MeV/u @ $A/Q = 6$
- 5× sc CH-Cavity, 5× sc Solenoid
- possible to place in HLI@GSI

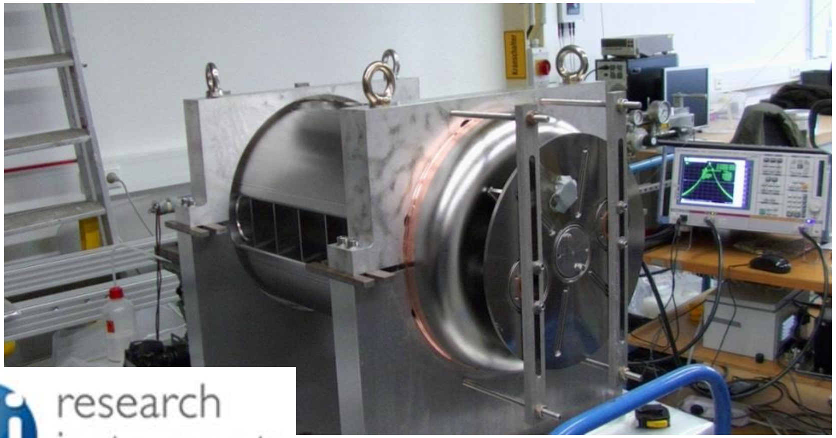
cooperation:
GSI, HIM, Uni Frankfurt

Courtesy of V. Gettmann / W. Barth

First components – October 2014



CRYOGENIC
CRYOGENIC LIMITED



research instruments

ASSOCIATION

GSI

JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Helmholtz Institute Mainz

Courtesy of V. Gettmann / W. Barth

Summary and Conclusions

- Direct high-precision mass measurements provide complementary tools to map nuclear structure effects in the heaviest elements
- Increased resolving power and higher precision of novel PI-ICR method opens the door for applications in fundamental physics
- Laser spectroscopy for Z > 100 allows studying the impact of relativistic effects on the atomic structure
- Laser spectroscopy will also provide information of nuclear properties such as spins, moments, and changes in charge radii (model independent)
- stepwise approach for new cw-linac underway -> GSI will maintain leading position in SHE research

Thank you for your attention !