Probing the heaviest elements using Penning Trap Mass Spectrometry at SHIPTRAP

Manuel J. Gutiérrez (HIM) for the SHIPTRAP collaboration

GSI

HIM
HELMHOLTZ
Helmholtz-Institut Mainz

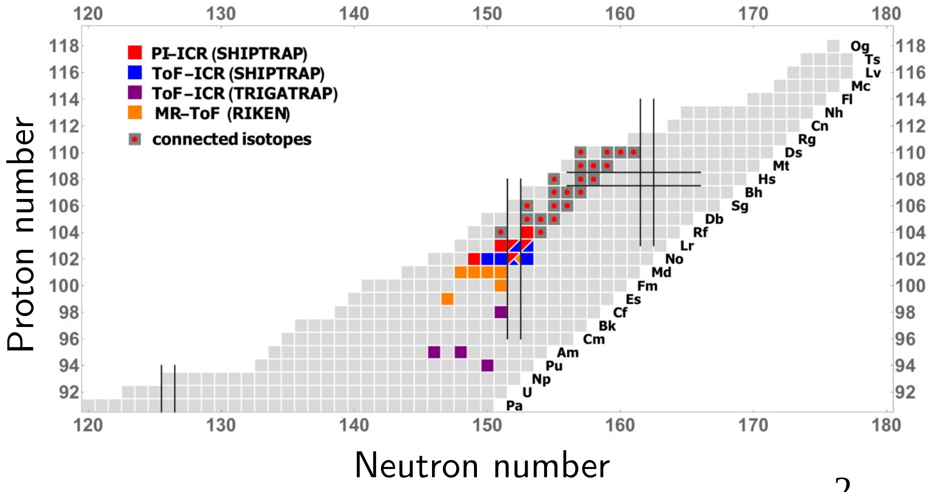
FAIR
Phase 0
Research Program

TASCA22: 19th Workshop on Recoil Separator for Superheavy Element Chemistry & Physics

Mass measurements of SHEs

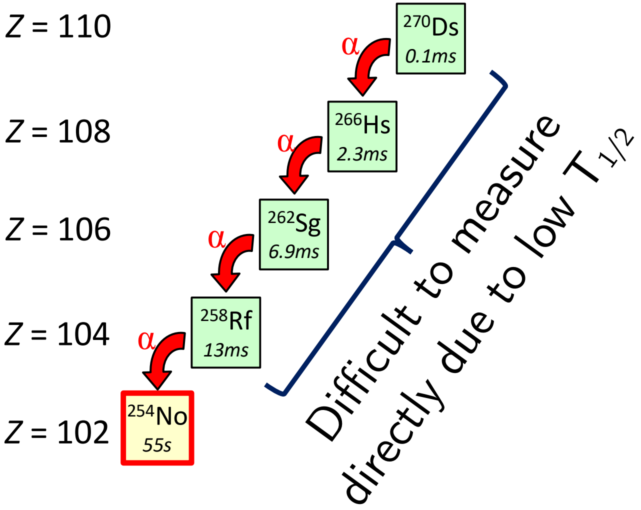
- With mass measurements of SuperHeavy Elements (SHEs):
  - Benchmark nucl. structure models at extreme conditions
  - Study isomers (if enough resolution)
  - Determine binding energies
  - Anchor points
- Produced in tiny amounts ($< 1/h$)
  - Efficiency is key!

Status as of 2018:

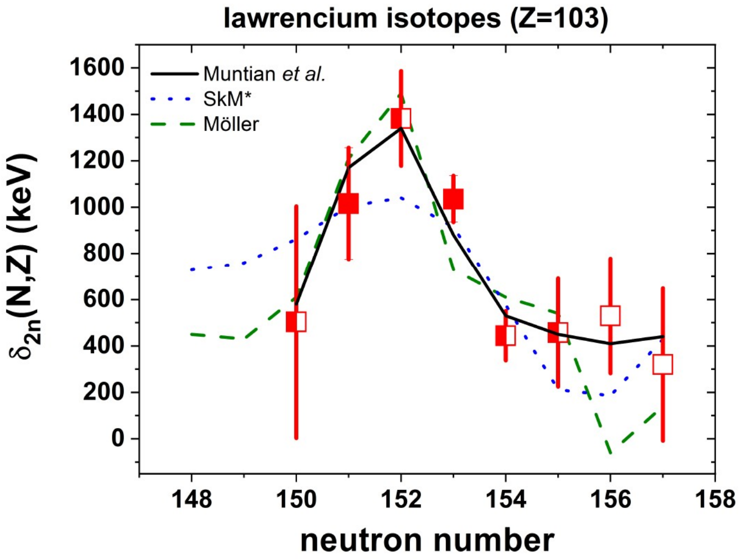


Mass measurements of SHEs

Anchor points:



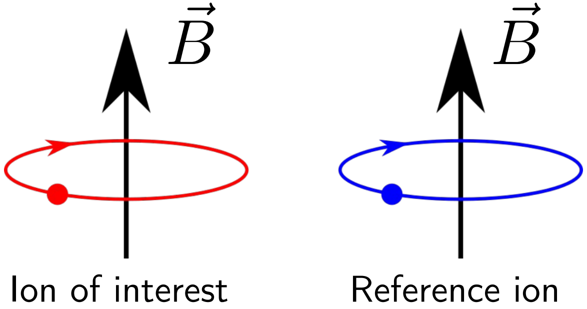
Shell closure position and strength:



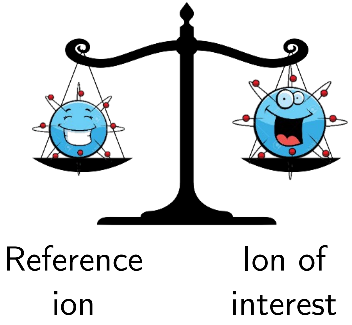
E. Minaya Ramirez *et al*, Science 337 1207 (2012)
M. Dworschak et al., PRC 81 (2010)
O. Kaleja *et al*, in preparation
O. Kaleja, PhD thesis

Penning Trap Mass Spectrometry

High, uniform B:

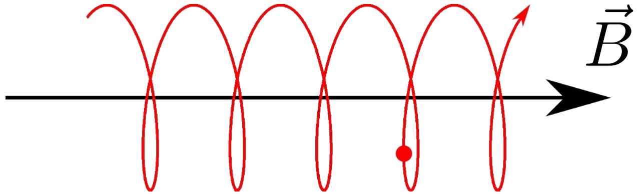


$$\nu_c = \frac{1}{2\pi}\frac{qB}{m} \Rightarrow \frac{\nu_c^{ioi}}{\nu_c^{ref}} = \frac{(m/q)^{ref}}{(m/q)^{ioi}}$$



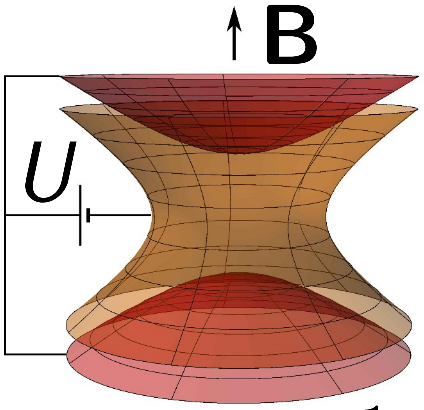
Important: $\nu_c^{ioi} \simeq \nu_c^{ref}$ (systematics) → choice of reference!

If no other fields are present...



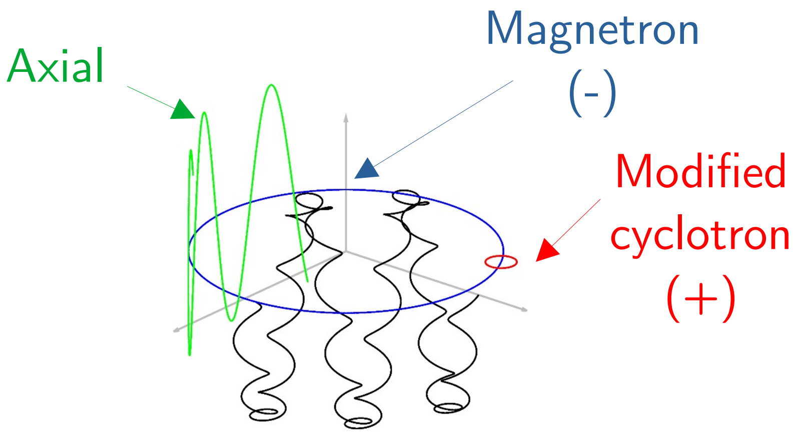
Penning Trap Mass Spectrometry

Penning trap



$$U(\vec{r}) \propto z^2 - \frac{1}{2}r^2$$

Resulting motion

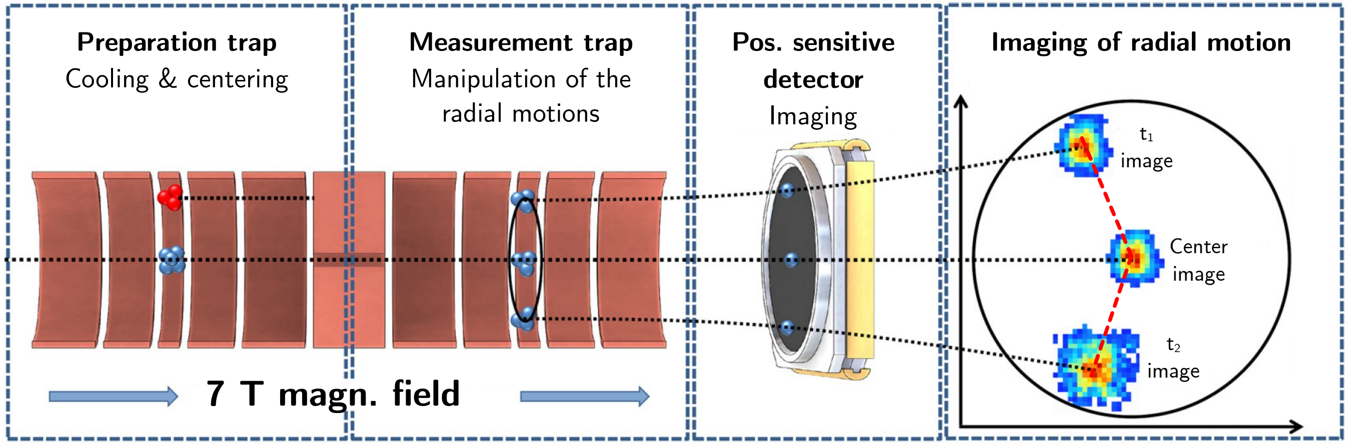


$$\nu_c \simeq \nu_+ \gg \nu_z \gg \nu_-$$

From the 'trap' frequencies: $\nu_c^2 = \nu_+^2 + \nu_z^2 + \nu_-^2$ or $\nu_c \simeq \nu_+ + \nu_-$
(sideband method precise up to 10^{-9})

Phase-Imaging Ion-Cyclotron-Resonance

Several ways to measure motional frequencies in Penning traps. Here we project radial motions onto pos. sensitive detector:



More details*:
S. Eliseev et al,
Appl. Phys. B 114 (2014)

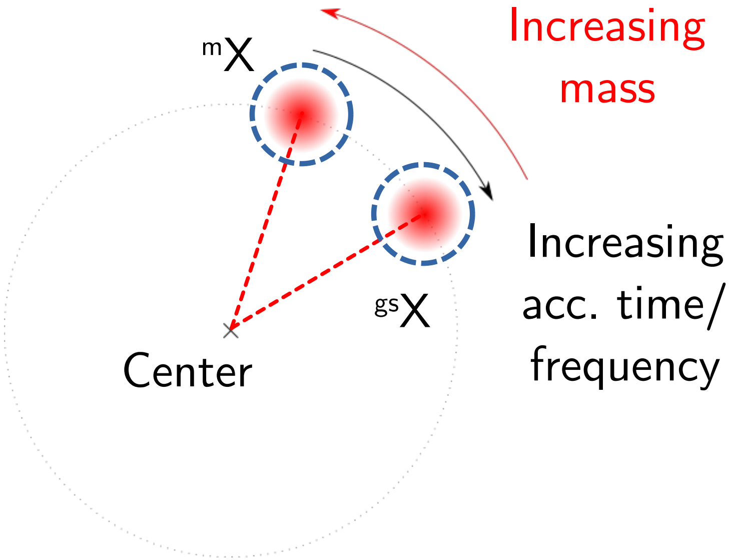
Figure adapted from:
P. Filianin et al,
Physics Letters B 758 (2016)

Then, freq = angle / time. Also, $\nu_c = \nu_+ + \nu_-$ directly is possible!*

Phase-Imaging Ion-Cyclotron-Resonance

Furthermore, difference in ν_+ allows to separating isomers & measuring their exc. energy and half life. Resolving power ≈ 11,000,000!

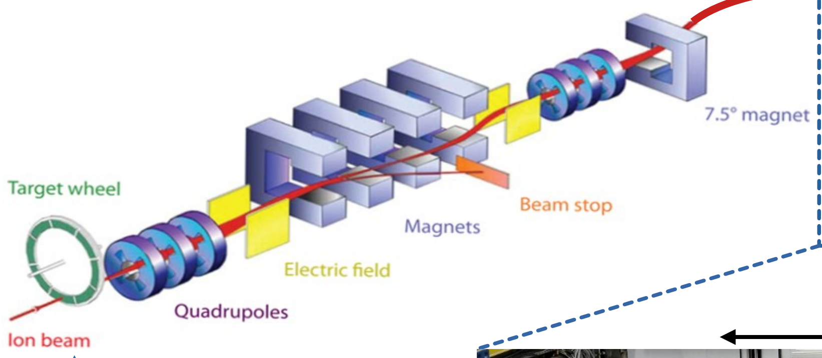
$$\begin{cases} \nu_c = \nu_+ + \nu_- \\ \nu_- \neq f(m) \end{cases} \implies \Delta\nu_c \simeq \Delta\nu_+$$

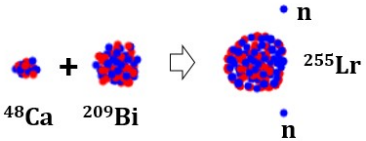


The ratio of counts in each 'spot' for different acc. times yields $T_{1/2}$

The setup

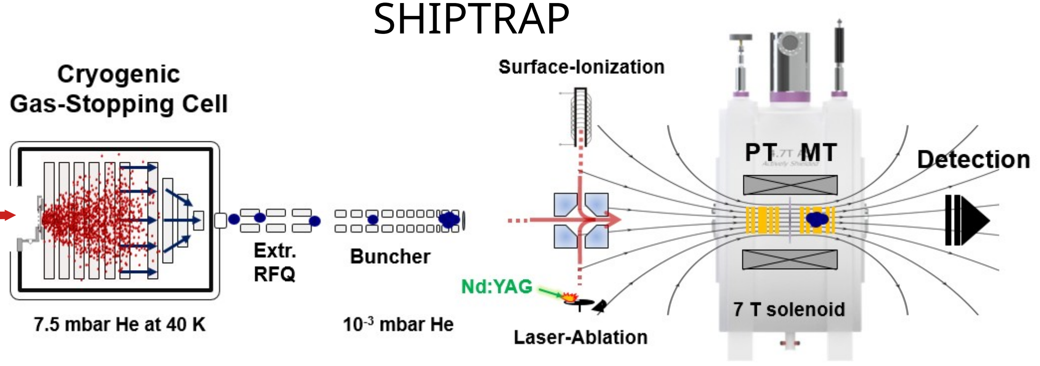
The SHIP separator





$K_{prod} \approx 40$ MeV

SHIPTRAP



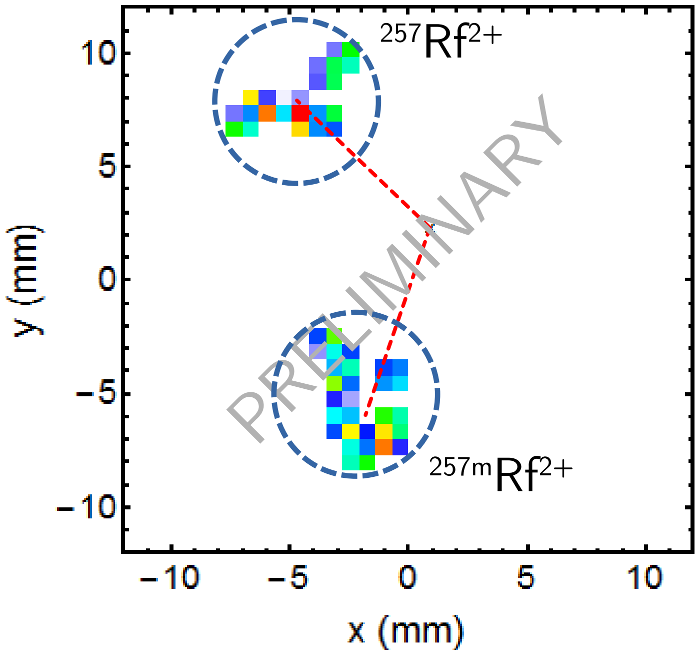
Stopping | Transport & bunching | Measurement

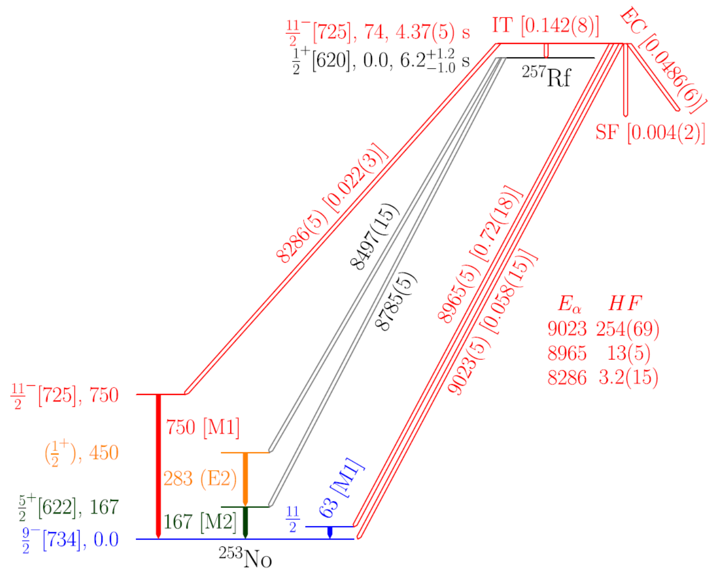
≈ 7 meters (23 feet)

Photo: G. Otto, GSI

^{257}Rf isomer

Isomer at ≈ 80 keV resolved with ≈ keV resolution. $\sigma = 10$ nb!

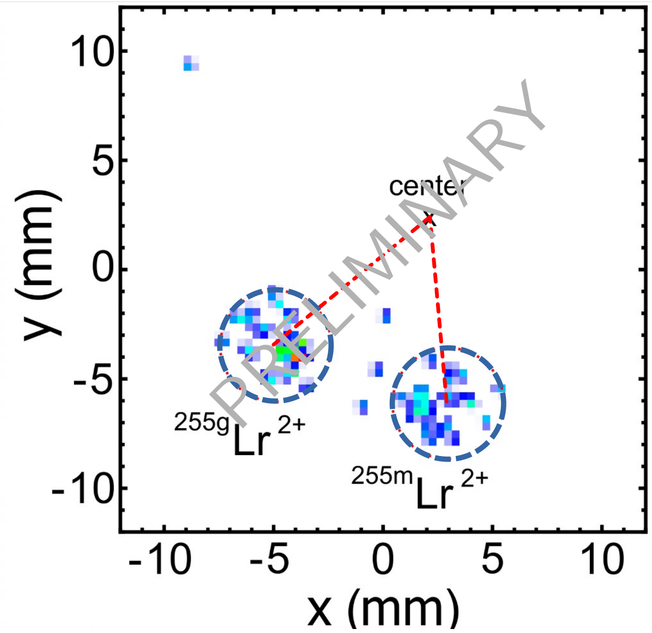




K. Hauschild *et al*, Eur. Phys. J. A **58** 6 (2022)

^{255}Lr isomer

Resolving power can be even higher – a look back at 2018:



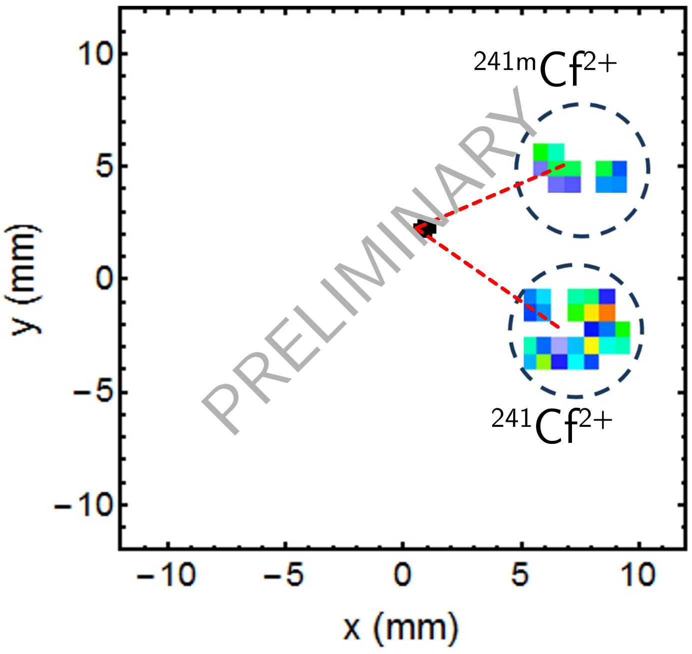
$E \approx 37$ keV $\rightarrow$

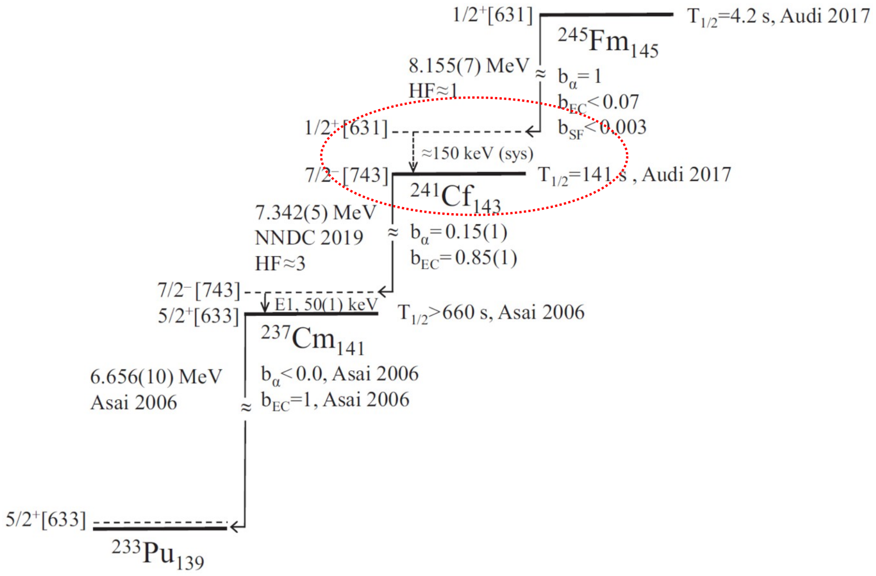
$m/\Delta m \approx 11{,}000{,}000$!

O. Kaleja *et al*, in preparation
O. Kaleja, PhD Thesis

^{241}Cf isomer

Proposed isomer* directly detected. Weisskopf estimation $T_{1/2} \approx 0.2$ ms, but it must be $\approx$ 100s of ms to be detected here!

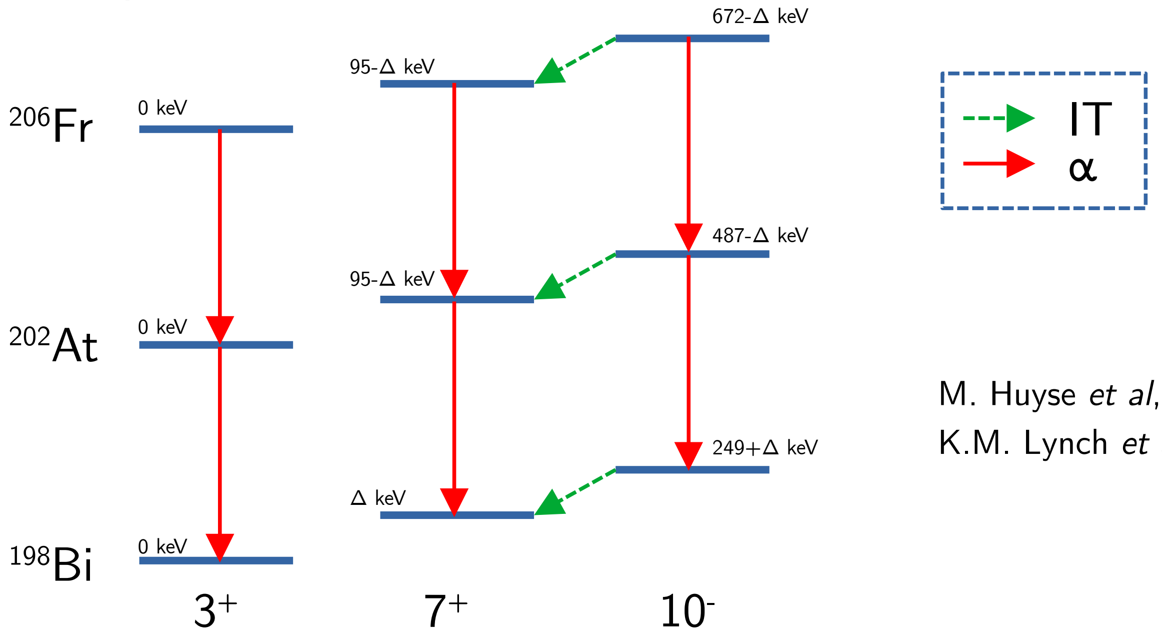




*J. Khuyagbaatar *et al*, PRC **102,** 044312 (2020)

Fr-At-Bi decay chains

Extending SHIPTRAP's range: complementing decay spectroscopy of lighter elements. Studied: ^{206}Fr – ^{202}At – ^{198}Bi and ^{204}Fr – ^{200}At – ^{196}Bi (double odd). Done with parasitic beam!

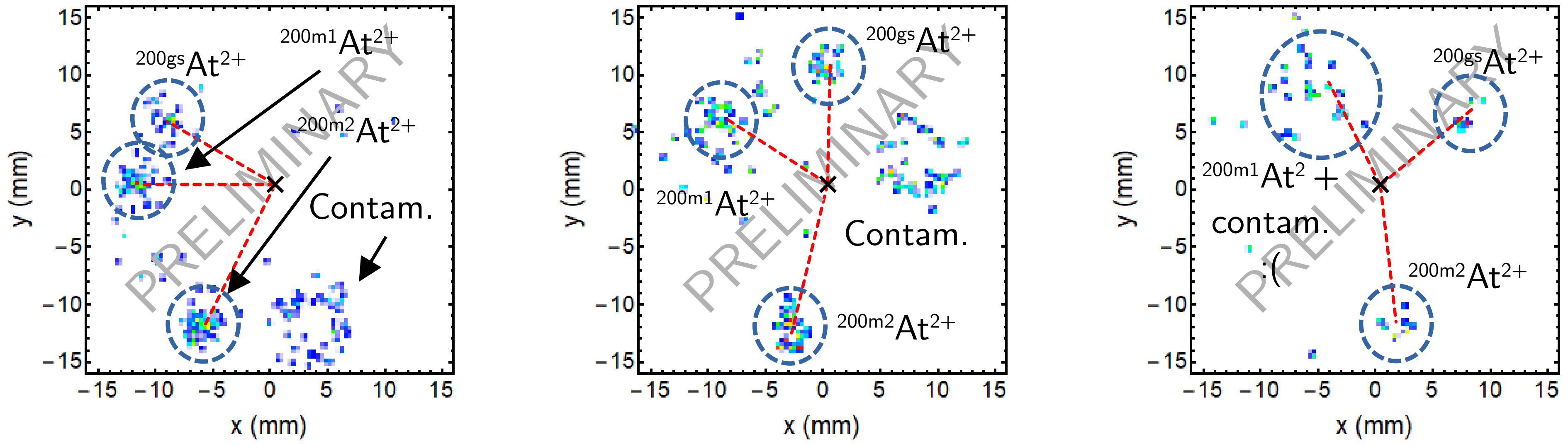


M. Huyse *et al*, PRC **46**-4 1209 (1992)
K.M. Lynch *et al*, PRC **93** 014319 (2016)

^{200}At

Two long-lived, low-lying (112 and 344 keV) isomers are resolved:

150 ms acc. time: 250 ms acc. time: 350 ms acc. time:



2021 online campaign

- Pushed the limit on SHEs even further:
  - First direct measurement of ^{258}Db (0.00002/s!)
  - Resolved isomeric state of ^{257}Rf
- Study of isomeric states of other interesting cases:
  - Californium-241
  - Francium-206 and -204 decay chains
  - ...

Recent developments

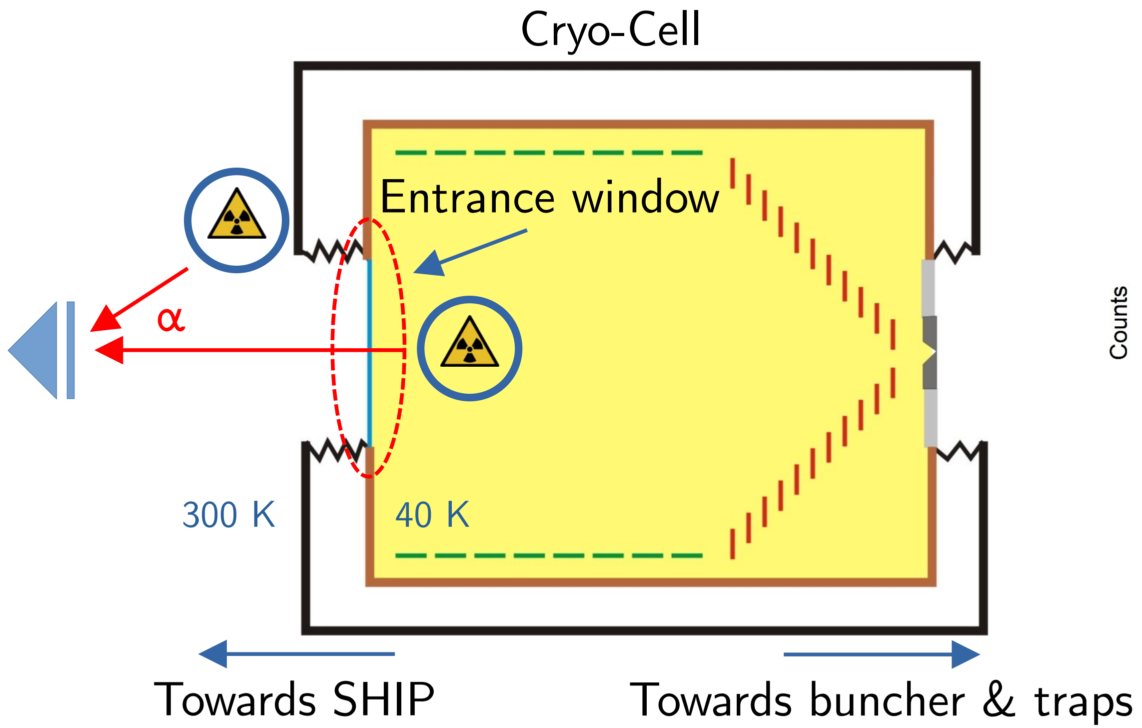
- Next candidates involve even longer measurement times (weeks).

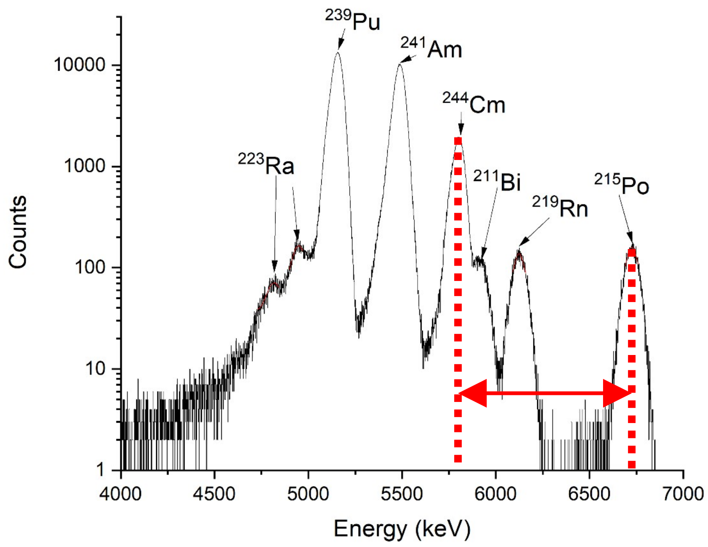
- From recent campaigns it became clear that the CGC stopping power changes with time.

- Cause has been found to be cryopumping by the entrance window. Window is at 40 K, but exposed to room temperature vacuum of SHIP $\rightarrow$ freezing of residual gases.

Thickness measurement

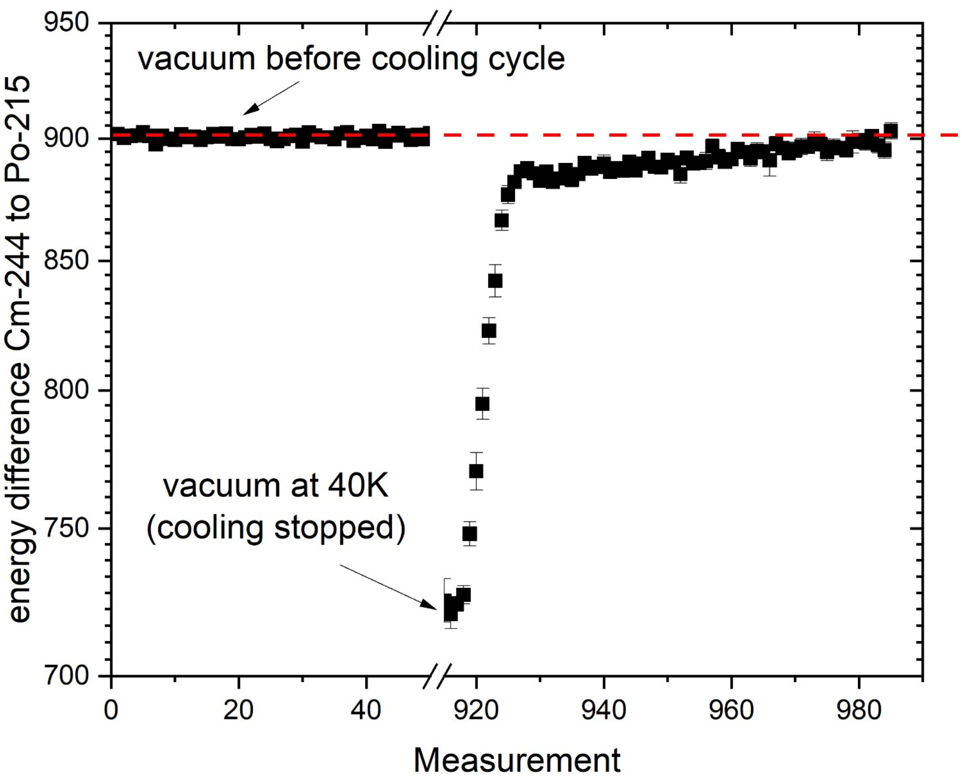
Idea: track the difference in α energy from inside and outside the cell:





Thickness measurement

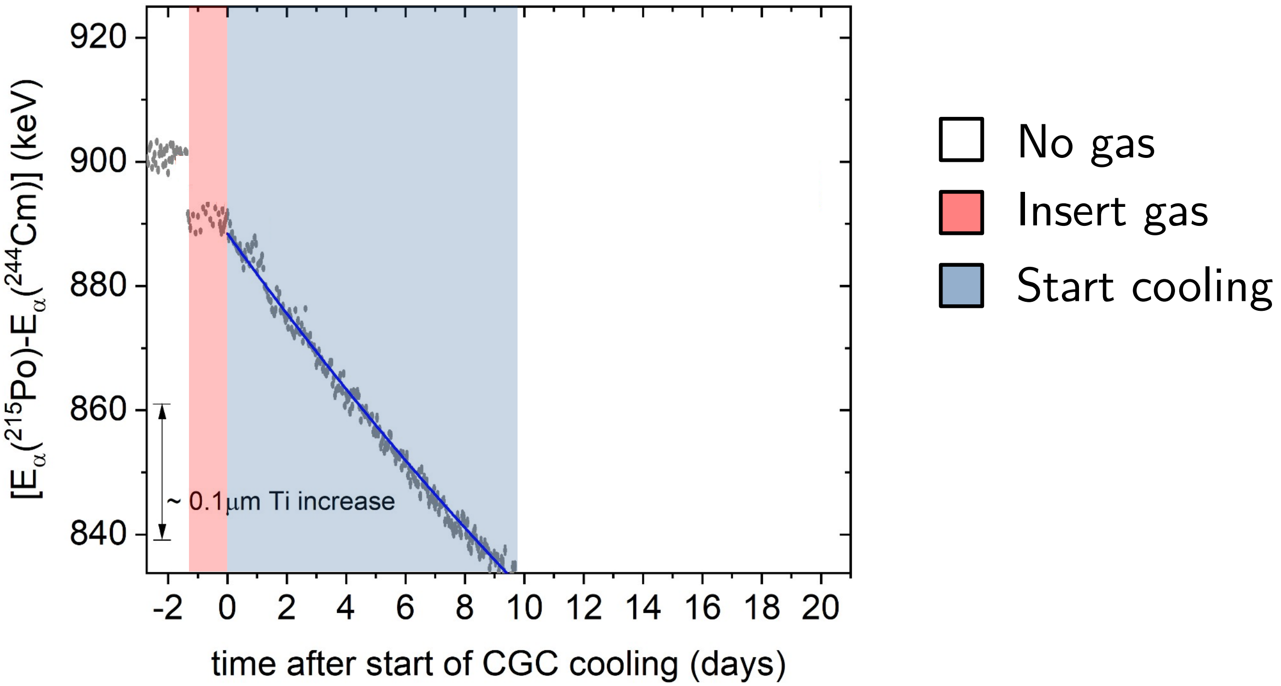
During warm up:



This indicates at least two substances accumulate on the window

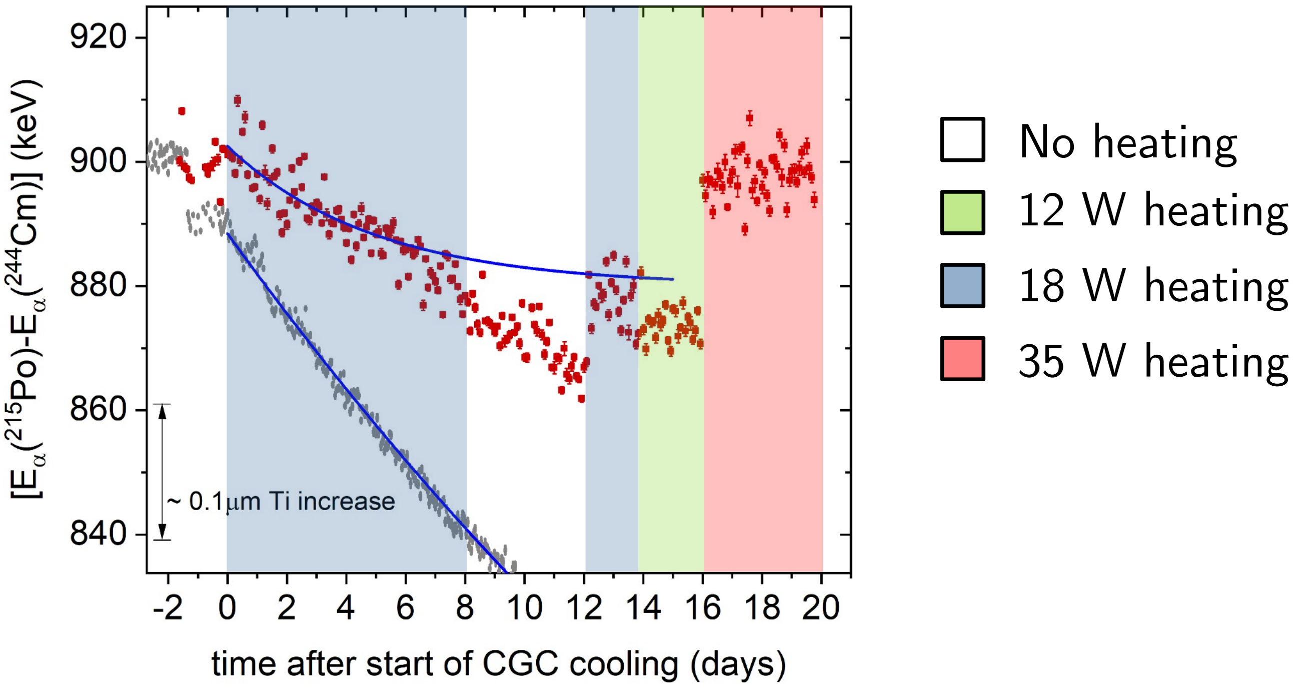
Thickness measurement

During cool down:



Thickness measurement

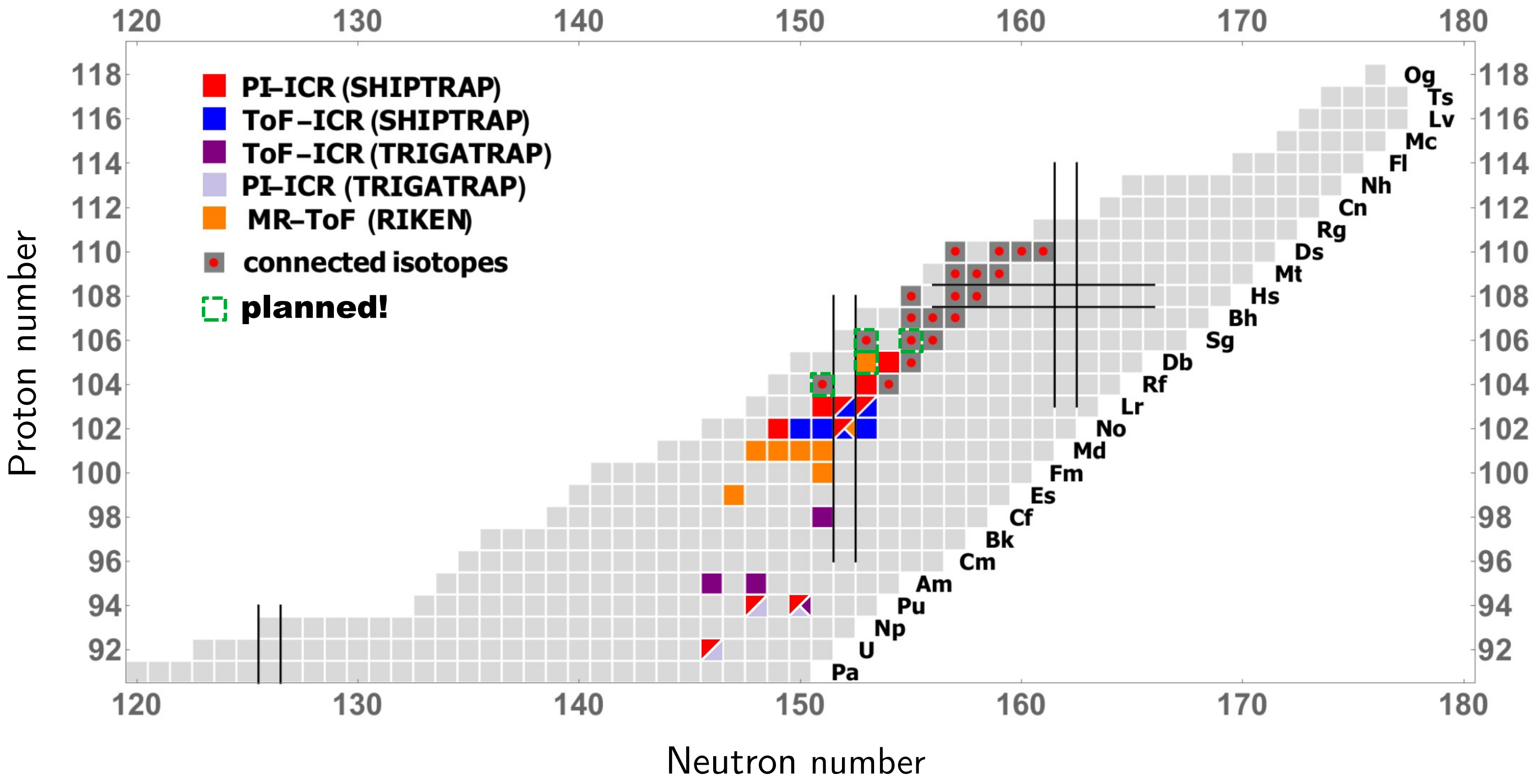
With heating (light bulb on SHIP side):



Summary

- The SHIPTRAP setup continues to progress in the SHE region: ^{258}Db measured for the first time, improved ^{257}Rf (incl. isomer!)
- PTMS (especially with PI-ICR) established as a powerful technique
  - Can also complement decay spectroscopy!
- Improvements are being made to enable longer campaigns with lower cross-sections
- Next candidates: ^{255}Rf, ^{257}Db, ^{259}Sg & ^{261}Sg

Summary



PI–ICR (SHIPTRAP)
ToF–ICR (SHIPTRAP)
ToF–ICR (TRIGATRAP)
PI–ICR (TRIGATRAP)
MR–ToF (RIKEN)
connected isotopes
planned!
Proton number
Neutron number
120
130
140
150
160
170
180
92
94
96
98
100
102
104
106
108
110
112
114
116
118
Pa
U
Np
Pu
Am
Cm
Bk
Cf
Es
Fm
Md
No
Lr
Rf
Db
Sg
Bh
Hs
Mt
Ds
Rg
Cn
Nh
Fl
Mc
Lv
Ts
Og

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Laboratoire de Physique des 2 Infinis

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