Nucleus Nucleus 2015 – Catania

Nuclear Structure of the Heaviest Elements revealed by High-Precision Mass Measurements

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Institut für Kernchemie der Johannes Gutenberg Universität Mainz

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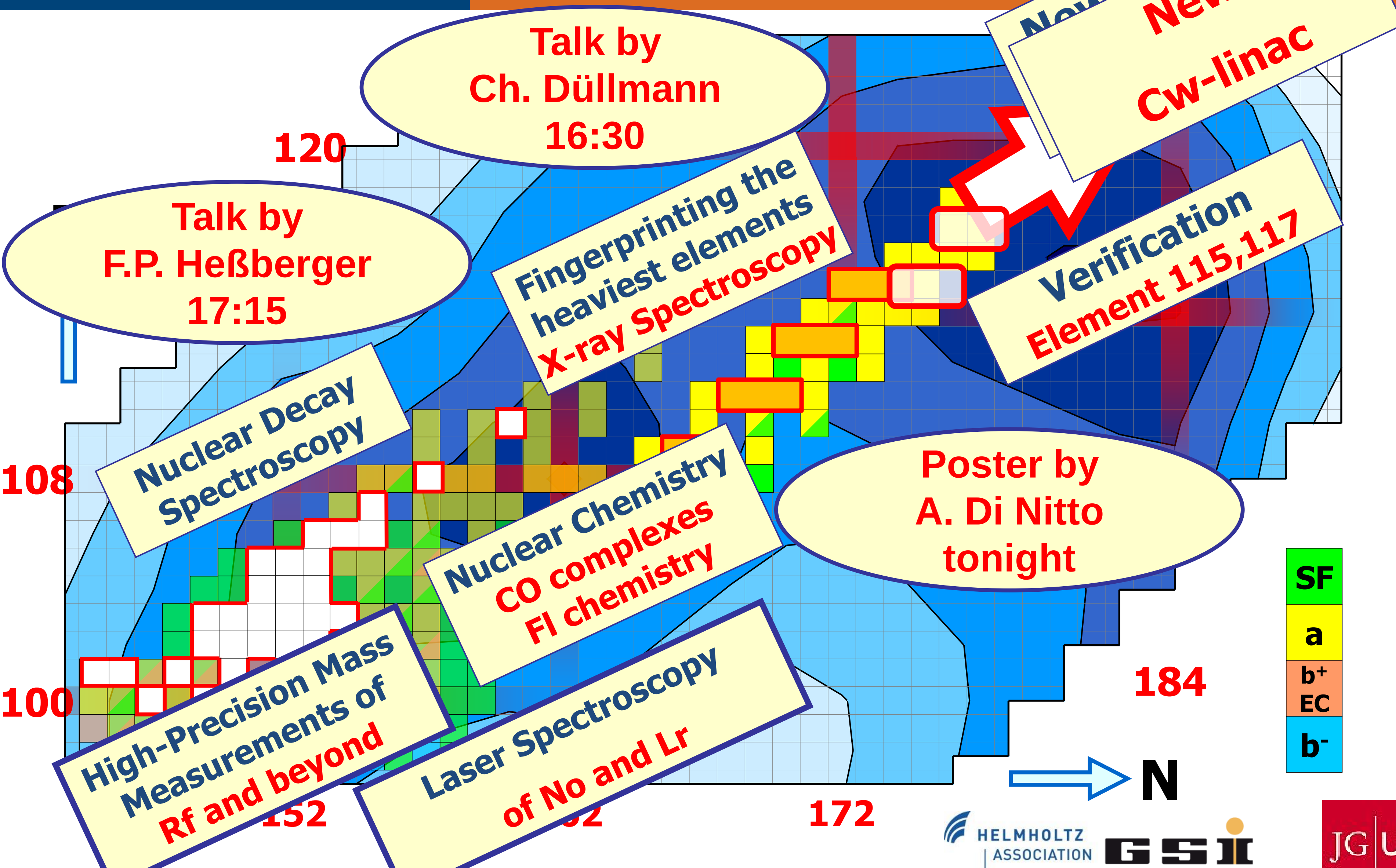
Future Directions in SHE Research at GSI



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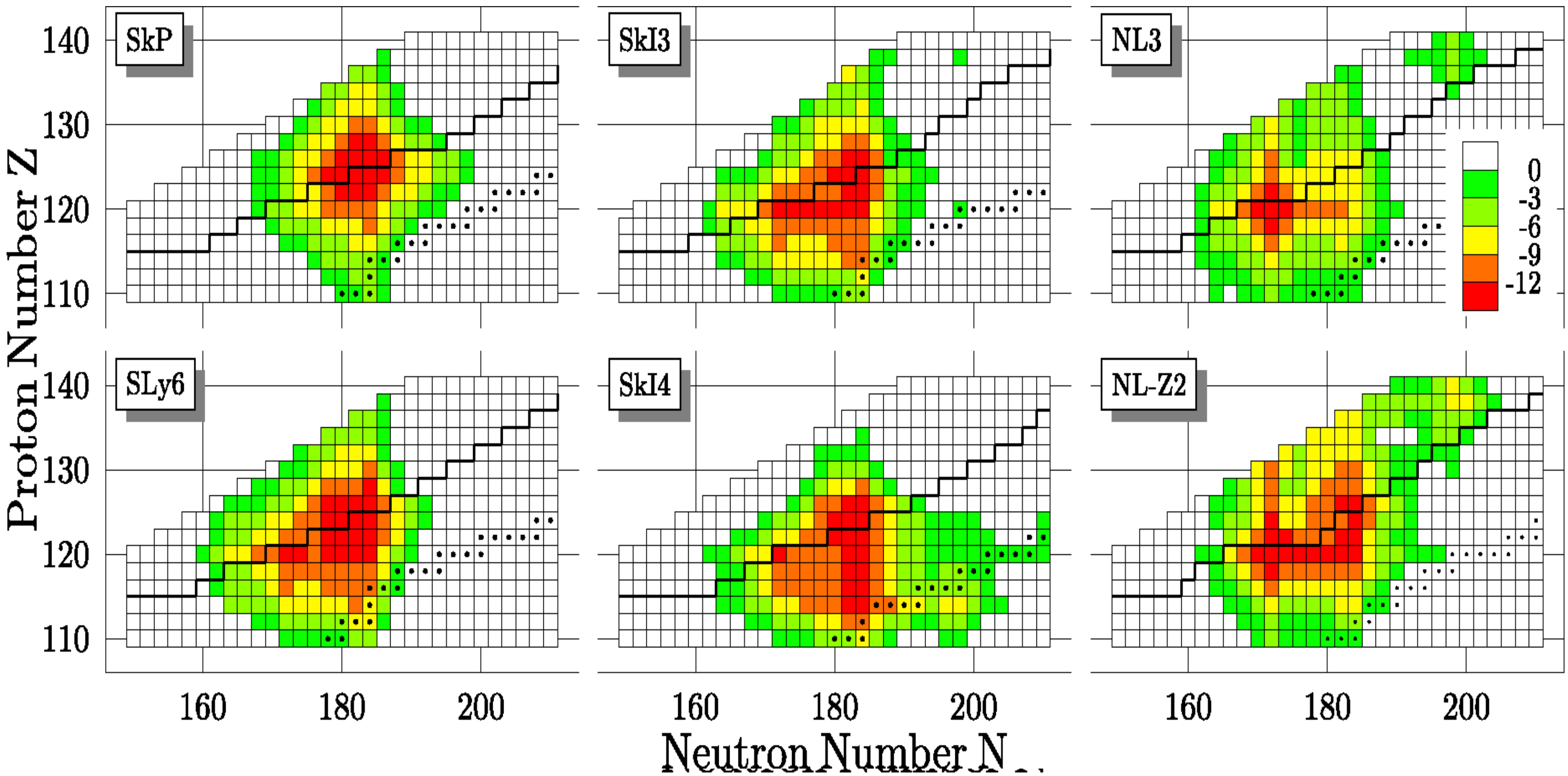
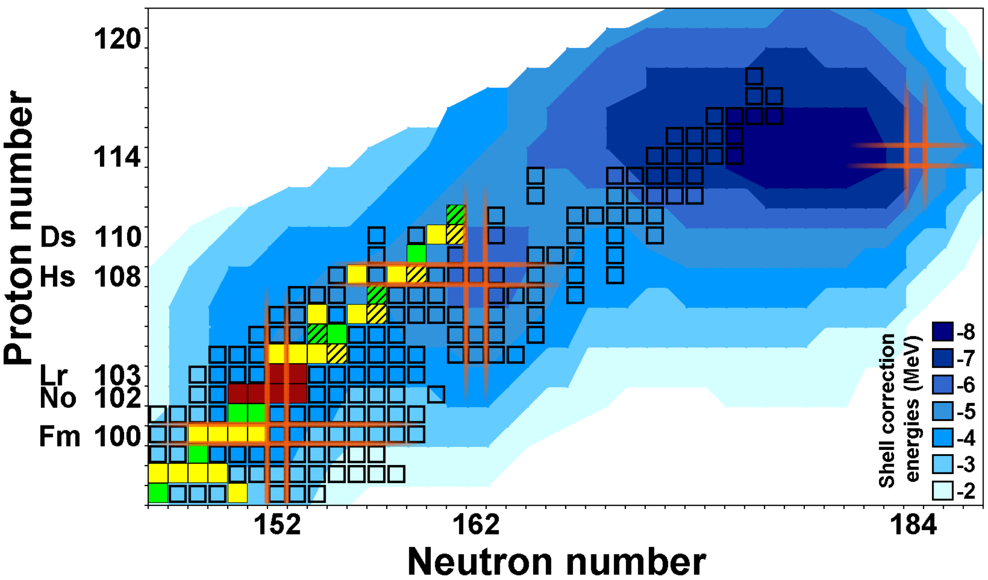
Courtesy Ch.E. Düllmann

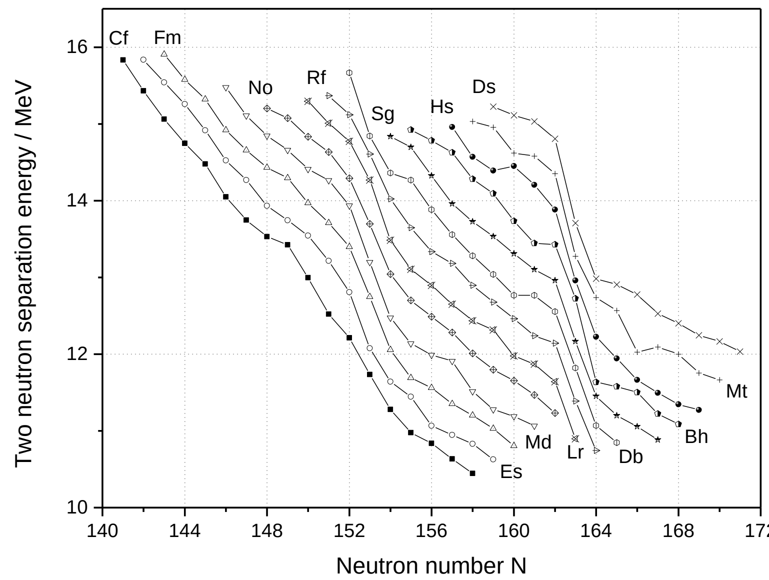
Nuclear Shells: Magic Numbers in SHE?



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

Importance of Masses for Z > 100



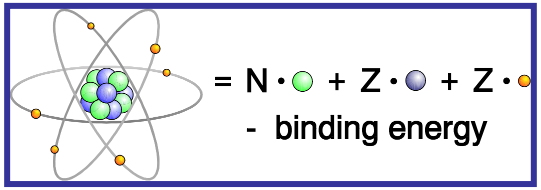


high-precision mass measurements provide

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

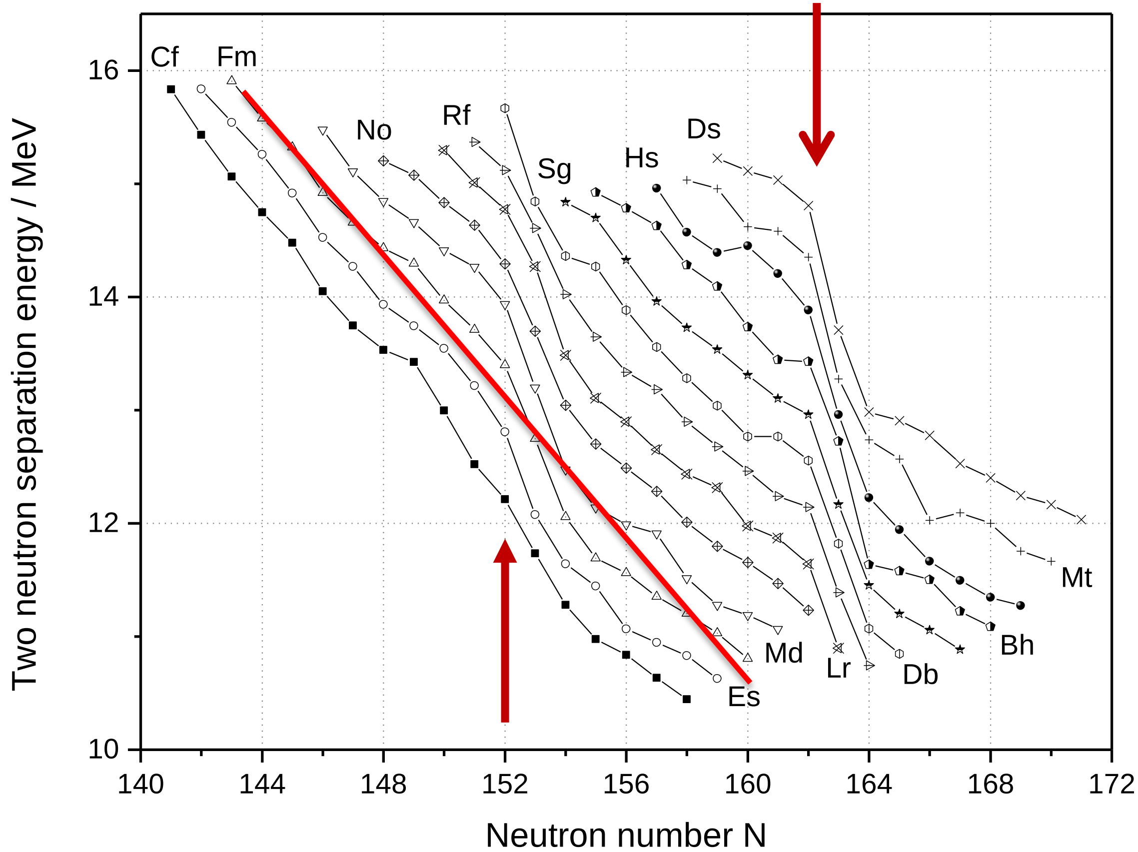
➡ Studies the nuclear structure evolution

➡ Benchmark theoretical nuclear models



Nuclear Structure Indicators from Masses

two-neutron separation energy $S_{2n}(N,Z) = M(N,Z) - M(N-2,Z) + 2\,m_n$



indication for shell closure at $N = 152$ & $N = 162$

Data from Atomic Mass Evaluation 2012:
M. Wang et al., CPC(HEP & NP), 2012, 36(12): 1603–2014

Nuclear Structure Indicators from Masses

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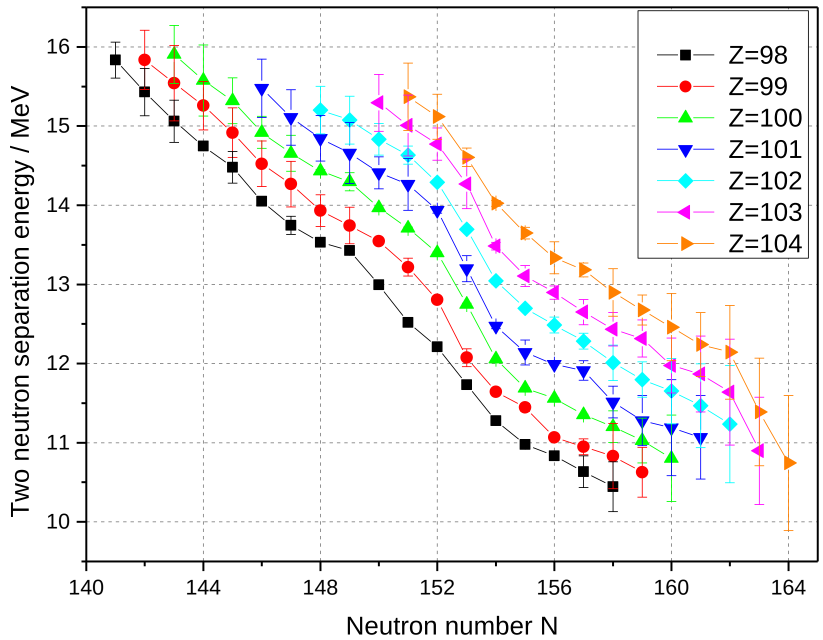
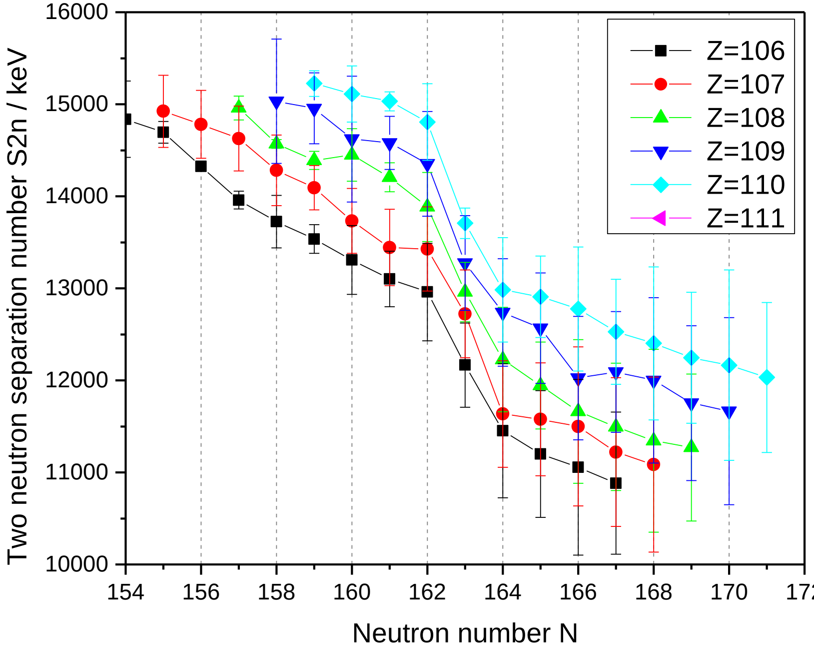




indication for shell closure at N = 152 & N = 162

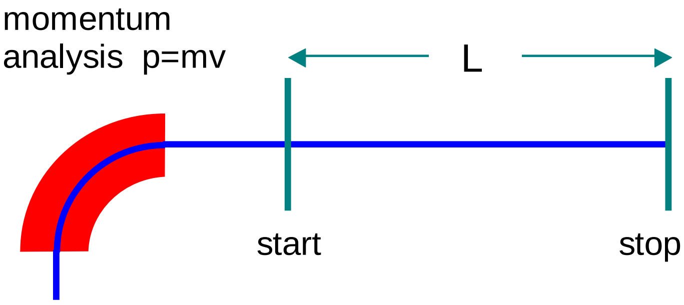
Data from Atomic Mass Evaluation 2012:
M. Wang et al., CPC(HEP & NP), 2012, 36(12): 1603–2014

Tools for Direct Mass Measurements

Time-of-flight spectrometry

single turn: SPEG/GANIL, S800/NSCL

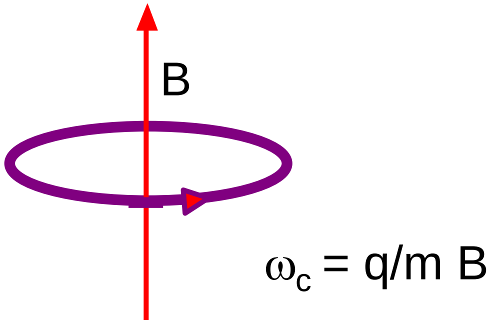
multi turn: ESR/GSI, CSR/Lanzhou, RIBF ring
electrostatic MR-ToF (Giessen, ISOLDE, RIKEN, ...)



Frequency measurements

storage rings ESR/GSI, CSR/Lanzhou, RIBF rings

Penning traps LEBIT/NSCL, ISOLTRAP/ISOLDE
JYFLTRAP/JYFL, CPT/ANL
SHIPTRAP/GSI, TITAN/TRIUMF,
TRIGATRAP/ Mainz, MLLTRAP,
…



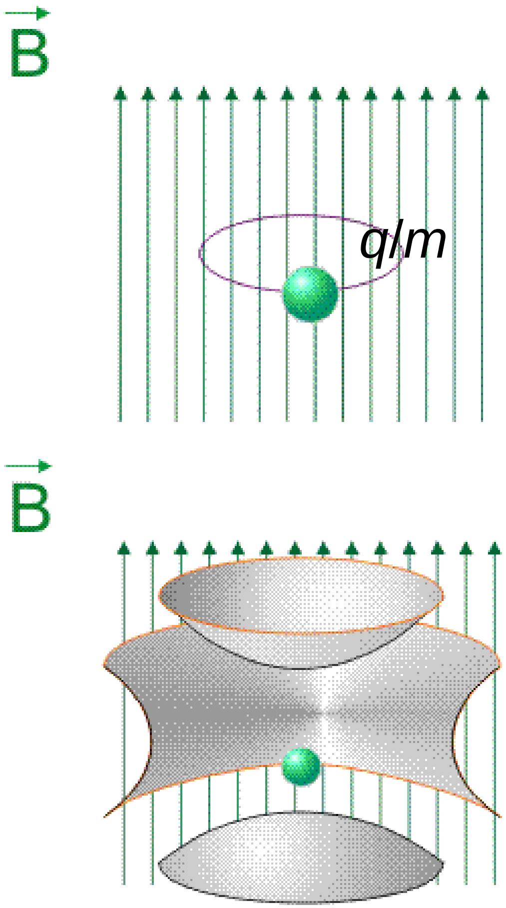
β-decays: masses from long-decay chains MUST be replaced by direct measurements

Proton and alpha decays: needed for fast proton emitters, super heavy elements

Reactions: (p,d) for masses (+excited states) of unbound nuclei beyond p-dripline

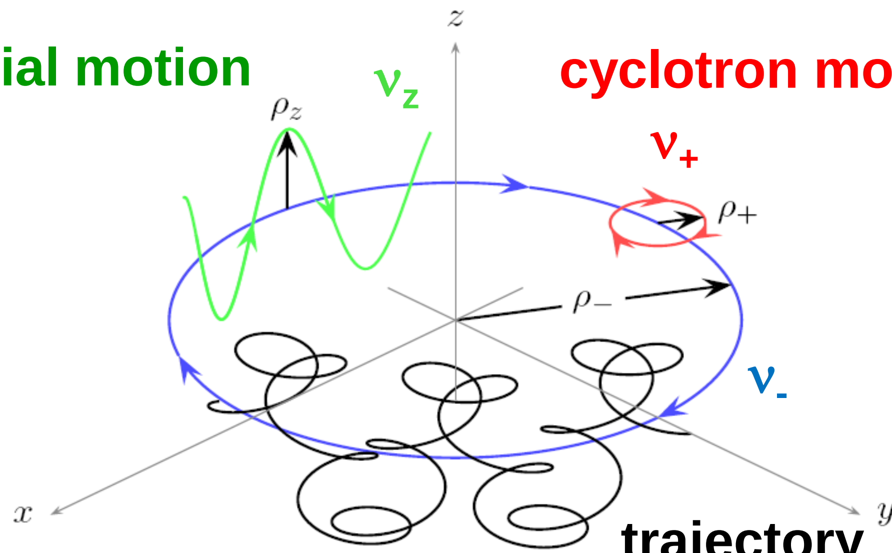
Principle of Penning Traps

PENNING trap



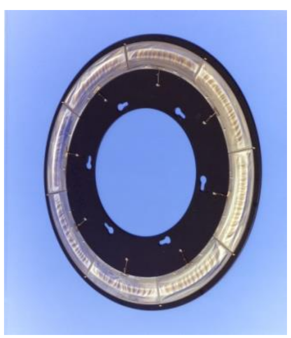
- Strong homogeneous magnetic field
- Weak electric 3D quadrupole field

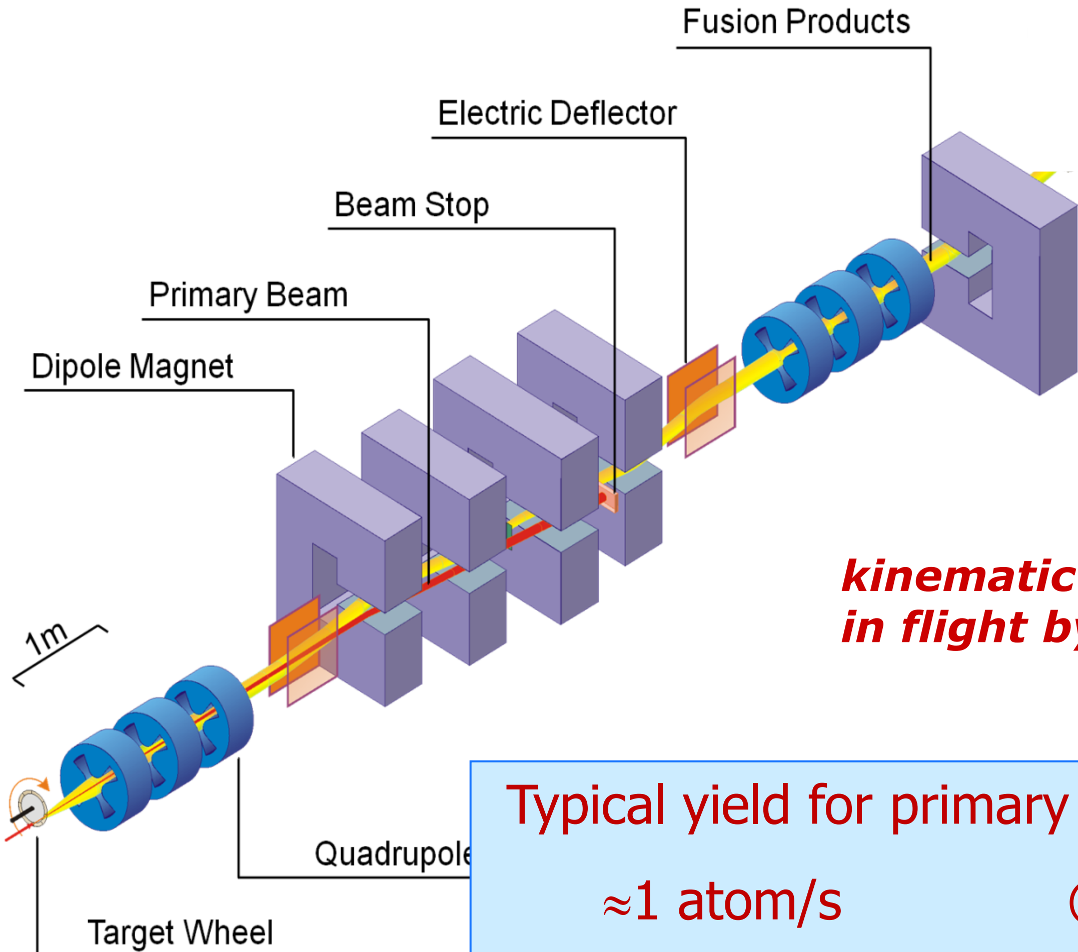
Cyclotron frequency: $f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$



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

Synthesis and Separation by SHIP





kinematic separation in flight by velocity filter

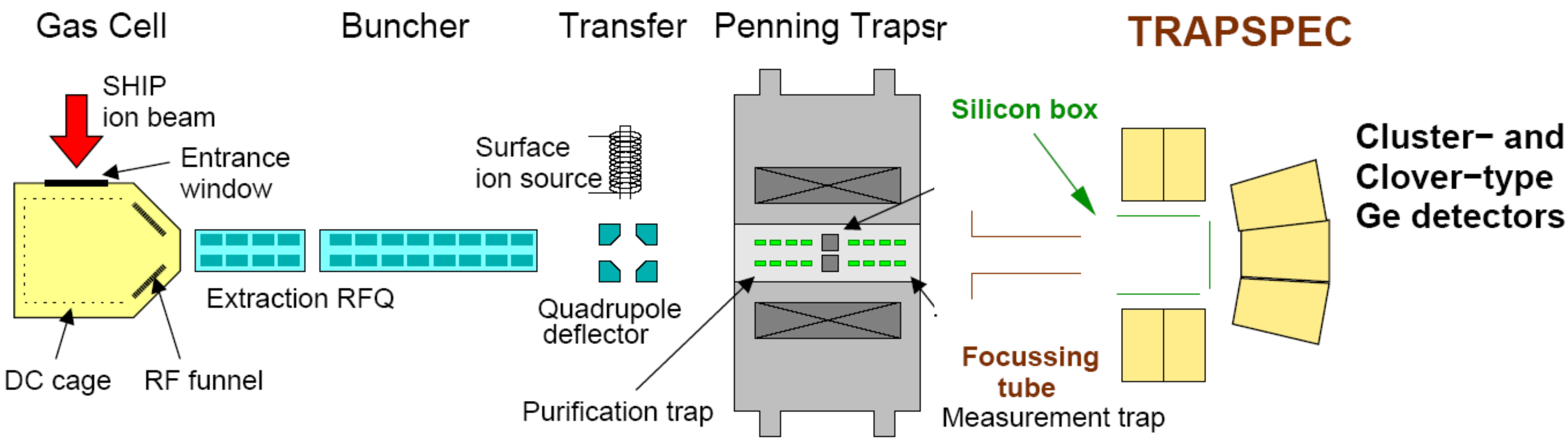
Typical yield for primary beam ≈ 6 x 10^{12} / s

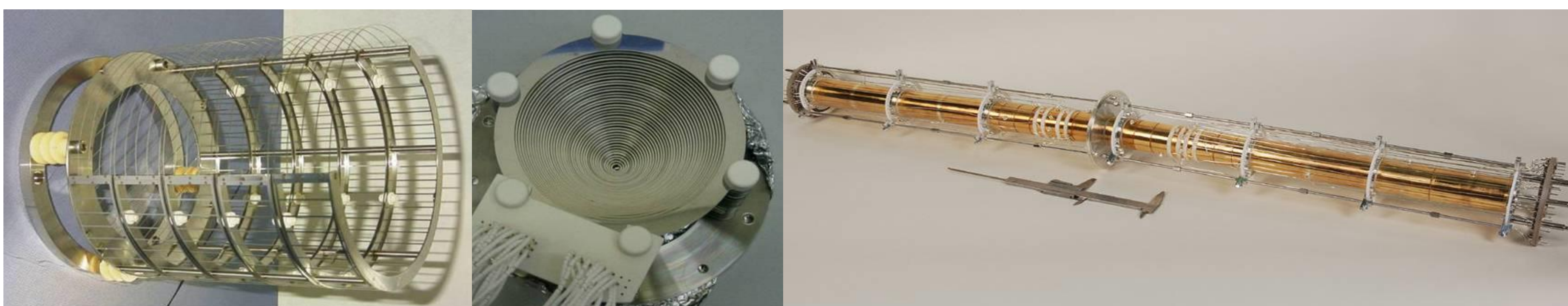
≈1 atom/s @ Z ≈ 102 (σ ≈ 1 μb)

≈1 atom/week @ Z= 112 (σ ≈ 1 pb)

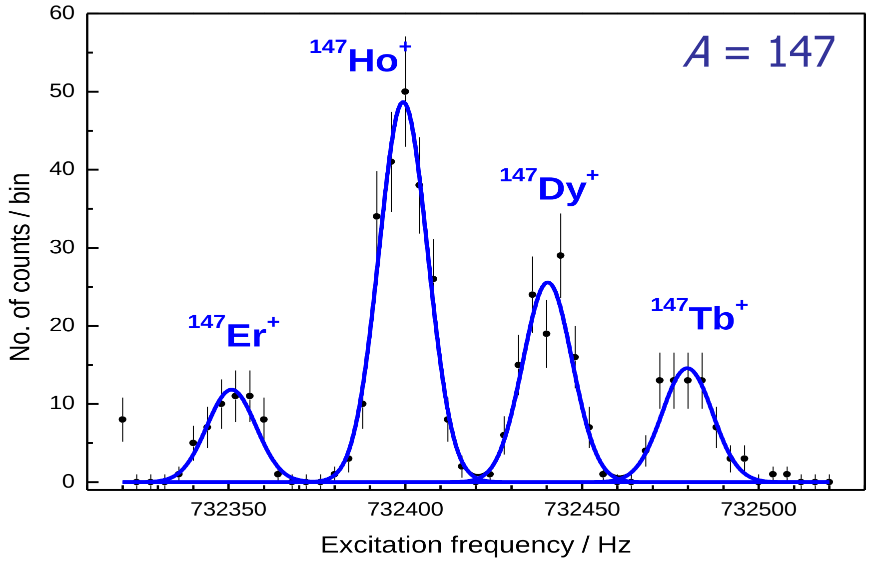
SHIPTRAP Setup

≈ 50 MeV → ≈ 1 eV → ≈ 1 keV





SHIPTRAP Performance

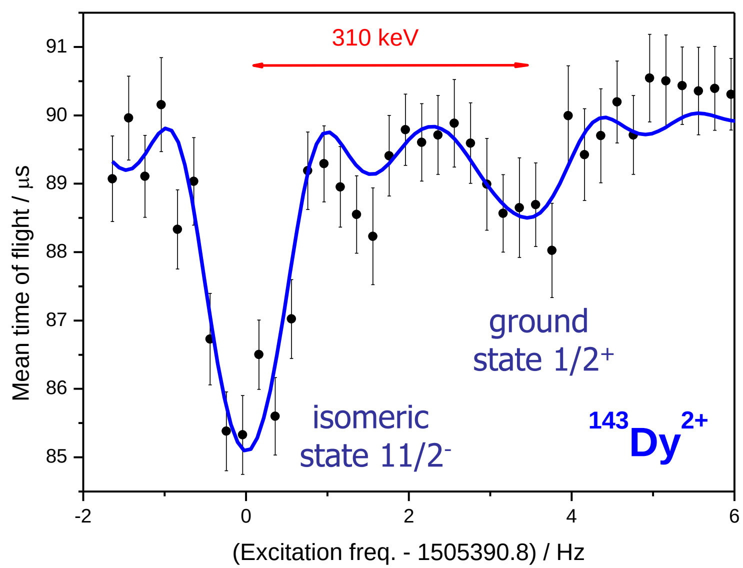


Mass resolving power of

m/δm ≈ 100,000

in purification trap:

⇒ separation of isobars



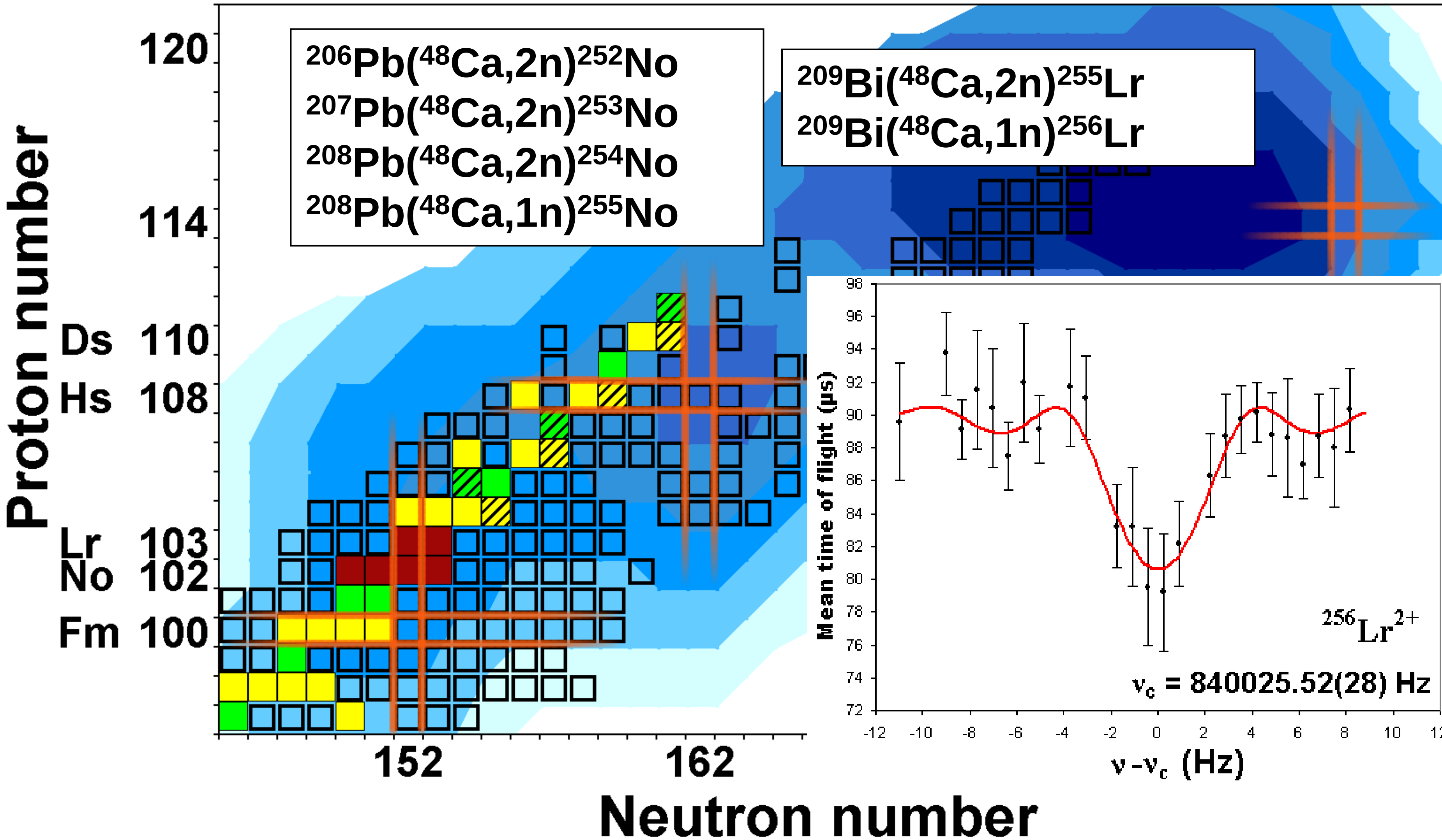
Mass resolving power of

m/δm ≈ 1,000,000

in measurement trap:

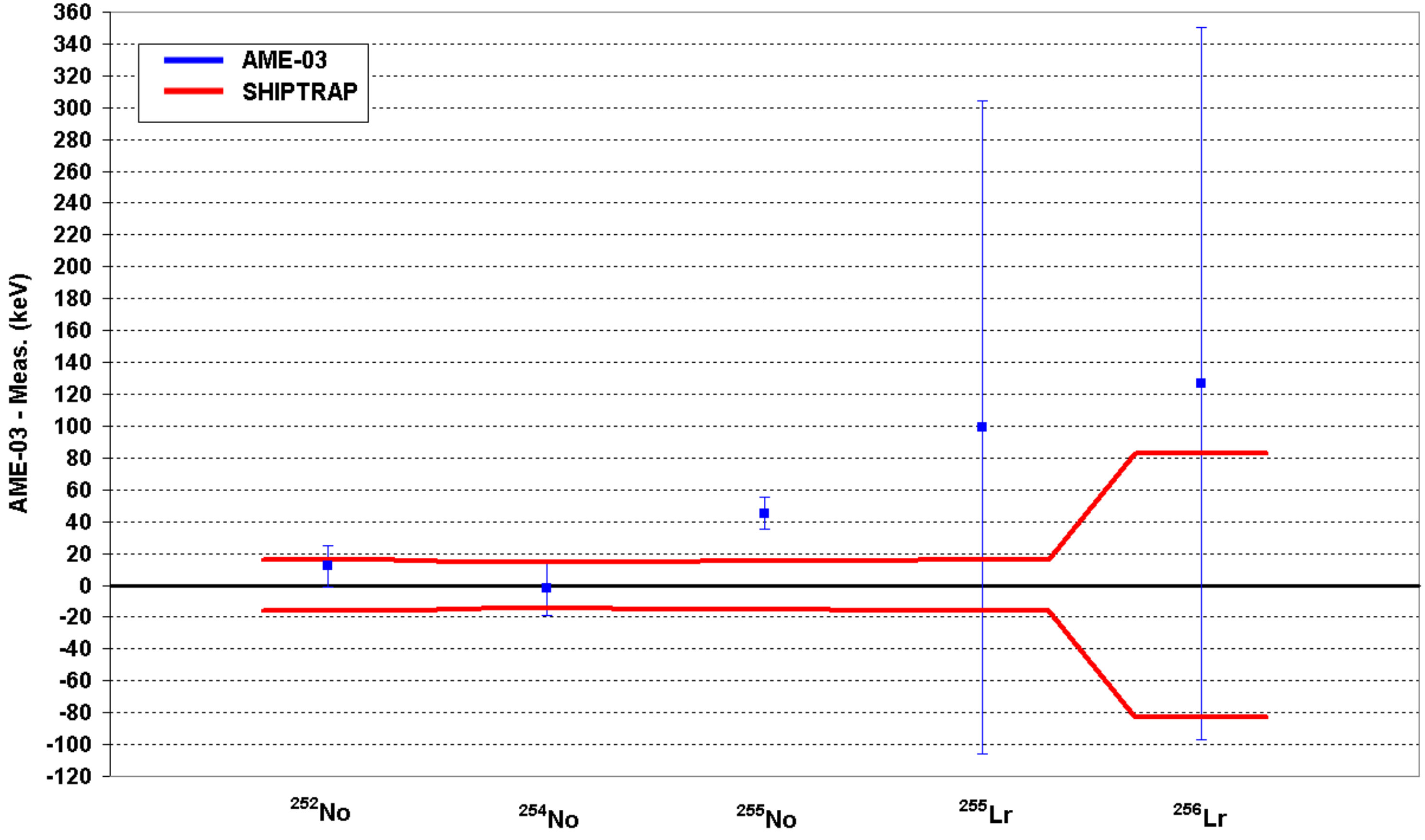
⇒ separation of isomers

Direct mass measurements with SHIPTRAP

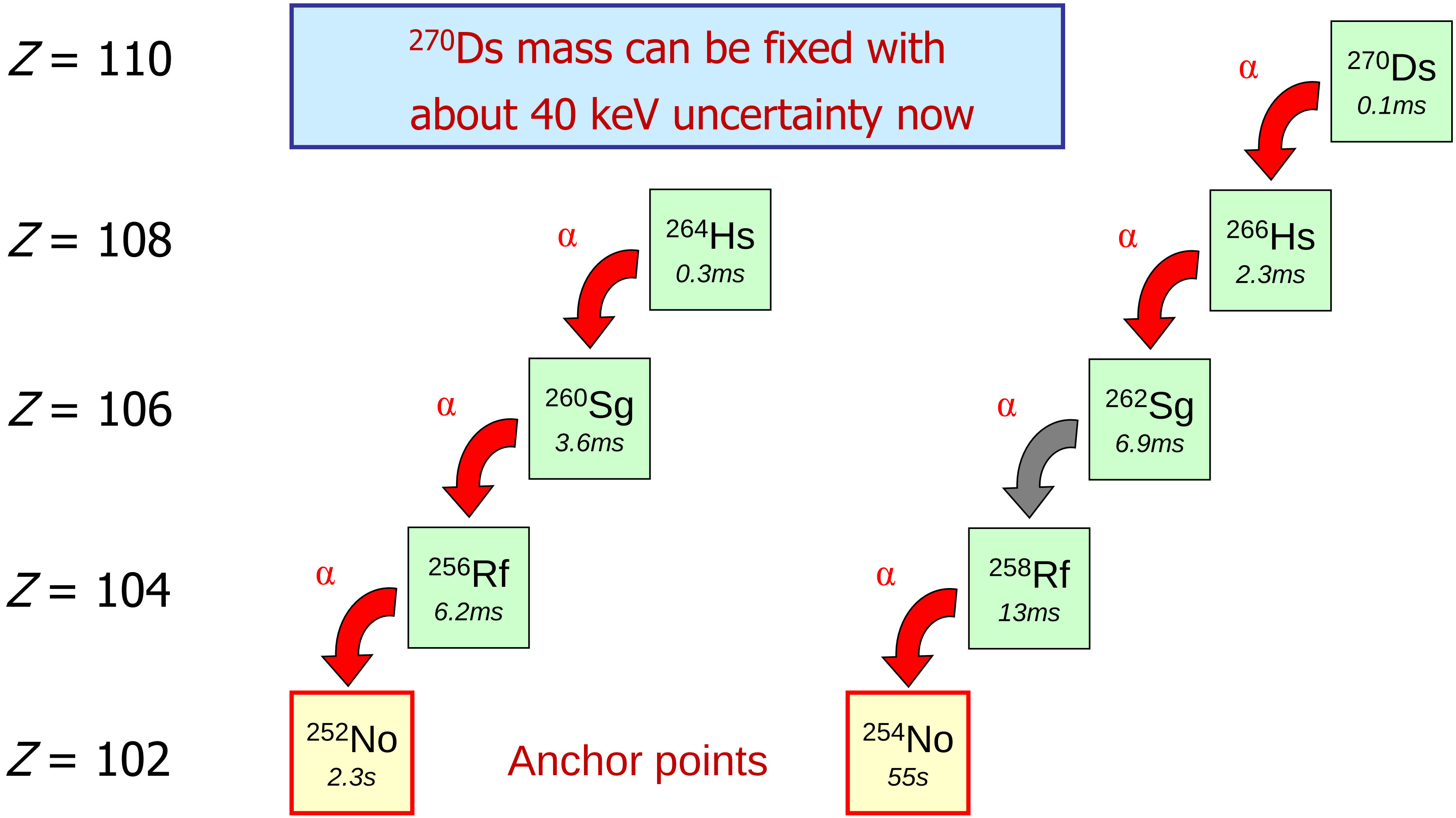


M. Block et al., Nature 463, 785 (2010), M. Dworschak et al., Phys. Rev. C 81, 064312 (2010)
E. Minaya Ramirez et al., Science 337, 1183 (2012)

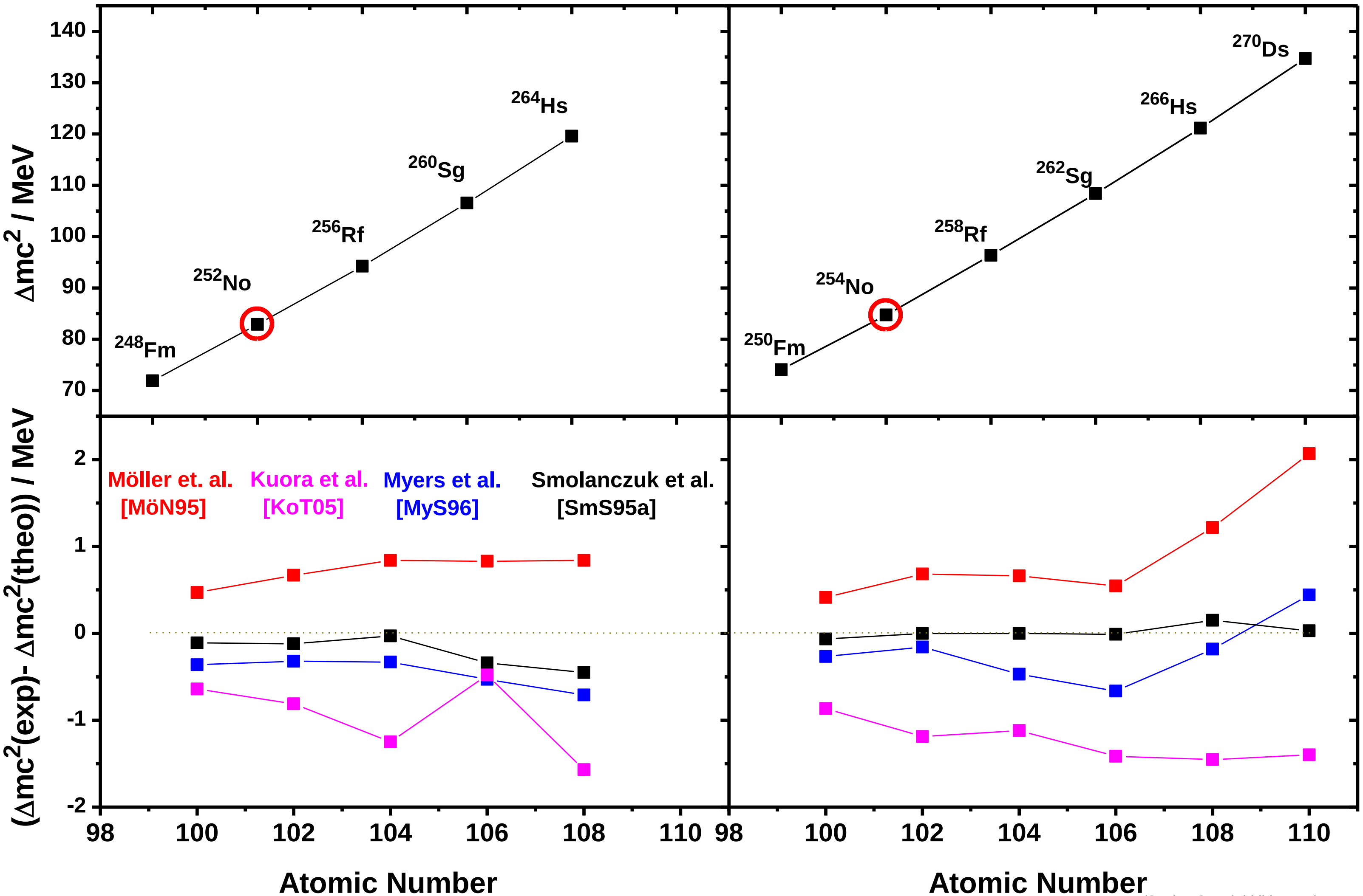
SHIPTRAP Results vs. Atomic Mass Evaluation



Pinning Down α-Decay Chains



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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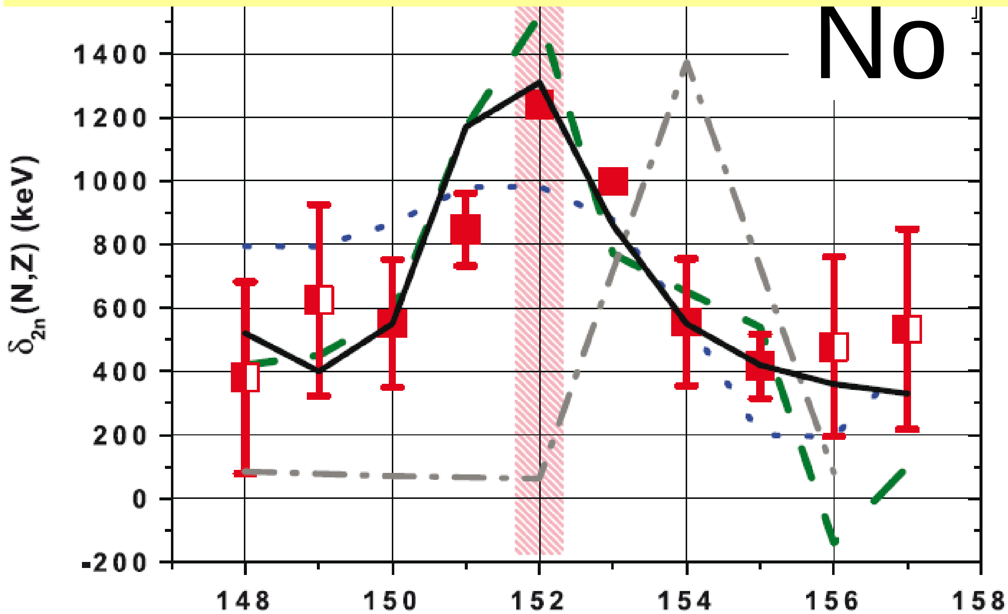
courtesy F. P. Hessberger

SHIPTRAP: Probing the Strength of Shell Effects

Direct Mapping of Nuclear Shell Effects in the Heaviest Elements

E. Minaya Ramirez,[1,2] D. Ackermann,[2] K. Blaum,[3,4] M. Block,[2*] C. Droese,[5] Ch. E. Düllmann,[6,2,1] M. Dworschak,[2] M. Eibach,[4,6] S. Eliseev,[3] E. Haettner,[2,7] F. Herfurth,[2] F. P. Heßberger,[2,1] S. Hofmann,[2] J. Ketelaer,[3] G. Marx,[5] M. Mazzocco,[8] D. Nesterenko,[9] Yu. N. Novikov,[9] W. R. Plaß,[2,7] D. Rodríguez,[10] C. Scheidenberger,[2,7] L. Schweikhard,[5] P. G. Thirolf,[11] C. Weber[11]

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



Experimental

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

Möller FRDM
Z=114 N=184

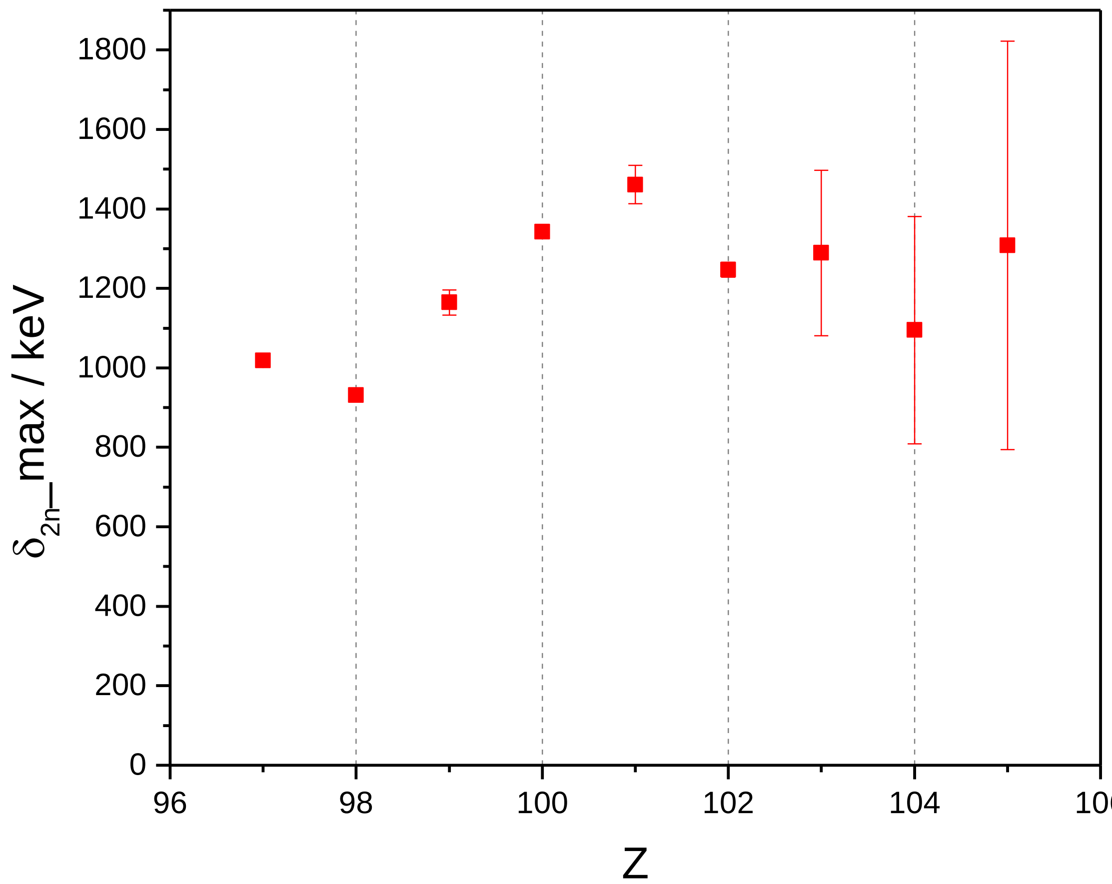
TW-99
Z=120 N=172

SkM*
Z=126 N=184

Science **337** (2012) 1207

Probing the Strength of Shell Effects

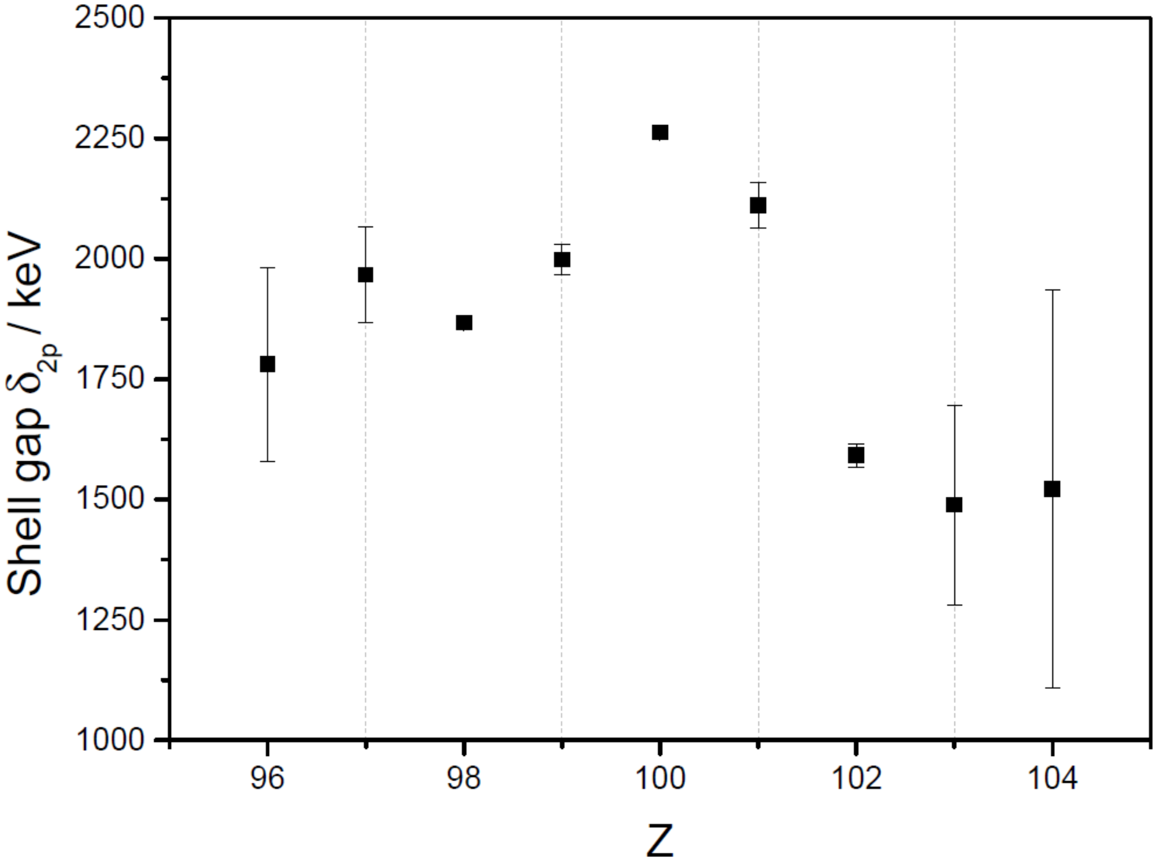
Evolution of *N* = 152 shell closure



Data taken from Atomic Mass Evaluation (AME) 2012: M. Wang et al.

Probing the Strength of Shell Effects

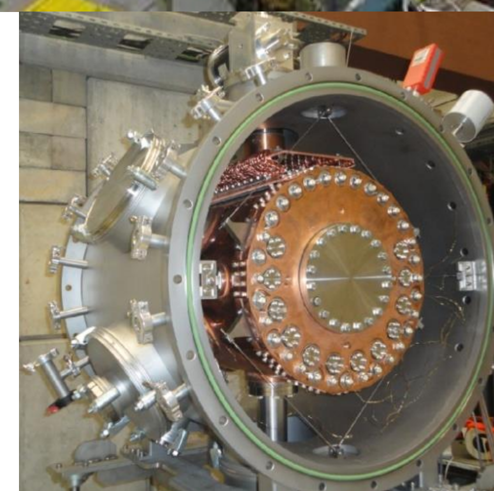
N = 152 isotones



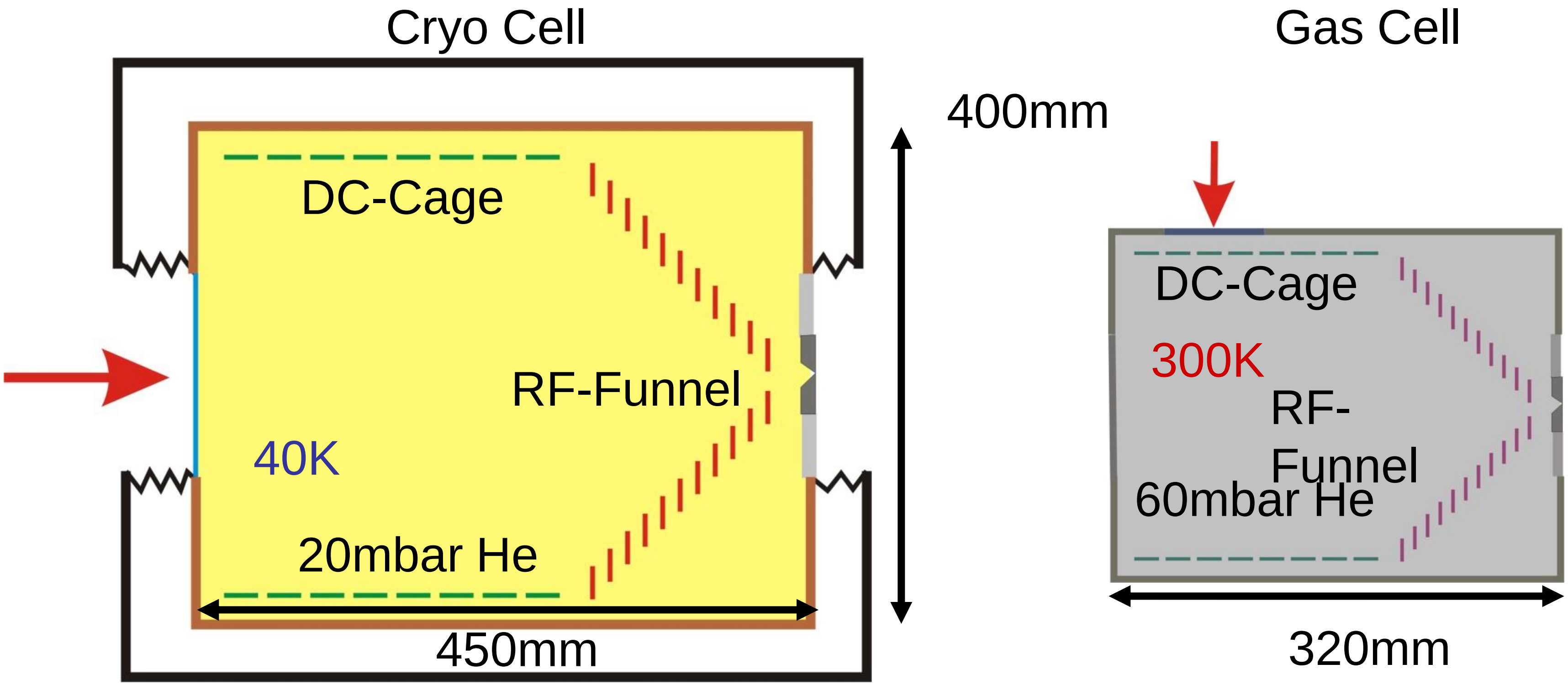
Data taken from Atomic Mass Evaluation (AME) 2012: M. Wang et al.

Upgrades and Combinations

- Novel experiments
  - trap-assisted decay spectroscopy
  - laser spectroscopy (gas cell, gas jet, trap)
  - gas phase chemistry
- Increase efficiency and sensitivity
  - novel measurement schemes (PI-ICR)
  - single-ion mass measurements (FT-ICR) (→ TRIGA-TRAP, TRAPSENSOR)
  - cryogenic gas cell



Cryogenic 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)

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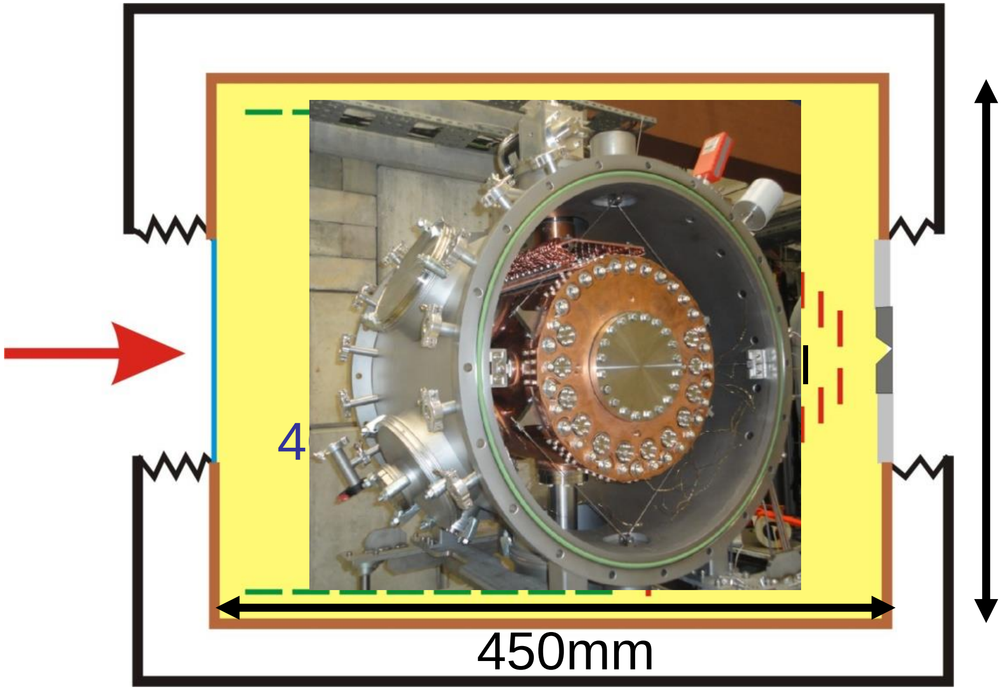
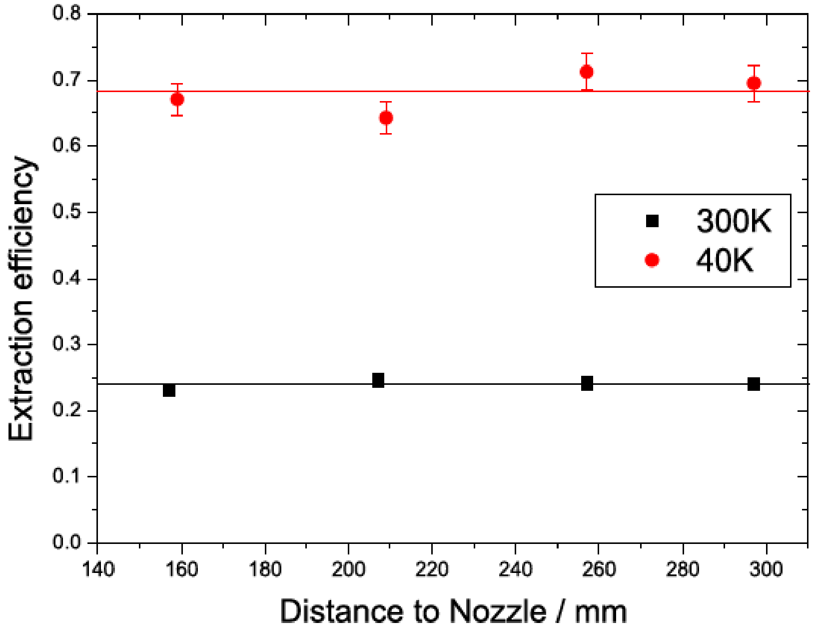
Cryogenic Gas Cell

Cryo Cell



Gas Cell



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

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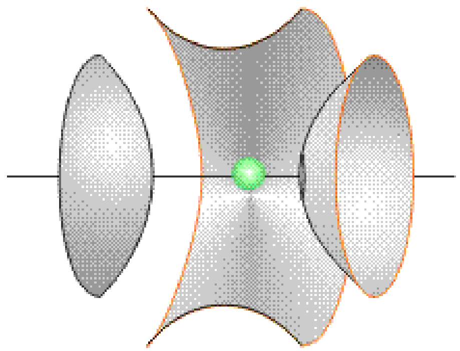
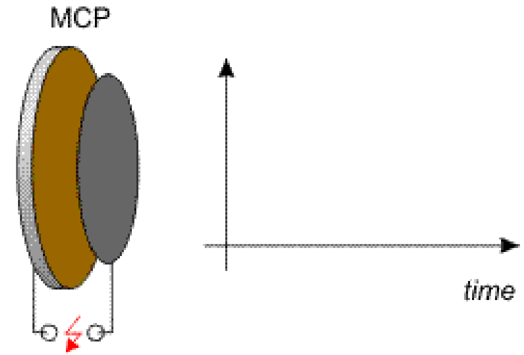
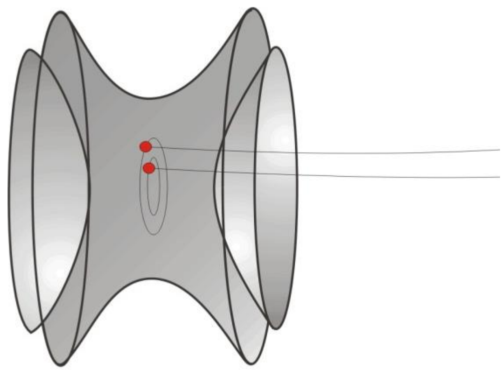
Recent Breakthrough

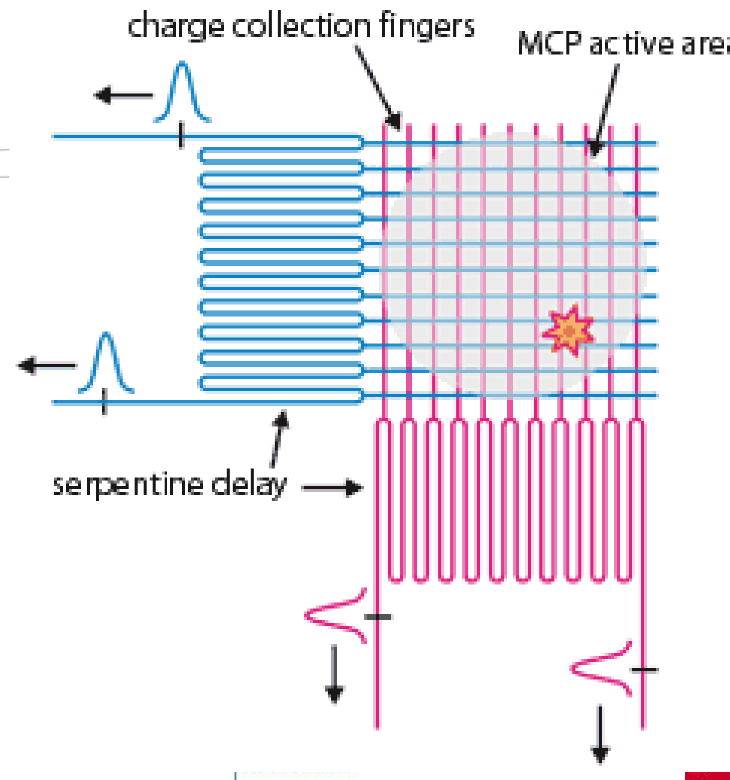
Destructive time-of-flight detection



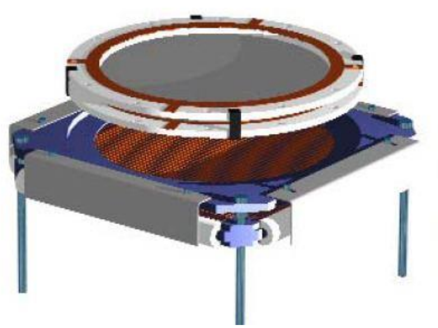


Spatially resolved detection



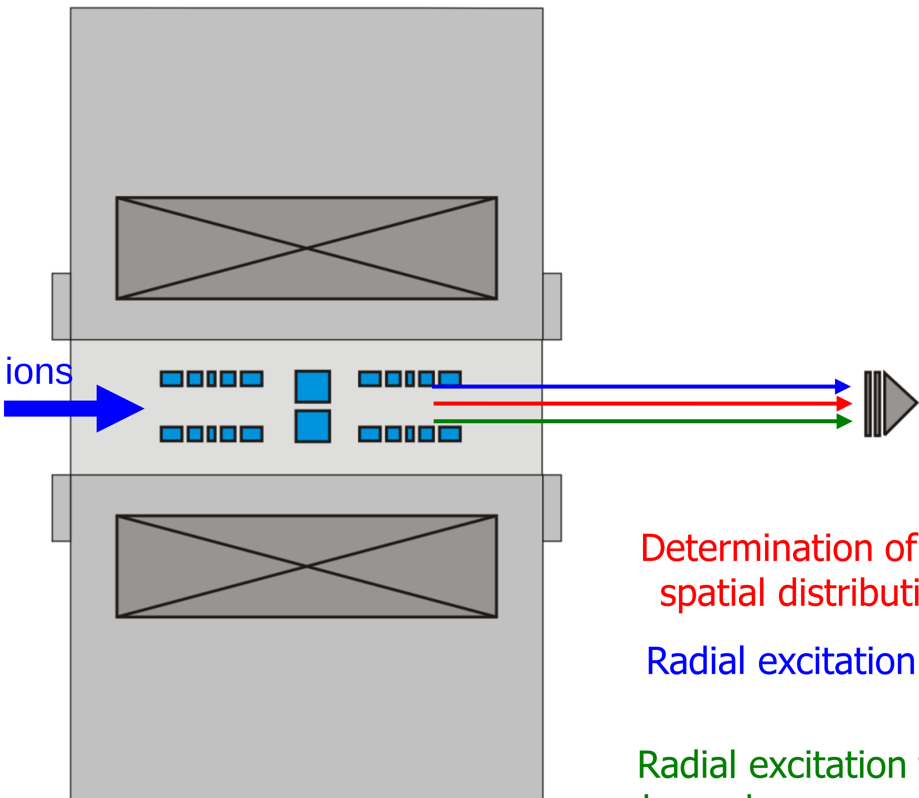


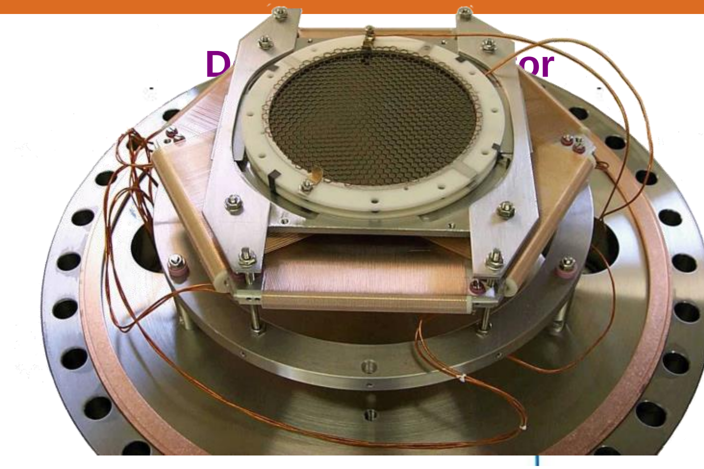
Delay-line detector



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

Phase-Imaging Ion-Cyclotron-Resonance Method



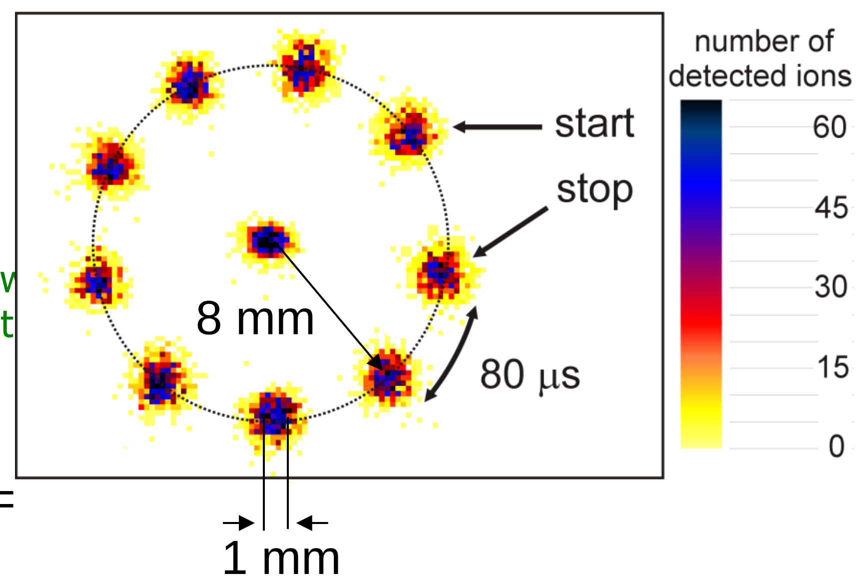


Determination of the spatial distribution

Radial excitation

Radial excitation follow
by a phase accumulat

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



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

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

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

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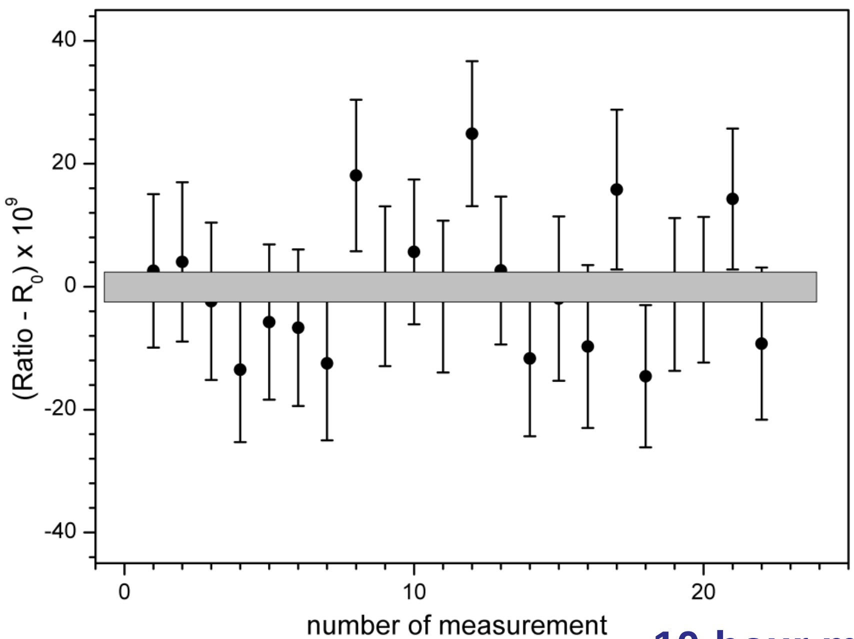
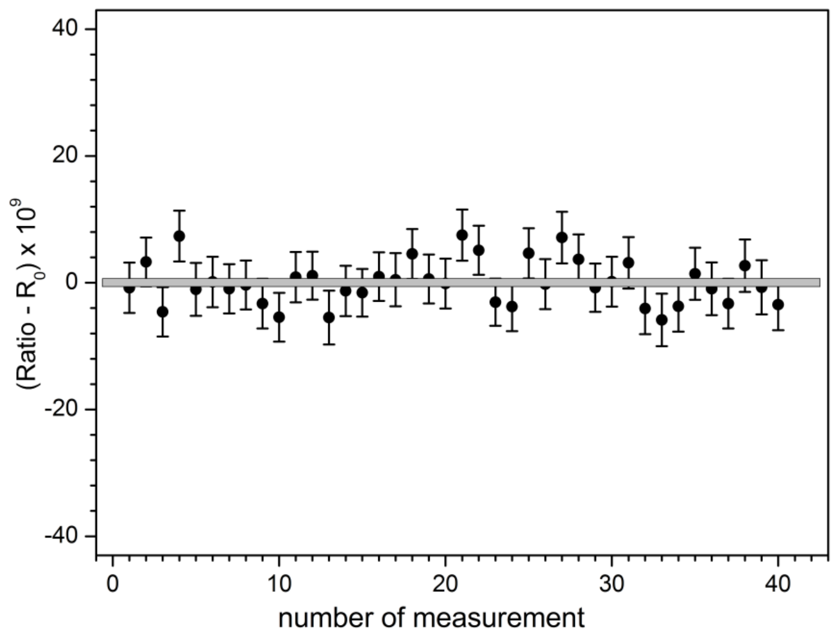
PI-ICR vs. ToF-ICR in experiment

ToF-ICR



PI-ICR



10-hour measurements

δ[M(^{124}Xe) - M(^{124}Te)] ~ 300 eV

δ[M(^{132}Xe) - M(^{131}Xe)] ~ 70 eV !!!

Gain in Precision ~ 4.5 !!!

S. Eliseev et al., Phys. Rev. Lett. 114, 107 (2014)

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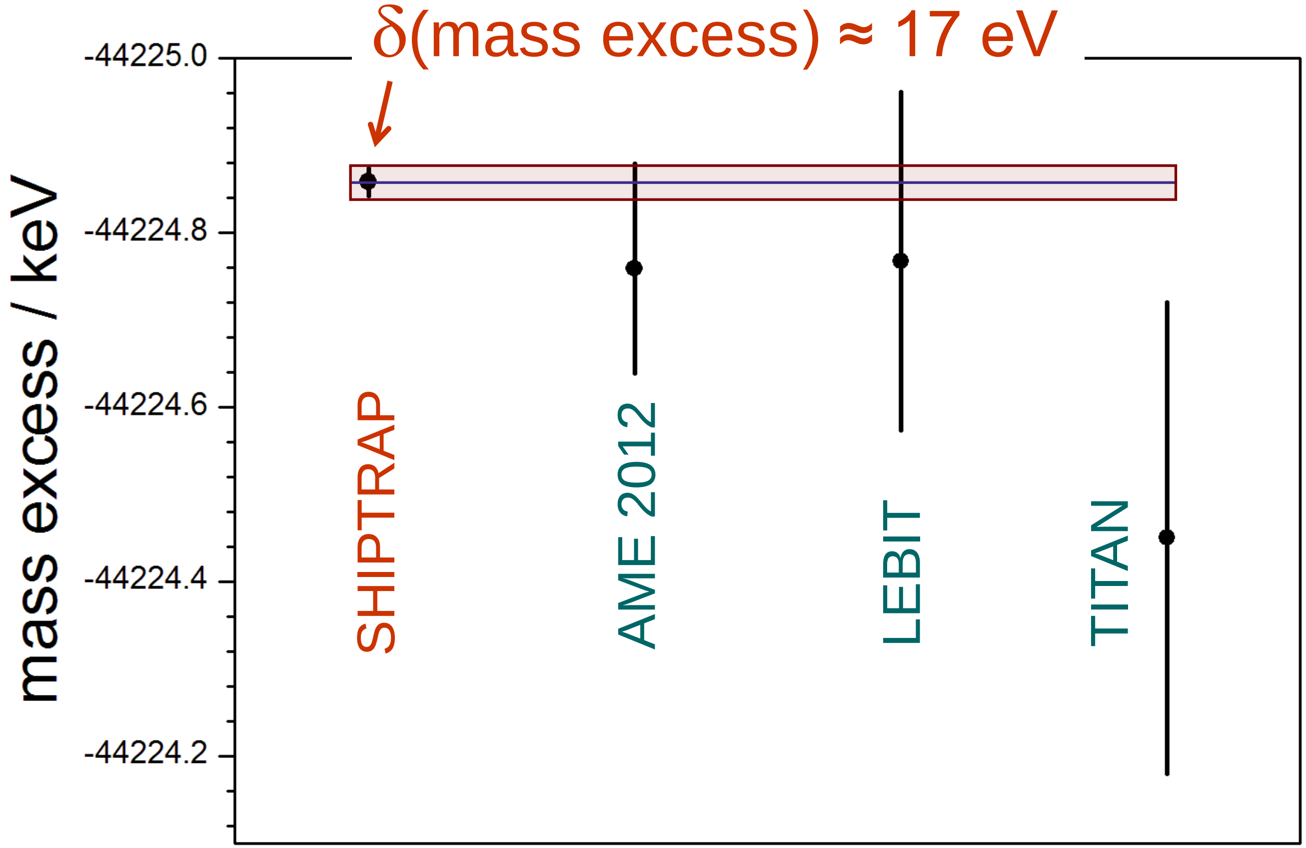
^{48}Ca Mass Measurements



$$\frac{\nu_c(^{48}Ca^+)}{\nu_c(C_4^+)} = 1.000\,990\,101\,75(36_{stat})\,(15_{sys})$$

PRELIMINARY

Helmholtz Institute Mainz

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)

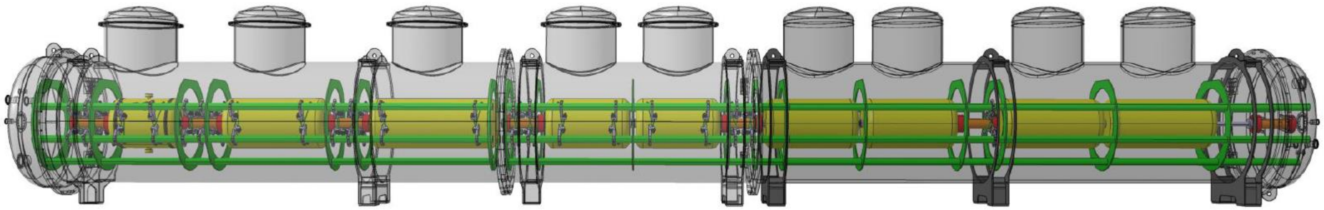
Currently includes 9 German and 17 international institutes

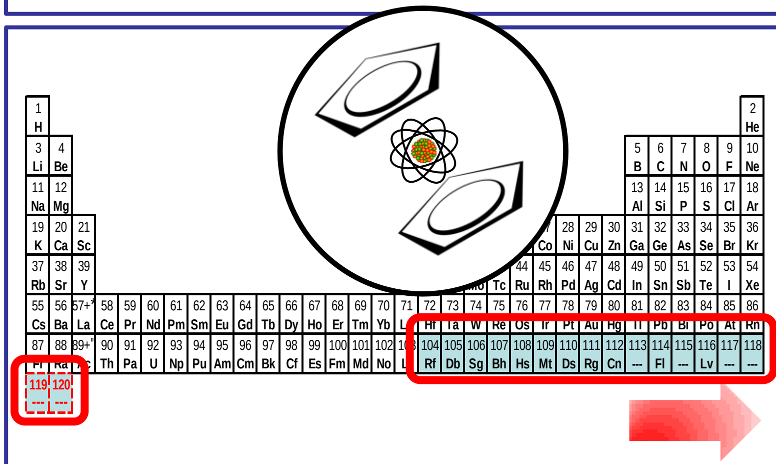
Endorsed by NUSTAR Collaboration Committee: Sept. 25, 2014
submission to FAIR management: summer 2015

SHE research 2020+

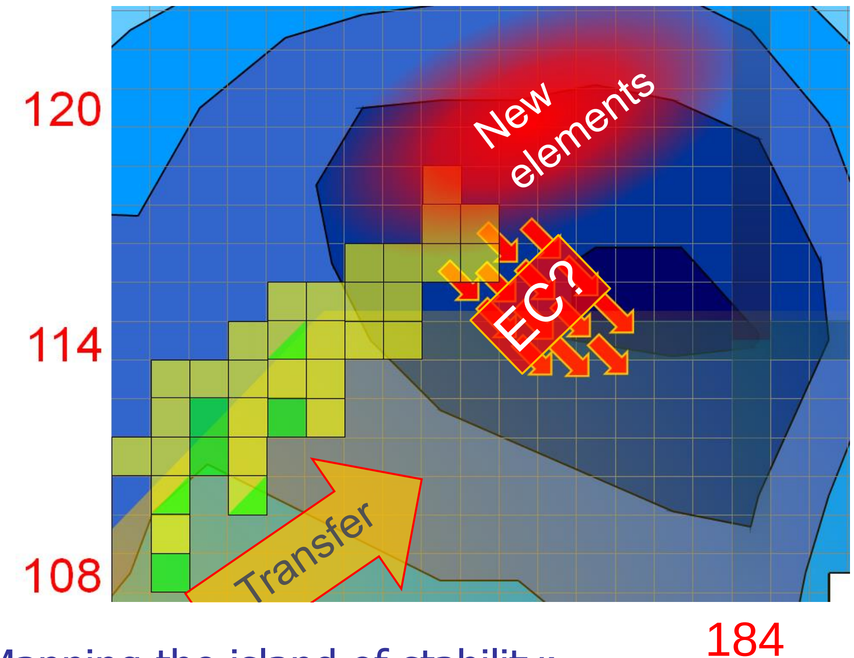
New cw linac

E_{Beam} up to 7.3 MeV/u
Length: 13.5 m





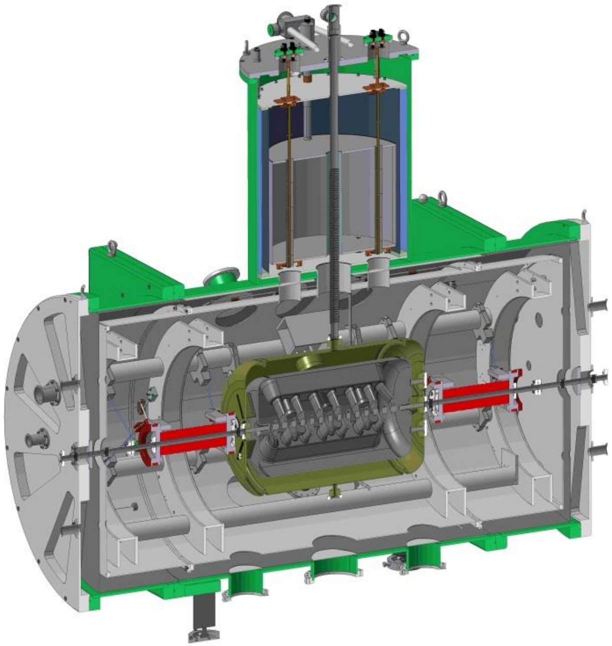
- Atomic structure beyond No (Z=102)
- Experiments with single SHE-ions (e.g. chemistry + mass spec)
- Chemical studies towards Eka-Rn
- New SHE molecules, their stability, formation kinetics
- New period in the periodic table

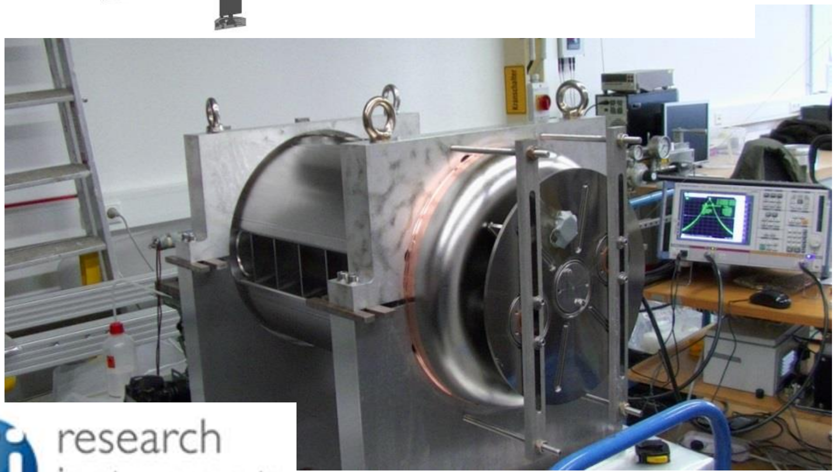


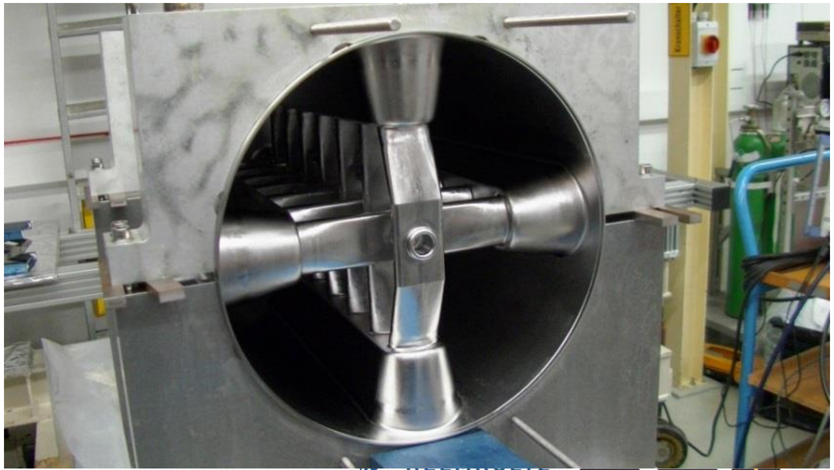
Mapping the island of stability:

- New elements with Z>118
- Neutron-rich isotopes in transfer reactions
- Weak EC decay channels towards center of island
- Direct mapping of shell evolution towards N=184

First components – October 2014







research instruments

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Courtesy of V. Gettmann / W. Barth

SHIPTRAP Collaborators

D. Ackermann, K. Blaum, S. Chenmarev, C. Droese, Ch. Duellmann, M. Eibach, S. Eliseev, P. Filanin, F. Giacoppo, M. Goncharov, E. Haettner, F. Herfurth, F. P. Heßberger, O. Kaleja, M. Laatiaoui, G. Marx, 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, …

Summary and Conclusions

- State-of-the-art mass spectrometry provides ... ses of exotic nuclides with high accuracy – anchor poin...
- High-precision mass measurements a... probing shell effects and tracking the evolution of nuclear s... ure in the heaviest elements
- Technical and methodical im... ments will extend the reach towards more exotic nuc... with higher *Z*
- *SHE research remai... nerstone of science program at GSI/FAIR*
- *New cw-linac w... eserve competitiveness in the future*

Thank you for your attention!