Penning-Trap Mass Spectrometry of the Heaviest Elements with SHIPTRAP

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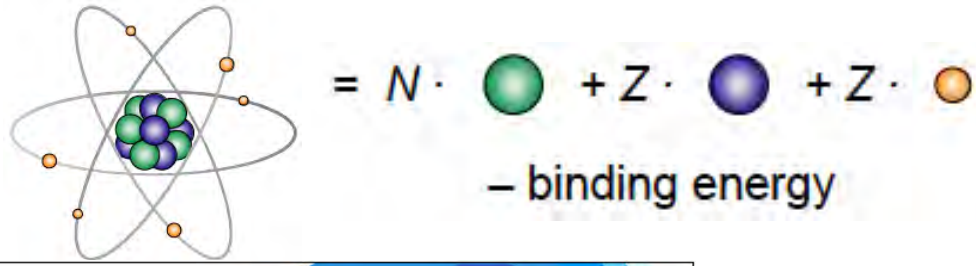
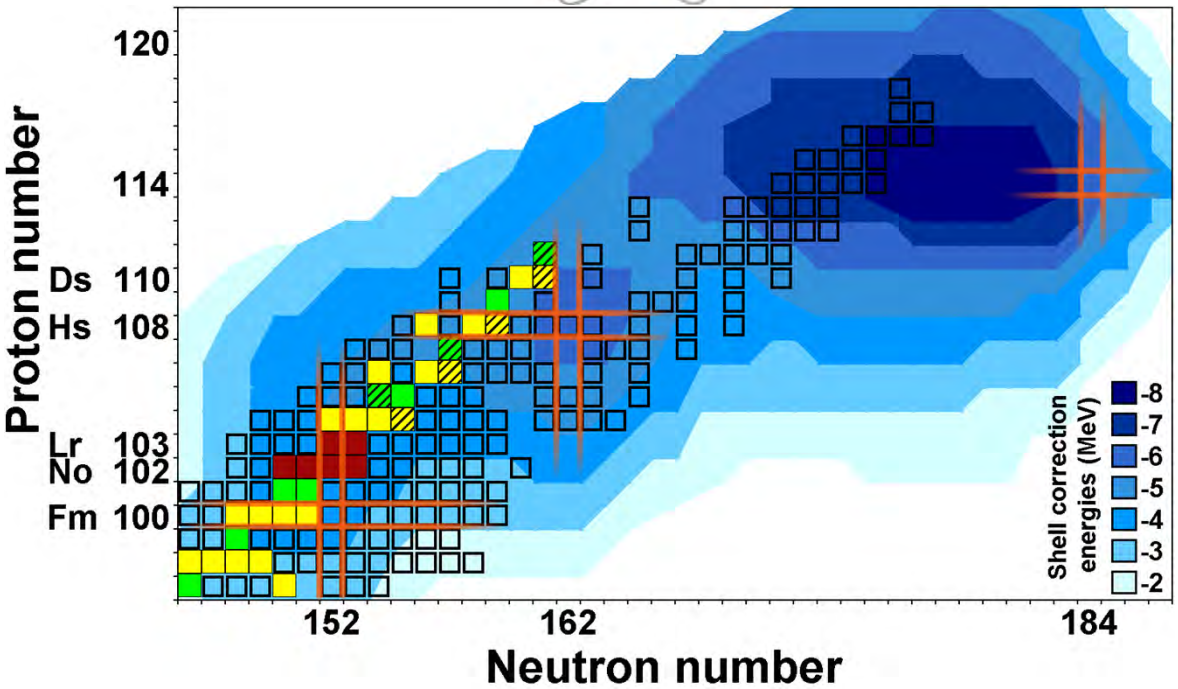
On behalf of the SHIPTRAP Collaboration

PTMS for SHE





Existence of SHEs (Z≥104)

- **How heavy can elements be?**
- **Where is the island of satbility?**
- **What is the structure of SHEs?**

  ...Stability due to shell effects

  → accurate binding energies!

Up to now masses of

$^{252\text{-}255}$No and ^{255,256}Lr

with $\delta m/m \sim 10^{-7}$ to 10^{-8}

High-precision mass spectrometry of the SHEs allow to...

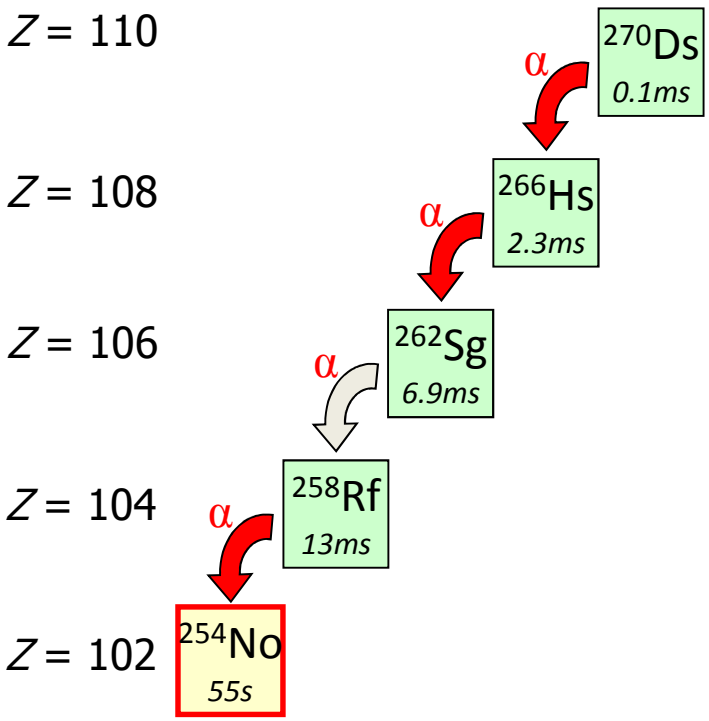
... map and study nuclear shell effects

... provide anchor points to fix alpha decay chains

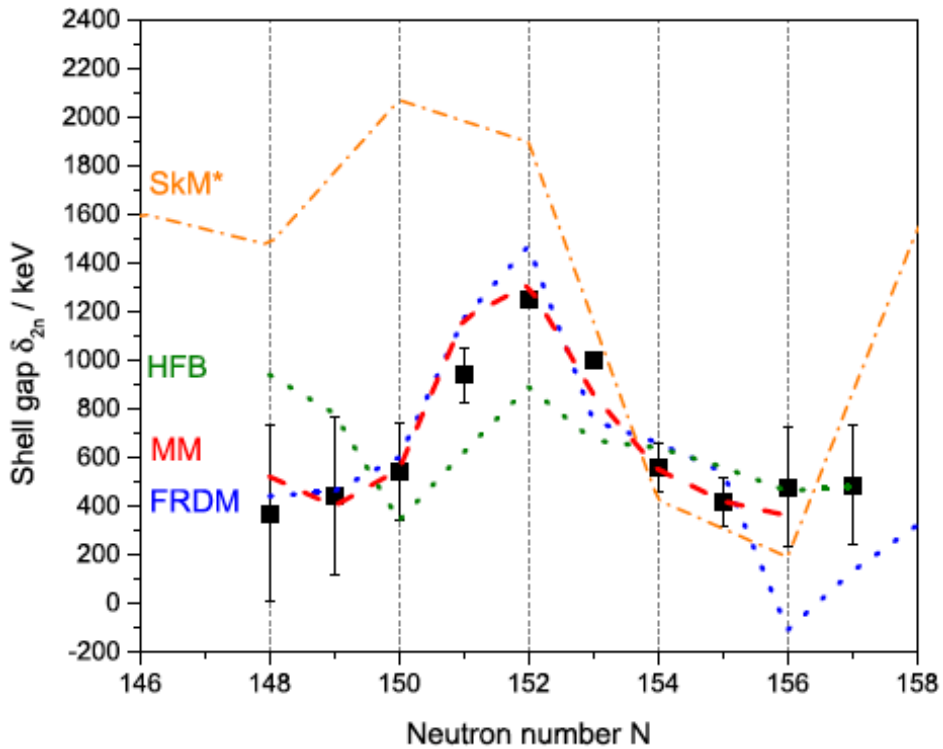
... benchmark theoretical models

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

Mapping nuclear shell effects with direct mass measurements



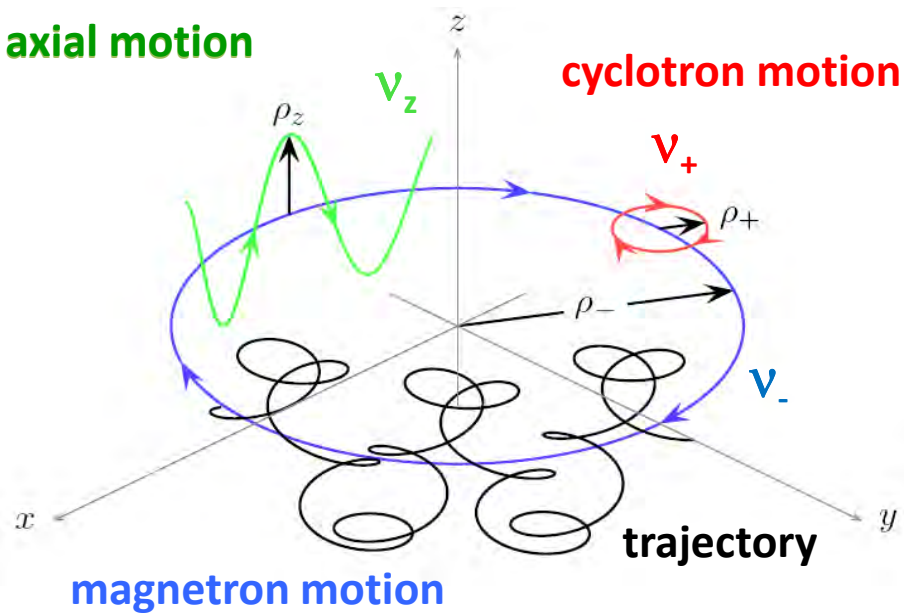
^{270}Ds mass can now be fixed with about 40 keV uncertainty

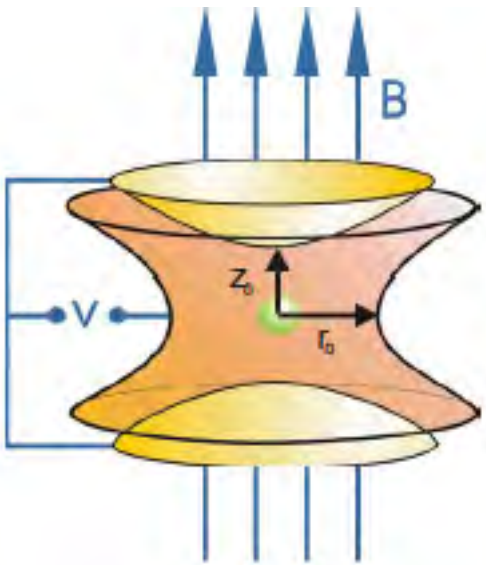


M. Block., Nucl. Phys. A 944, 471 (2015)

M. Dworschak et al., Phys. Rev. C 81, 064312 (2010)

Ion storage in a Penning Trap



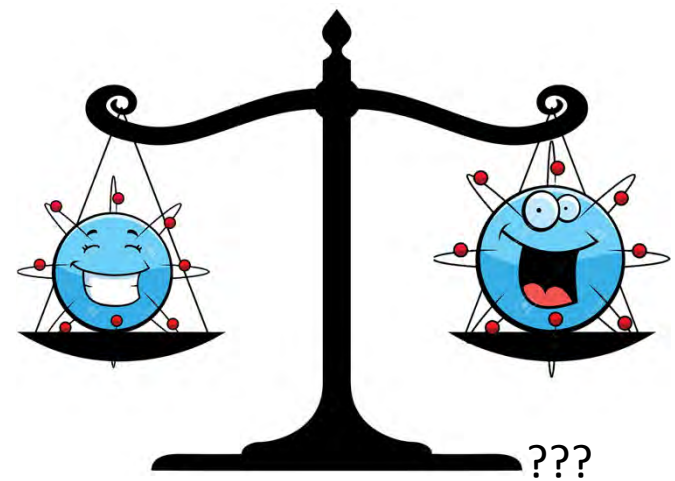


The free cyclotron frequency is inverse proportional to the mass of the ions!

$$\nu_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$

$$\nu_c = \nu_+ + \nu_-$$

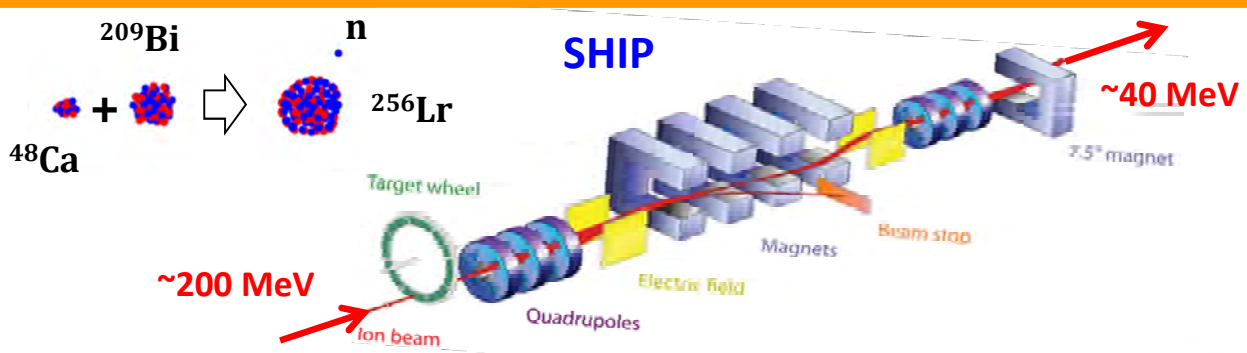
$$R = \frac{\nu_{ref}}{\nu_c} = \frac{m}{m_{ref}}$$

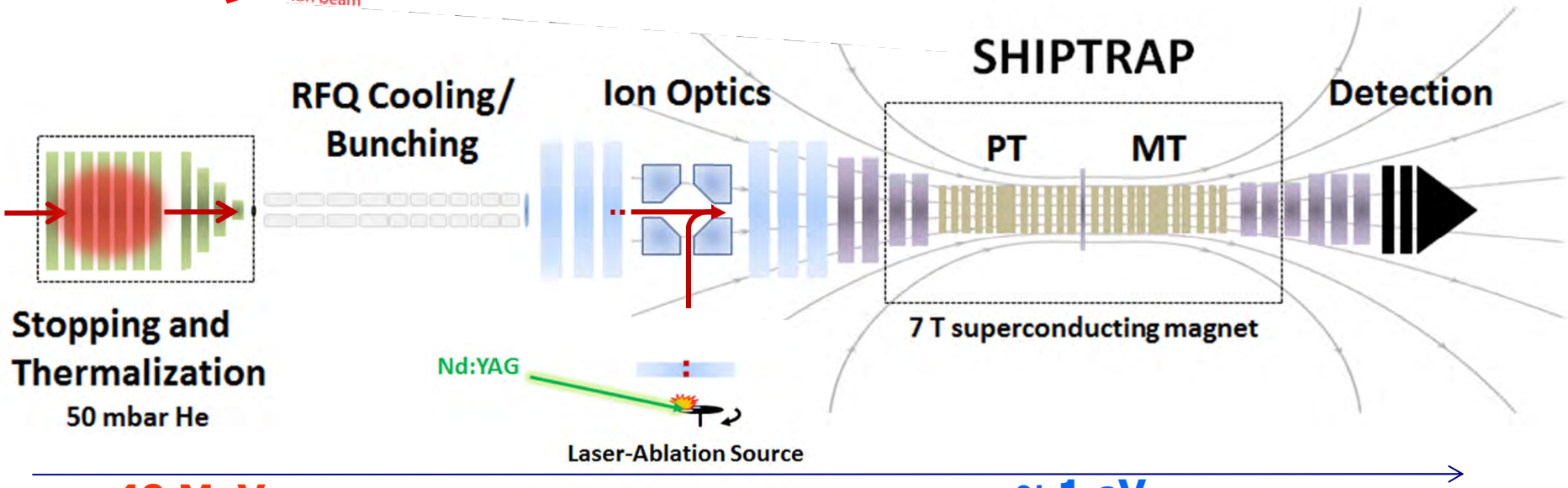


$^{133}Cs^+$ / ^{12}C clusters

radioactive

The SHIPTRAP setup

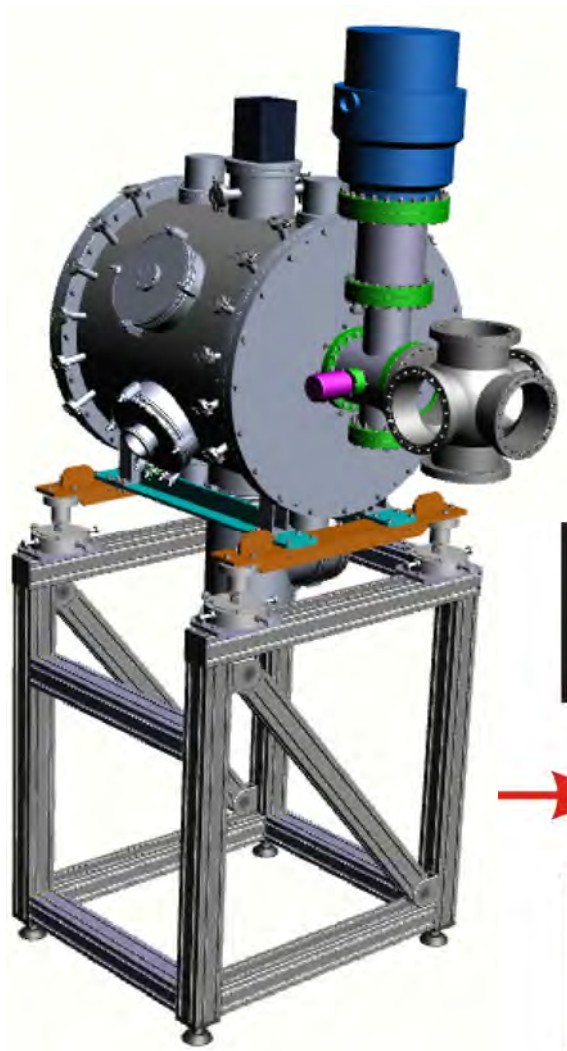




$\delta m/m = 10^{-9}$ short-lived exotic nuclei

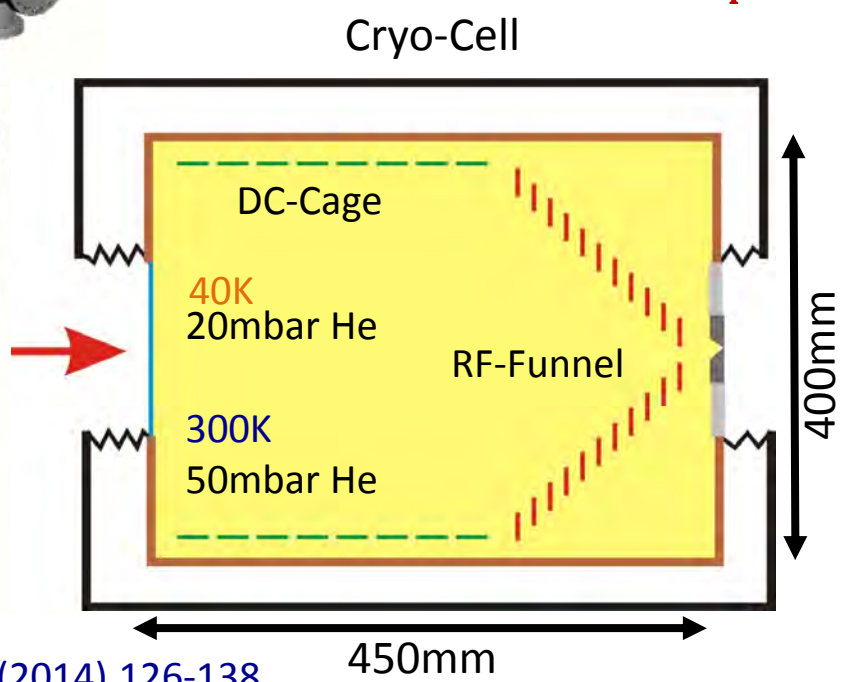
$\delta m/m = 10^{-10}$ stable nuclei

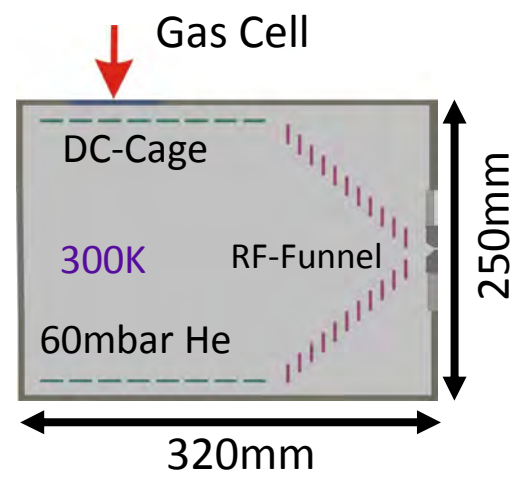
The Cryogenic Gas Cell



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

For ^{254}No: $\varepsilon_{overall} = \varepsilon_{stop}\,\varepsilon_{extr} = 33(5)\%$

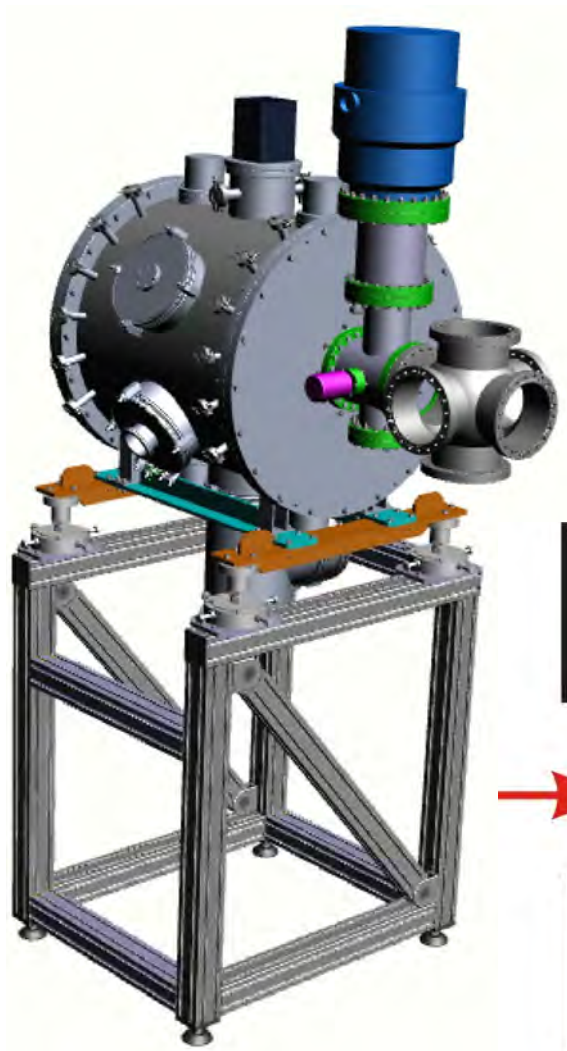




$\varepsilon_{cell} = \varepsilon_{stop}\,\varepsilon_{extr} < 10\%$

C. Droese et al., NIMB 338 (2014) 126-138

The Cryogenic Gas Cell



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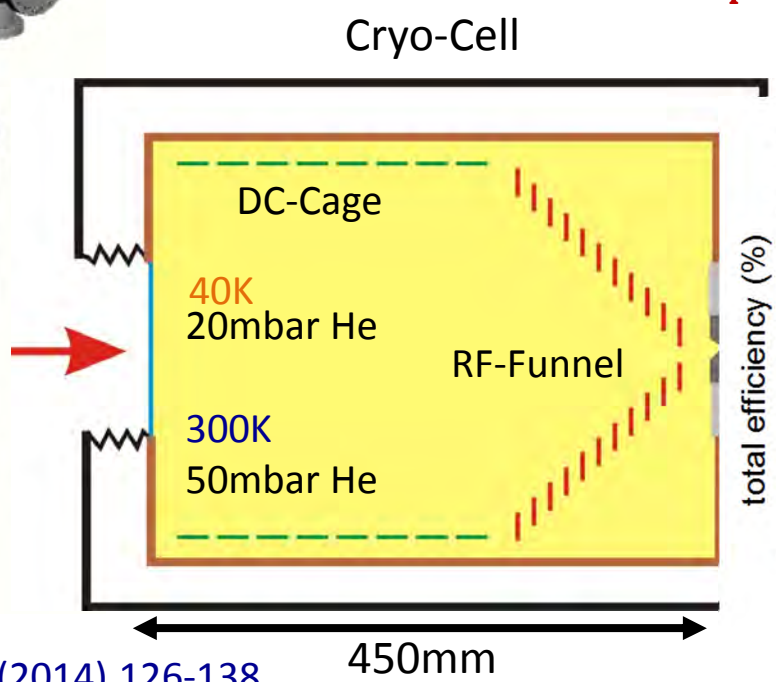
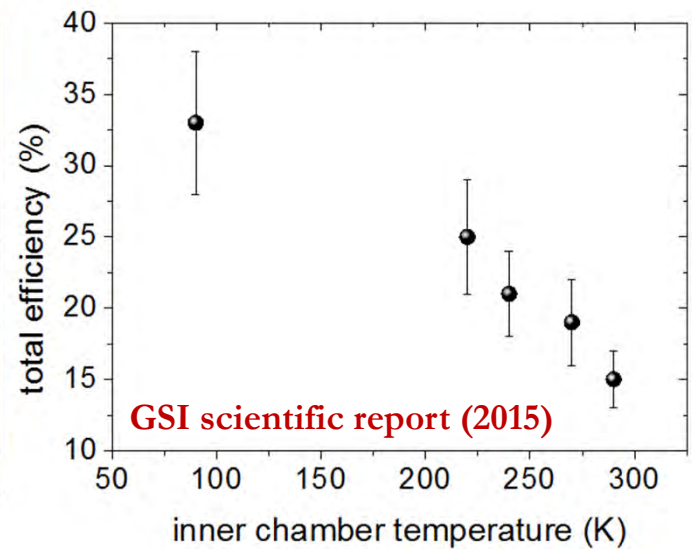
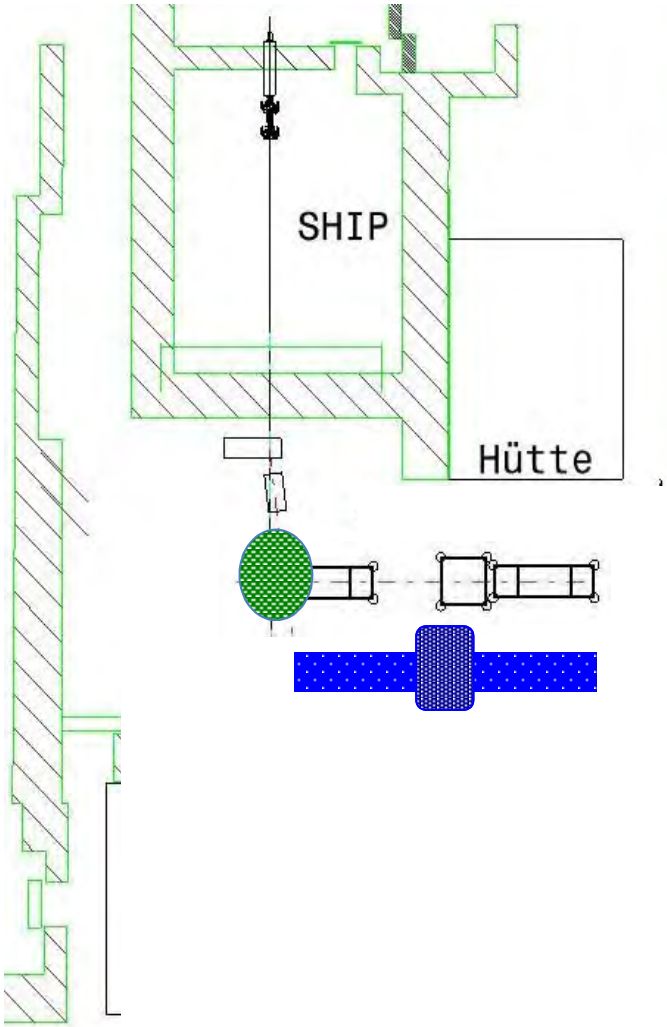
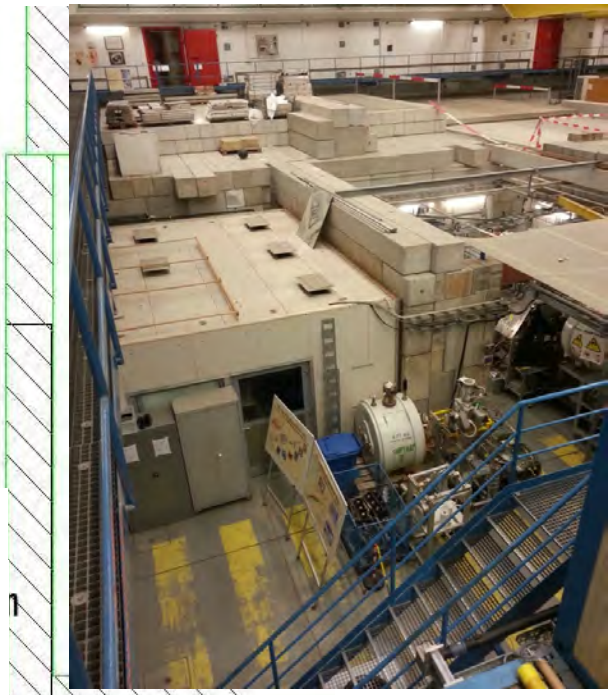


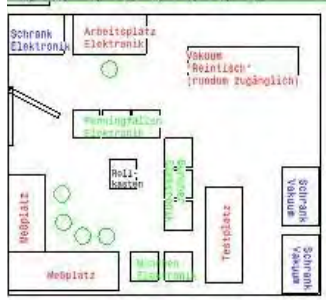


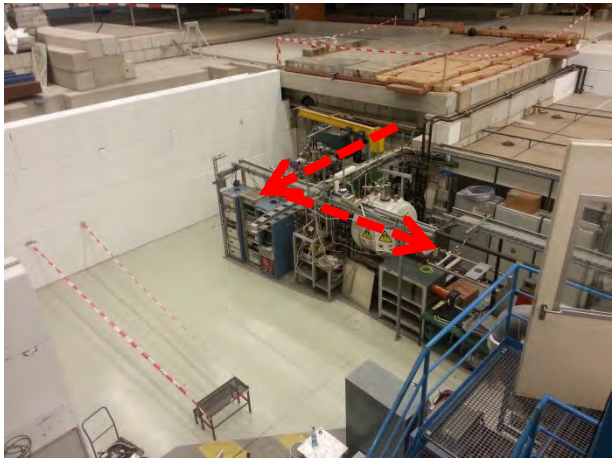
C. Droese et al., NIMB 338 (2014) 126-138

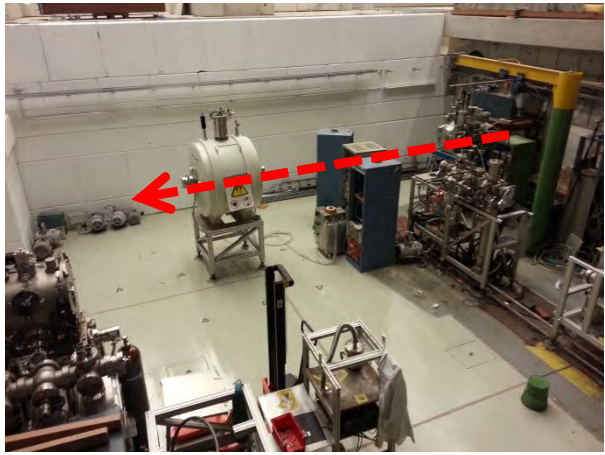
2015-2016: Setup relocation



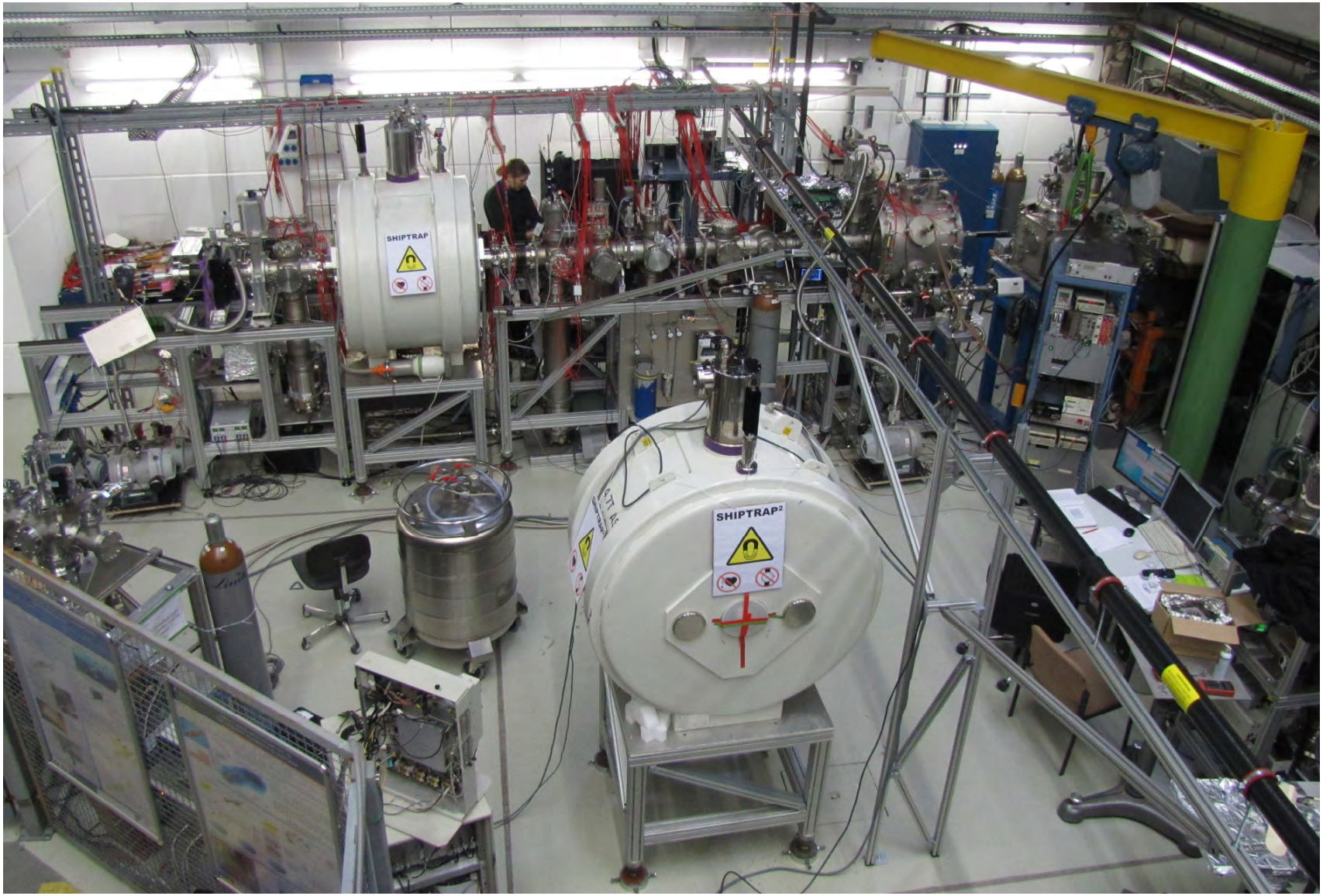






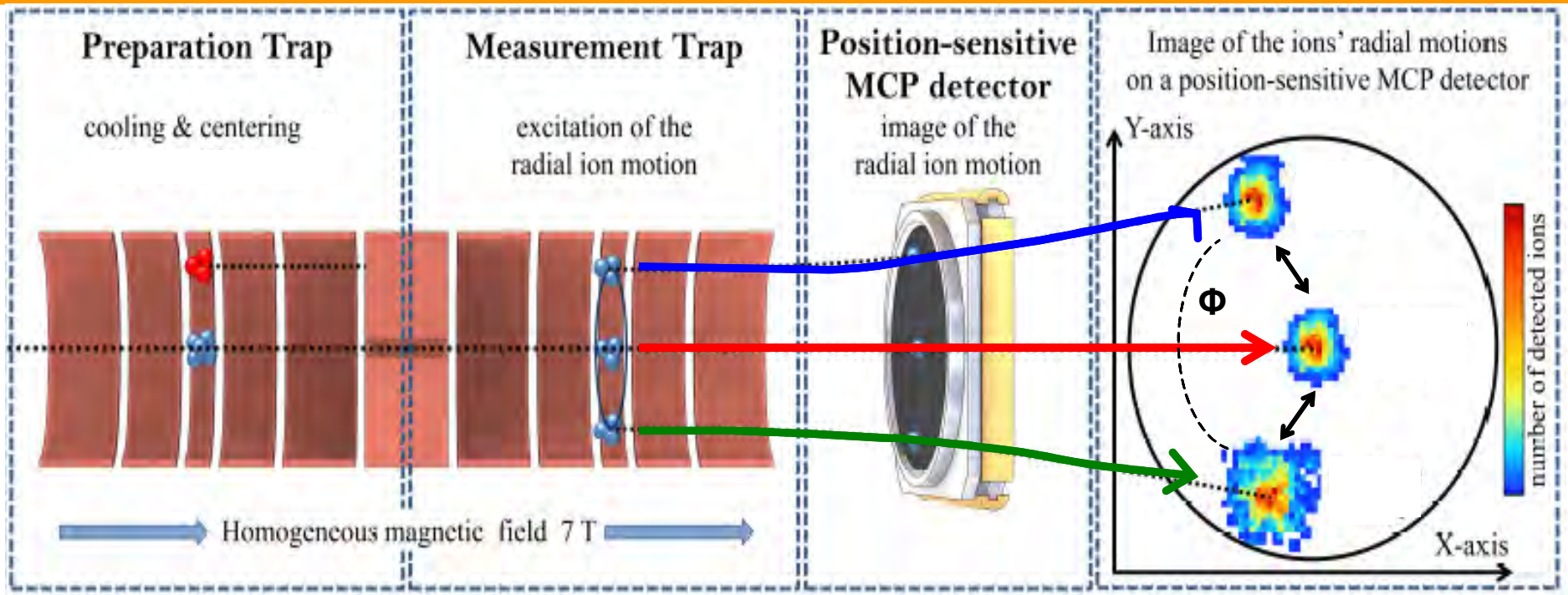


The experimental hall today



Q3/2016 - G. Otto, GSI, Darmstadt

Phase Imaging Ion-Cyclotron Resonance method PI-ICR



Radial excitation

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

Determination of the spatial distribution

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

Radial excitation followed by a phase accumulation time

Gain in Precision ≈ 4.5
Gain in resolving power ≈ 40

S. Eliseev et al., Phys. Rev. Lett. 110, 082501 (2013)
S. Eliseev et al., Appl. Phys. B114, 107 (2014)

Beamtime June-July 2018

	Production cross section [nb]	(Rough) Incoming ion Rate
^{254}No gs & isomer	1800	1,5/s
^{255}Lr gs & isomer	200/52	0.2 /s
^{256}Lr gs	60	0.05/s
^{251}No gs & isomer	30	0.05/s
^{254}Lr gs & isomer	22	0.03/s
^{257}Rf	15	0.03/s

Beamtime June-July 2018: ^{256}Lr

^{254}No

Less than 8 h → 10 times better δm/m,
resolved GS and E*≈1,2 MeV isomer

^{256}Lr

In 2010 ToF –ICR → 48 ions in 93 h δm/m =10^{-7}
In 2018 PI –ICR → 133 ions in 60 h **δm/m =10^{-9}**

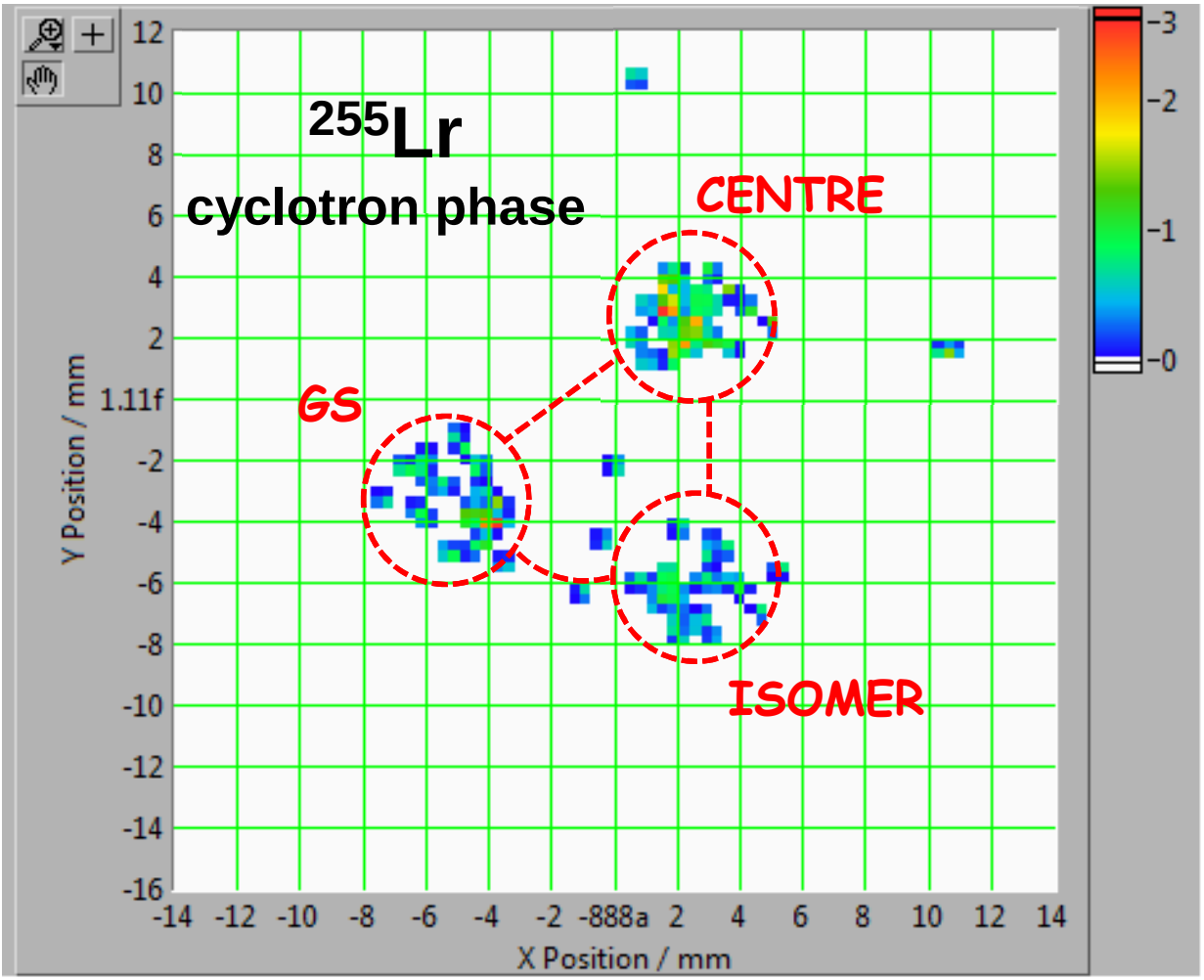
Low ion rate = long measurements

Challenges:

✧ Reduced drift of the magnetic field → Two/three step temperature stabilization of the magnet bore
(temperature fluctuations reduced to ~ 25mV)

✧ Reduced drift of the trapping voltage → More stable power supplies for MT temperature-controlled cabinet
(fluctuations < 1 mV)

Beamtime June-July 2018: ^{255m}Lr

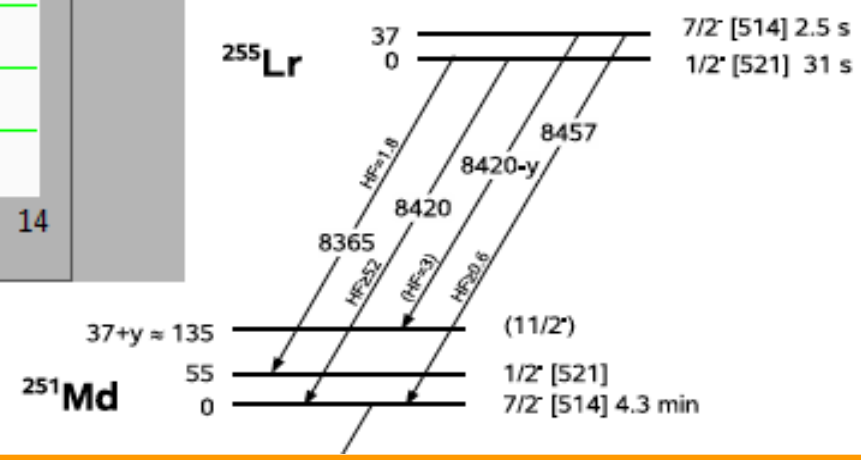


^{255m}Lr

$E^* \approx 30$ keV

$T_{1/2} \approx 2.5$ s

Resolving power ≈ 11 000 000 !!!



A. Chantillon et al., Eur. Phys. J. A 30 (2006) 397
F. Hessberger et al., Phys. At. Nucl. 70 (2007) 14
S. Antalic et al., Eur. Phys. J. A 38 (2008) 219

Summary

- High-precision mass measurements allow probing shell effects and tracking the evolution of nuclear structure in the heaviest elements.
- Technical and methodical improvements at SHIPTRAP allow now extending the reach towards more exotic nuclides with higher *Z*.
  - Implementation of the Cryogenic buffer-gas cell
  - Re-arrangement of the whole beam line successfully completed
  - Development of a new measurement method, the PI-ICR technique

Successful direct measurements of the mass of ^{257}Rf (σ=15 nb)

and low-lying isomeric states in ^{254,255}Lr and ^{251}No!

SHIPTRAP collaborators

B. Anđelić, O. Bezrodnova, K. Blaum, M. Block, S. Chenmarev, P. Chhetri, C. Droese, M. Eibach, S. Eliseev, J. Even, P. Filianin, S. Götz, Y. Gusev, M. Gutierrez, F. P. Hessberger, O. Kaleja, J. van de Laar, M. Laatiaoui, S. Lohse, N. Martynova, E. Minaya Ramirez, A. Mistry, T. Murboeck, Yu. Novikov, S. Raeder, D. Rodriguez, F. Schneider, L. Schweikhard, P. Thirolf

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