ASRC Workshop Tokai 2014

Nuclear Structure Studies with Penning Traps

Michael Block

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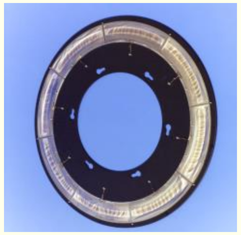
Helmholtz Institute Mainz

Unique Combination for SHE Studies

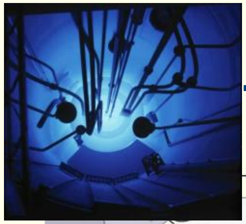
ECR/PIG + UNILAC

Beam



Stable targets

Actinide targets



TRIGA-

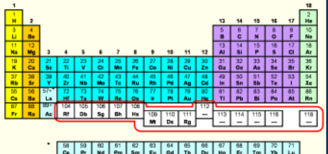
-LASER

-TRAP

Radiochem. labs

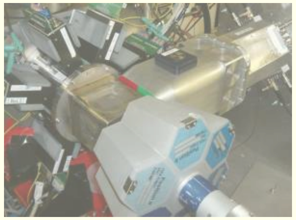
SHIP

TASCA

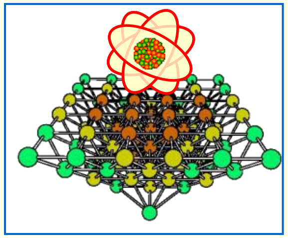


Chemistry

SHIPTRAP

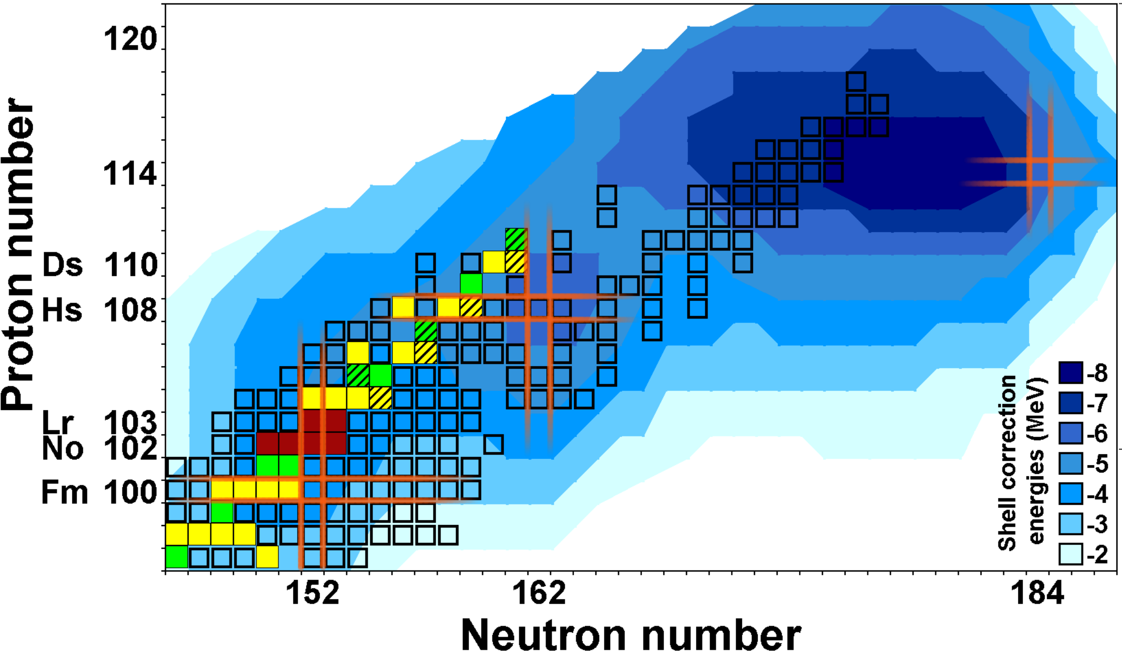


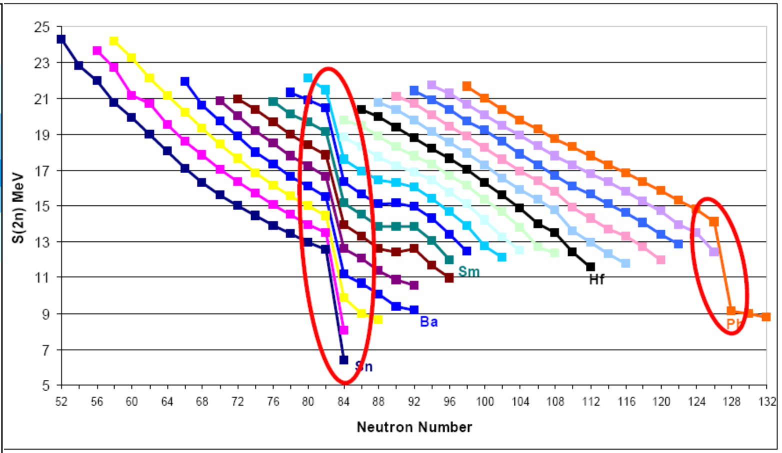
TASISpec

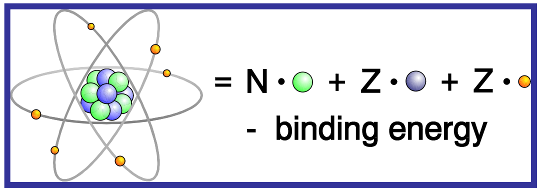


Chemical theory

Importance of Masses for Z > 100







high-precision mass measurements provide

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

➡ Studies the nuclear structure evolution

➡ Benchmark theoretical nuclear models

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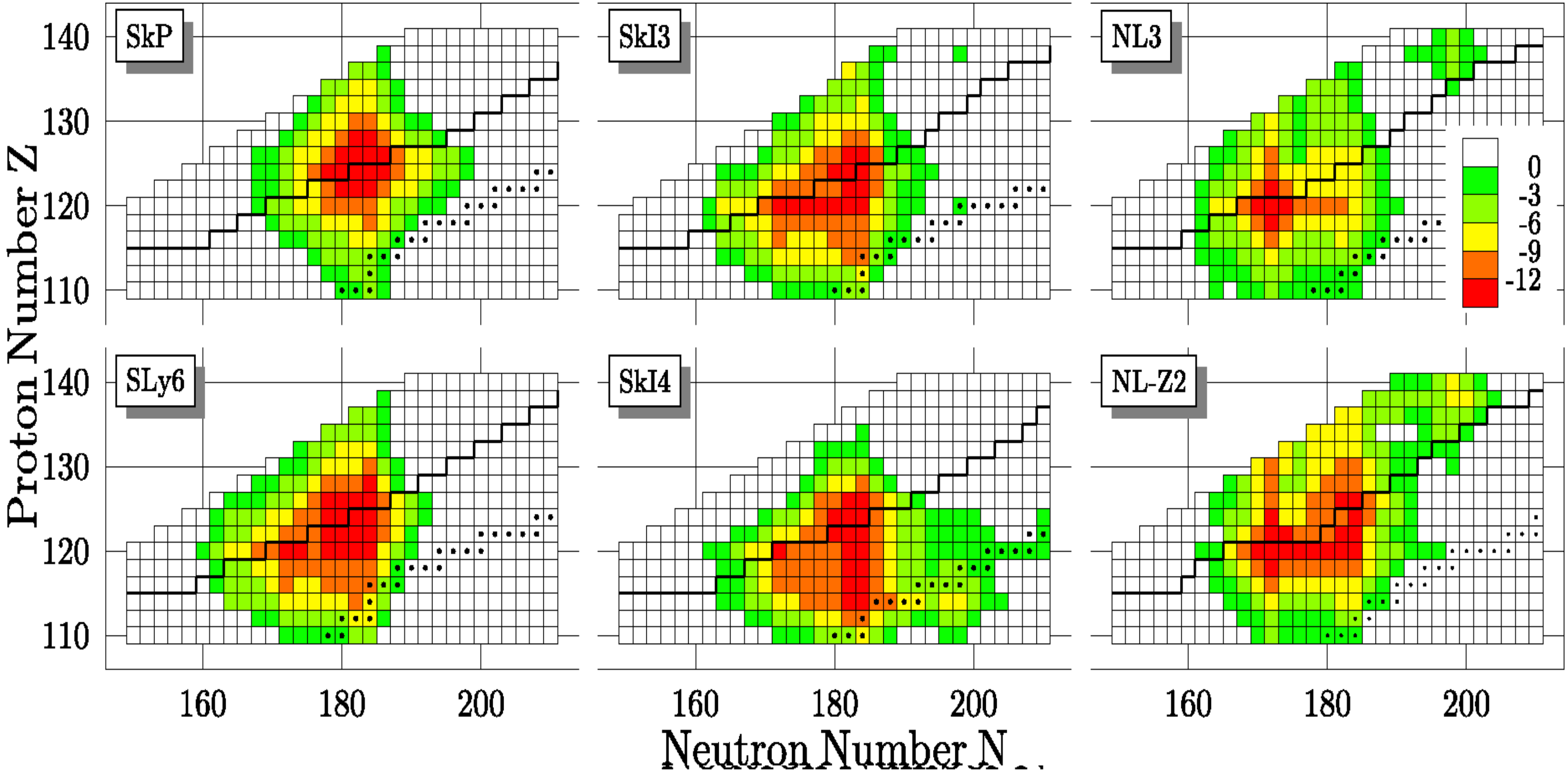
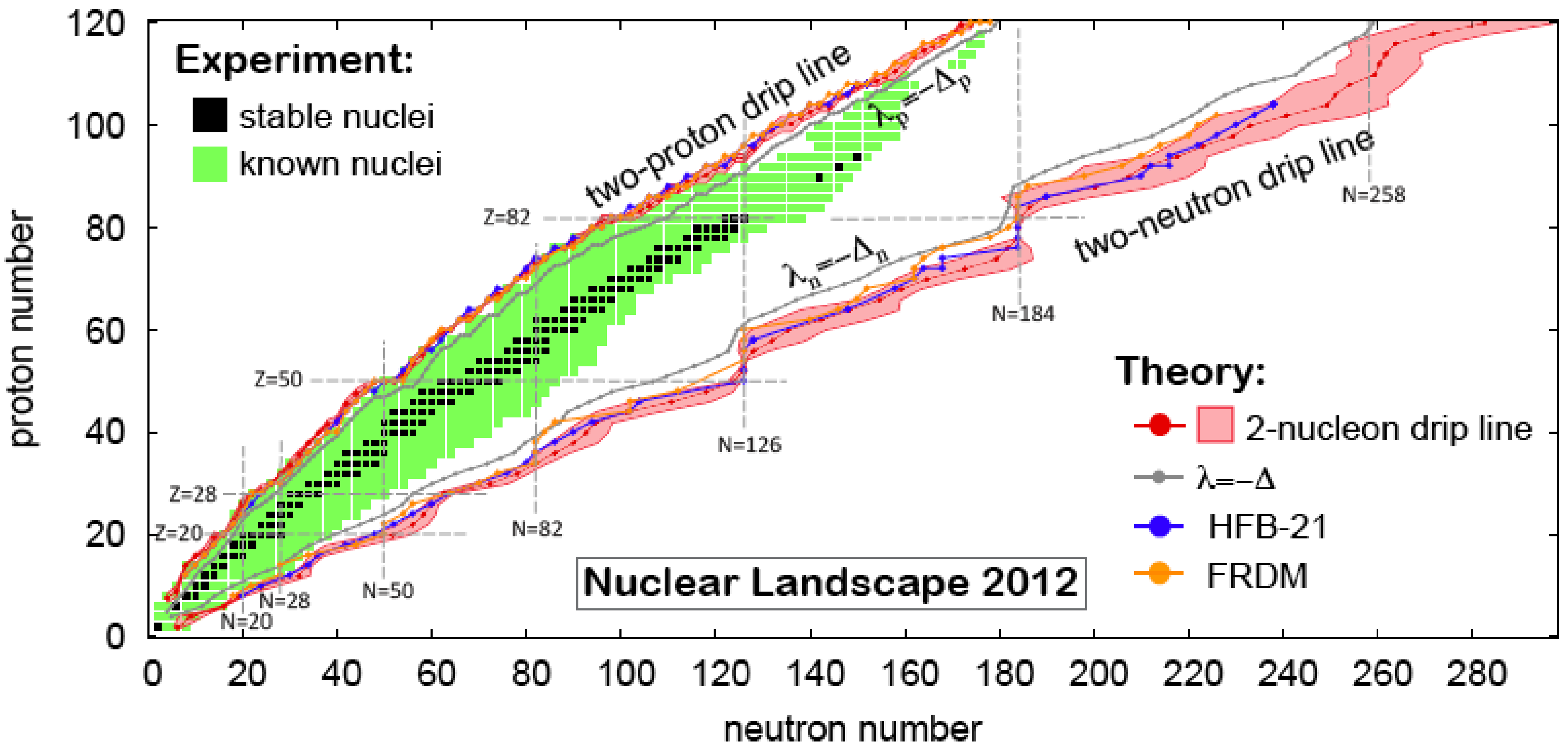
Nuclear Shells: No Magic Numbers in SHE?



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

Exploring the Limits of Nuclear Chart



Prediction: about 7000 nuclides exist

J. Erler et al., Nature 486, 509 (2012)

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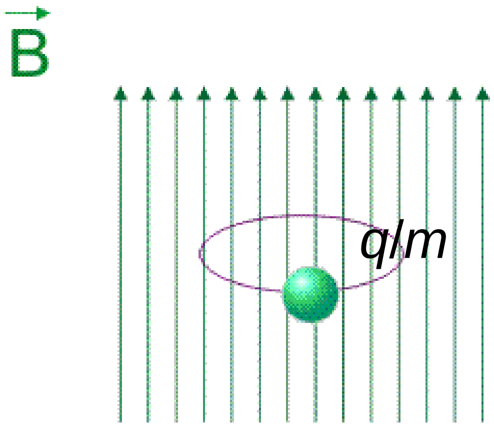
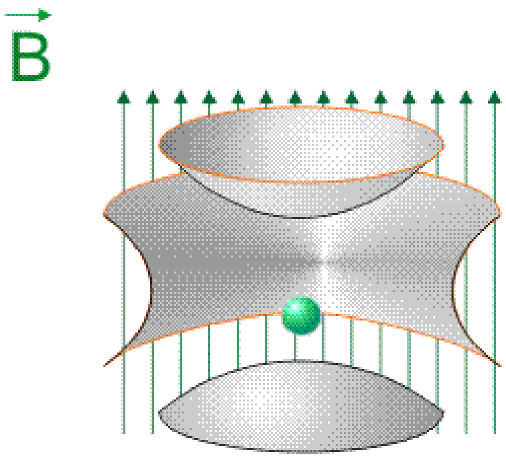
Principle of Penning Traps

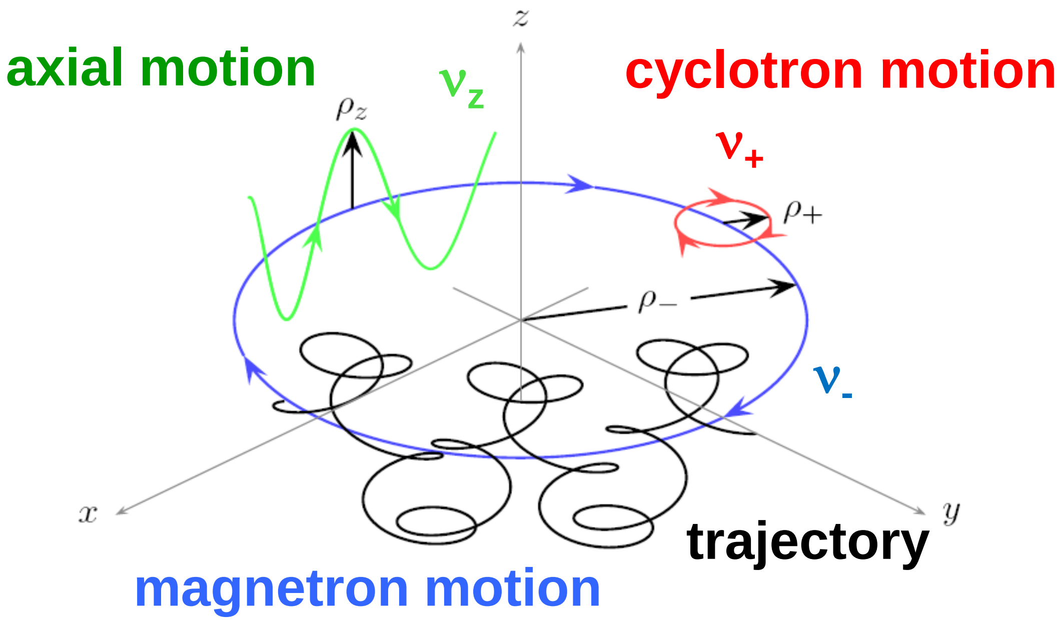
PENNING trap





- 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

Complementarity of Penning Traps

Type of Reacion	ISOL TRAP	CPT	SHIP TRAP	JYFL TRAP	LEBIT	TITAN	TRIGA TRAP	CARIBU	MLL TRAP	MATS @FAIR
ISOL	X					X			X	
Fusion		X	X							
IGISOL				X						
Fragm.					X					X
Neutron induced fission							X		X	
Spontaneous fission								X		X
HCI						X				X

Present Performance of PTMS for RIBs

- required yield: at present ≈1 particle per minute
- accessible half-life ≈10 ms
- relative mass uncertainty $\approx 10^{-8}$ (for mass doublets 10^{-9})
- required number of ions for a mass measurement ≈ 30

Yield often still not the limiting factor but contaminants

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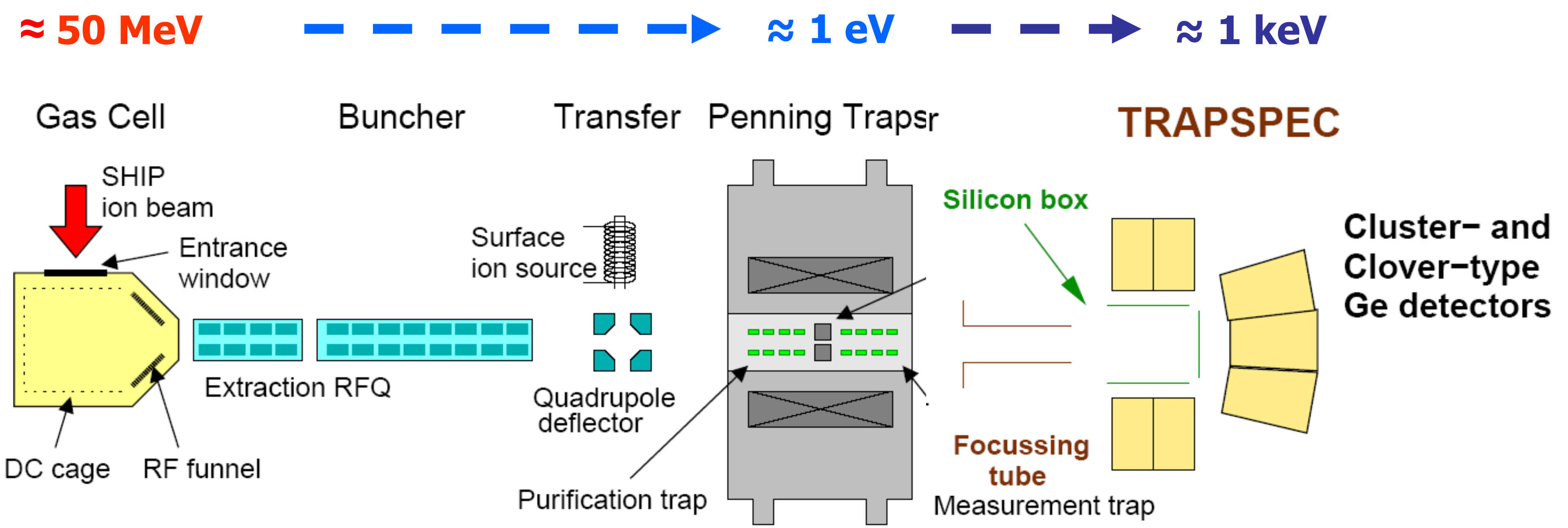
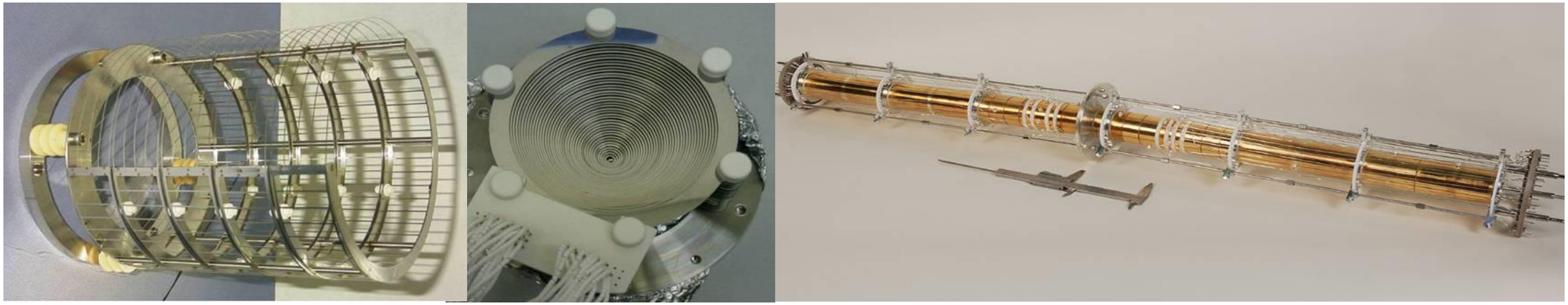
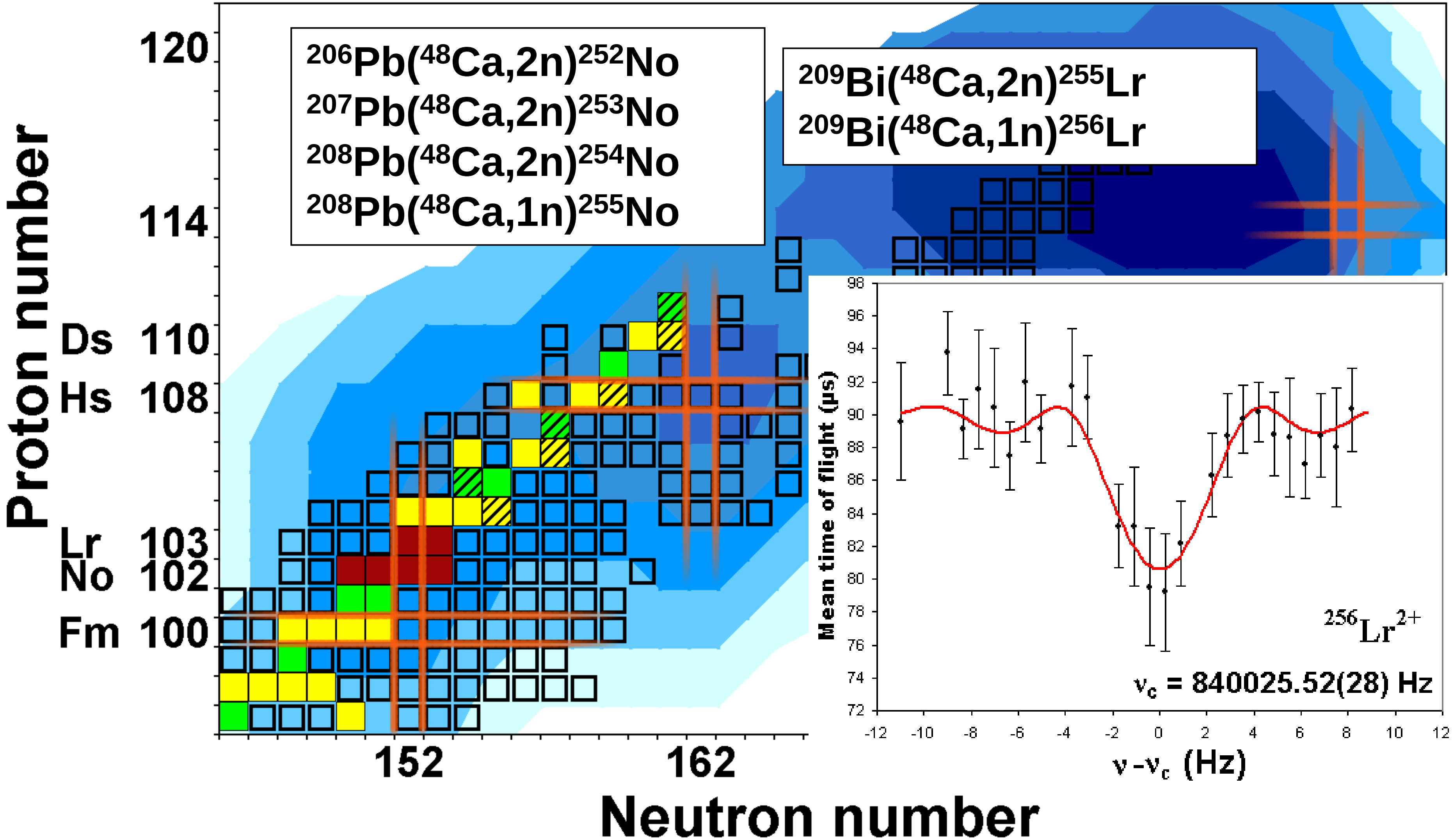
SHIPTRAP Setup



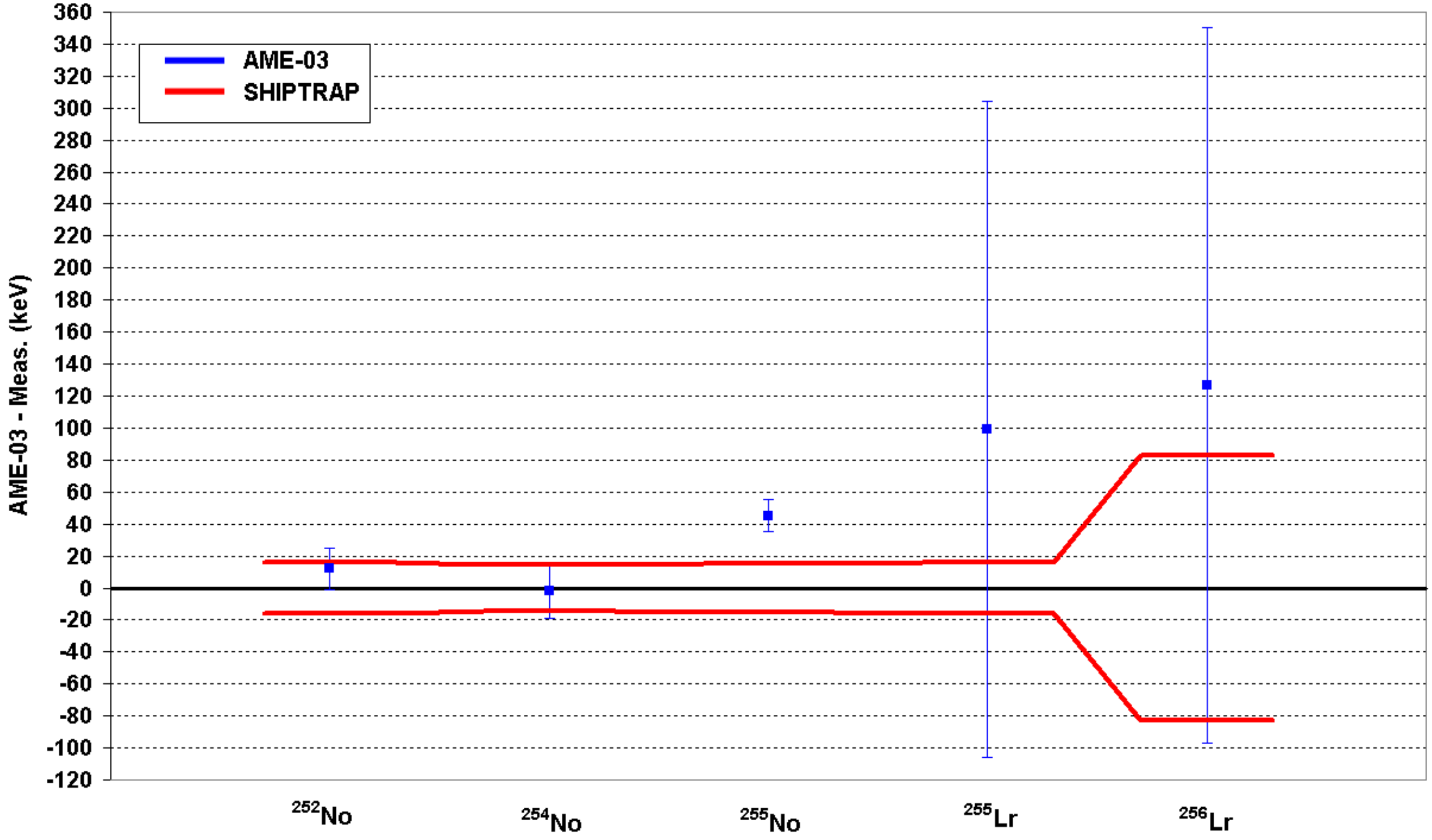


Direct mass measurements with SHIPTRAP

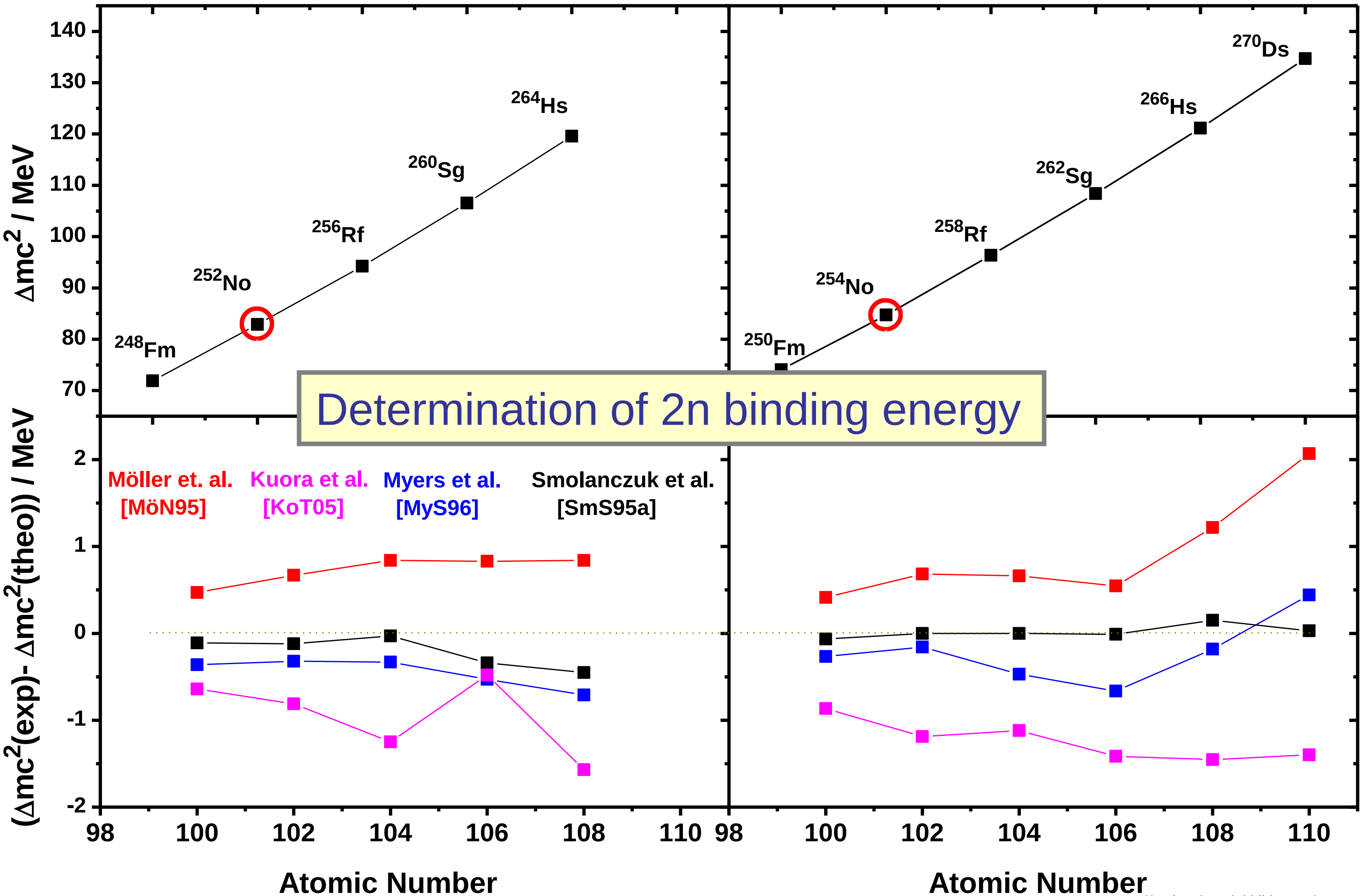


M. Block et al., Nature 463, 785 (2010), M. Dworschak et al., Phys. Rev. C 81, 064312 (2010)
E. Minaya Ramirez et al., Science 337, 1183 (2012)

Comparison of SHIPTRAP results to the AME



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



Determination of 2n binding energy

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

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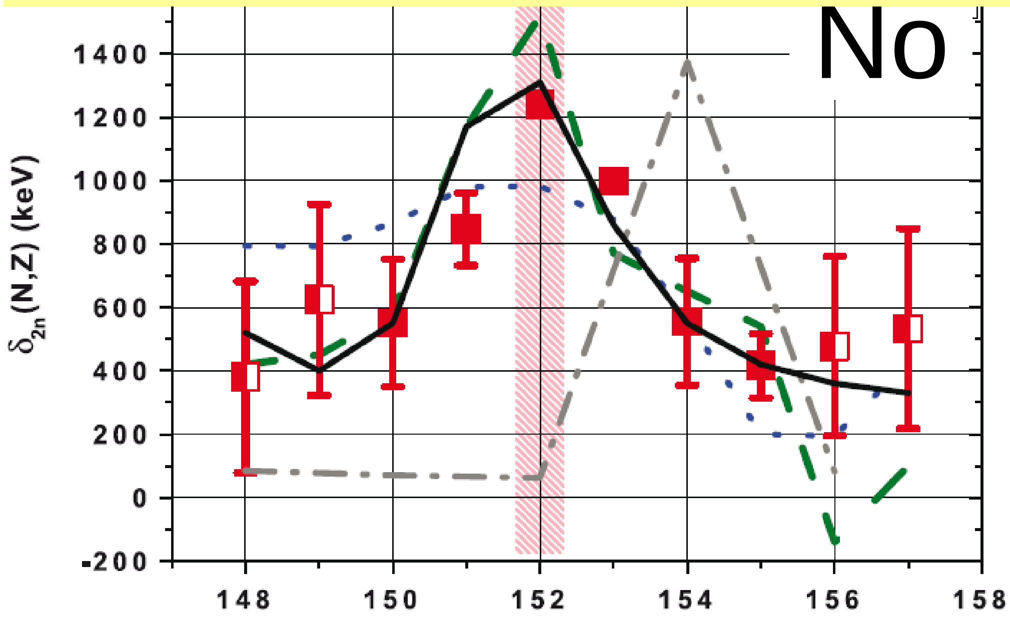
SHIPTRAP: Probing the Strength of Shell Effects

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]

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



Experimental

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

Möller FRDM Z=114 N=184

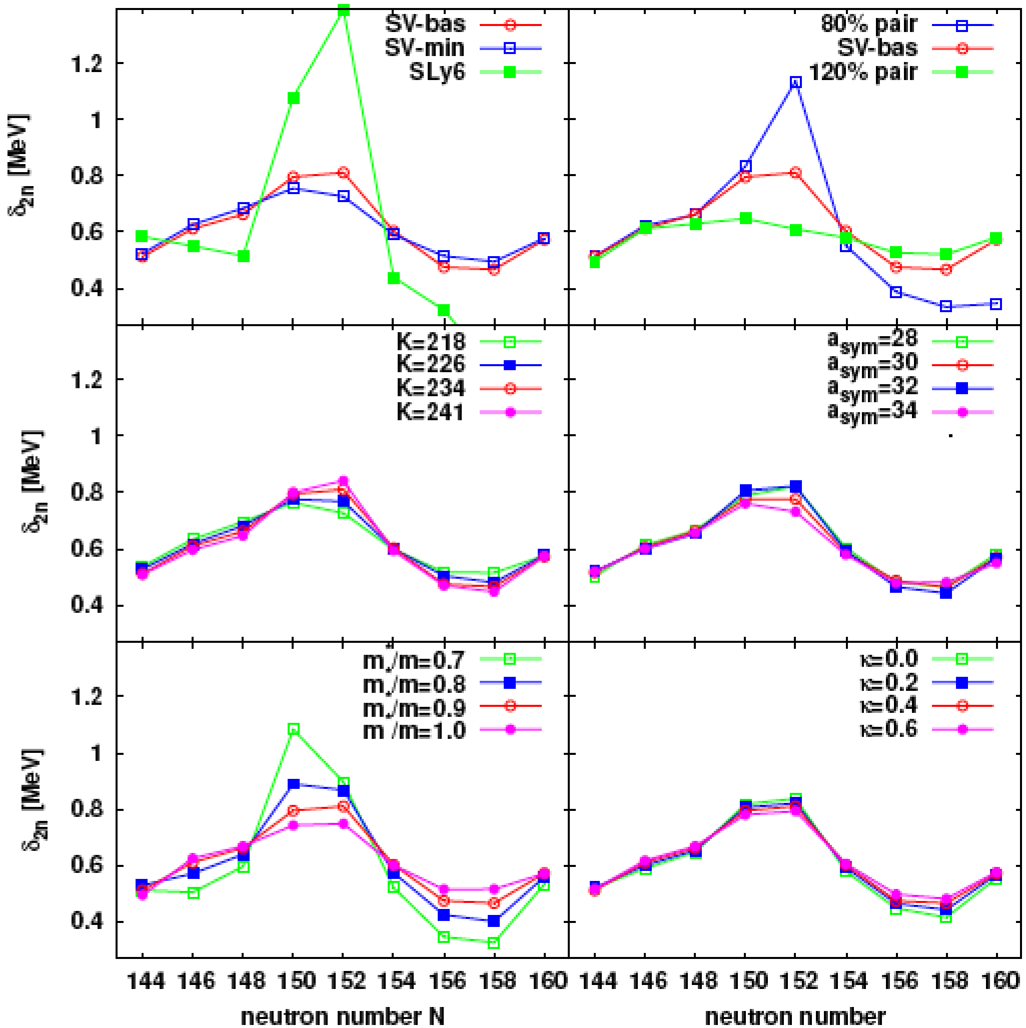
TW-99 Z=120 N=172

SkM* Z=126 N=184

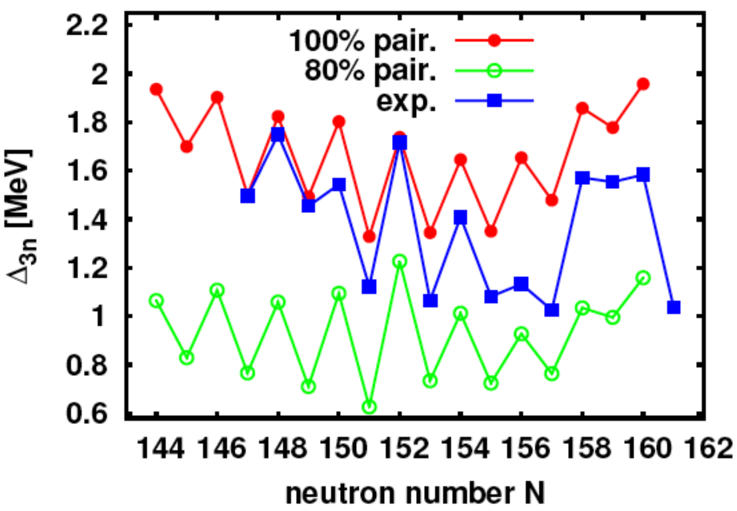
Science 337 (2012) 1207

Calculations with Skyrme Forces

No isotopes

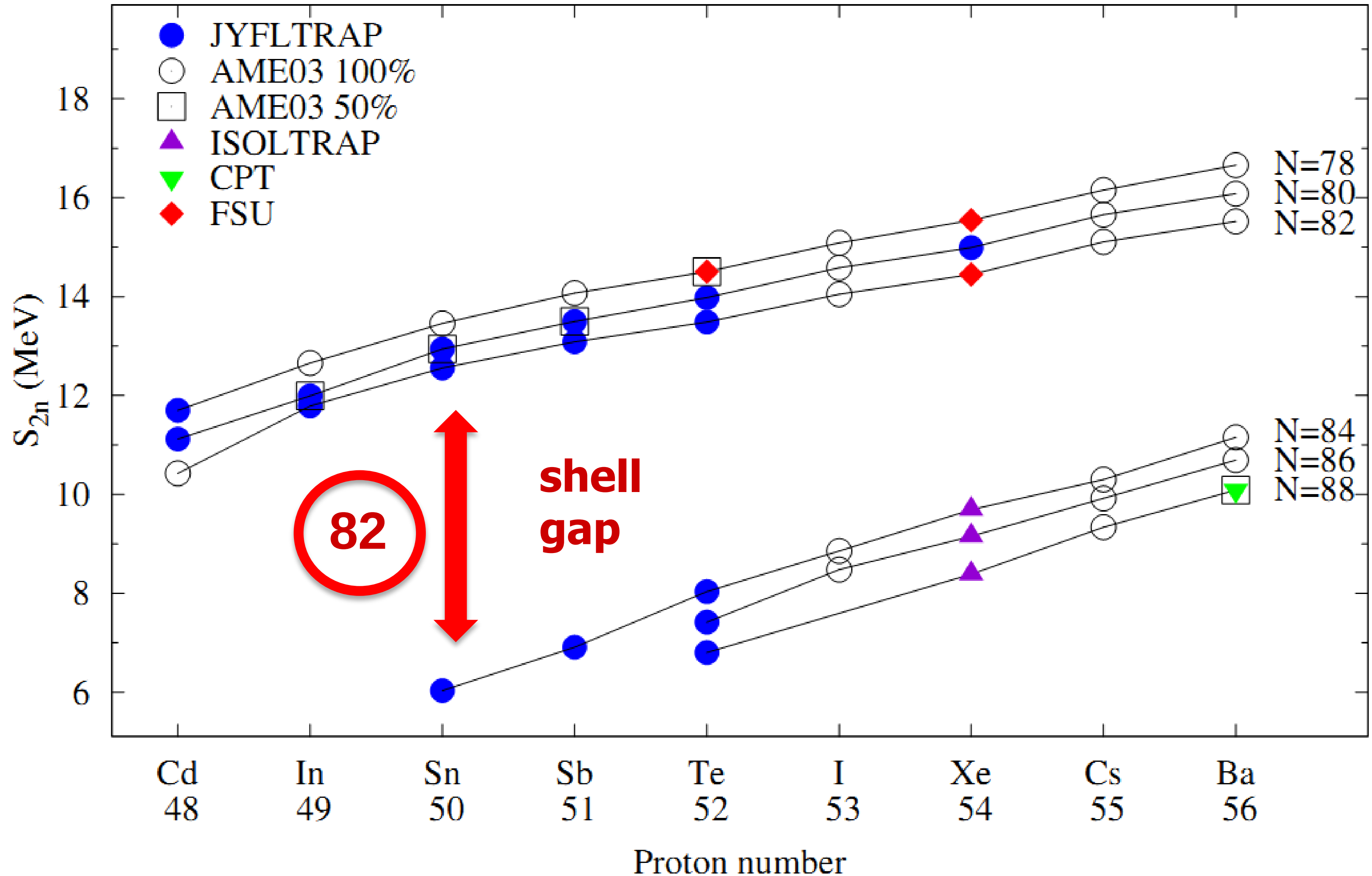


3-point difference (pairing gap), No isotopes



P. G. Reinhard

Shell Gap at N = 82 via S_{2n}



J. Hakala et al., PRL 2012
A. Kankainen et al., Phys. Rev. C 2013

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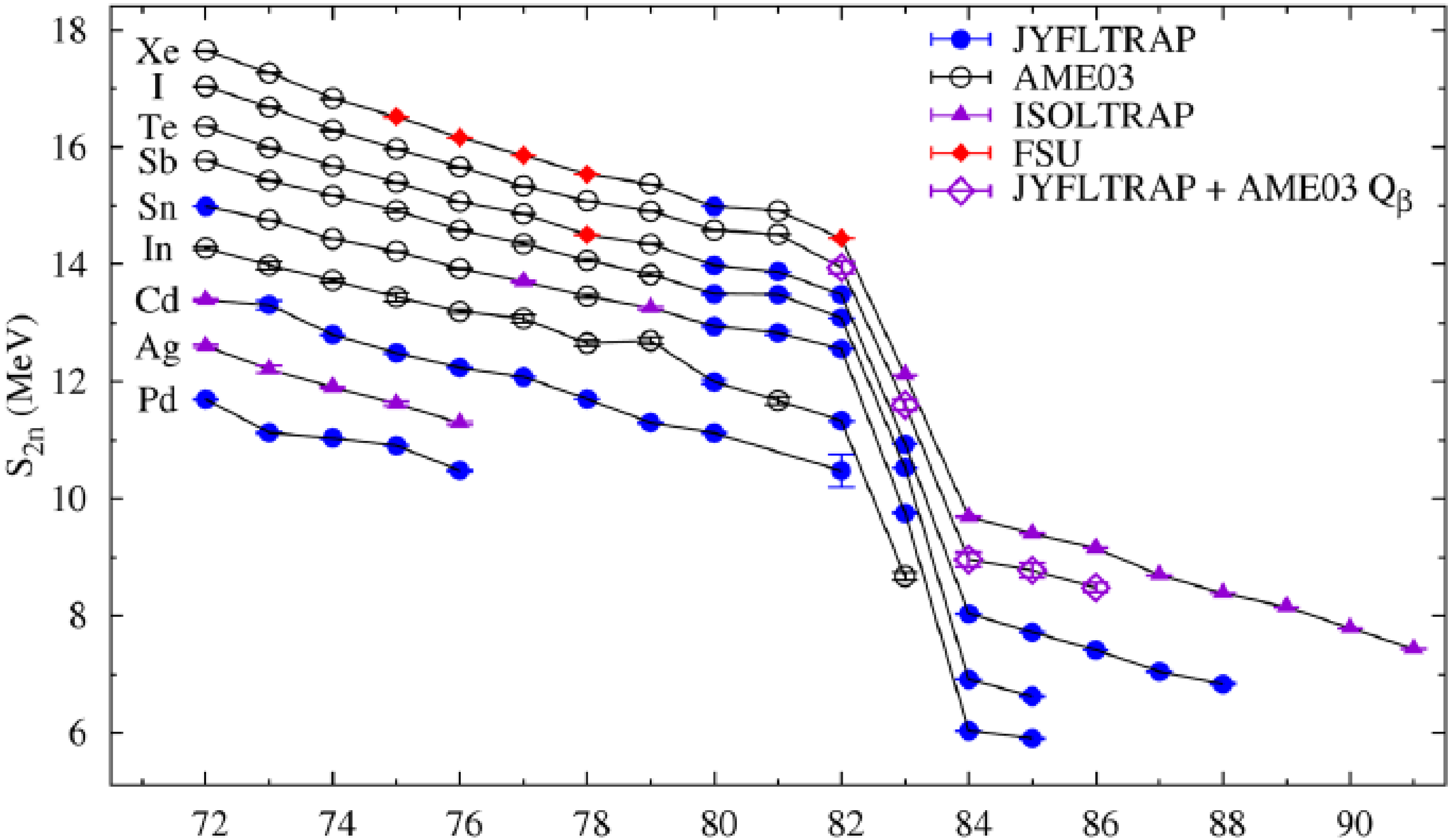
Shell Gap at N = 82 via S_{2n}



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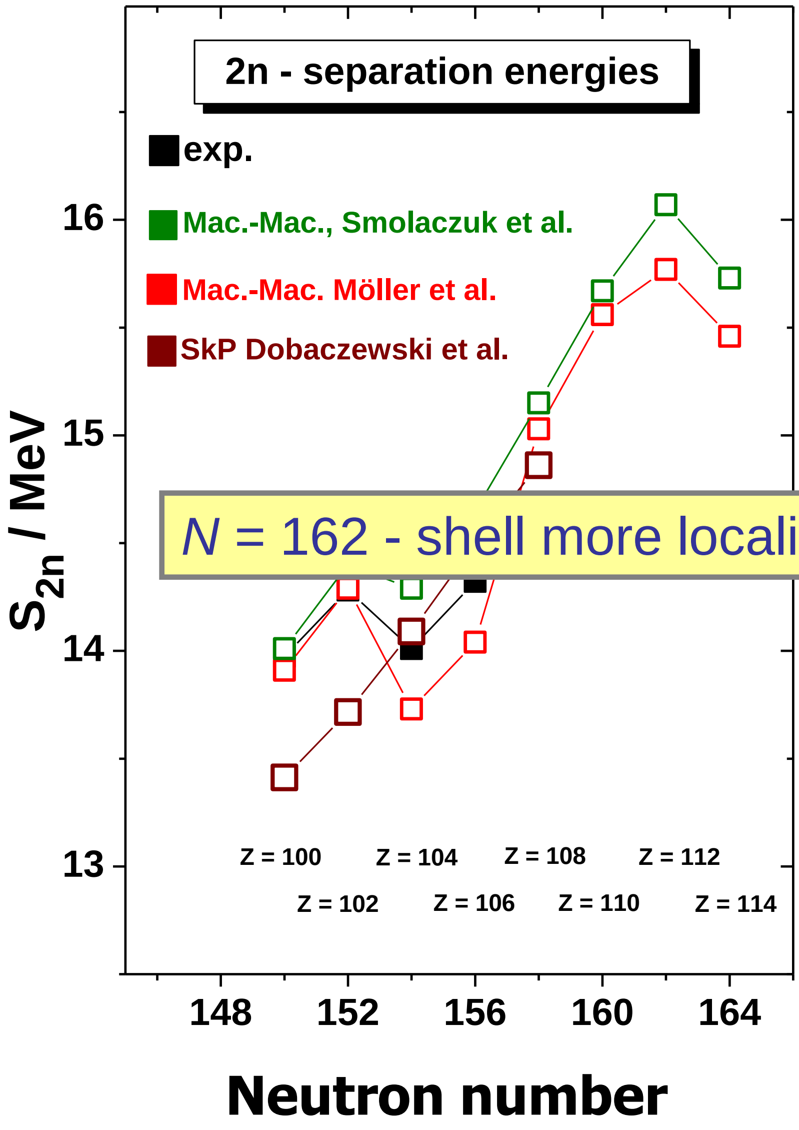
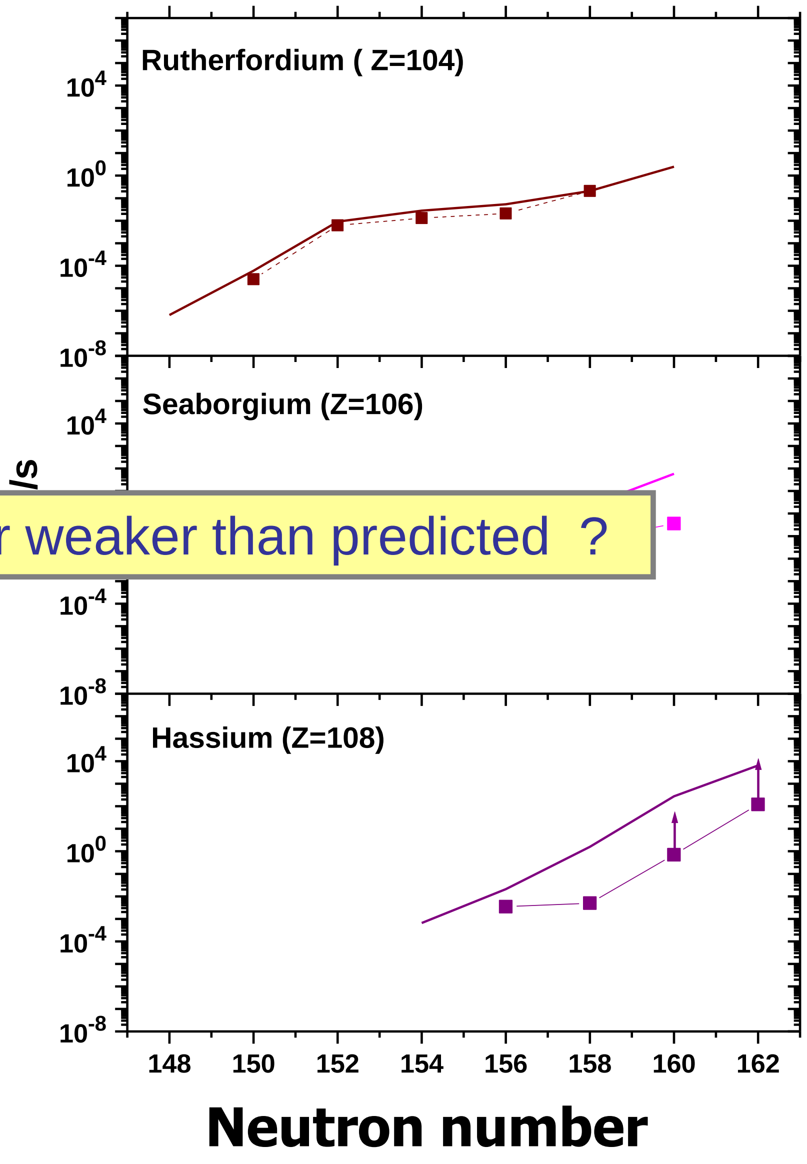
Shell strength towards $N = 162$

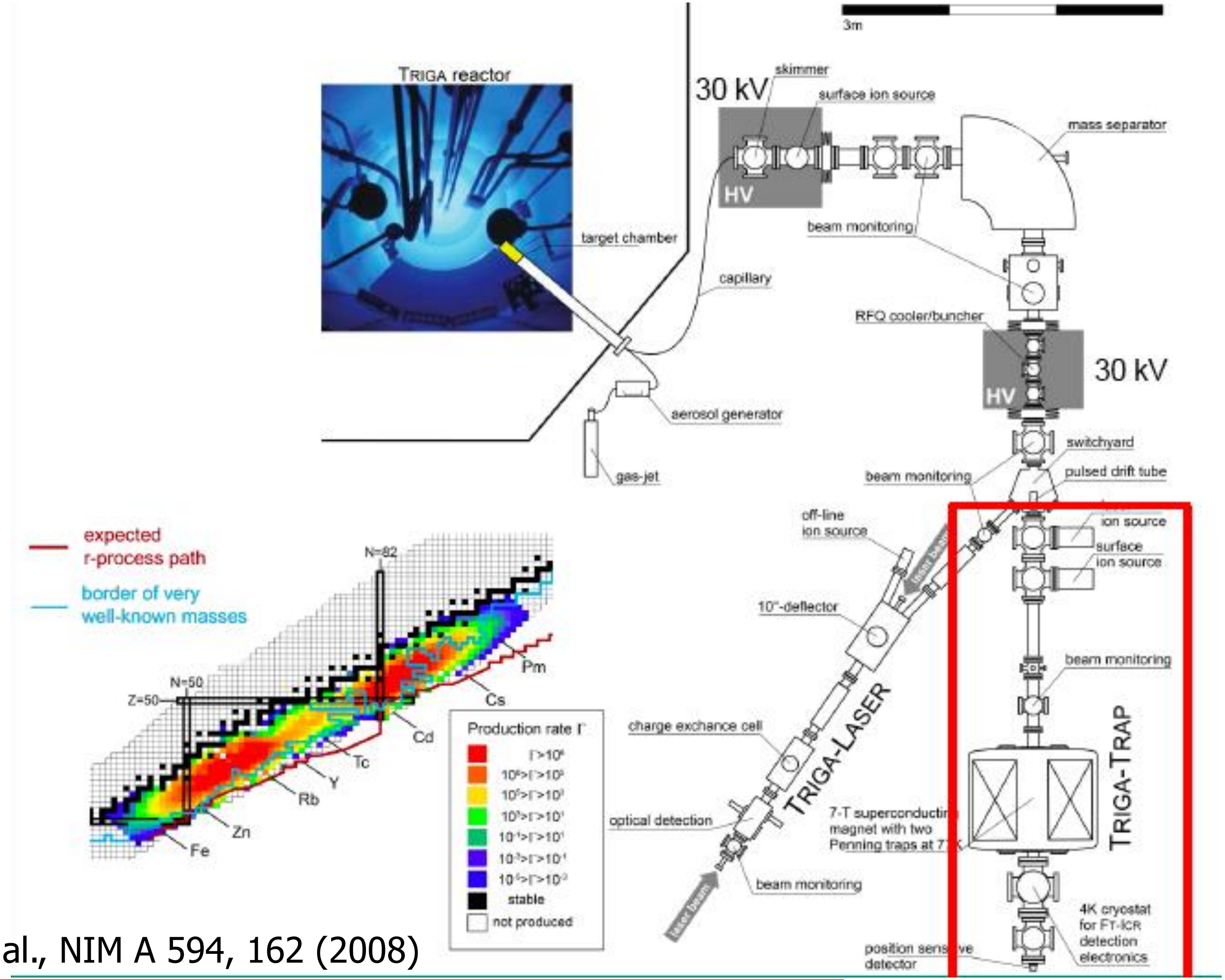




N = 162 - shell more localized or weaker than predicted ?

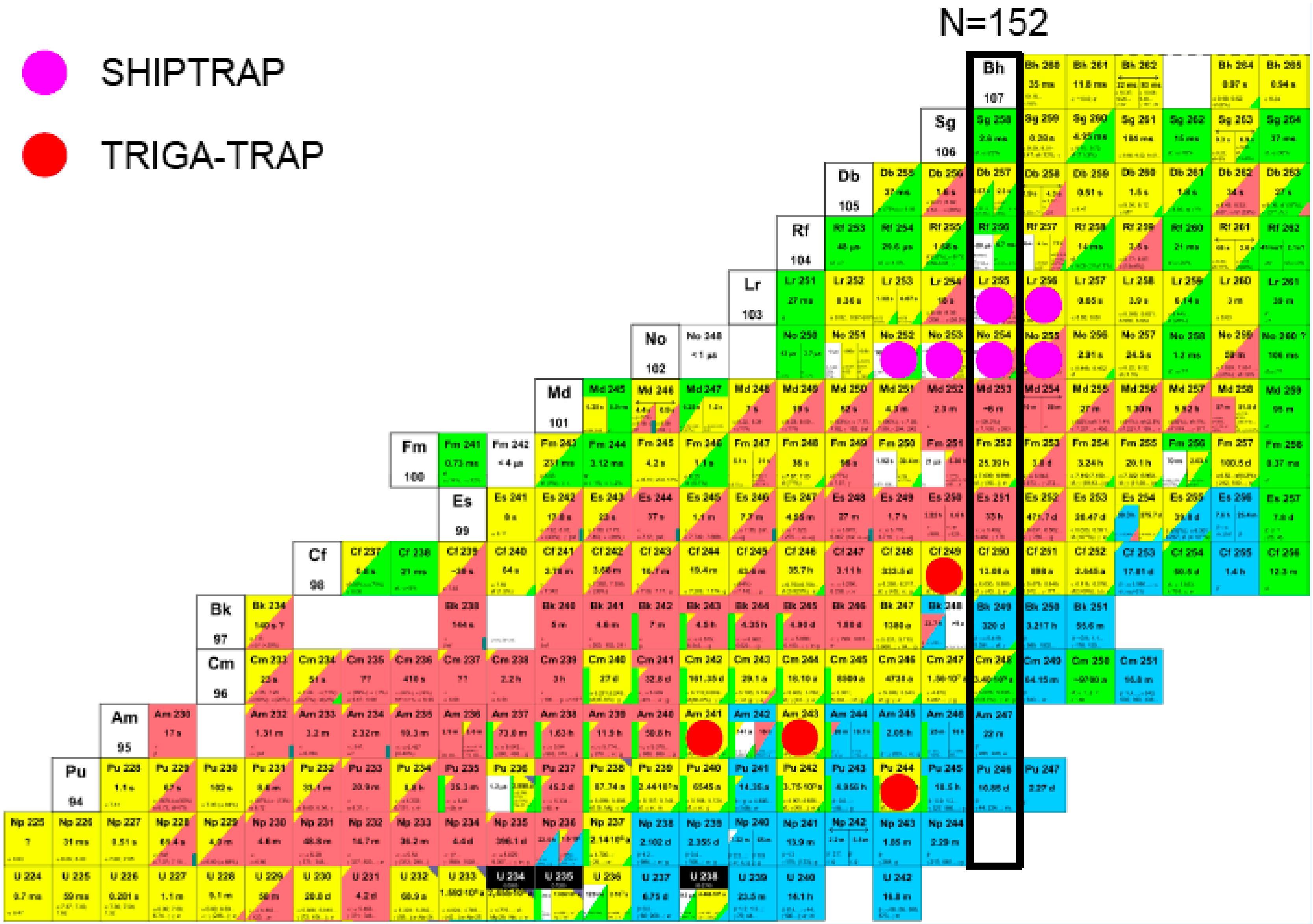
courtesy F. P. Hessberger

TRIGA-SPEC Setup in Mainz

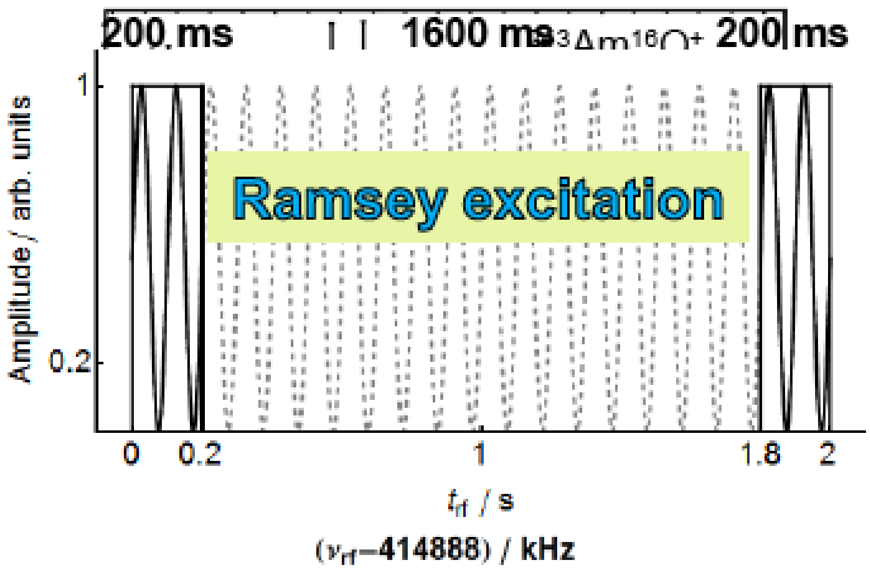


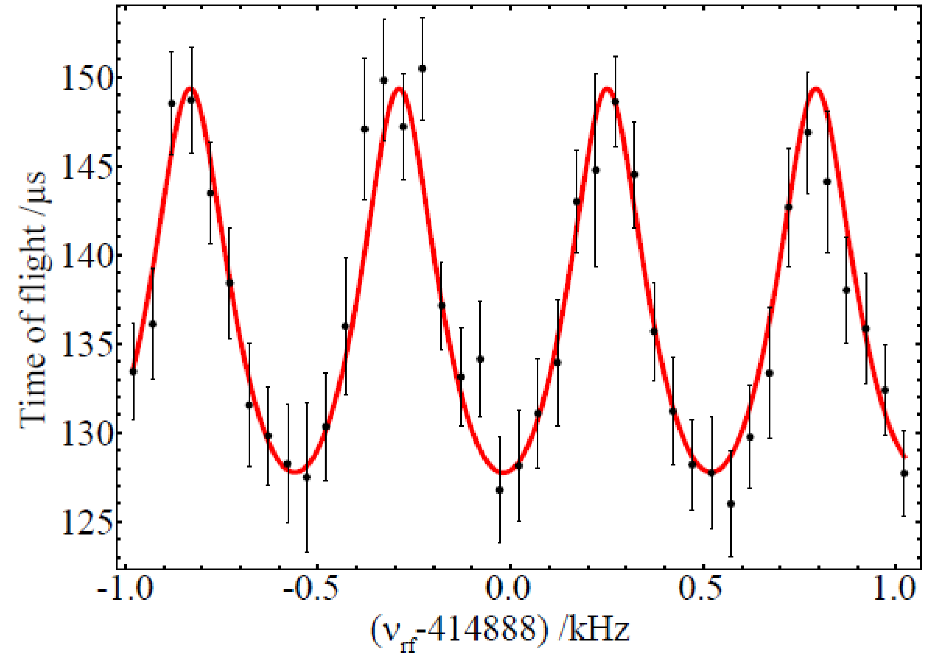
J. Ketelaer et al., NIM A 594, 162 (2008)

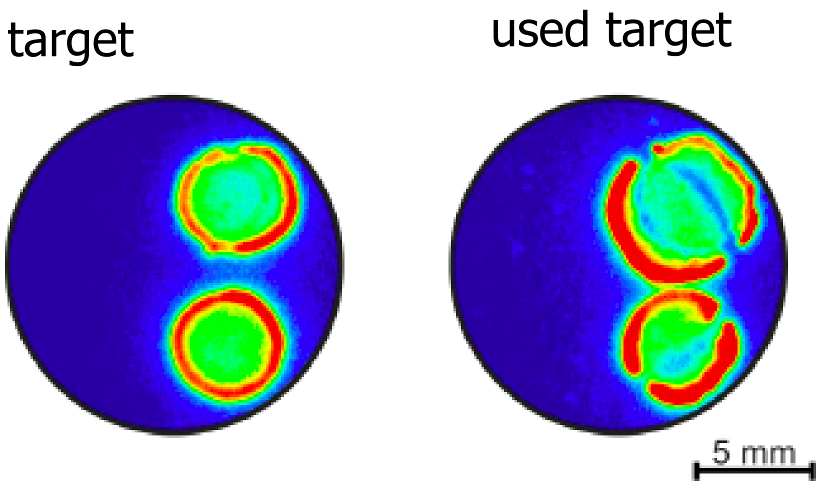
Probing the Strength of Shell Effects @ $N = 152$



TRIGA-TRAP Results 2013

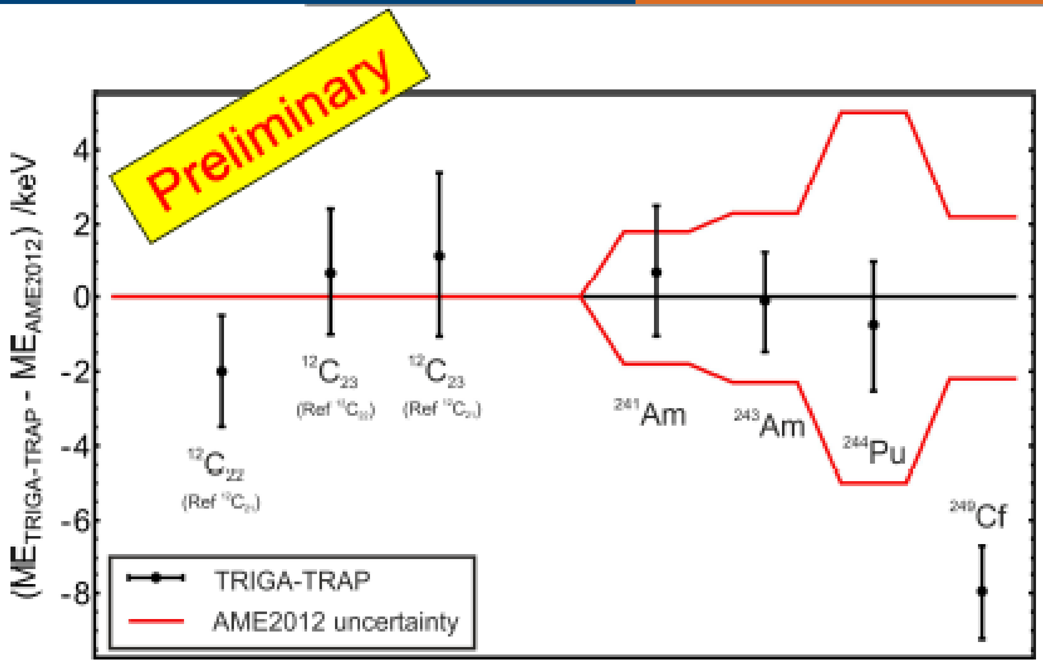


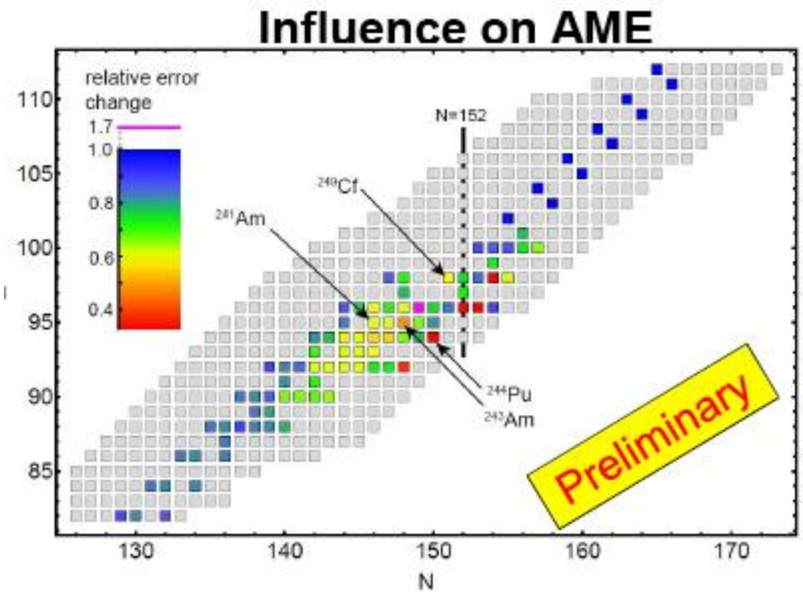




Mass measurement with only 10^{15} atoms target material.

Probing the Evolution of Shell Effects @ *N* =152





Accurate mass measurements with keV precision on long-lived actinides can be performed to provide anchor points and cross check masses obtained by other techniques

PhD thesis M.Eibach / submitted to Phys. Rev. C

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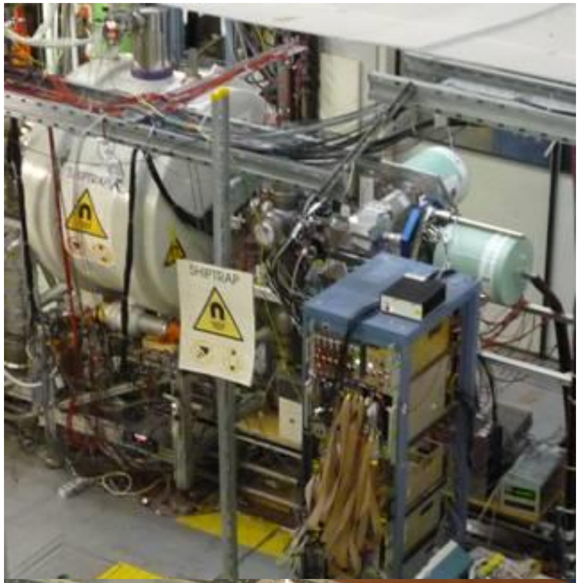
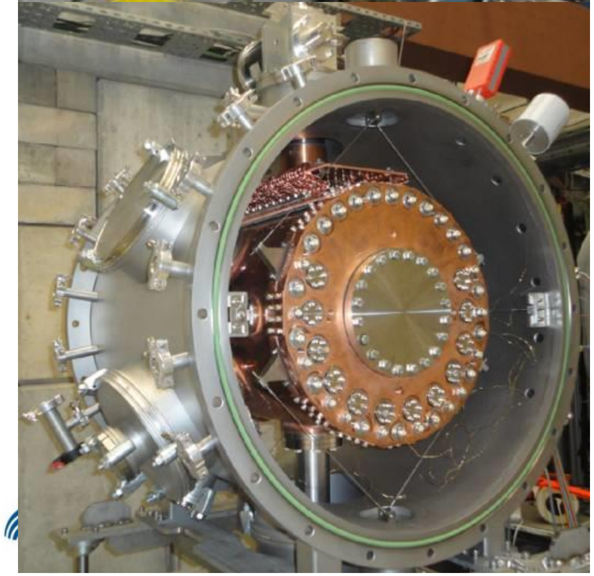
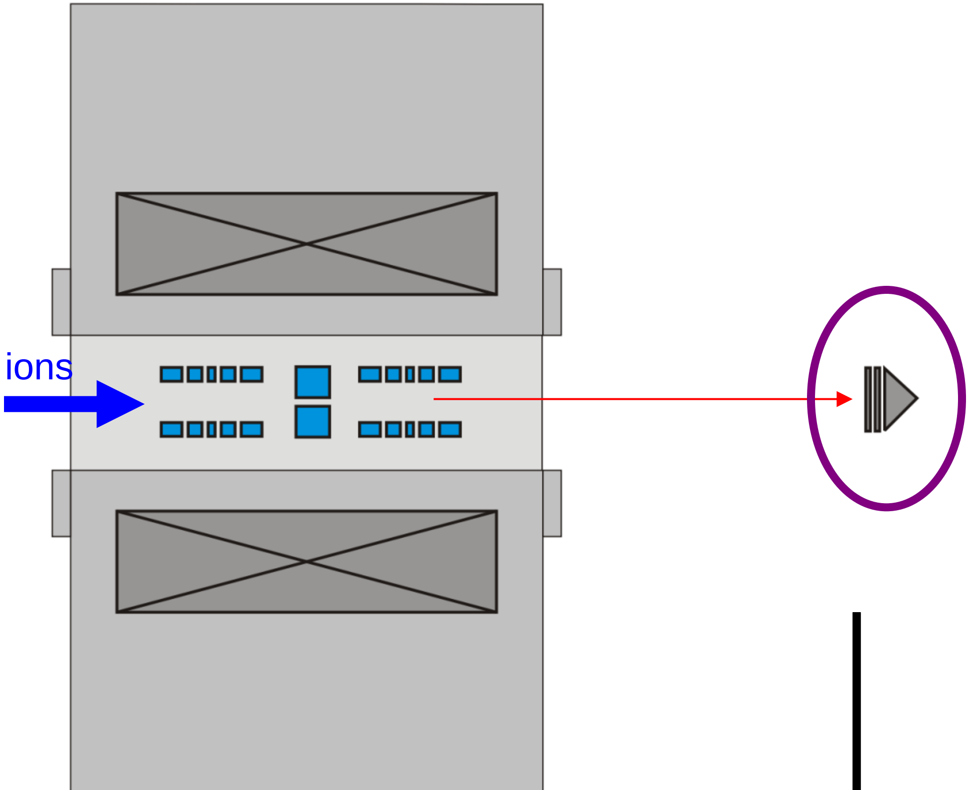
Improvements and Extensions

- **novel experiments**
  - trap-assisted decay spectroscopy
  - in-trap decay spectroscopy
  - in-trap and in-gas cell ion chemistry
- **increasing efficiency, sensitivity, and resolving power**
  - cryogenic gas stopper
  - single-ion mass measurement scheme
  - new measurement techniques

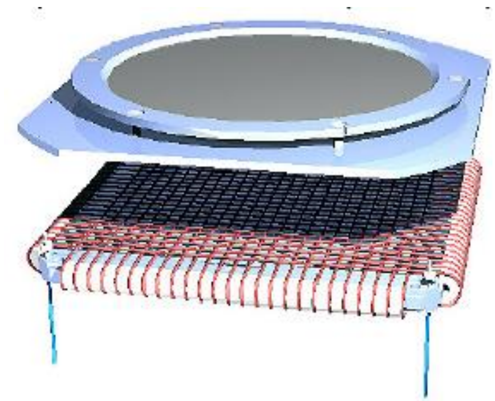




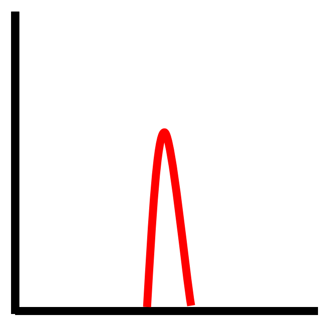
Phase Imaging Ion Cyclotron Resonance (PI-ICR)

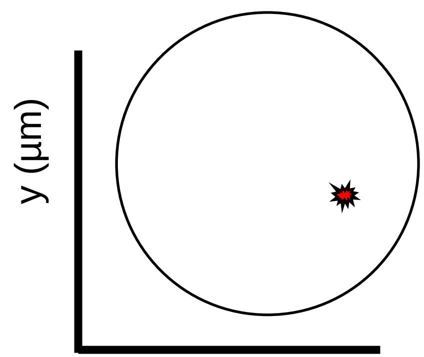


Delay-Line Detector by Roentdek GmbH



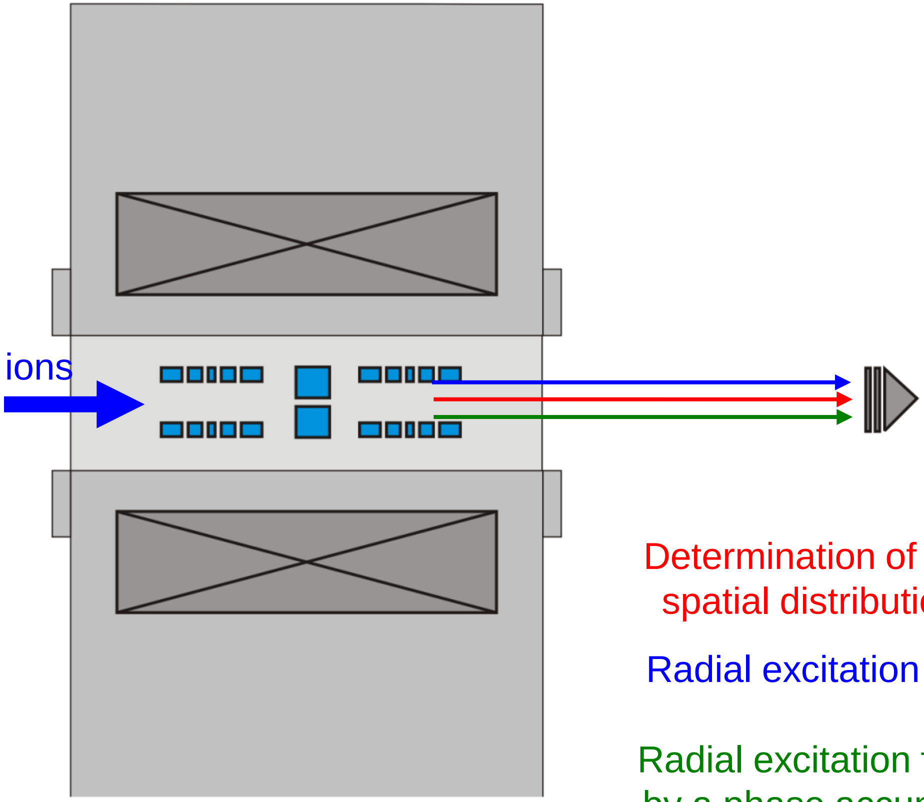
Position sensitive detector





- **position resolution : 70 µm**
- **active diameter : 42 mm**

Phase Imaging Ion Cyclotron Resonance (PI-ICR)

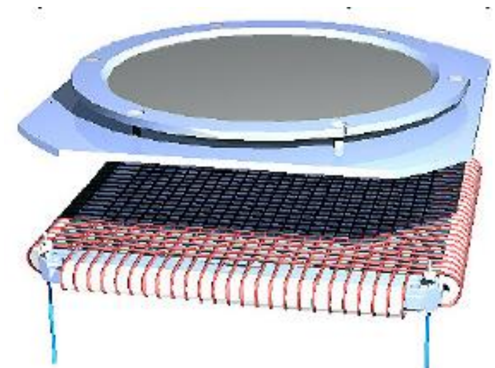


Determination of the spatial distribution

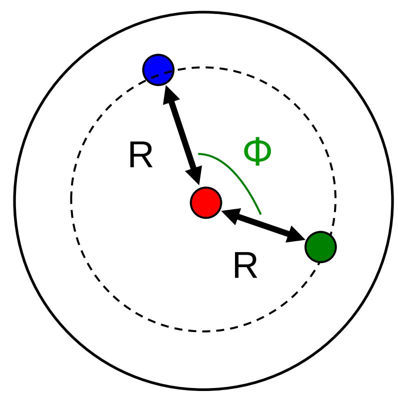
Radial excitation

Radial excitation followed by a phase accumulation time

Delay-Line Detector by Roentdek



Independent Measurements of Eigenfrequencies ν_+ and ν_-



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

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

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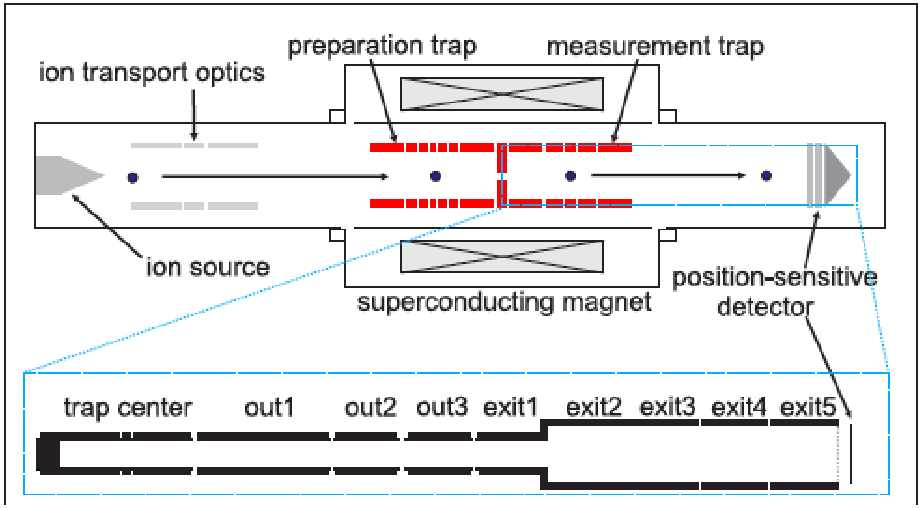
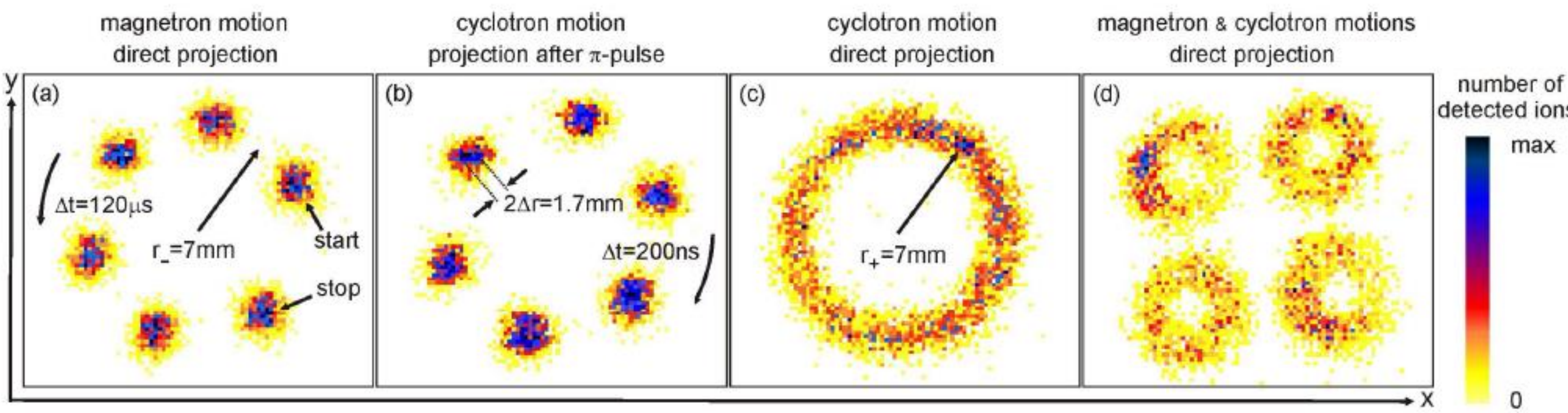
Phase Imaging-Ion Cyclotron Resonance Method



- Image ion motion
- Determine phase of ion motion
- Excite ions
- Determine phase after evolution time



S. Eliseev et al., Phys. Rev. Lett. 110, 082501 (2013)
S. Eliseev et al., Appl. Phys. B (2013) in press

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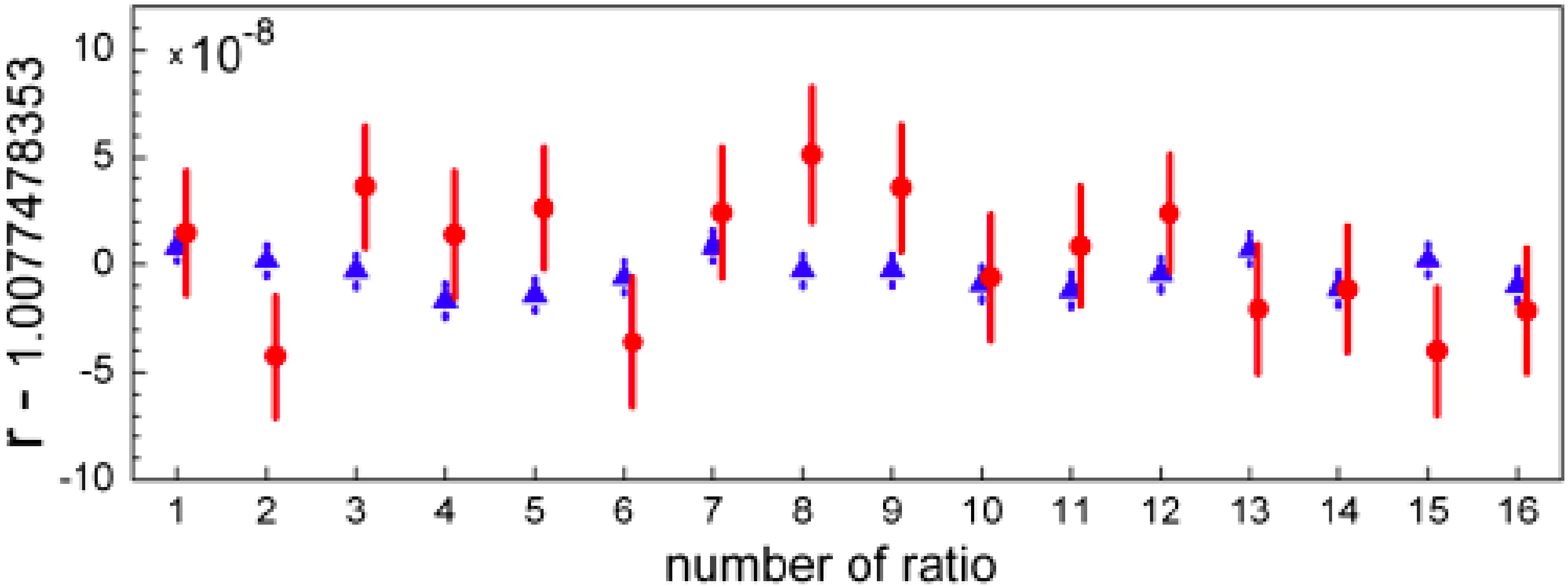
Phase Imaging-Ion Cyclotron Resonance



^{129}Xe-^{130}Xe mass difference $\Delta m_{SHIPTRAP\text{-}FSU} = 180(240)$ eV

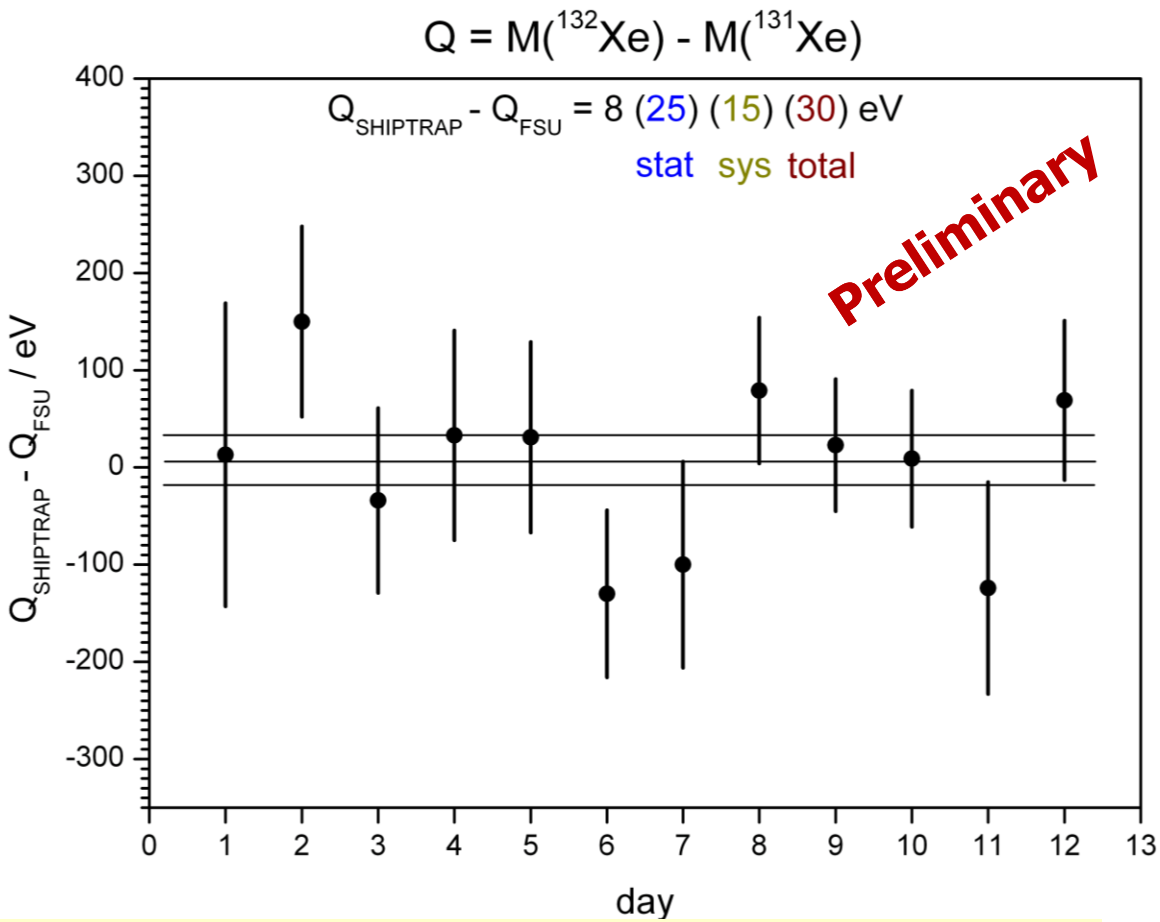
Improved performance compared to conventional method:

- **40x gain in resolving power**
- **5x gain in precision**

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

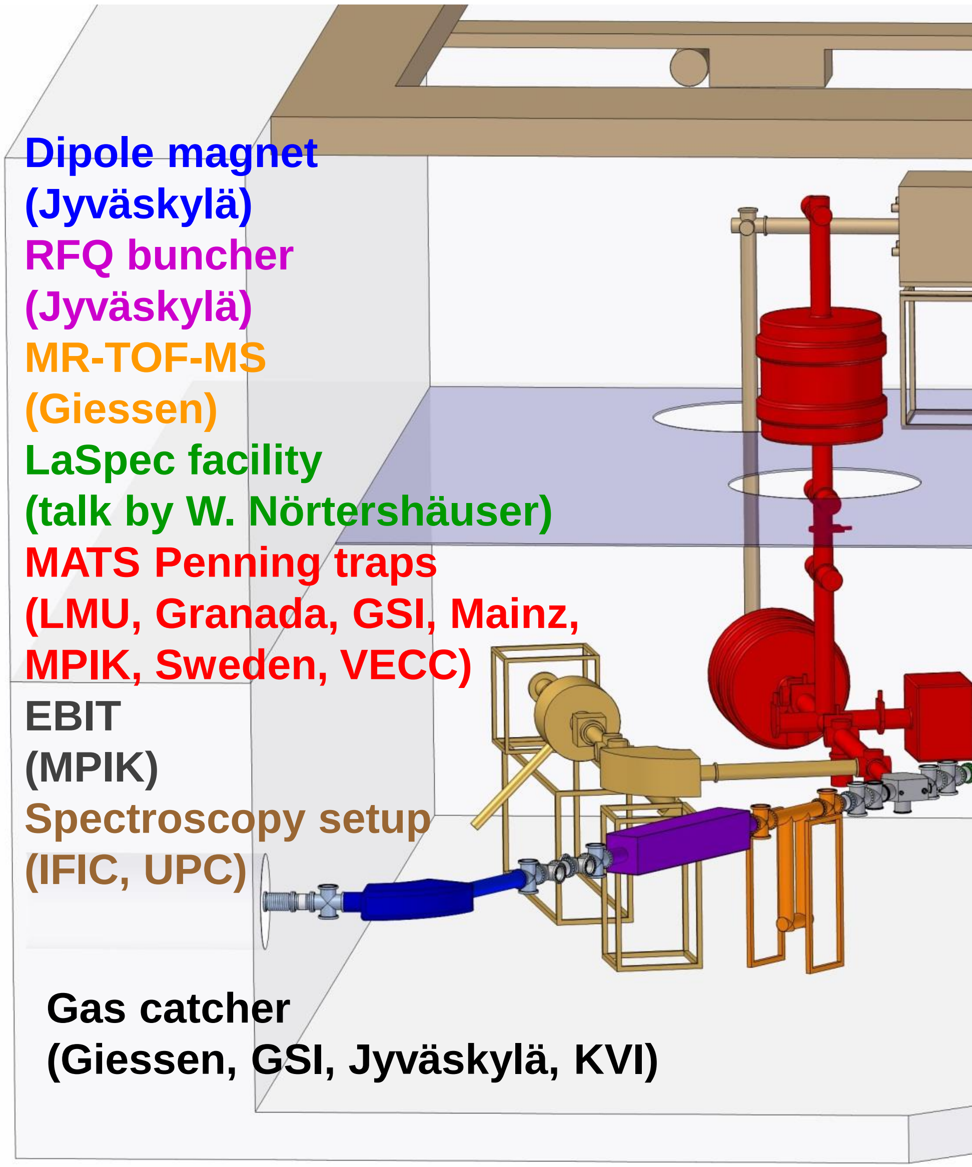
Phase Imaging-Ion Cyclotron Resonance

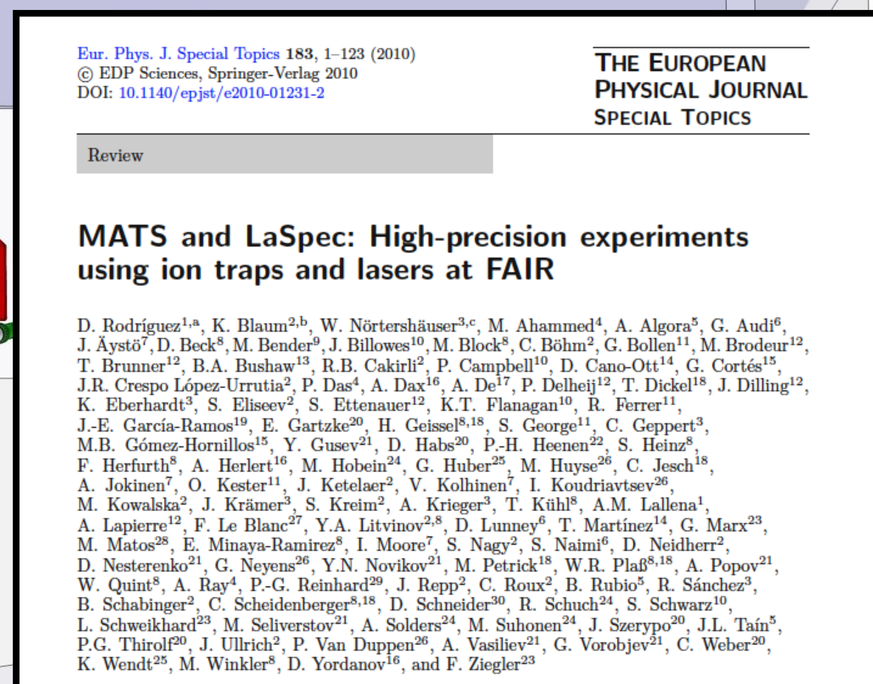
Outstanding performance of PI-ICR technique
$\delta m \approx 10^{-9}$ for stable xenon isotopes demonstrated



Next step: 187-Re/187-Os Q value measurement (ongoing)

Future at FAIR: MATS
TDR approved by FAIR STI in May 2010





Eur. Phys. J. Special Topics **183**, 1–123 (2010)
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DOI: 10.1140/epjst/e2010-01231-2

THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

Review

MATS and LaSpec: High-precision experiments using ion traps and lasers at FAIR

D. Rodríguez[1,a], K. Blaum[2,b], W. Nörtershäuser[3,c], M. Ahammed[4], A. Algora[5], G. Audi[6], J. Äystö[7], D. Beck[8], M. Bender[9], J. Billowes[10], M. Block[8], C. Böhm[2], G. Bollen[11], M. Brodeur[12], T. Brunner[12], B.A. Bushaw[13], R.B. Cakirli[2], P. Campbell[10], D. Cano-Ott[14], G. Cortés[15], J.R. Crespo López-Urrutia[2], P. Das[4], A. Dax[16], A. De[17], P. Delheij[12], T. Dickel[18], J. Dilling[12], K. Eberhardt[3], S. Eliseev[2], S. Ettenauer[12], K.T. Flanagan[10], R. Ferrer[11], J.-E. García-Ramos[19], E. Gartzke[20], H. Geissel[8,18], S. George[11], C. Geppert[3], M.B. Gómez-Hornillos[15], Y. Gusev[21], D. Habs[20], P.-H. Heenen[22], S. Heinz[8], F. Herfurth[8], A. Herlert[16], M. Hobein[24], G. Huber[25], M. Huyse[26], C. Jesch[18], A. Jokinen[7], O. Kester[11], J. Ketelaer[2], V. Kolhinen[7], I. Koudriavtsev[26], M. Kowalska[2], J. Krämer[3], S. Kreim[2], A. Krieger[3], T. Kühl[8], A.M. Lallena[1], A. Lapierre[12], F. Le Blanc[27], Y.A. Litvinov[2,8], D. Lunney[6], T. Martínez[14], G. Marx[23], M. Matos[28], E. Minaya-Ramirez[8], I. Moore[7], S. Nagy[2], S. Naimi[6], D. Neidherr[2], D. Nesterenko[21], G. Neyens[26], Y.N. Novikov[21], M. Petrick[18], W.R. Plaß[8,18], A. Popov[21], W. Quint[8], A. Ray[4], P.-G. Reinhard[29], J. Repp[2], C. Roux[2], B. Rubio[5], R. Sánchez[3], B. Schabinger[2], C. Scheidenberger[8,18], D. Schneider[30], R. Schuch[24], S. Schwarz[10], L. Schweikhard[23], M. Seliverstov[21], A. Solders[24], M. Suhonen[24], J. Szerypo[20], J.L. Taín[5], P.G. Thirolf[20], J. Ullrich[2], P. Van Duppen[26], A. Vasiliev[21], G. Vorobjev[21], C. Weber[20], K. Wendt[25], M. Winkler[8], D. Yordanov[16], and F. Ziegler[23]

Conclusions

Ion traps are powerful tools for nuclear structure studies

- mass measurements for yields of ≈ 1 / min demonstrated
- novel techniques increase sensitivity, resolving power, and accuracy
- Powerful tool to track shell structure evolution
- precise Manipulation and purification of samples for trap-assisted decay spectroscopy (state-selected beams) possible
- push towards more exotic (short-lived) nuclides at next-generation RIB facilities

Thank you for your attention !

The SHIPTRAP collaboration 2010

GSI

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LUND UNIVERSITY

LMU

Max-Planck-Institut für Kernphysik

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

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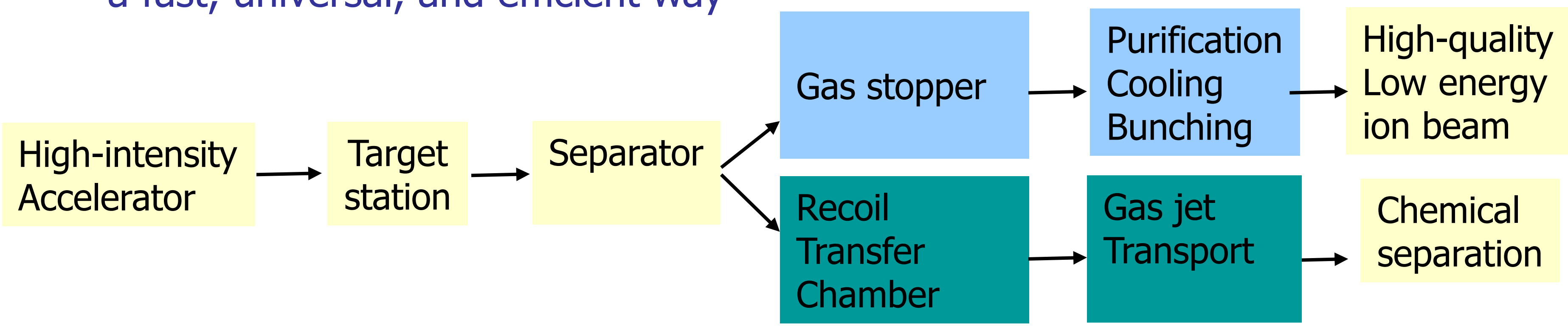
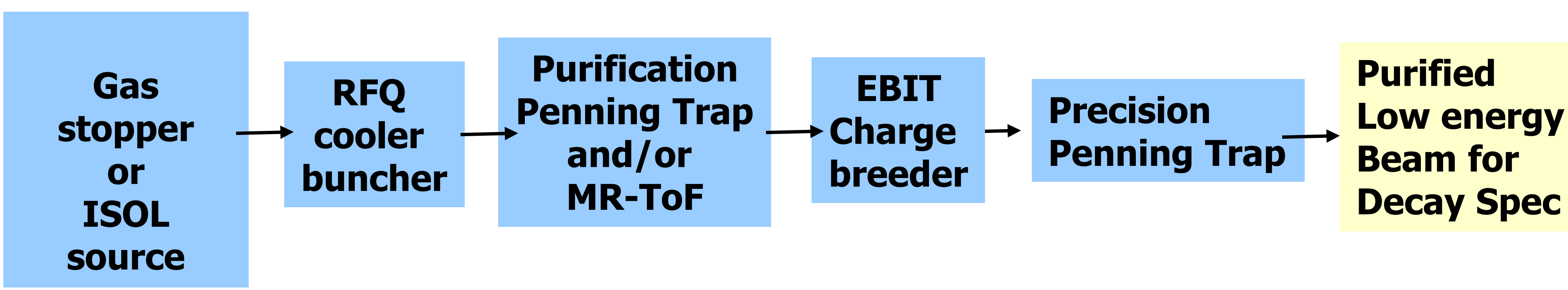
Preparing Rare Isotopes for Precision Experiments

Task: prepare rare isotopes of all elements for experiments at low-energy in a fast, universal, and efficient way





Gas cells successfully employed at Caribu/Argonne, SHIPTRAP/GSI, IGISOL/JYFL, LISOL/Louvain-la-Neuve, and for fragment beams at NSCL/MSU, RIKEN, FRS/GSI

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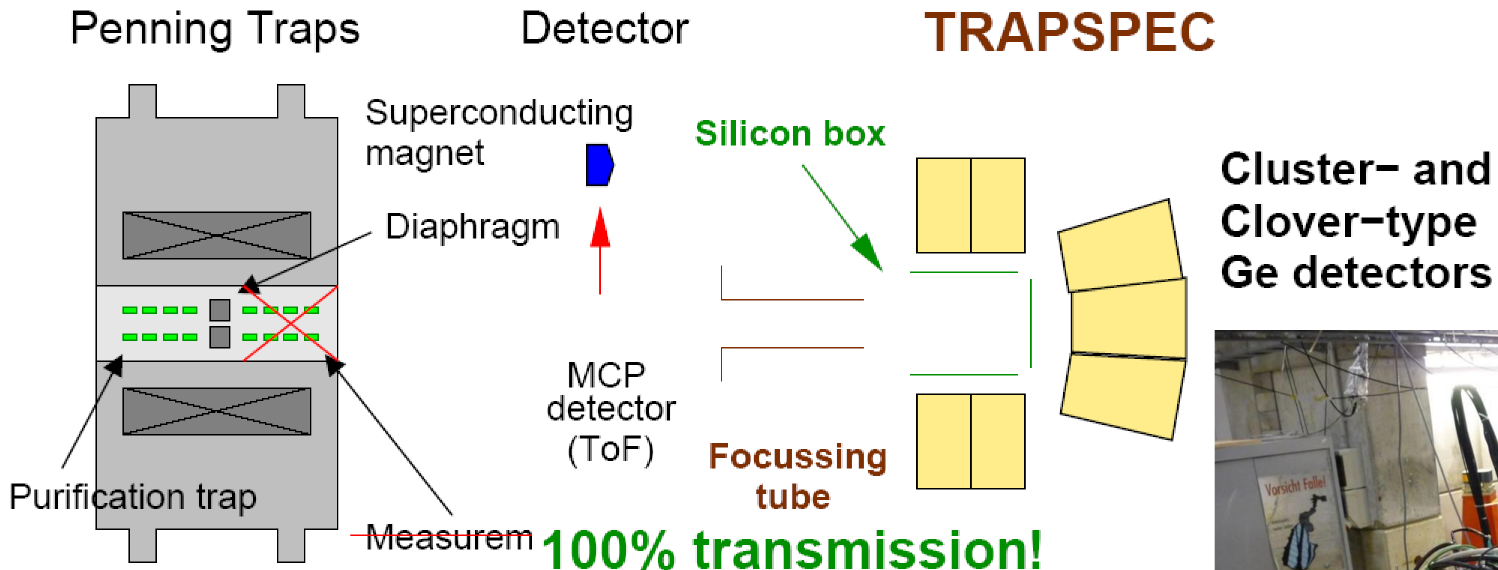
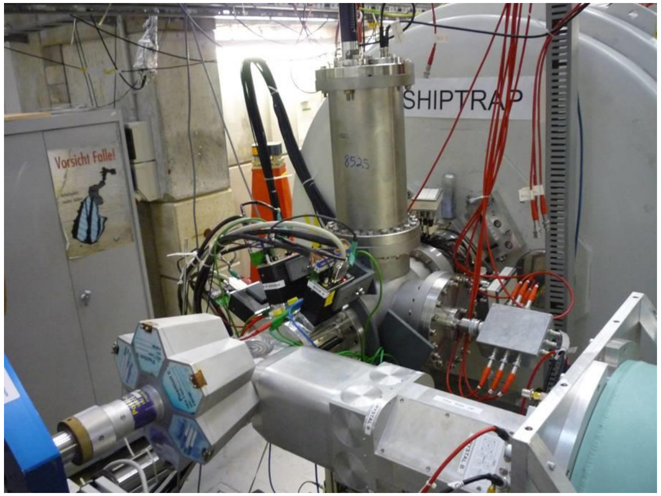
TRAPSPEC: Trap-assisted Spectroscopy



100% transmission!



Penning trap as high-resolution mass separator to prepare state-selected pure sample

M. B., D. Rudolph et al.

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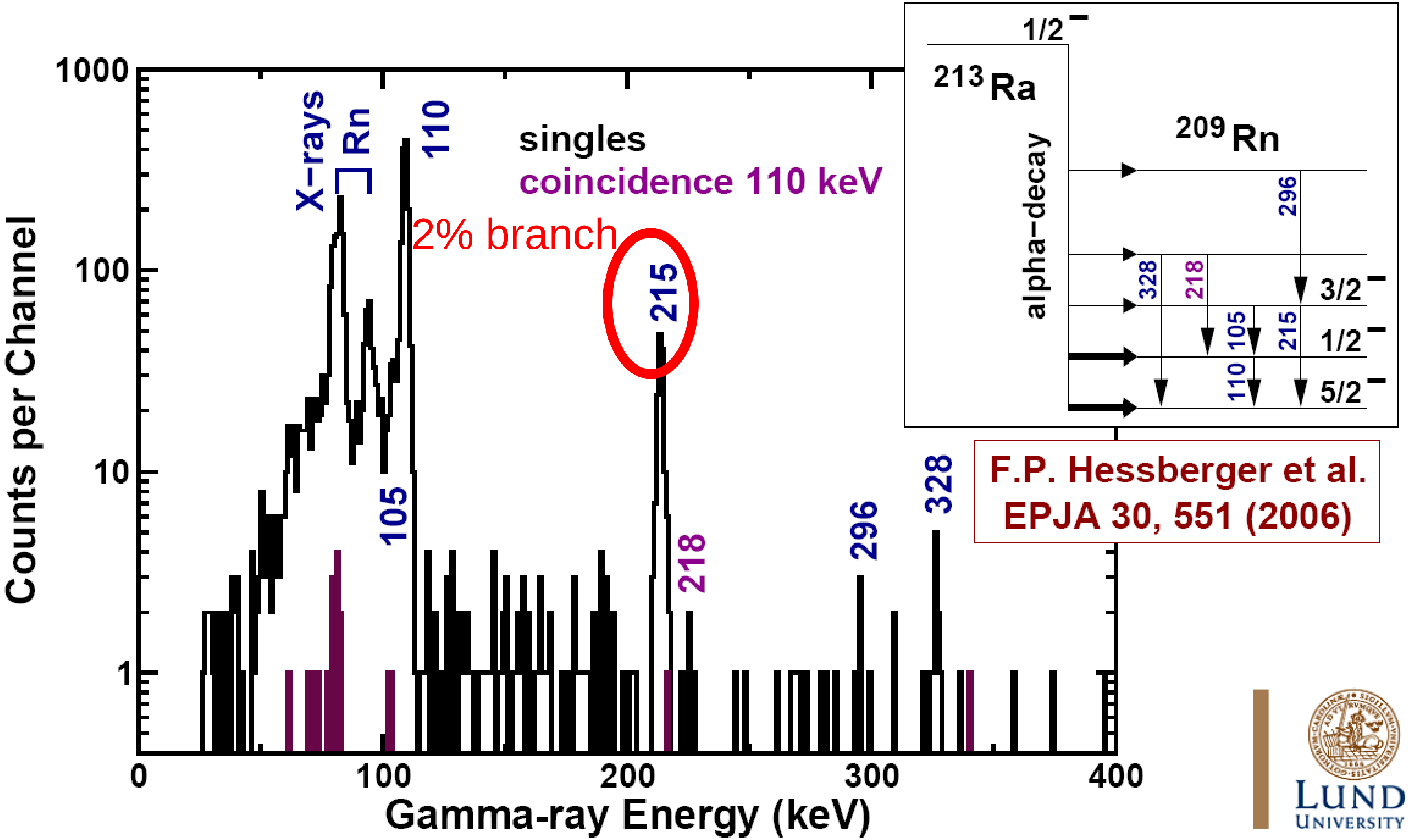
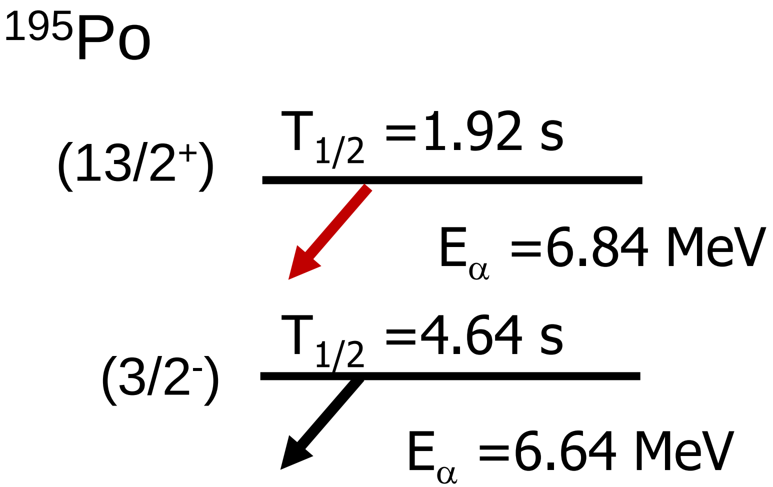
TRAPSPEC – Decay studies ^{213}Ra

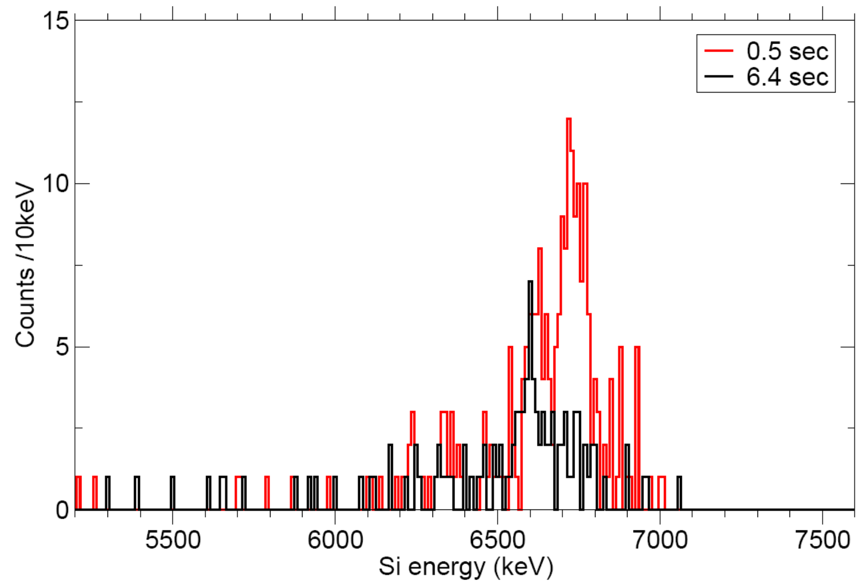


F.P. Hessberger et al.
EPJA 30, 551 (2006)

D. Rudolph al., GSI Scientific Report, NUSTAR-SHE-08, 177 (2009)

TRAPSPEC – State selection by half-life





α-spectrum for different storage time in the Penning trap:

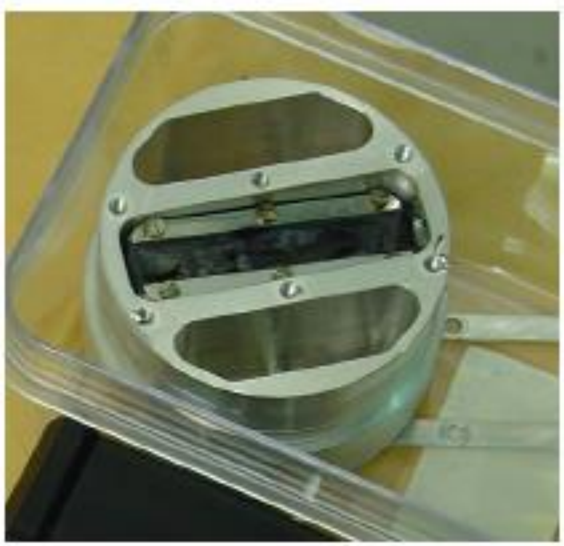
- short-lived state decays
- α-daughter not captured due to high recoil
- preparation of a single state
- in addition: mass spectrometric cleaning possible

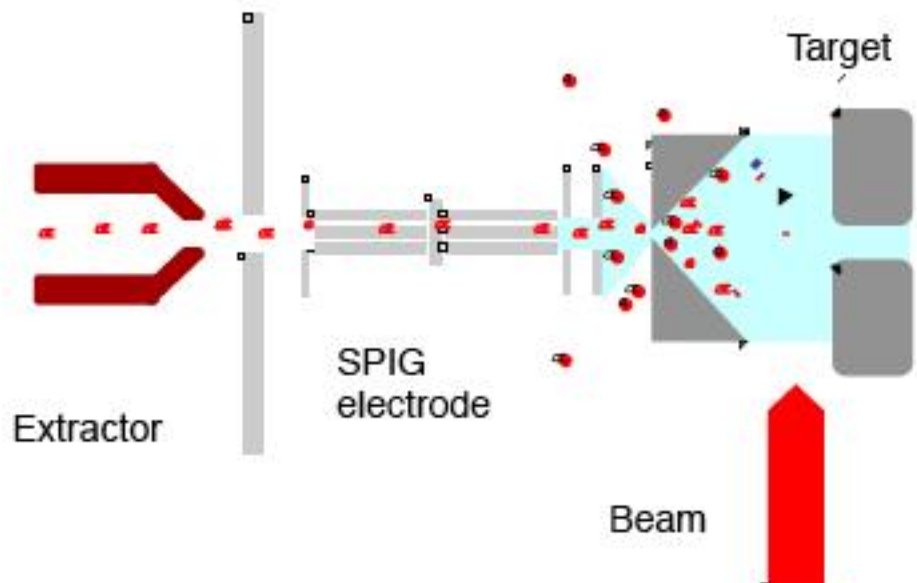
L.-L. Andersson al., GSI Scientific Report, NUSTAR-SHE (2011)

JYFL: Fission Ion Guide technique

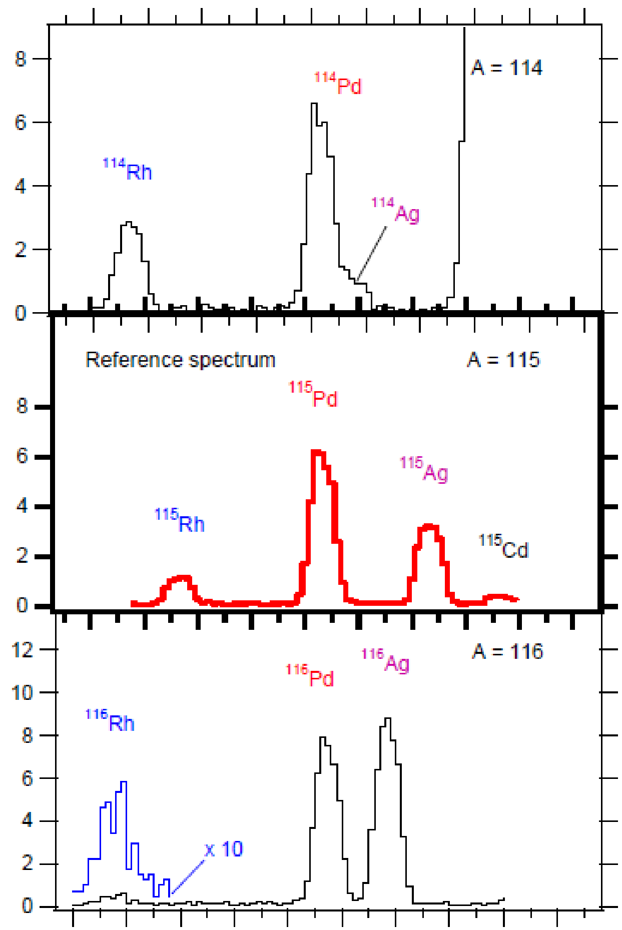
- Based on survival of primary ions from nuclear reaction in helium buffer gas
- Fast extraction of ions is required to prevent neutralisation
- Charge state concentration: (0), +1, (+2)
- **Ion formation independent of chemistry**
  - Produces ions of any element
- Millisecond time scale
  - Very small decay losses

- All ions come **directly from fission**
  - Ion rate corresponds to the independent fission yield -
  - no*) accumulation effects
- No gaps in the systematic studies
- Study the most neutron rich nuclei produced in the fission (isobaric background usually sets the limit)



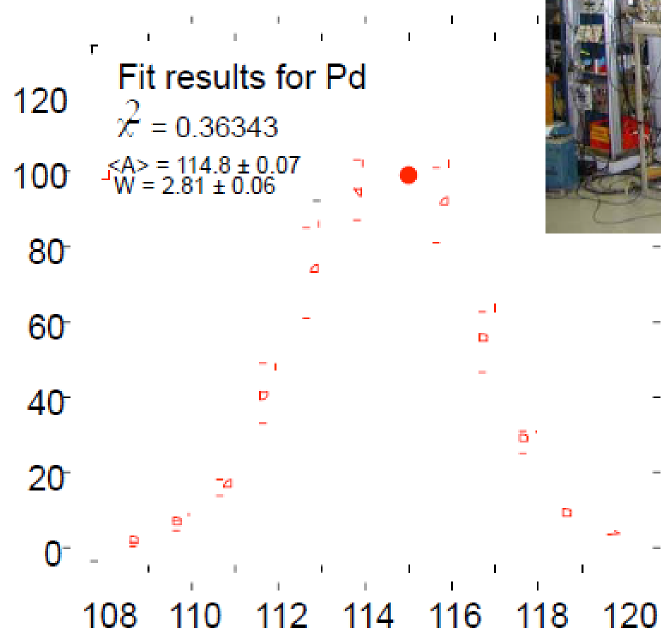


JYFL: Fission Yields with Penning Traps



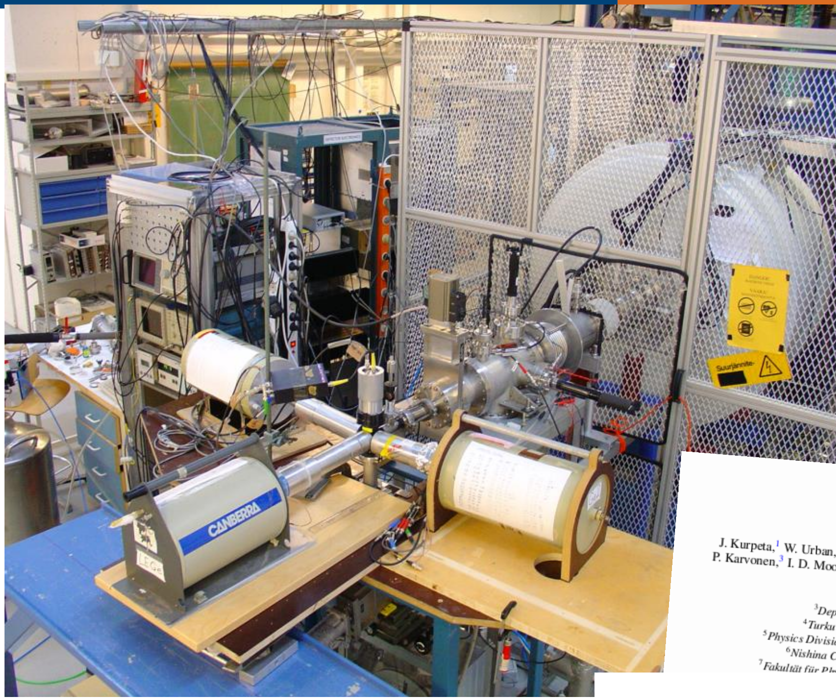
Based on unambiguous identification of isotopes by their **mass only**.

- No further knowledge on e.g. decay is needed
- Fast
- Yield of long-lived and stable isotopes can be determined



- Eur. Phys. J. Special Topics 150 (2007) 317
- Nucl. Instr. and Meth. A 576 (2007) 371
- Eur. Phys. J. A 44 (2010) 140
- Eur. Phys. J. A 48 (2012) 43

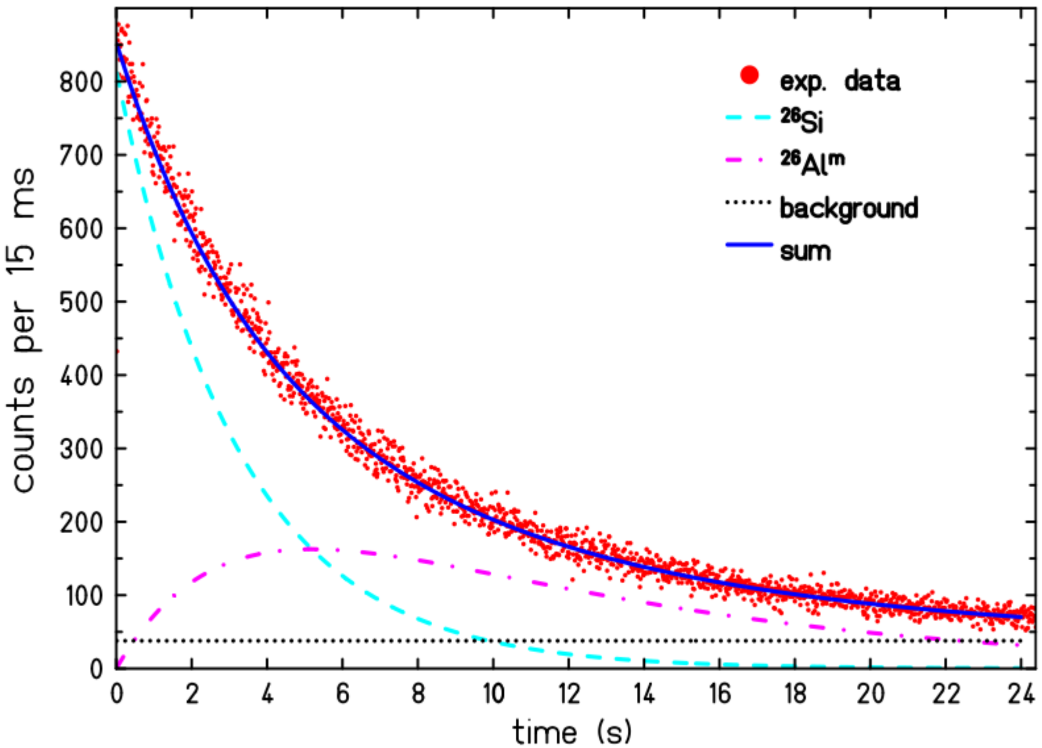
Trap-assisted spectroscopy at JYFL



courtesy A. Jokinen

JYFLTRAP: Multiple loading: Ex. $T_{1/2}(^{26}Si)$

- Bbeta counting -> requires a clean sample
- Measurement cycle requires 25 s decay period
- Accumulation in RFQ, bunches sent to purification trap
- Purification trap saturates in 300 ms -> use multiple loading
- In 25 s 8 cycles and 6-7 times more ^{26}Si than in single loading



$t_{½} = 2228.3(27)$ ms

^{26}Si, EPJ A 37 (2008) 151
^{42}Ti, PRC 80 (2009) 035502
^{30}S, EPJ A 47 (2010) 40
^{31}S, EPJ A 48 (2012) 155

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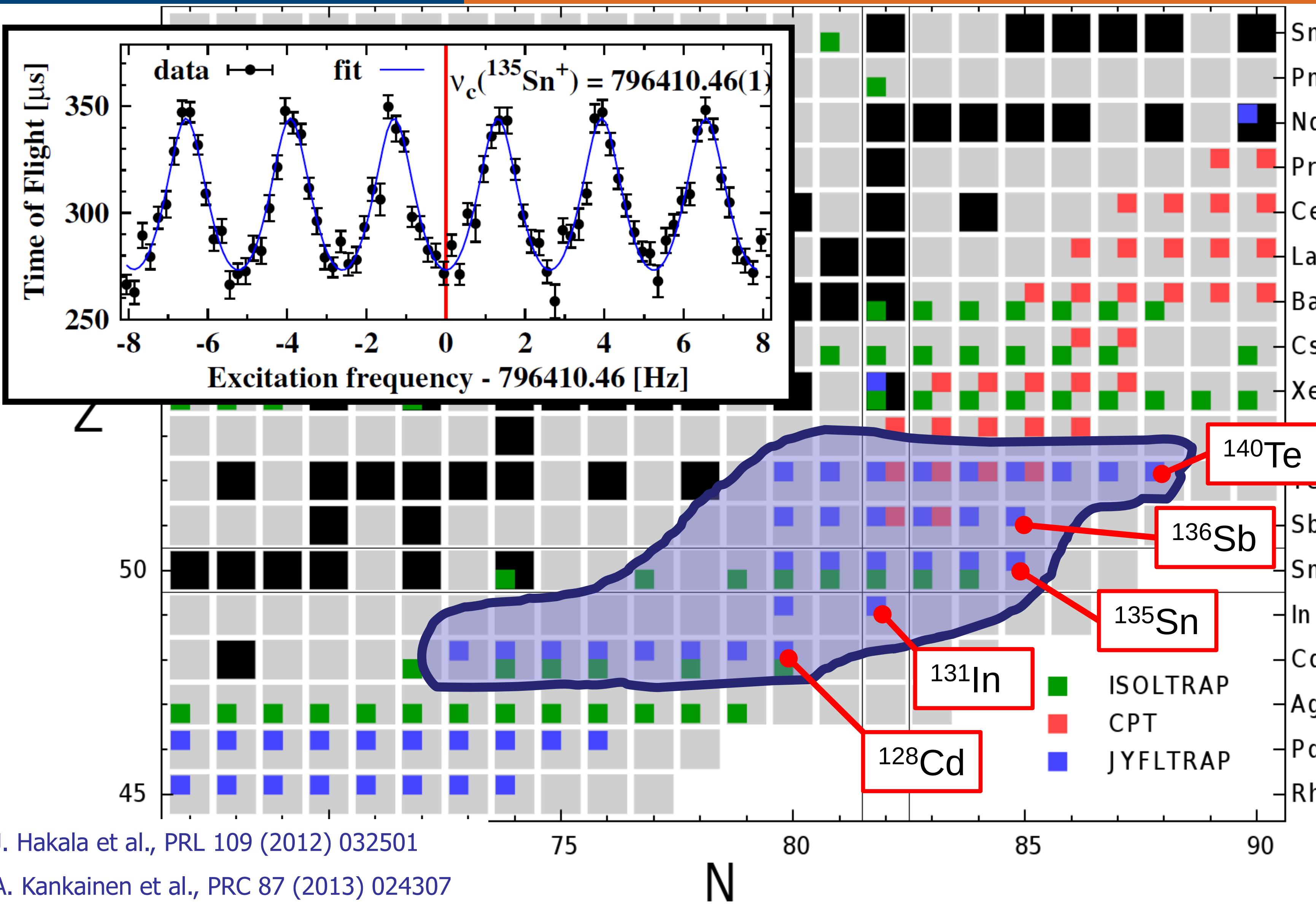
courtesy A. Jokinen

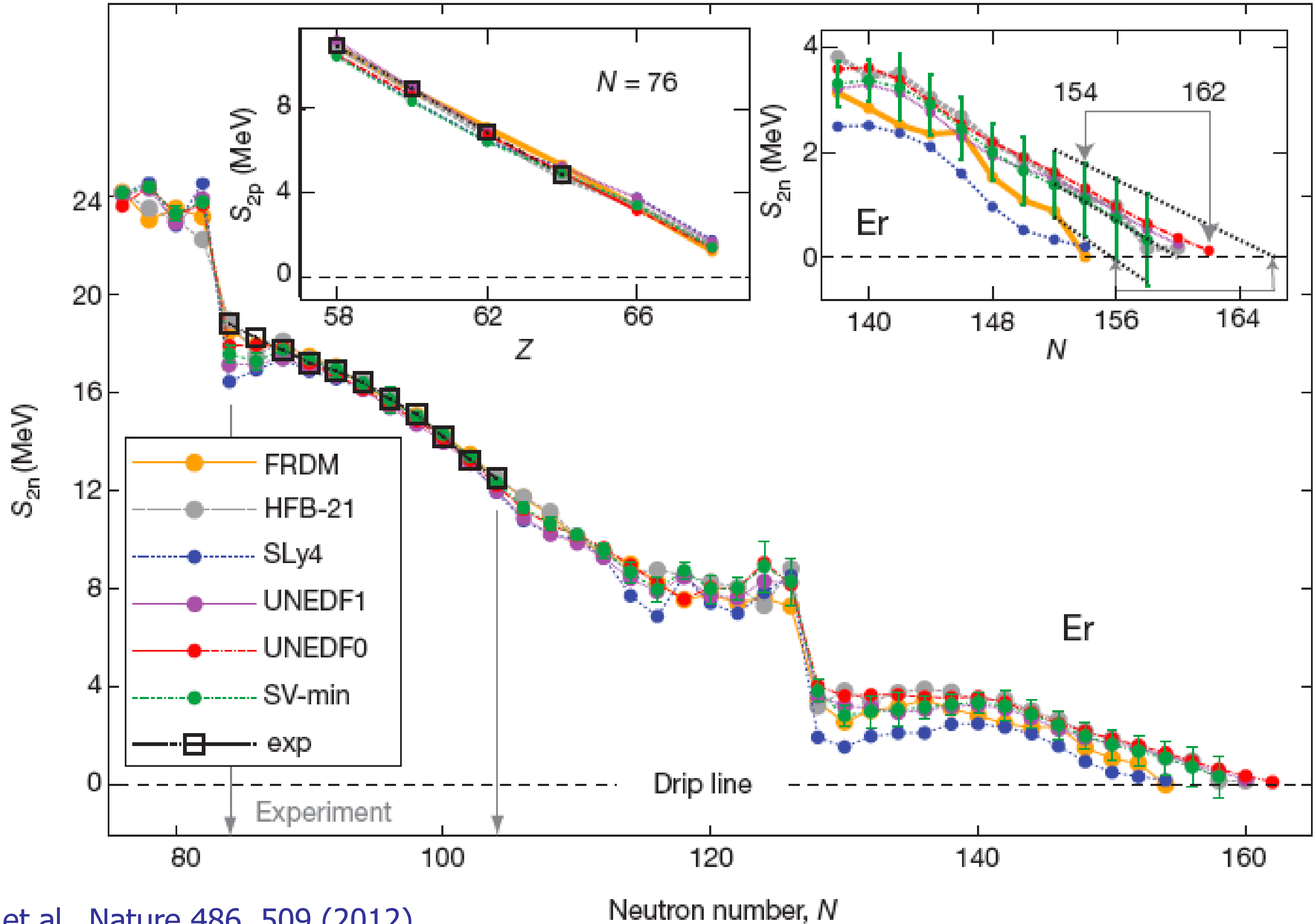
JYFLTRAP data in ^{132}Sn region



J. Hakala et al., PRL 109 (2012) 032501

A. Kankainen et al., PRC 87 (2013) 024307

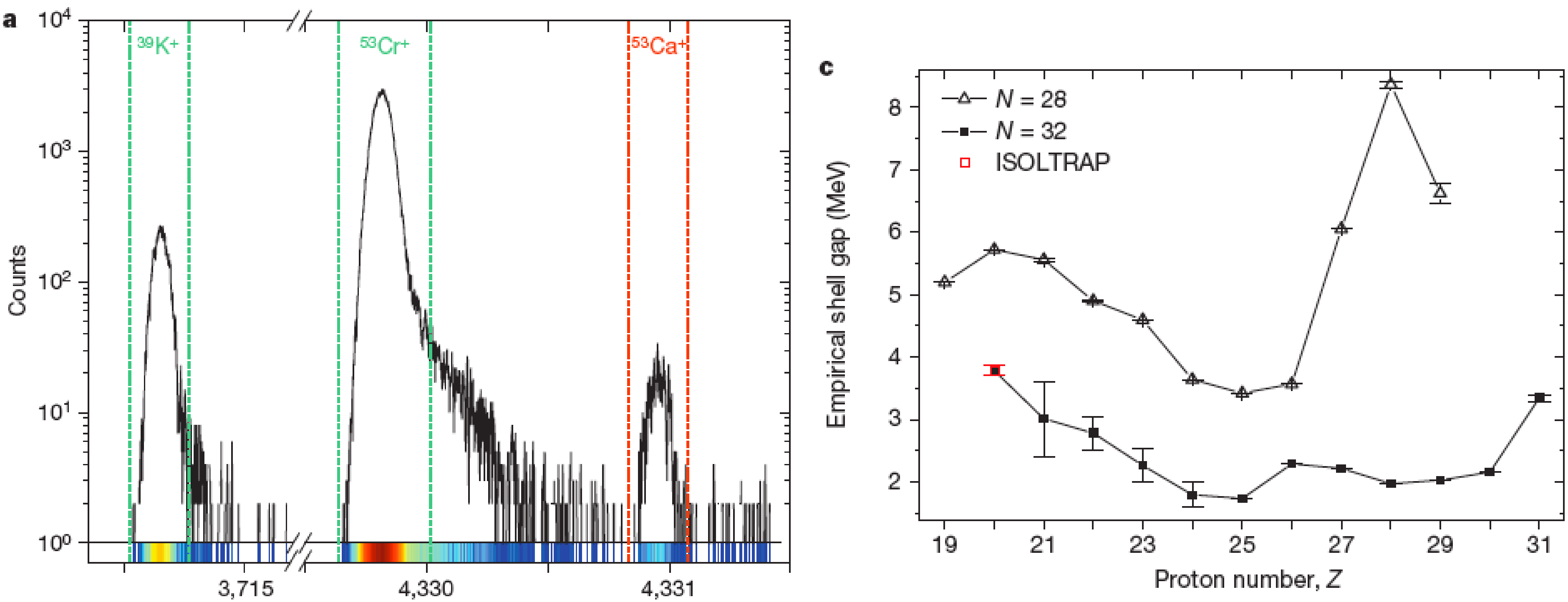
Indicators of Nuclear Structure Evolution



J. Erler et al., Nature 486, 509 (2012)

Nuclear Structure in Neutron-rich Nuclides

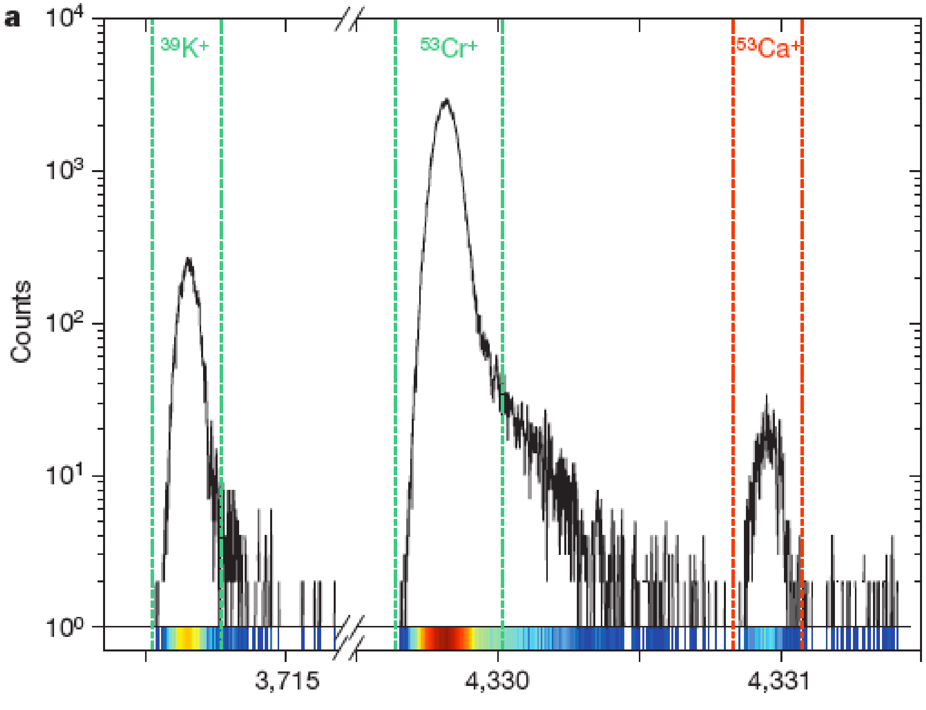
Masses of neutron-rich calcium isotopes measured by ISOLTRAP

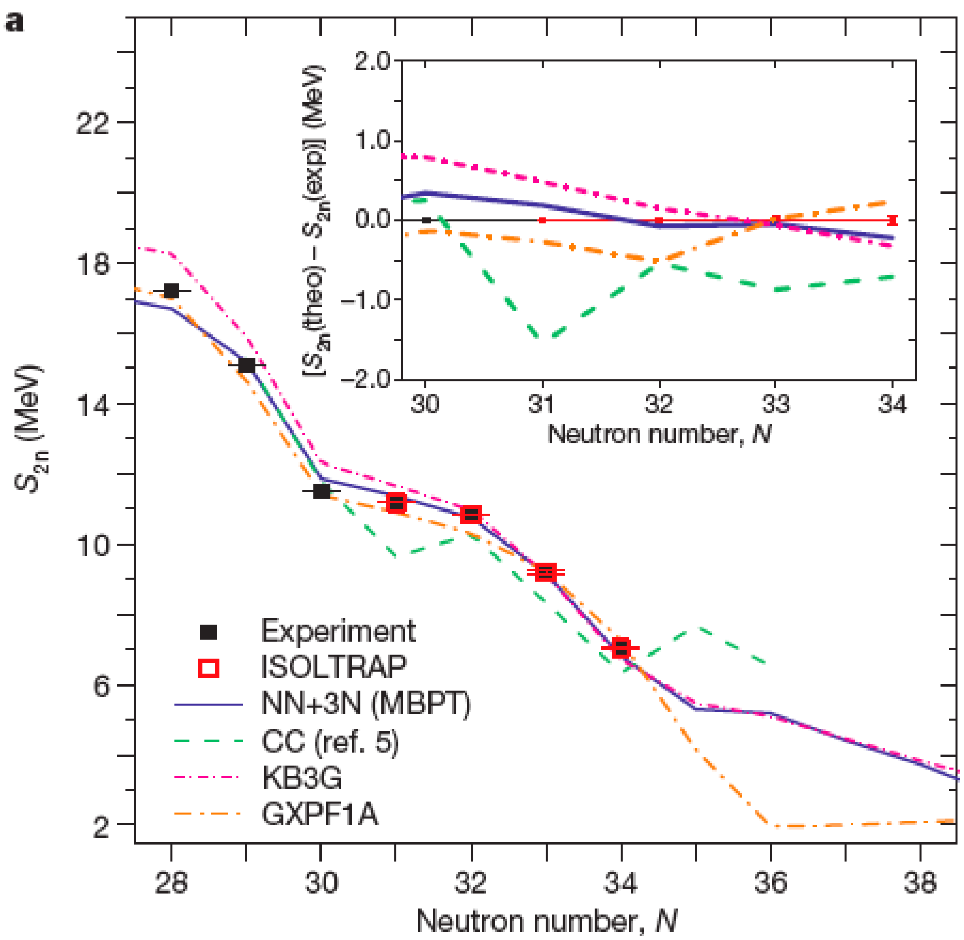


F. Wienholtz et al., Nature 2013

Nuclear Structure in Neutron-rich Nuclides

Mass measurements by ISOLTRAP





F. Wienholtz et al., Nature 2013