EURORIB Conference 2015 – Hohenroda

Mass Measurements and Laser Spectroscopy of the Heaviest Elements

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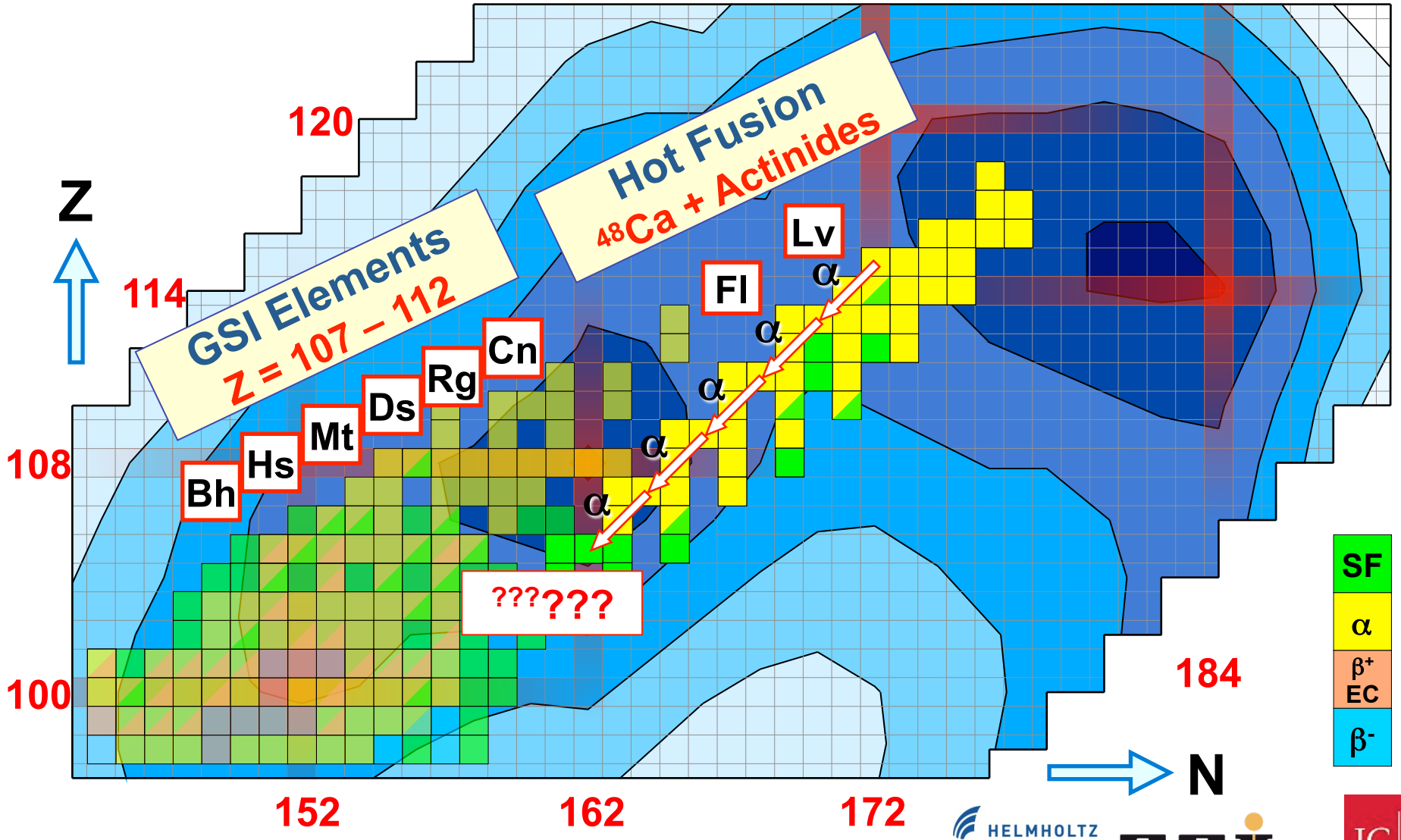
Outline

- Nuclear structure evolution displayed by masses
- Mass spectrometry basics
- Direct mass measurements of nobelium and lawrencium isotopes
- Some recent SHIPTRAP improvements
- Resonance ionization laser spectroscopy of the heaviest elements
- Toward laser spectroscopy of nobelium
- Summary and conclusions

Superheavy Nuclides – Current Landscape



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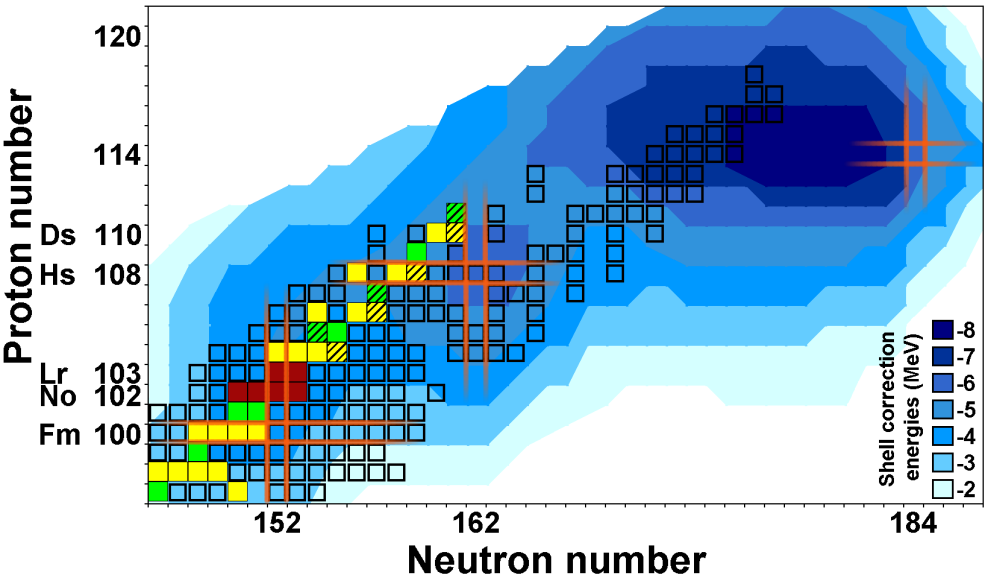
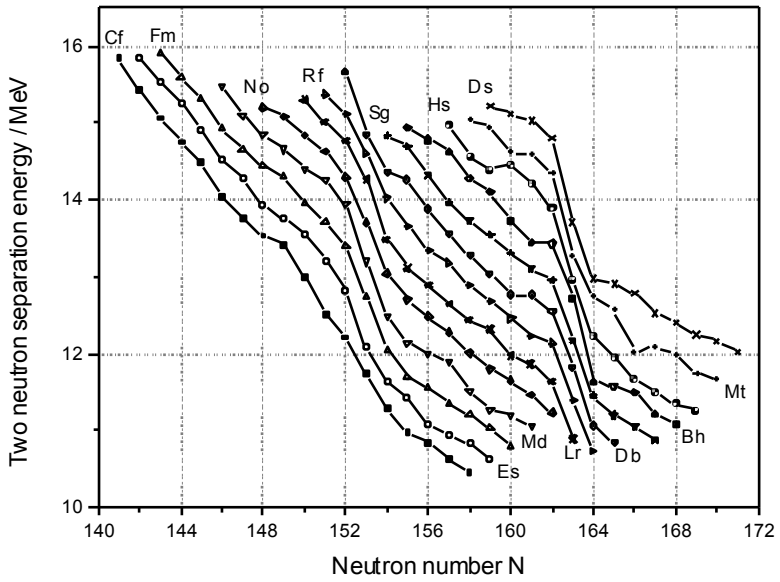
Courtesy Ch.E. Düllmann

Importance of Masses for Z > 100



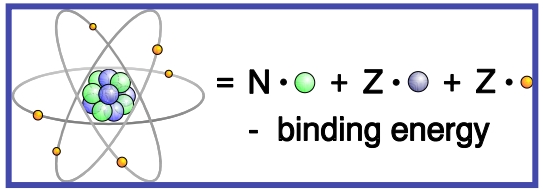


high-precision mass measurements provide

- 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



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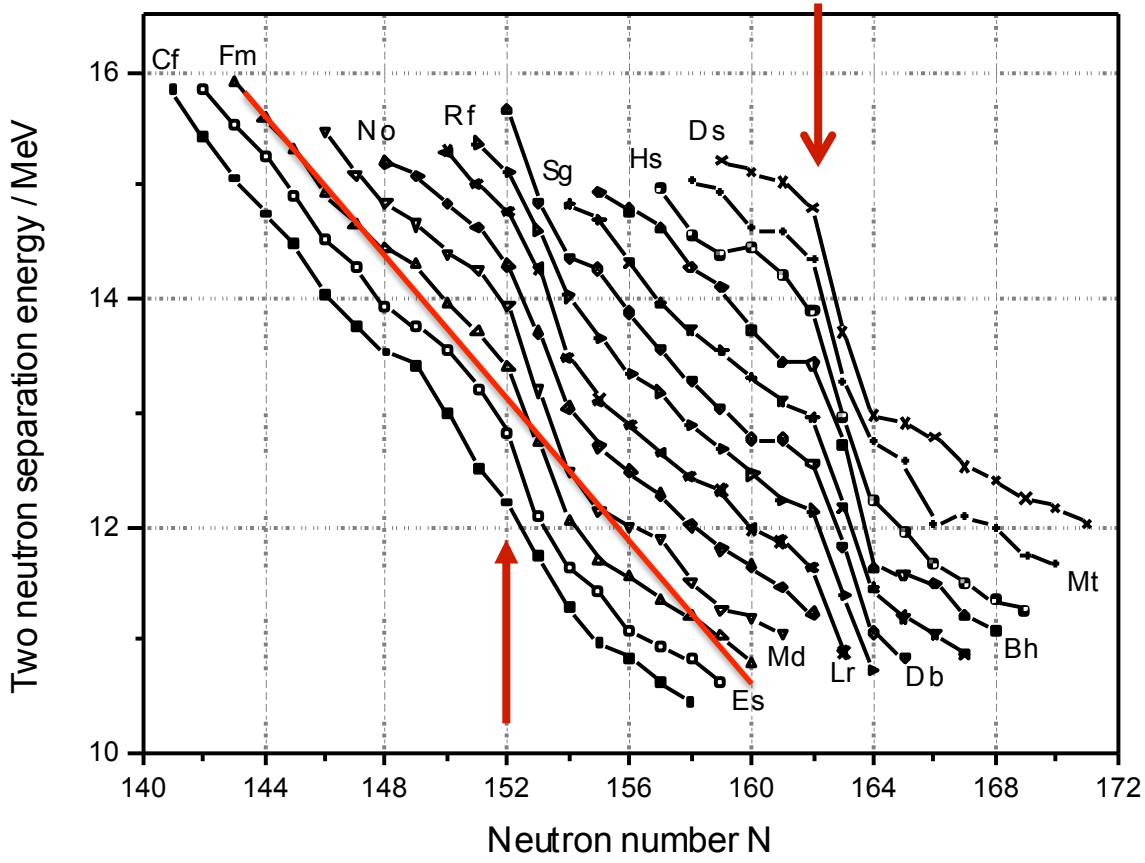
Nuclear Structure Indicators from Masses

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

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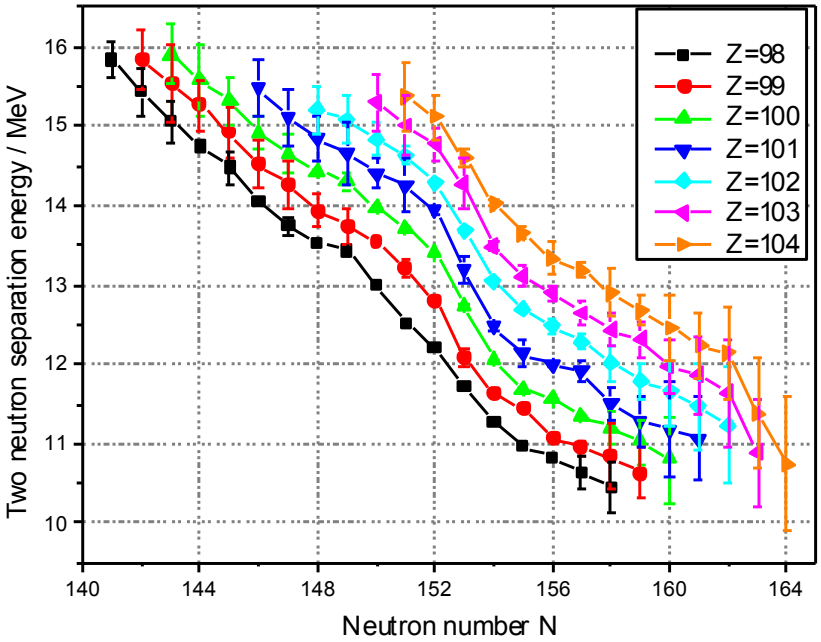
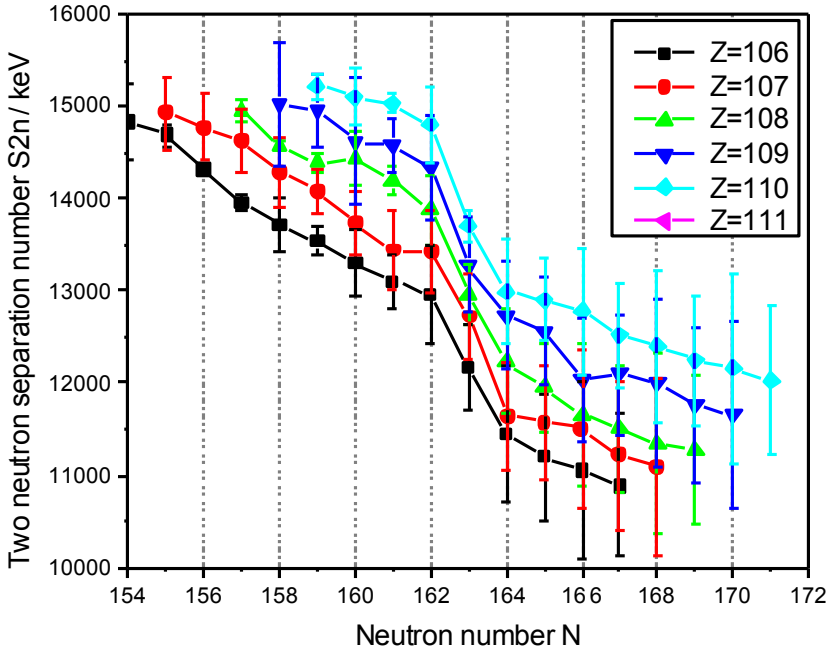




indication for shell closure at $N = 152$ & $N = 162$

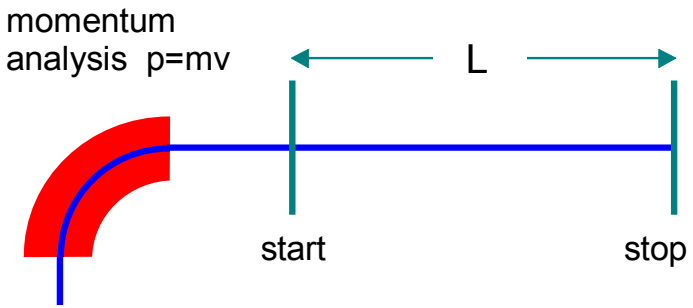
Data from Atomic Mass Evaluation 2012:
M. Wang et al., CPC(HEP & NP), 2012, 36(12): 1603–2014

Tools for Direct Mass Measurements

Time-of-flight spectrometry

single turn: SPEG/GANIL, S800/NSCL

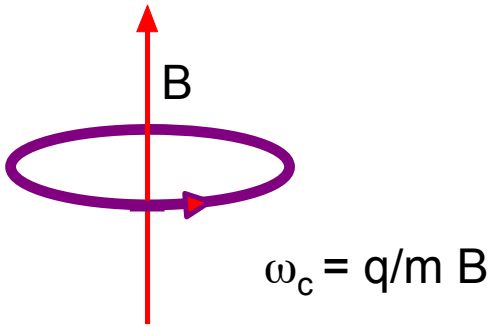
multi turn: ESR/GSI, CSR/Lanzhou, RIBF ring
electrostatic MR-ToF (Giessen, ISOLDE, RIKEN, ...)



Frequency measurements

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

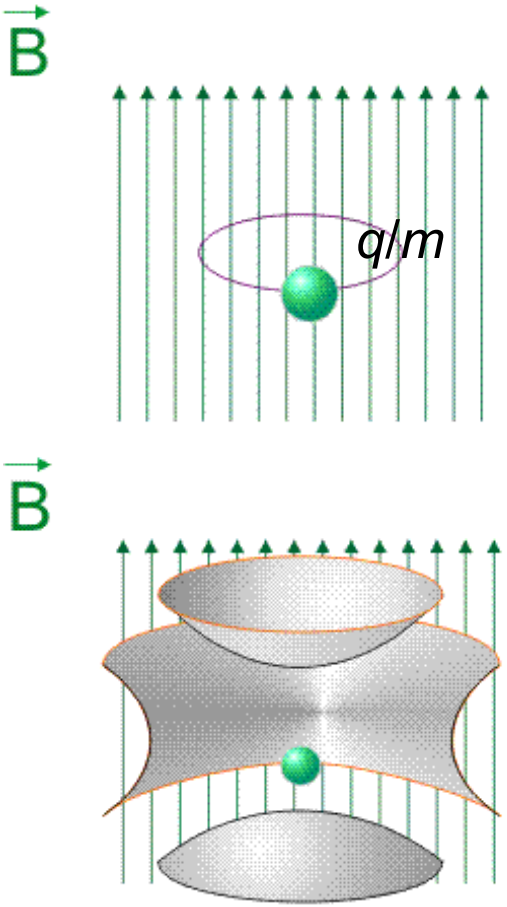
Penning traps LEBIT/NSCL, ISOLTRAP/ISOLDE
JYFLTRAP/JYFL, CPT/ANL
SHIPTRAP/GSI, TITAN/TRIUMF,
TRIGATRAP/ Mainz, MLLTRAP,
...



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

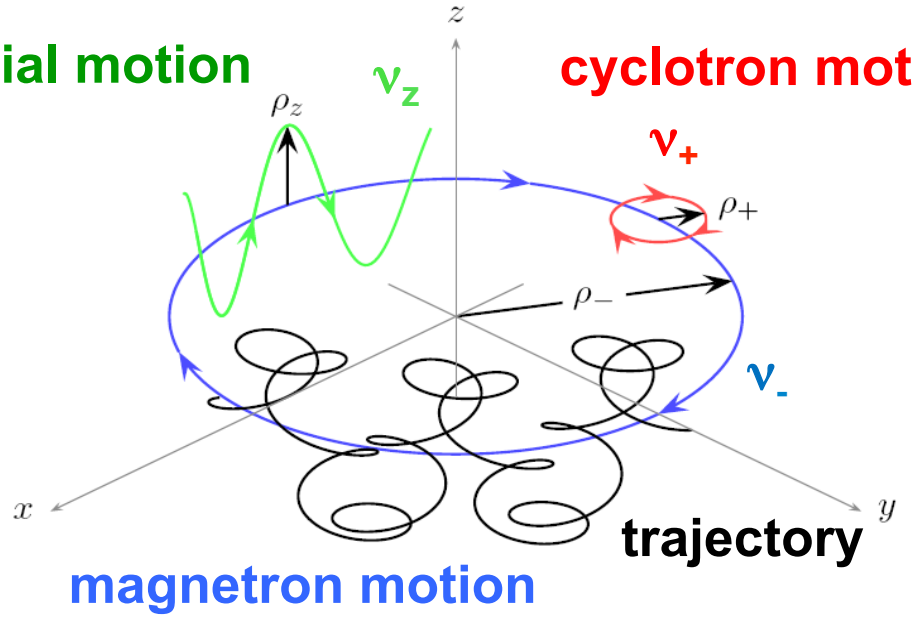
Principle of Penning Traps

PENNING trap



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

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

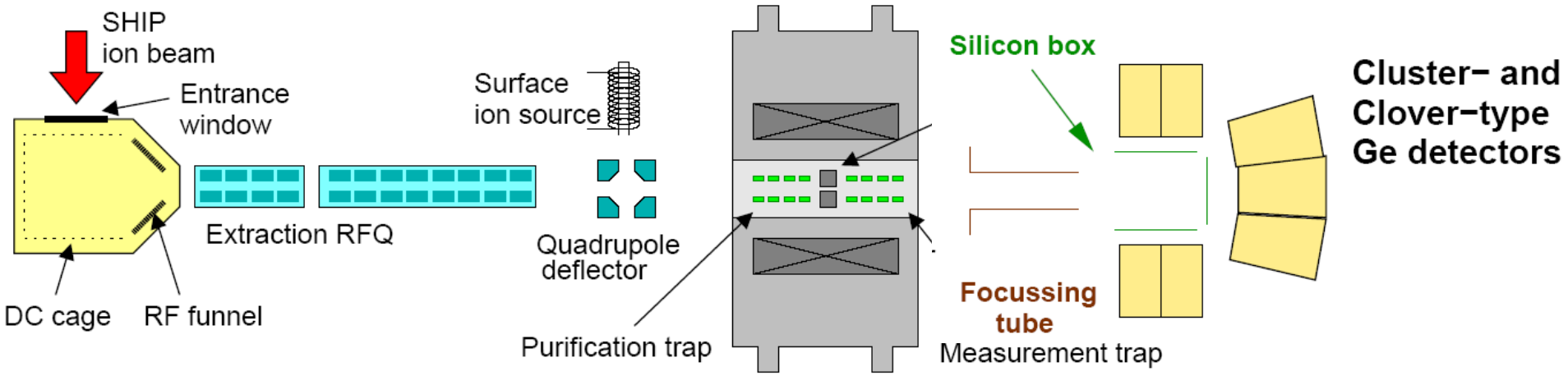


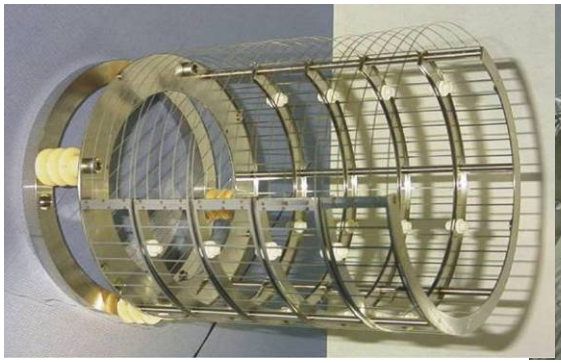
L. S. Brown and G. Gabrielse, Rev. Mod. Phys. 58 (1986) 233
G. Gabrielse, Int. J. Mass Spectr. 279, (2009) 107

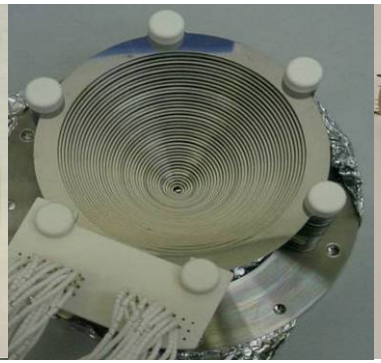
SHIPTRAP Setup

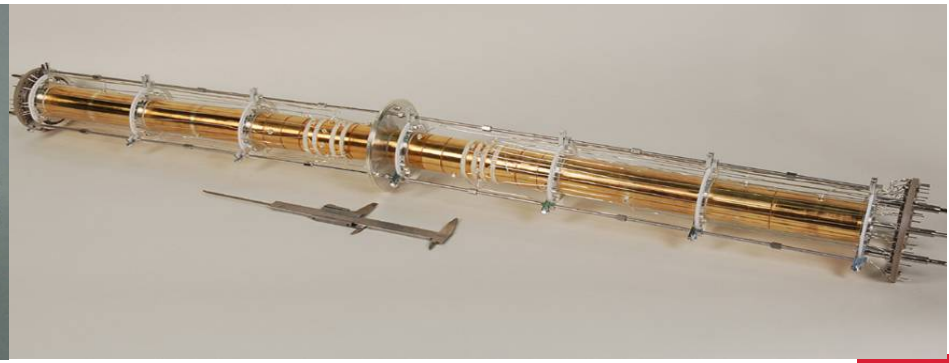
≈ 50 MeV → ≈ 1 eV → ≈ 1 keV

Gas Cell | Buncher | Transfer | Penning Traps | TRAPSPEC

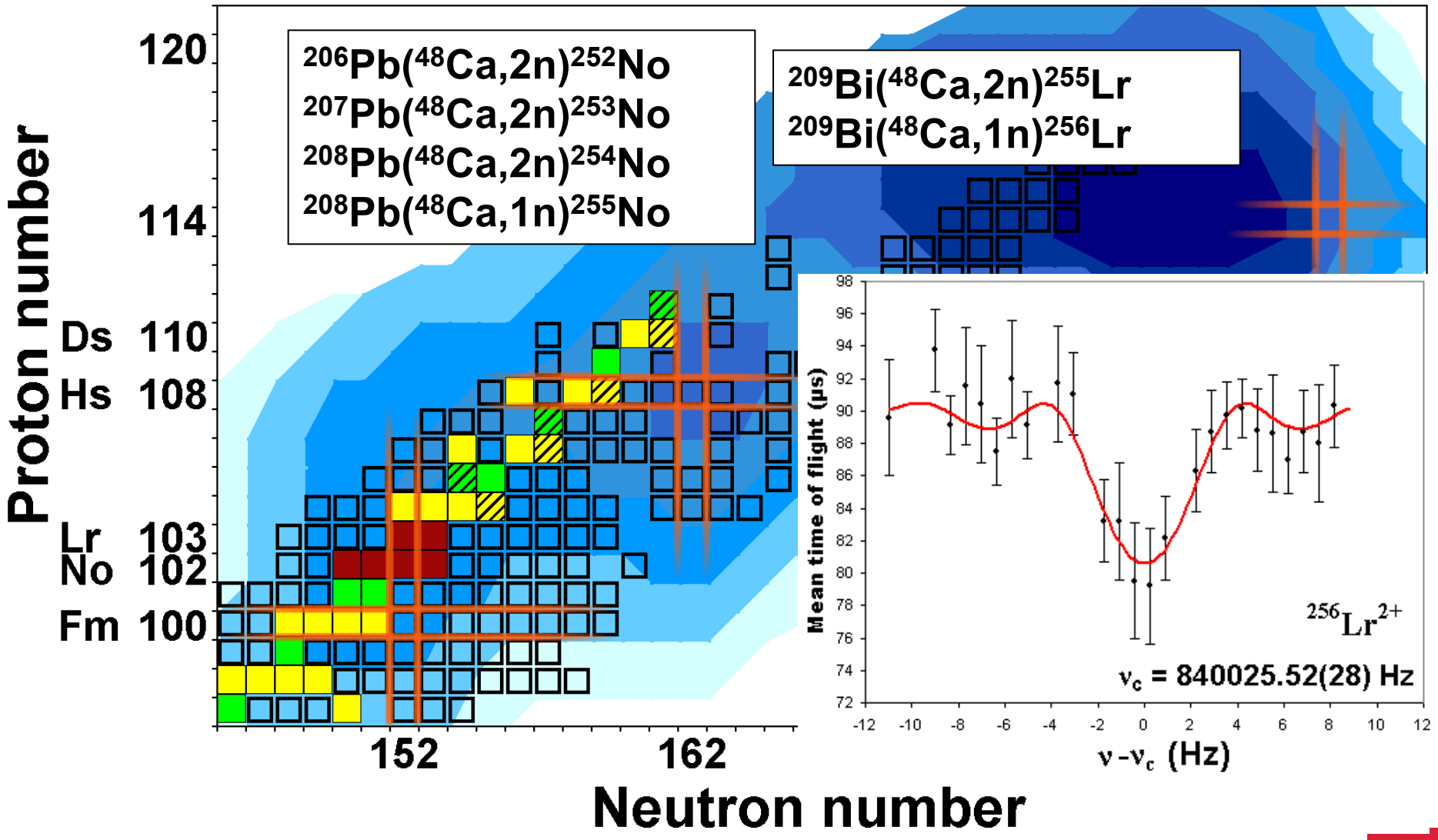






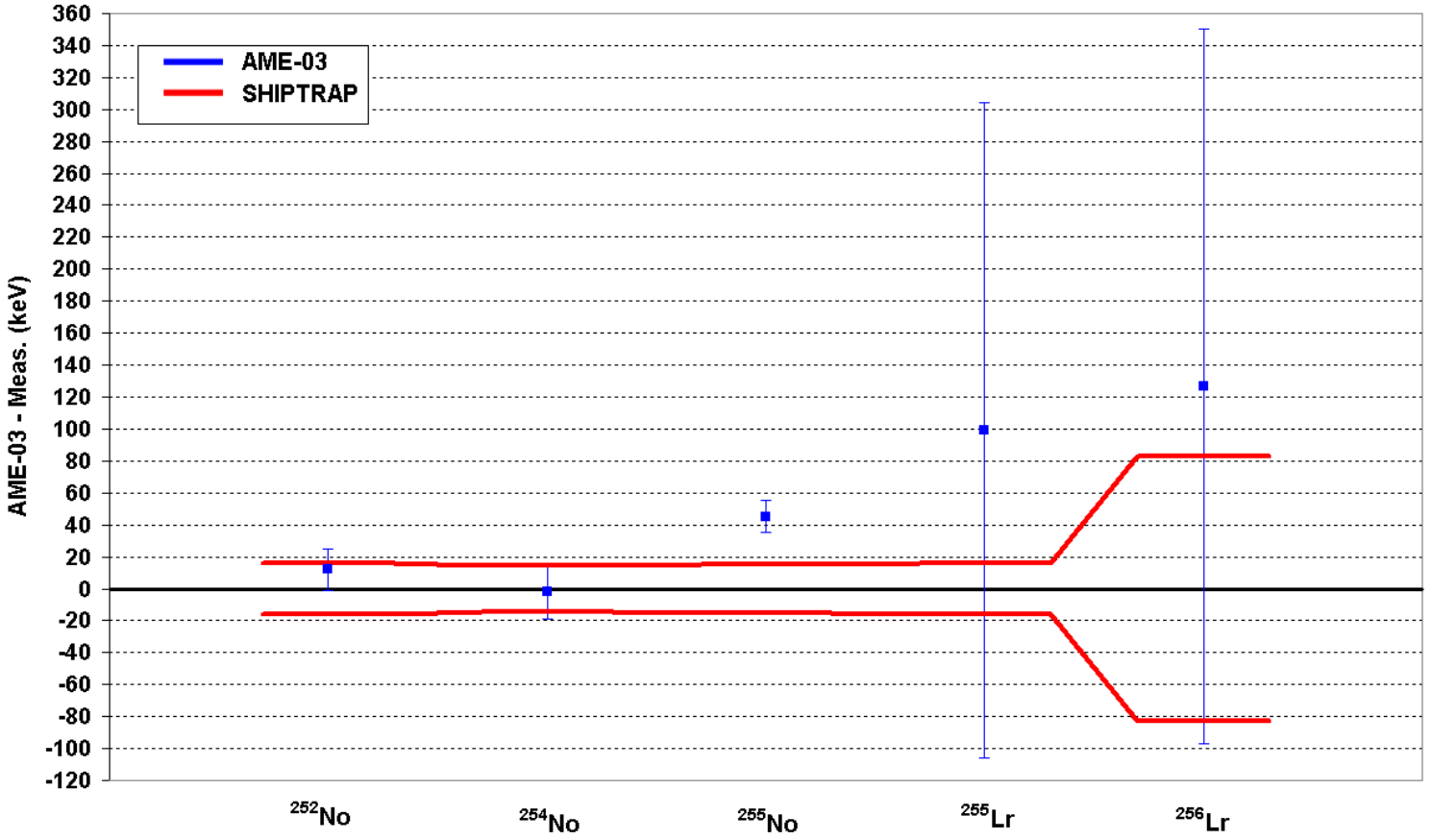


Direct mass measurements with SHIPTRAP

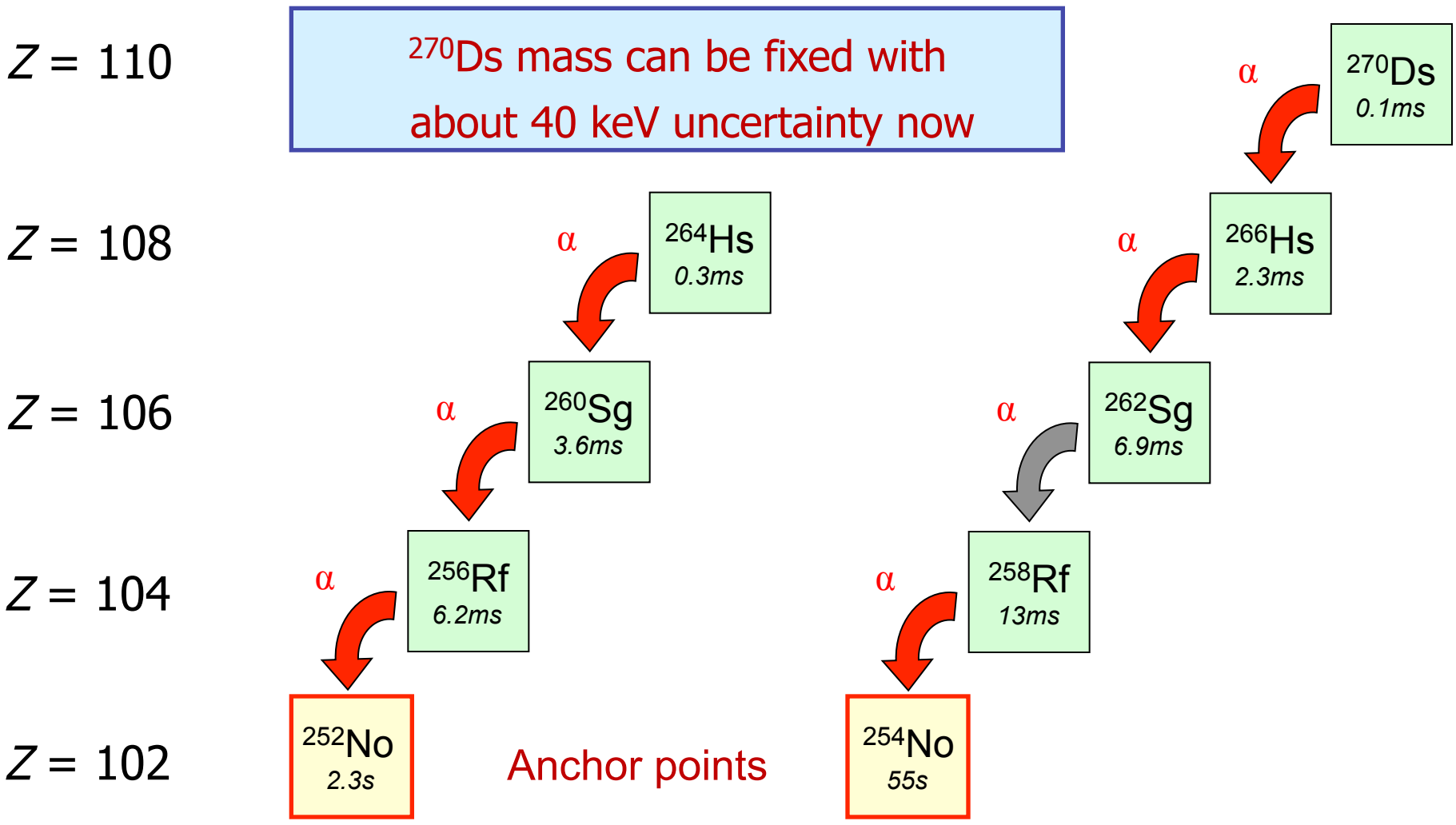


M. Block et al., Nature 463, 785 (2010), M. Dworschak et al., Phys. Rev. C 81, 064312 (2010)
E. Minaya Ramirez et al., Science 337, 1183 (2012)

SHIPTRAP Results vs. Atomic Mass Evaluation



Pinning Down α-Decay Chains



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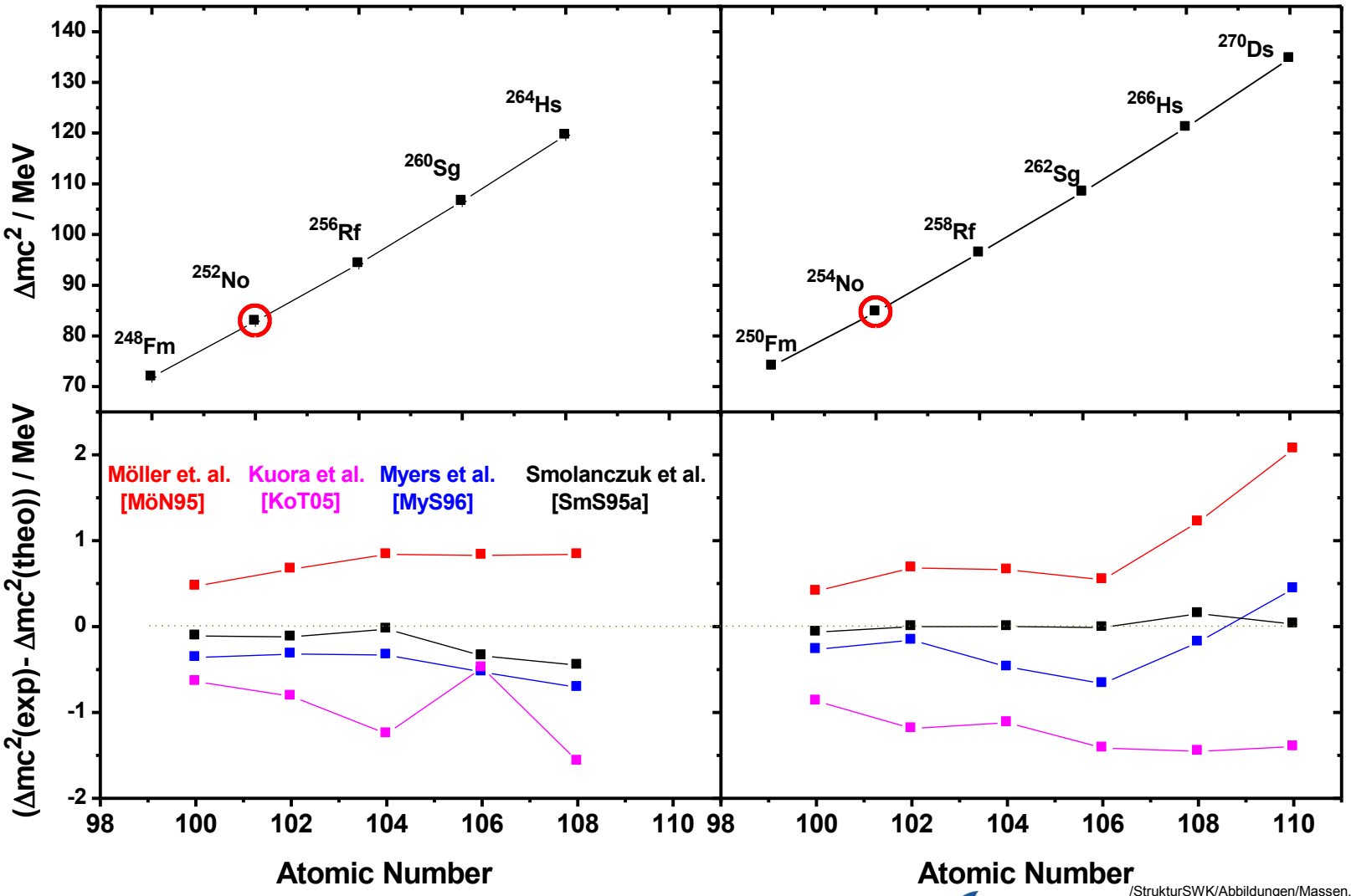
Masses of even-even $N-Z = 48$ and $N-Z = 50$ Nuclei



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

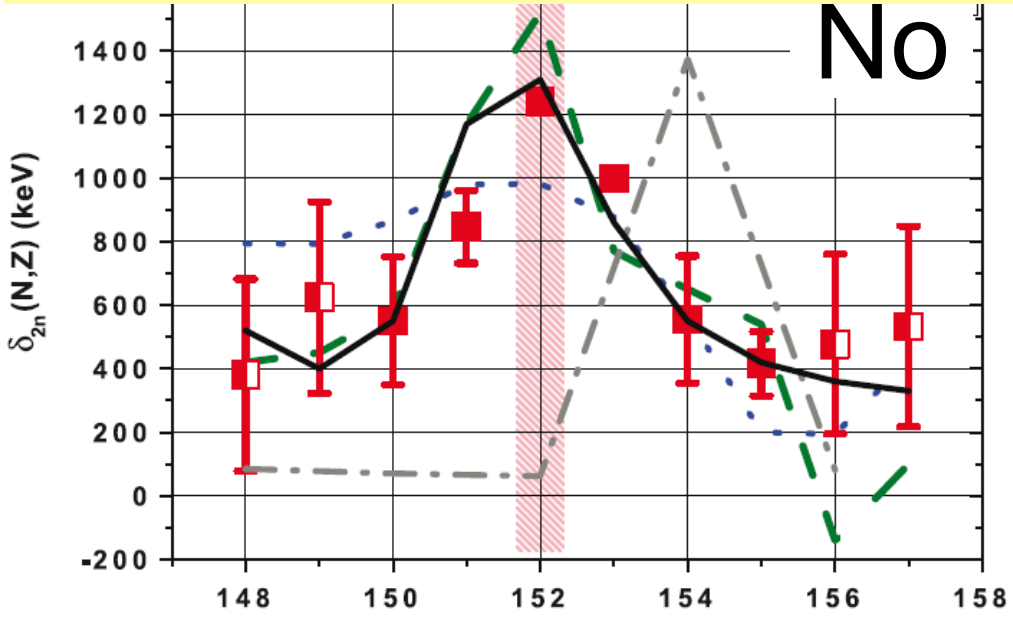
courtesy F. P. Hessberger

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]

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

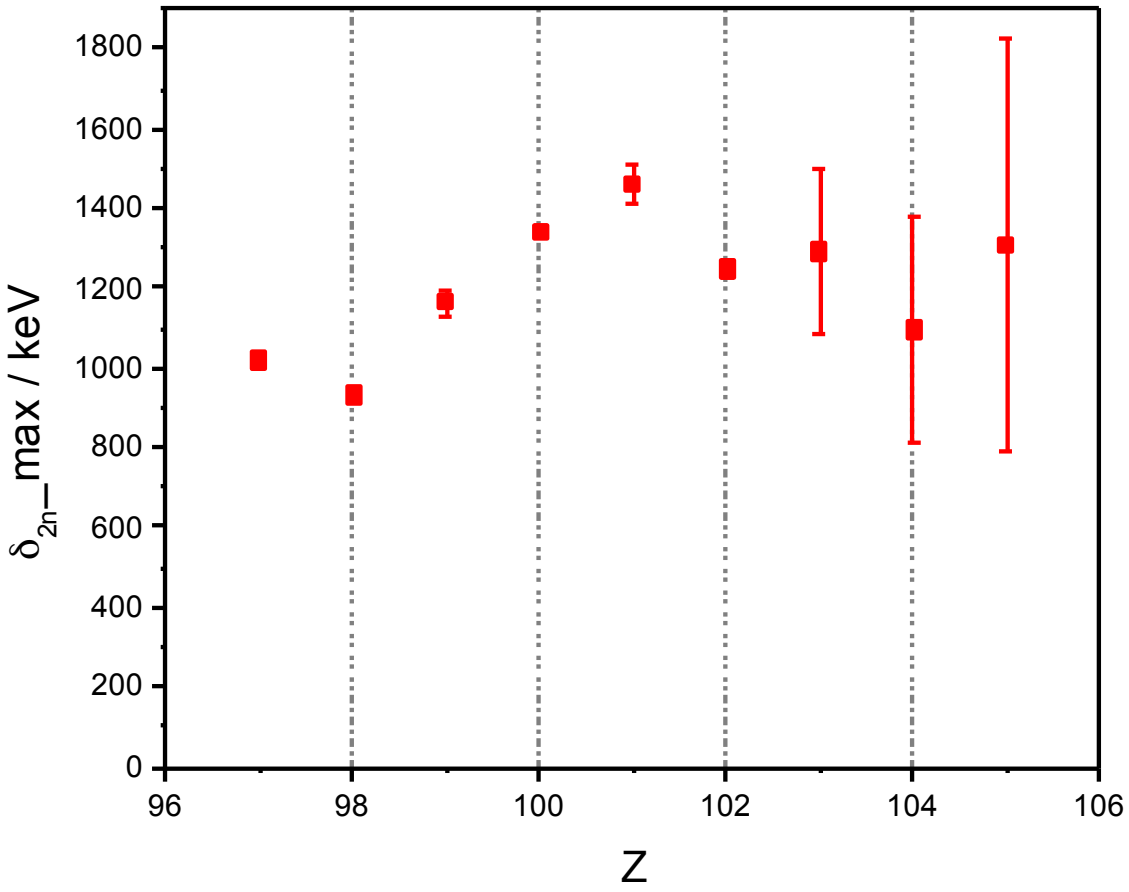


Science **337** (2012) 1207

- 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

Probing the Strength of Shell Effects

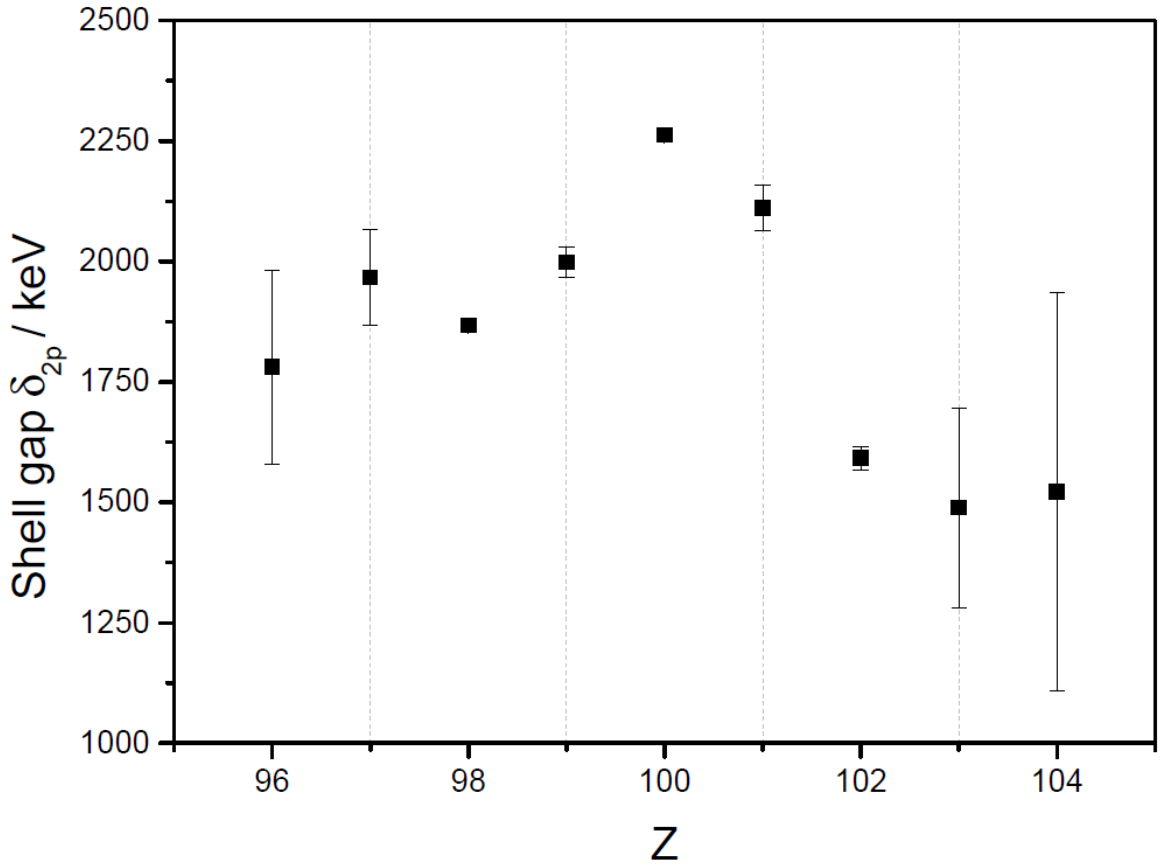
Evolution of $N = 152$ shell closure



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

Probing the Strength of Shell Effects

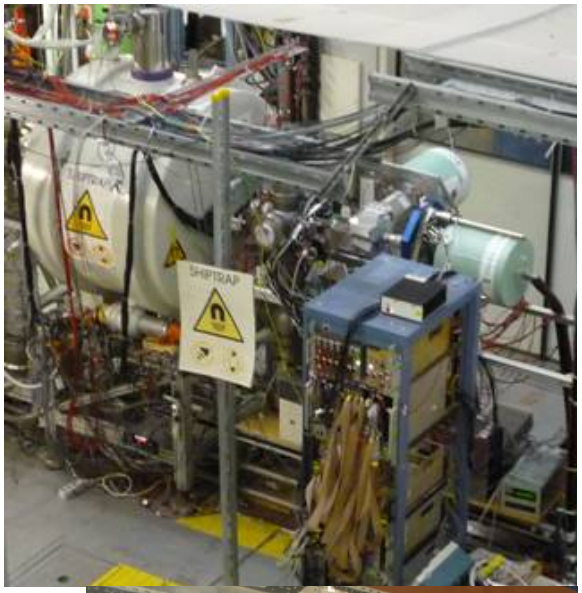
N = 152 isotones

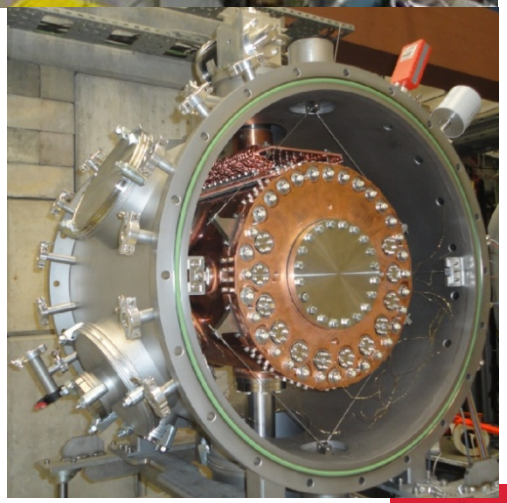


Data taken from Atomic Mass Evaluation (AME) 2012: M. Wang et al.

Upgrades and Combinations

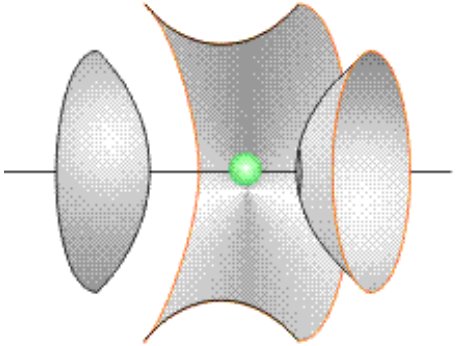
- Novel experiments
  - trap-assisted decay spectroscopy
  - laser spectroscopy (gas cell, gas jet, trap)
  - gas phase chemistry
- Increase efficiency and sensitivity
  - novel measurement schemes (PI-ICR)
  - single-ion mass measurements (FT-ICR)
    (→ TRIGA-TRAP, TRAPSENSOR)
  - cryogenic gas cell

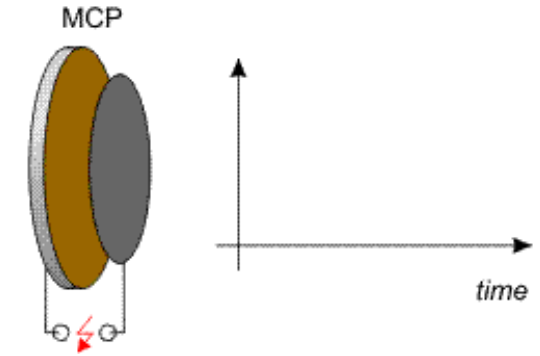




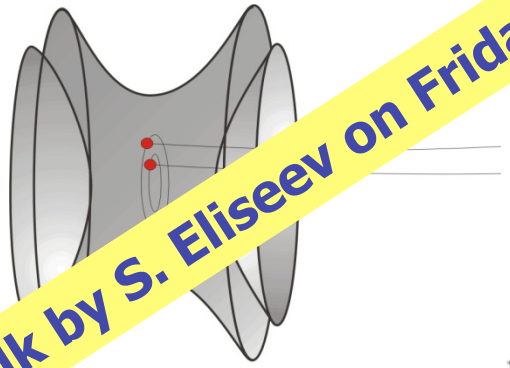
Recent Breakthrough

Destructive time-of-flight detection

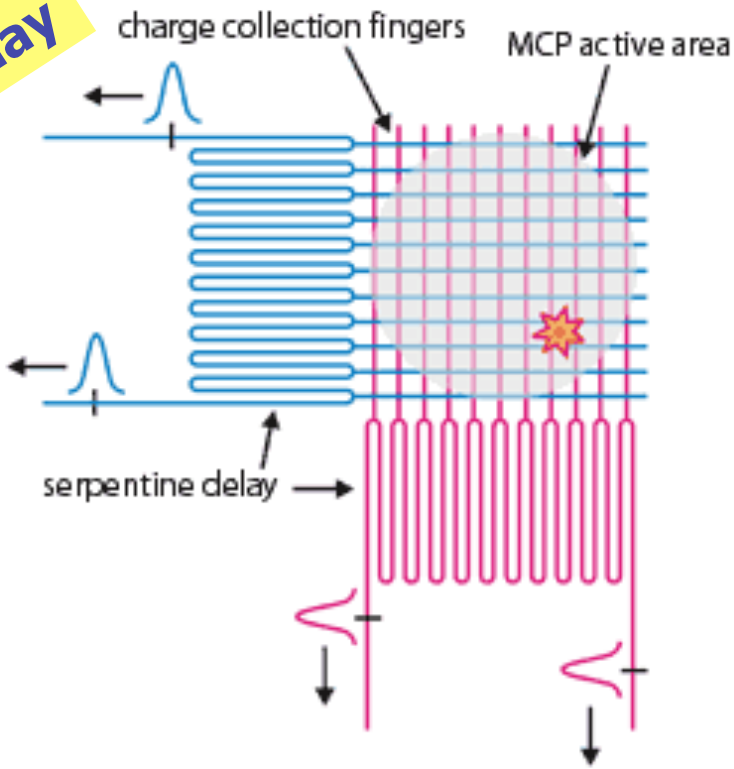




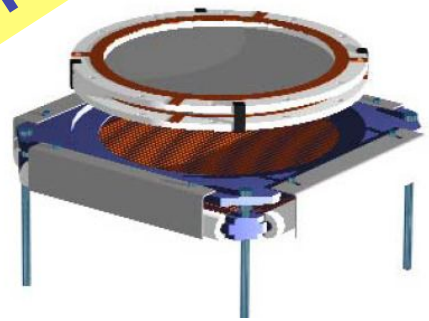
Spatially resolved detection



Talk by S. Eliseev on Friday

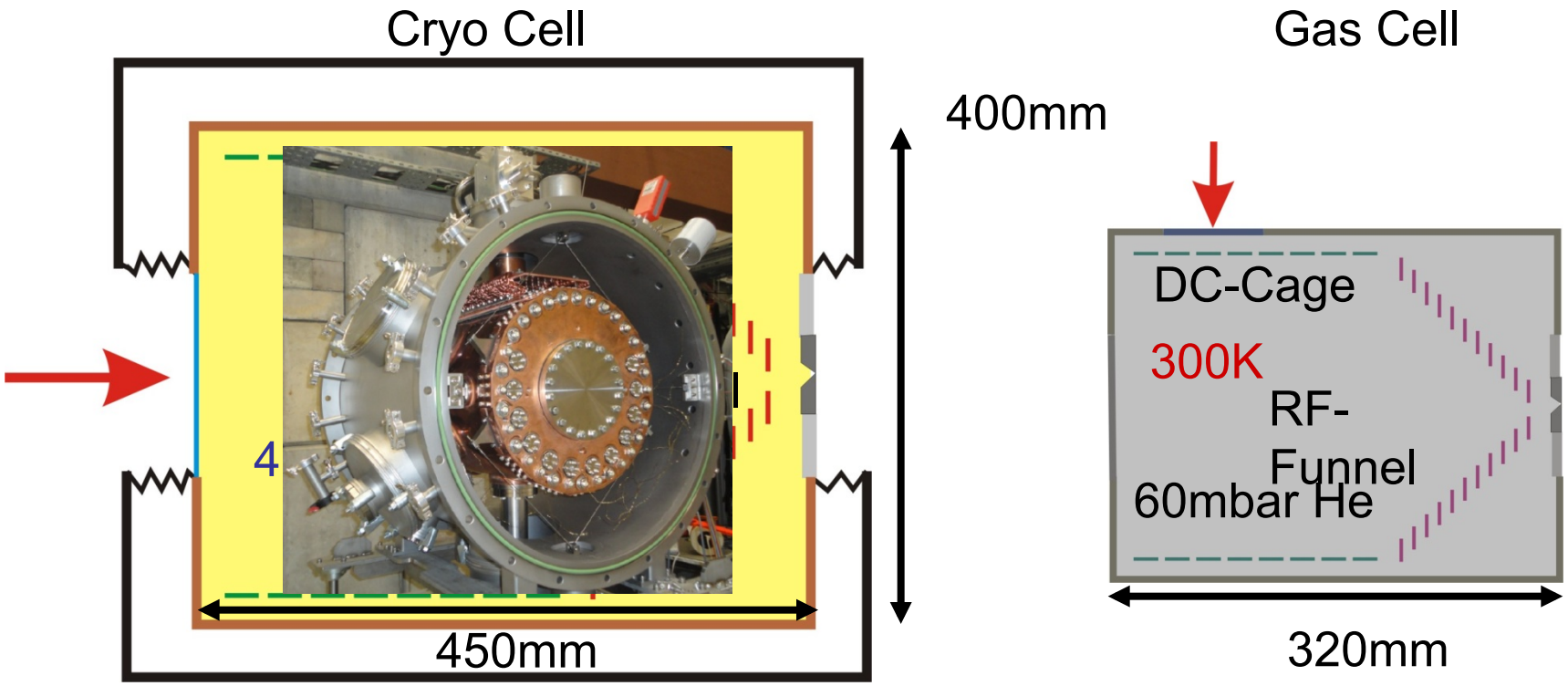


Delay-line detector



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

Cgenic 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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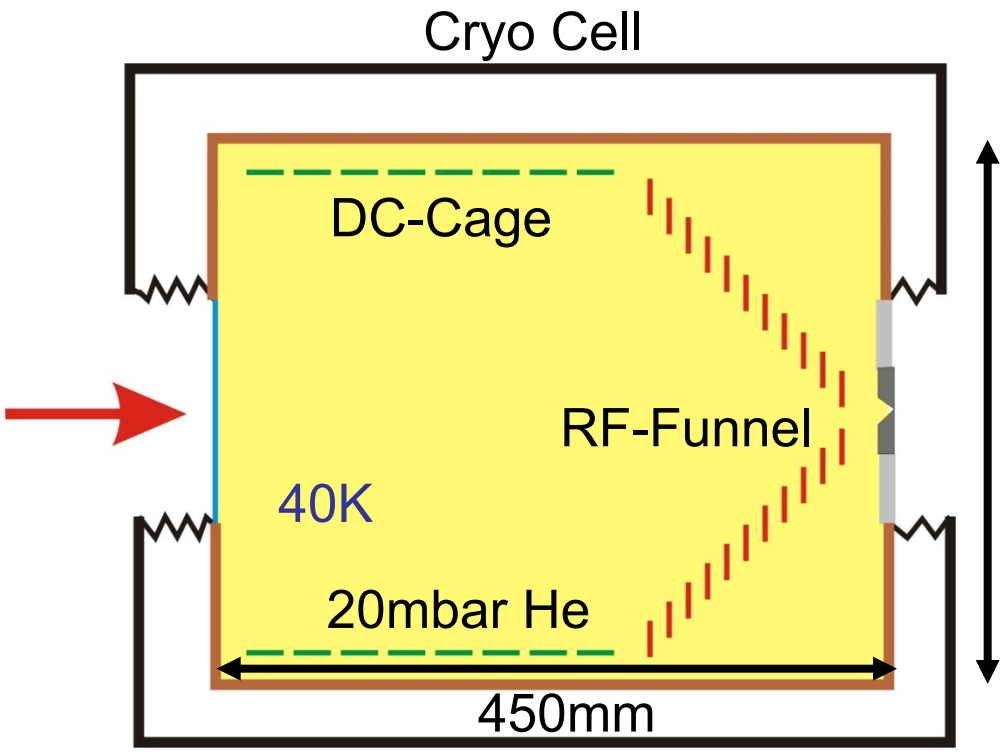
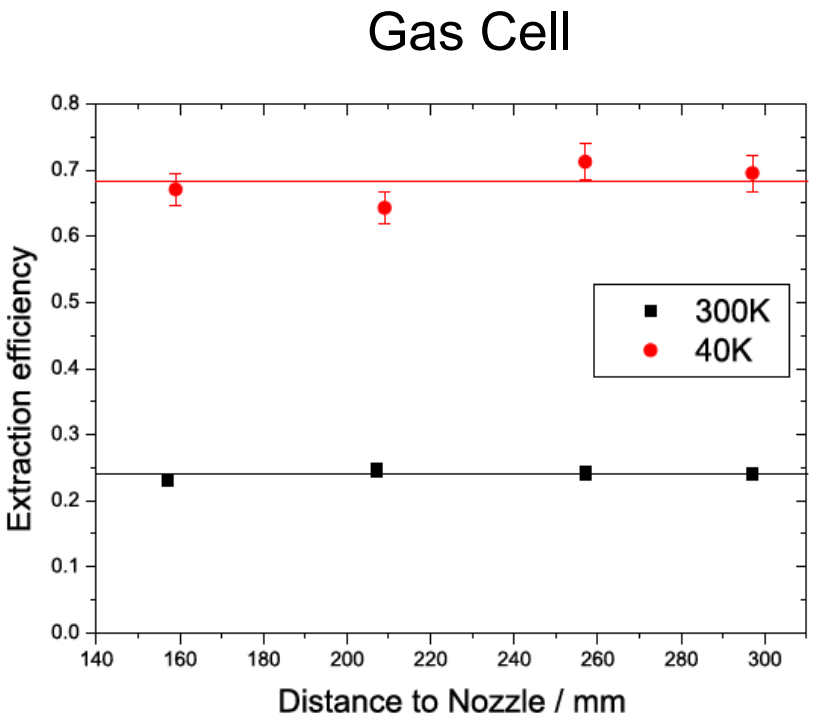
Cgenic Gas Cell





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

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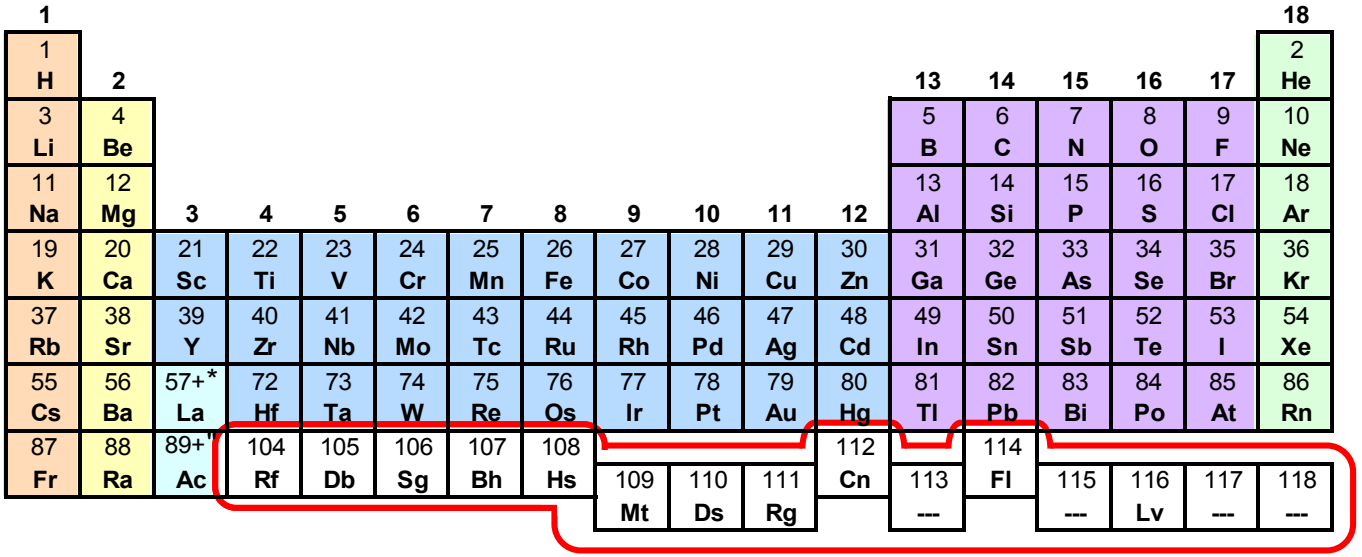
Atomic Physics Studies of the Heaviest Elements



1																	18
1 H	2											13	14	15	16	17	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg	3	4	5	6	7	8	9	10	11	12	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

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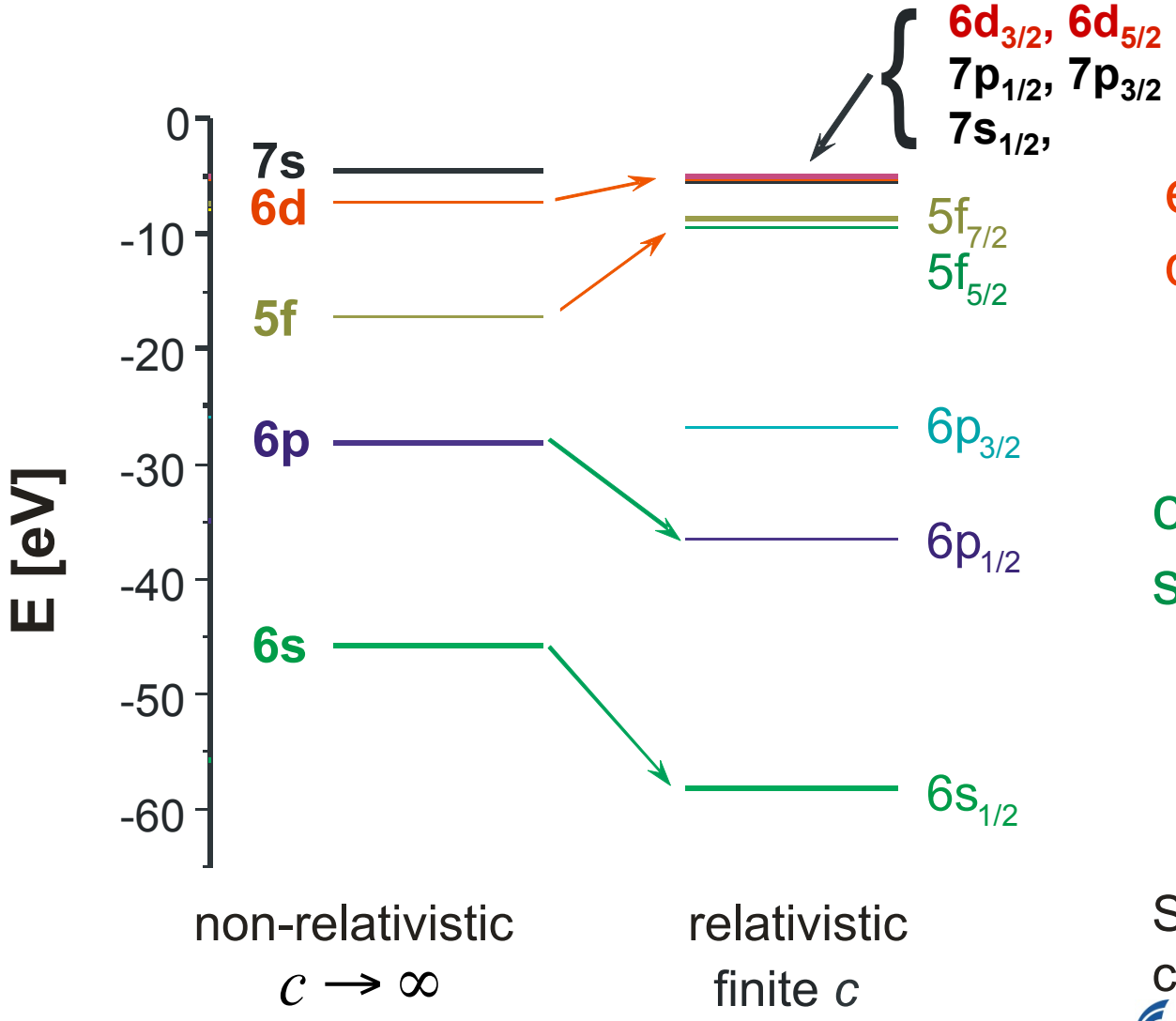
Relativistic Effects in Uranium



expansion of d, f orbitals

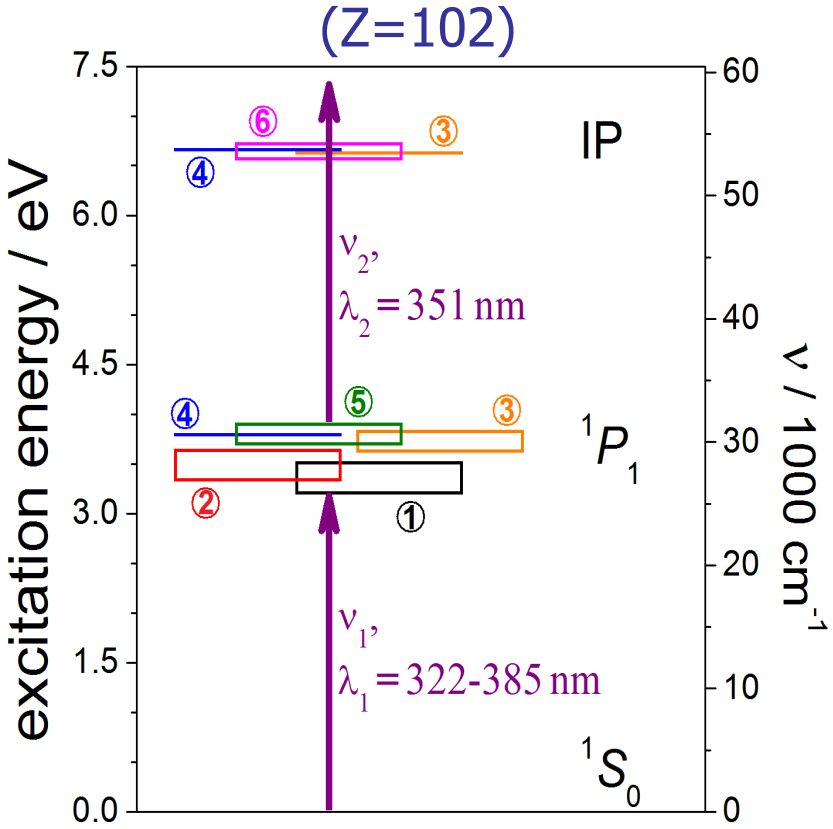
contraction of $s_{1/2}$, $p_{1/2}$ orbitals

Spin-orbit coupling

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

Search for Atomic Transitions in Nobelium

Theoretical predictions for the $^1S_0$-$^1P_1$- transition in the element nobelium



- 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 for $^{251\text{-}255}$No

[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

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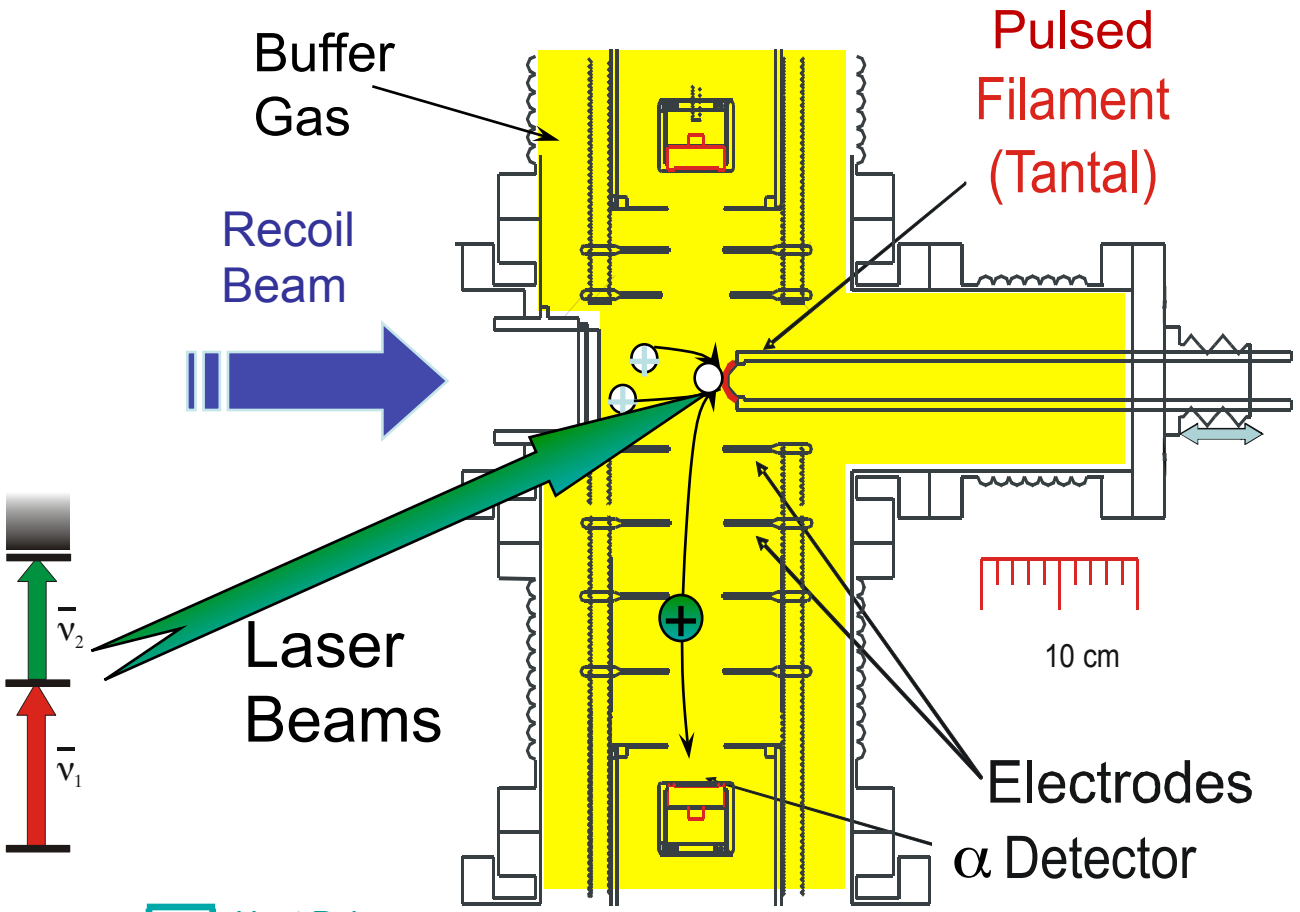
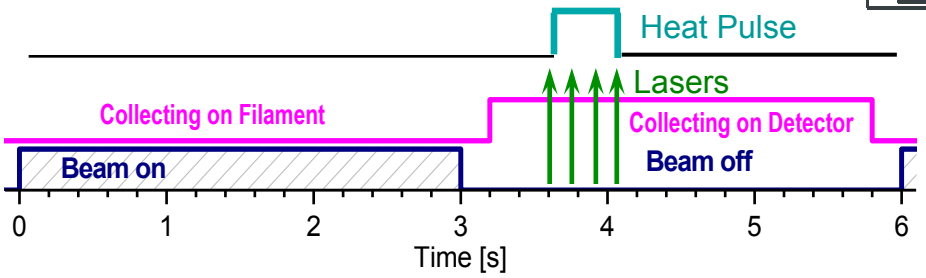
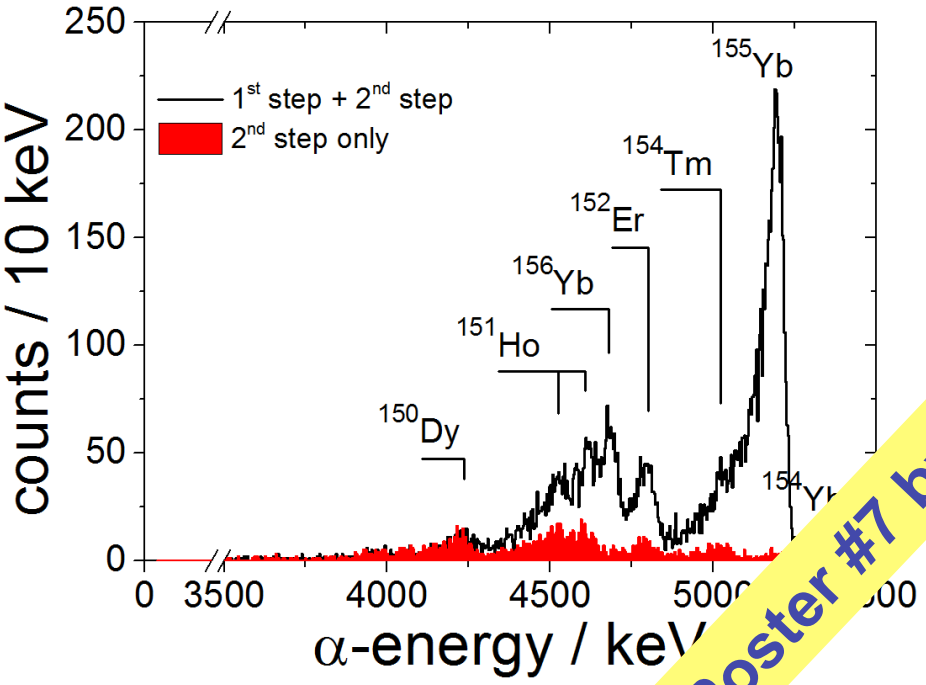
Resonant Ionization Laser Spectroscopy of Nobelium

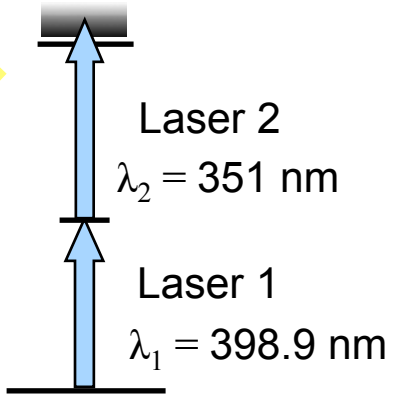




RADRIS-optimization: on-line experiments (^{155}Yb)



2-step excitation ^{155}Yb



overall efficiency 1% achieved

selectivity > 10

See also: Poster #7 by P. Chhetri

experiments on the ch[illegible]al homolog Yb allow:

- optimizatio[illegible]ll setup
- localizing th[illegible] atom cloud
- monitoring of overall efficiency during level-search in nobelium

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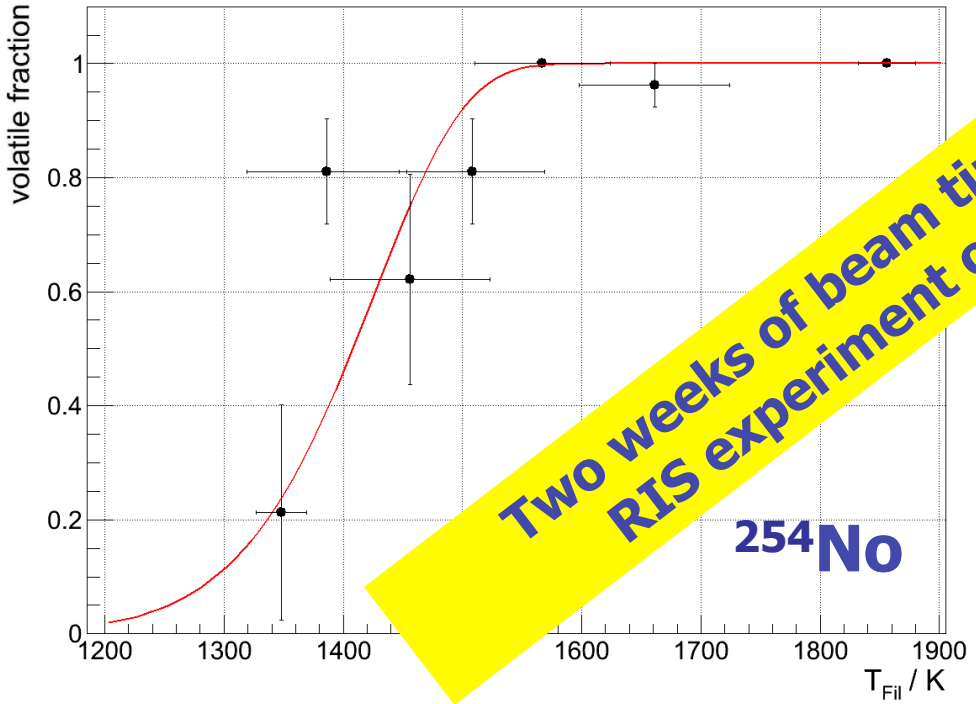
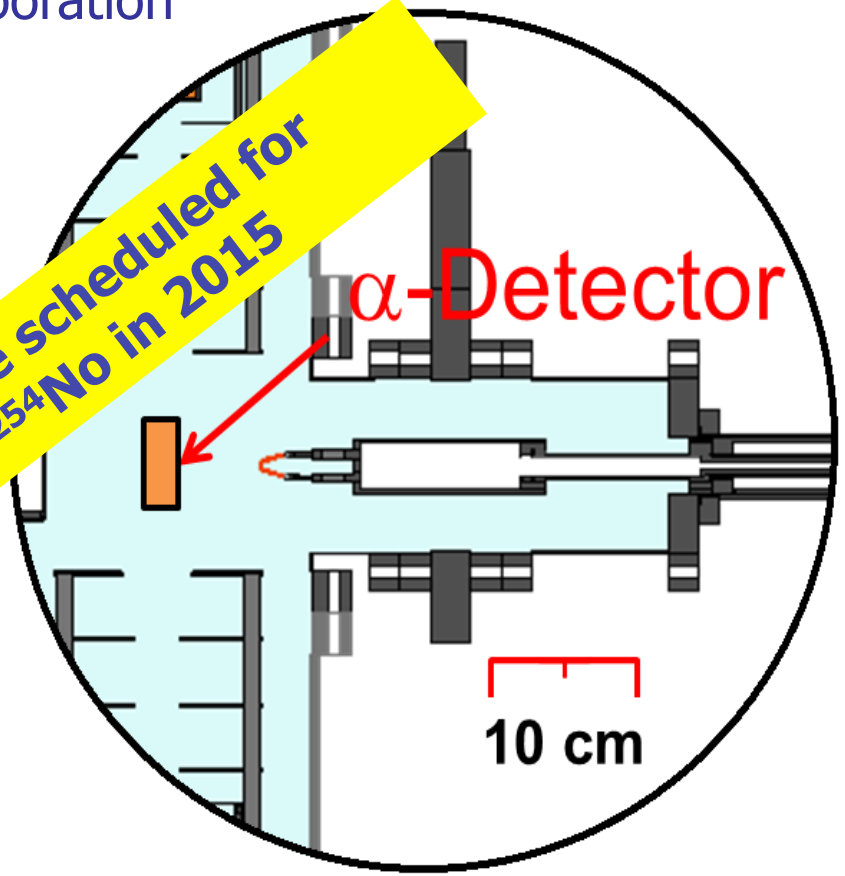
Evaporation of ^{254}No from Ta Filament

- 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 in 2015



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

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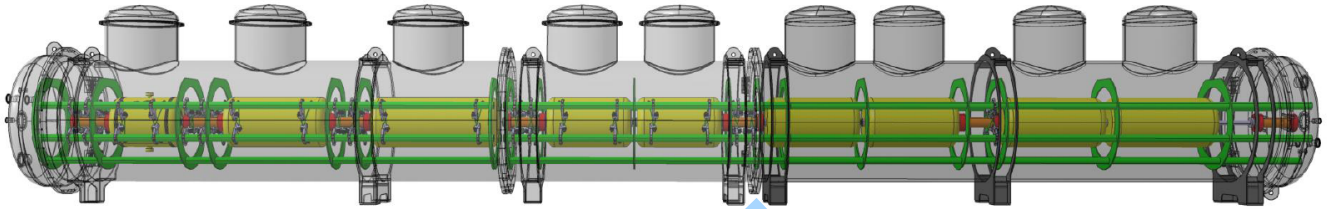
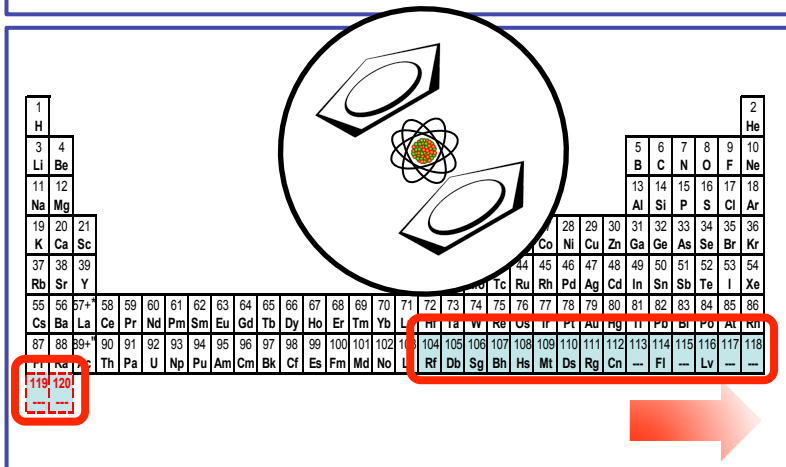
SHE research 2020+

New cw linac

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





- Atomic structure beyond No (Z=10
- Experiments with single SHE-ic
  (e.g. chemistry + mass spe
- Chemical studies towar kn
- New SHE molecules, tability,
  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

Thank you for your attention!

Summary and Conclusions

- State-of-the-art mass spectrometry provides masses of exotic nuclides with high accuracy – anchor points
- High-precision mass measurements allow probing the evolution of nuclear shell effects in the heaviest elements
- Laser spectroscopy gives access to atomic properties studying relativistic effects
- In the future laser spectroscopy will provide model independent data on nuclear spins and moments
- Technical and methodical improvements will extend the reach towards more exotic nuclides with higher Z

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