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Mass measurements of neutron-rich refractory elements at JYFLTRAP

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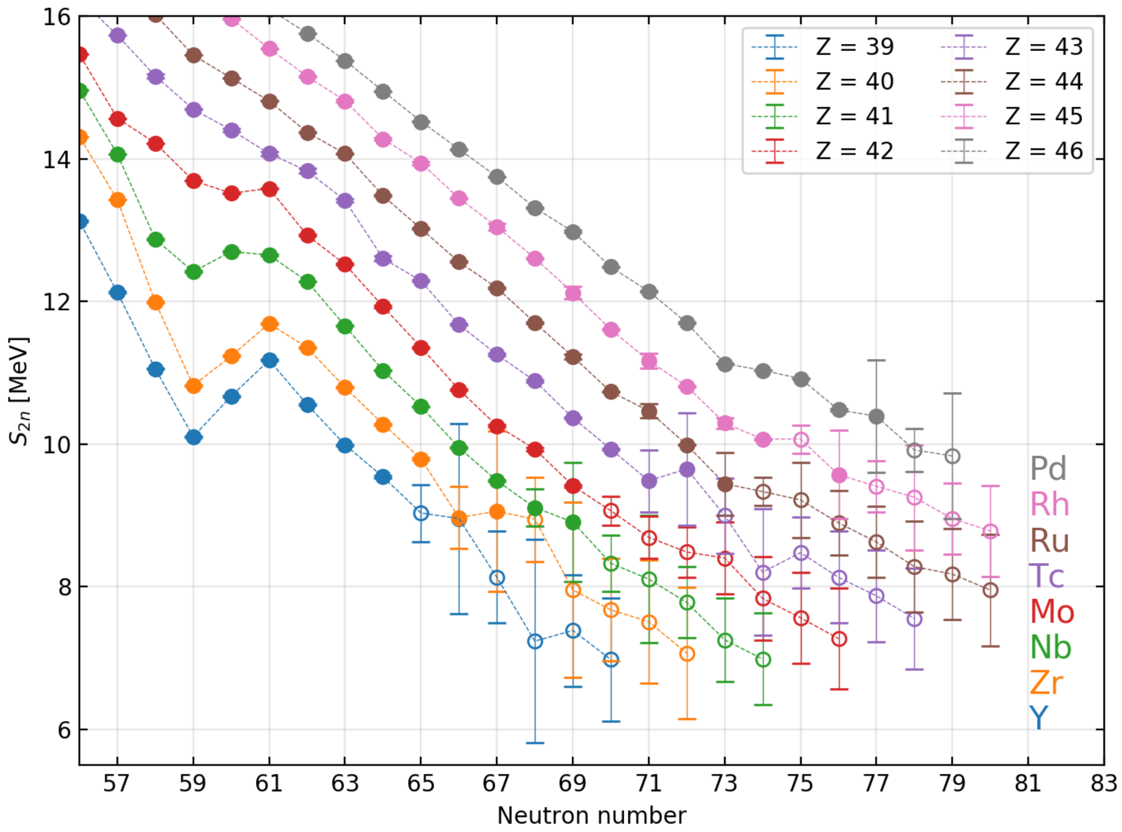
Outline

1. Motivation (nuclear structure, r-process)
2. Methods (IGISOL, JYFLTRAP, TOF-ICR and PI-ICR)
3. Precision mass meauruements of Ru and Rh isotopes
4. Summary

Nuclear structure in the A ≈ 100 region

- Region where rapid changes in nuclear structure are known to happen. For example a rapid onset of deformation can be observed at N=60 in the lighter isotopic chains but it fades out in the heavier elements.
- More neutron-rich isotopes could be less deformed or have soft triaxial shapes
- Many masses have been measured in this region but the measurements may have suffered from low-lying isomeric states shifting the mass values and the most exotic ones have never been measured



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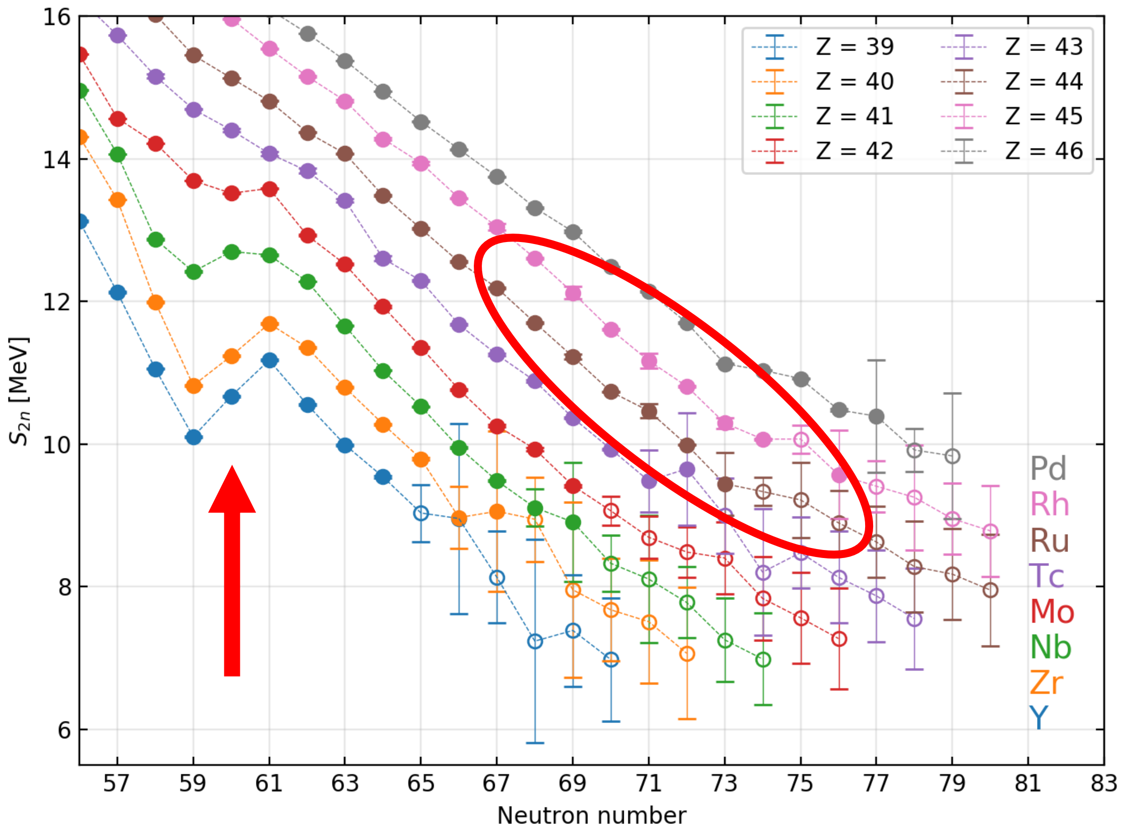
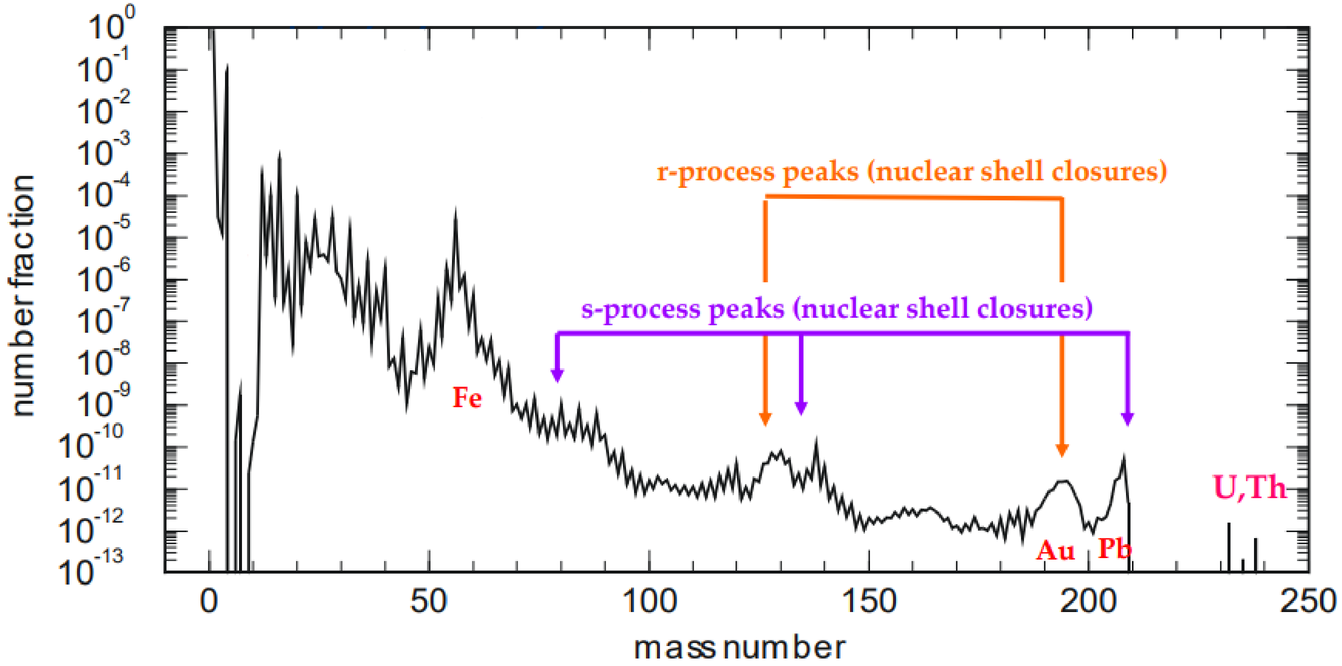


Rapid neutron capture process (r-process)

- The r-process is responsible for the production of around half of the heavy elements beyond iron.
- In r-process the neutron captures and beta decay compete, usually the environment has a high amount of neutrons and the multiple captures can happen before beta decay leading to the r-process path moving toward the neutron dripline.
- The refractory elements region is between the first (A ≈ 80) and the second abundance peak (A ≈ 130)

- Possible astrophysical sites for r-process include neutron star mergers and core-collapse supernovae

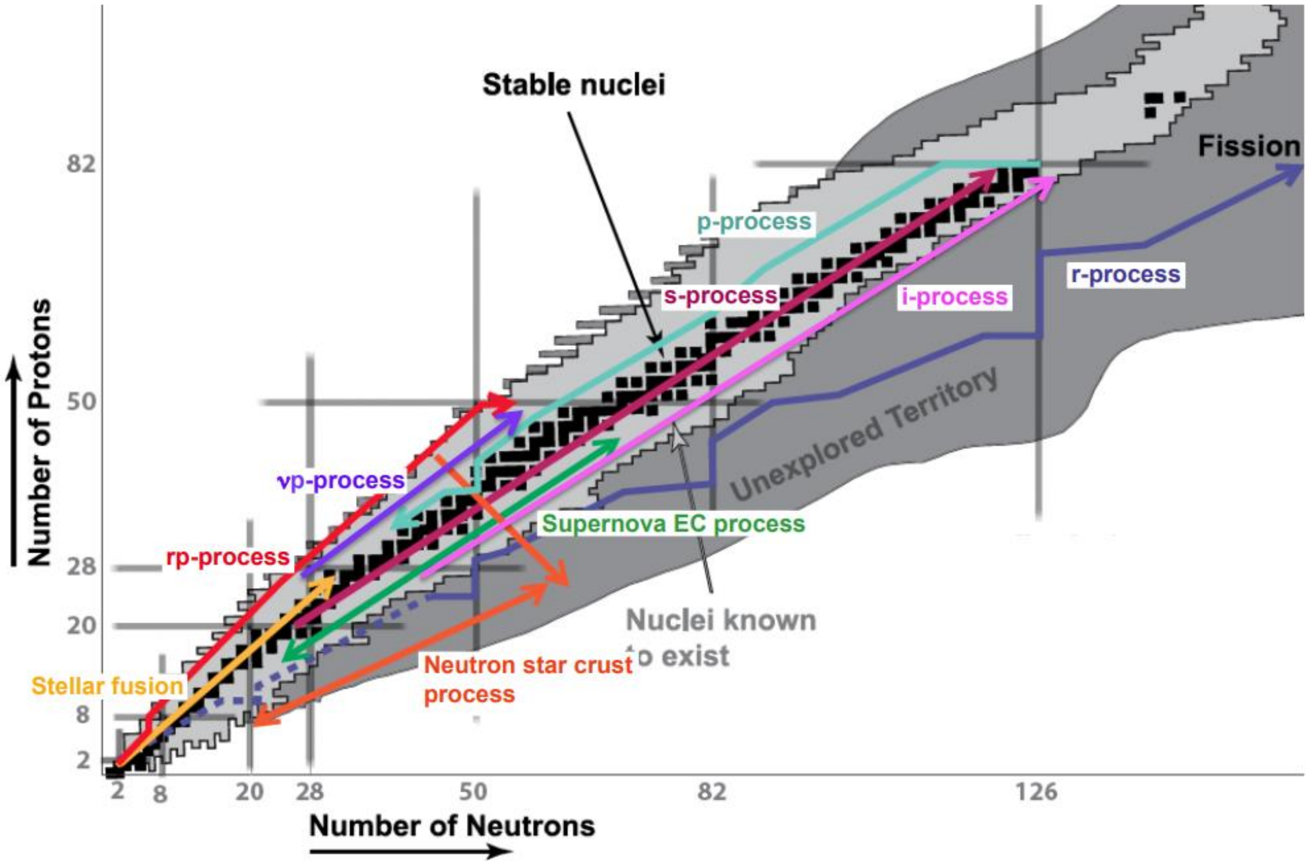


John J. Cowan et al., Rev. Mod. Phys., Vol. 93, No. 1, January–March 2021

Lodders et al., (2003)

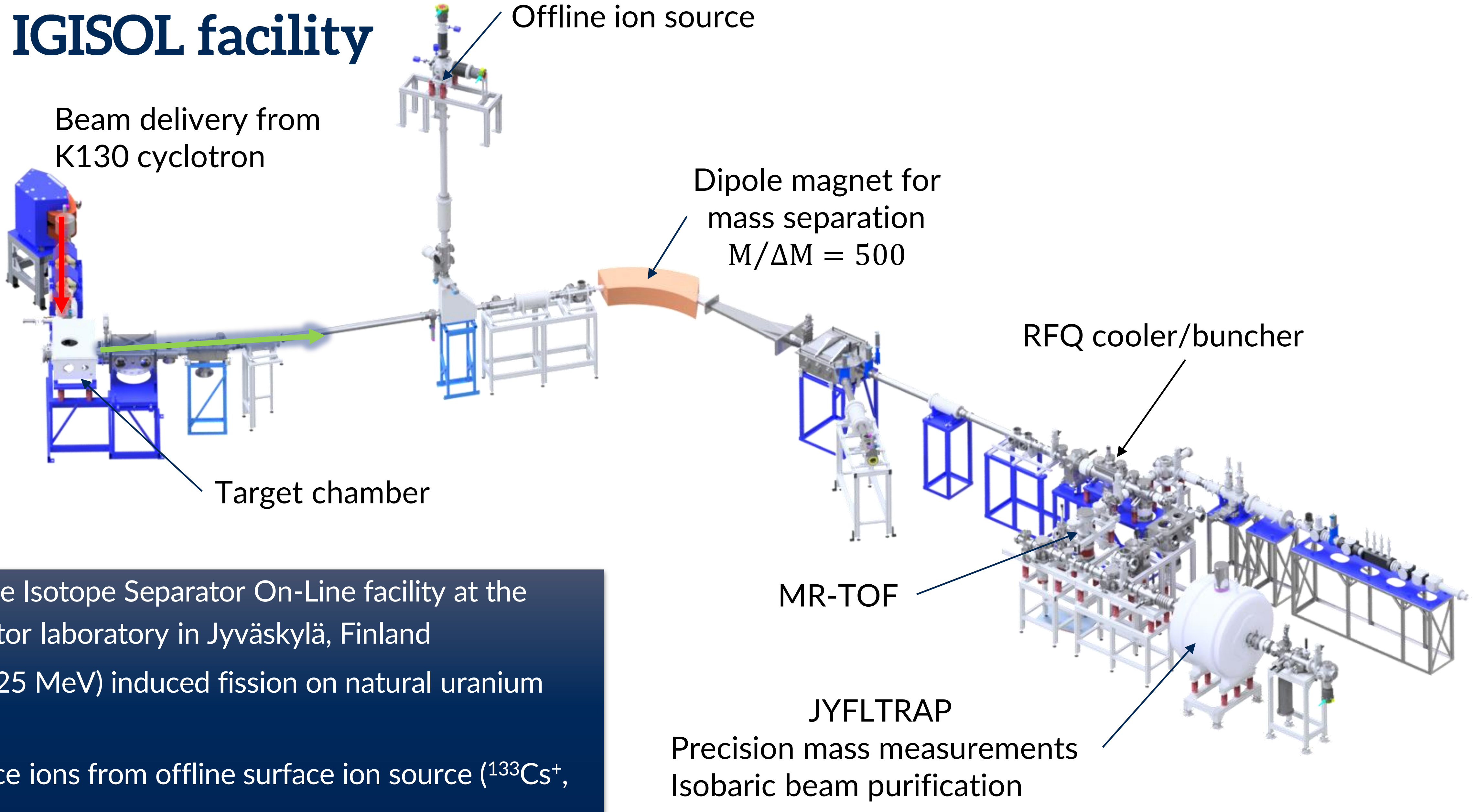
Mass measurements for the r-process

- Important for improving the theoretical mass models, thus affecting the predictions of the r-process path
- During a freezeout phase, deformation and kinks in the neutron separation energies can funnel the reaction flow and affect the final abundances.
- For r-process calculations masses should be measured with a precision of better than ~10^{-7}



H. Schatz, J. Phys. G: Nucl. Part. Phys. 43 (2016) 064001

IGISOL facility

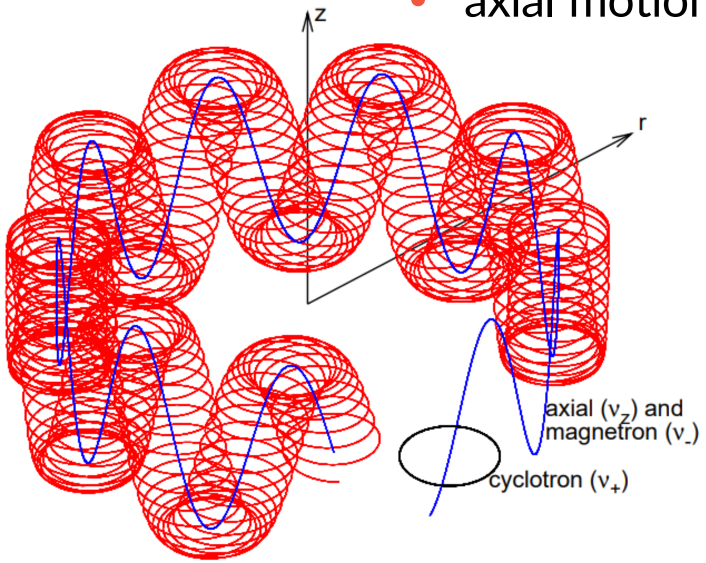


- Ion Guide Isotope Separator On-Line facility at the accelerator laboratory in Jyväskylä, Finland
- Proton (25 MeV) induced fission on natural uranium target
- Reference ions from offline surface ion source ($^{133}Cs^+$, $^{85}Rb^+$)

JYFLTRAP double Penning trap

- 7 T superconducting magnet housing a cylindrical double Penning trap
- Operational since 2004, over 300 masses measured
- Trapping of ions and studying them utilizing their eigenmotions:
  - magnetron ν_-
  - reduced cyclotron ν_+
  - axial motion ν_z

→Talk by A. de Roubin

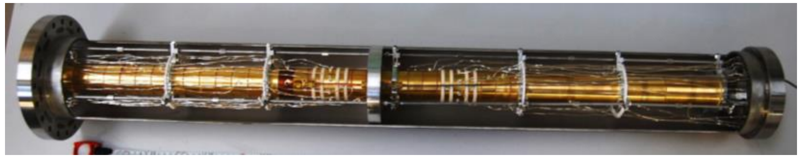


Sideband frequency:

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

Cyclotron frequency:

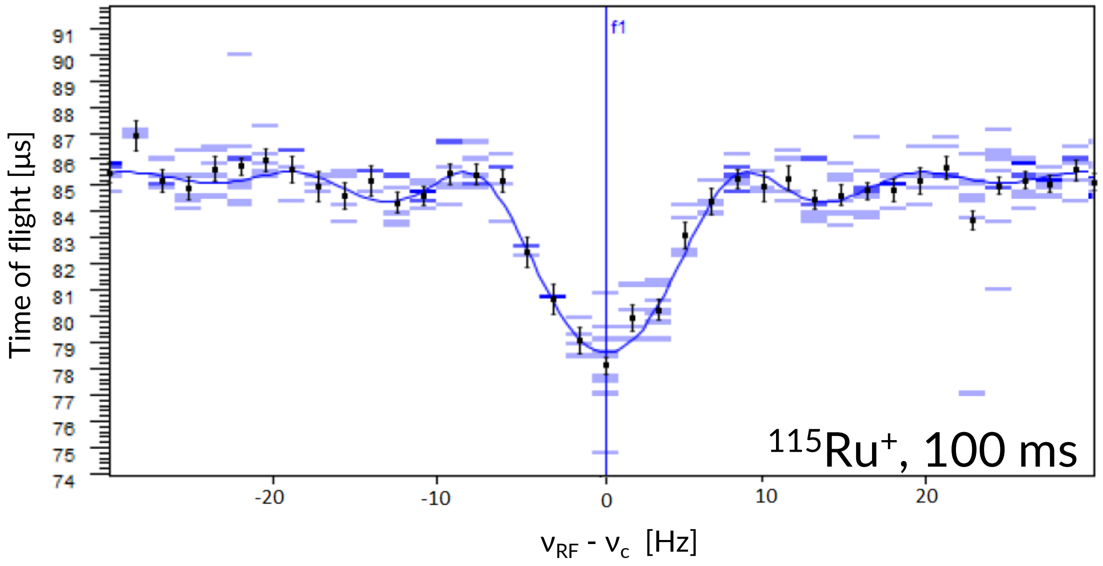
$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$



Time-Of-Flight Ion-Cyclotron-Resonance technique (TOF-ICR)

- Initial magnetron motion ν_- converted to cyclotron motion via quadrupolar excitation at the sideband frequency $\nu_c = \nu_- + \nu_+$
- Scanning based technique: each frequency point measured several times
- Precision of 10^{-7} was reached during our measurements.

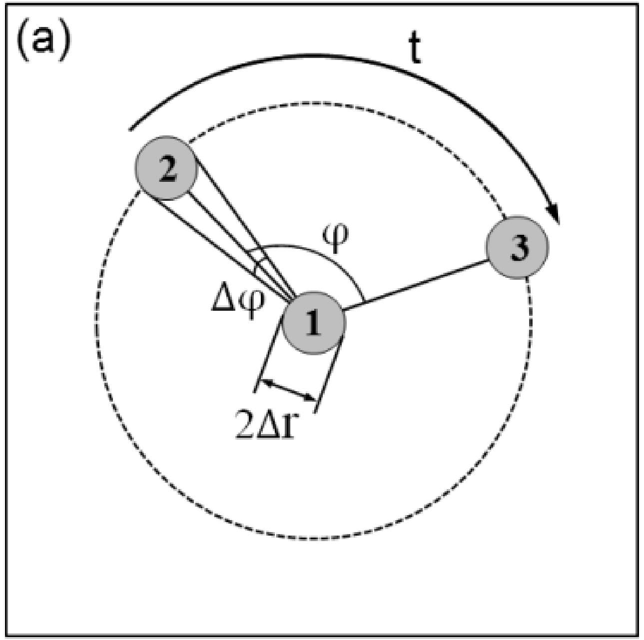
$$T(E_{rad}) = \int_0^{z_{det}} \sqrt{\frac{m}{2(E_0 - qU(z) + |\mu(Er)B(z)|)}}\,dz$$



Phase-Imaging Ion-Cyclotron-Resonance method (PI-ICR)

- The ion motion projected on a position sensitive detector (delay lines and micro channel plate detector)
- Longer time to set up than in TOF-ICR, since the ions need a more careful preparation – but every ion counts

$$\nu = \frac{\varphi + 2\pi n}{2\pi t}$$



- PI-ICR provides higher resolving power and better precision than TOF-ICR
  - 40 times higher resolving power
  - 5 times increase in precision compared to TOF-ICR

D.A. Nesterenko et. al., Eur. Phys. J. A (2018) 54: 154 ; S. Eliseev et al., PRL 110 082501 (2013)

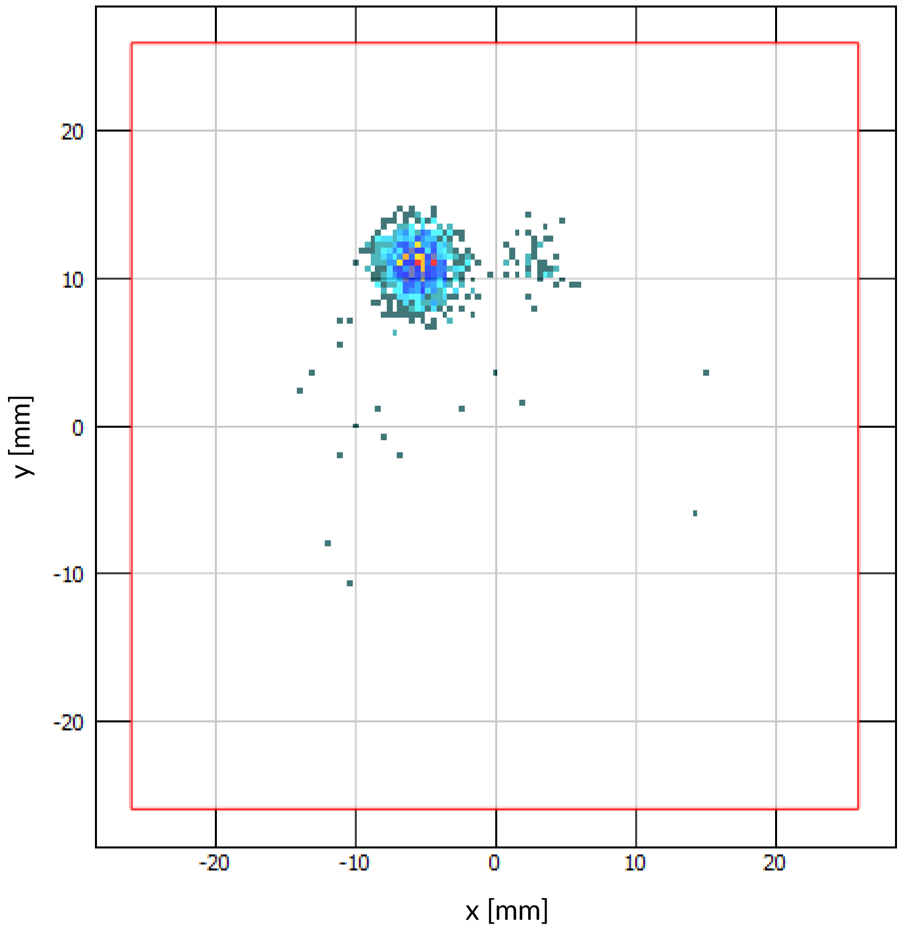
Mass measurements of neutron-rich refractory elements

- Altogether 14 ground-state masses and 7 isomeric states were measured
- Masses for several long-living states were measured for the first time and the precision improved for most of the studied states
- Isomeric states were resolved and measured with uncertainties < 10 keV with the PI-ICR technique
- TOF-ICR used for the most exotic cases
- The lowest excitation energy we were able to resolve with the PI-ICR technique was around 30 keV

1st campaign	2nd campaign
$^{110, 110m}$Rh	^{104,104m}Nb
$^{112, 112m}$Rh	^{104}Y
$^{114, 114m}$Rh	^{106}Zr
$^{116, 116m}$Rh	^{109}Nb
$^{118, 118m}$Rh	^{111}Mo
^{120}Rh	^{112}Mo
$^{115, 115m}$Ru	
^{117}Ru	

Separation of the ground state and isomeric state in ^{115}Ru

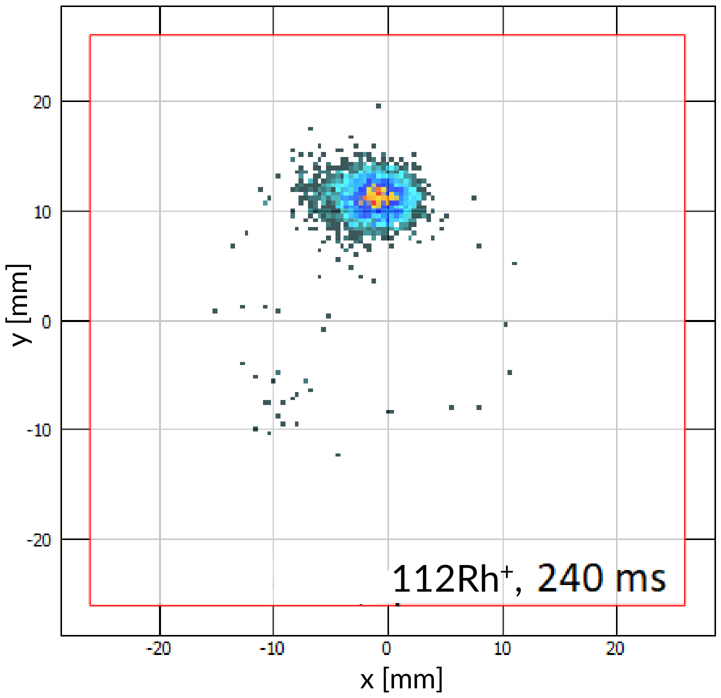
- Phase accumulation time 100 ms
- Difference between states around 130 keV
- The isomeric state is close in energy and the state is weakly produced compared to the ground state – no possibility that this would have been separated on a measurement done with the TOF-ICR technique.
- PI-ICR very powerful for studying the isomeric states!

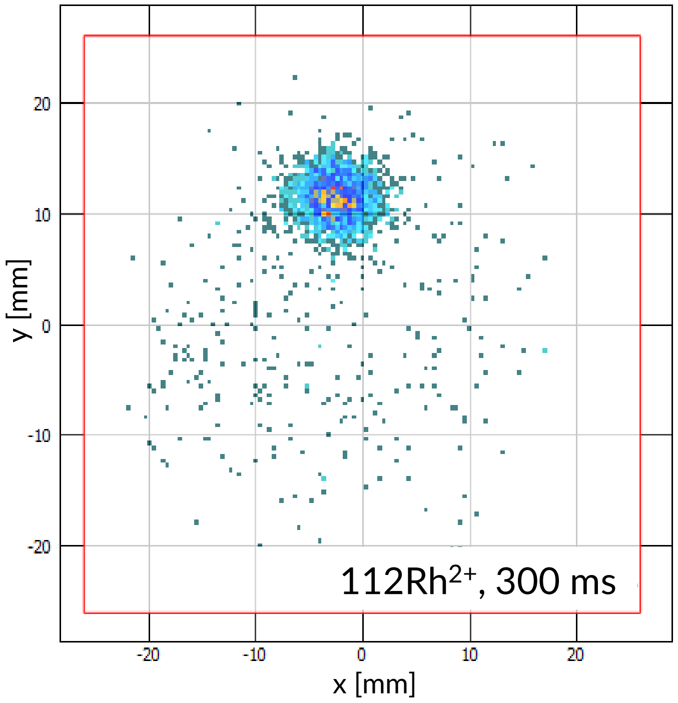


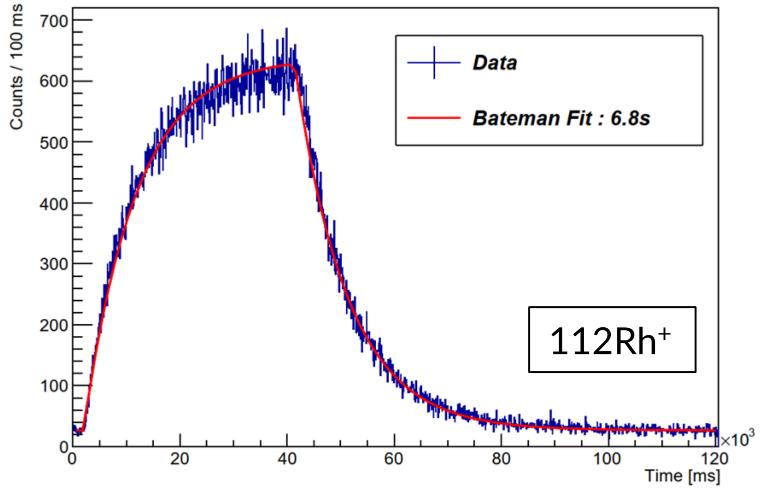
^{112}Rh case

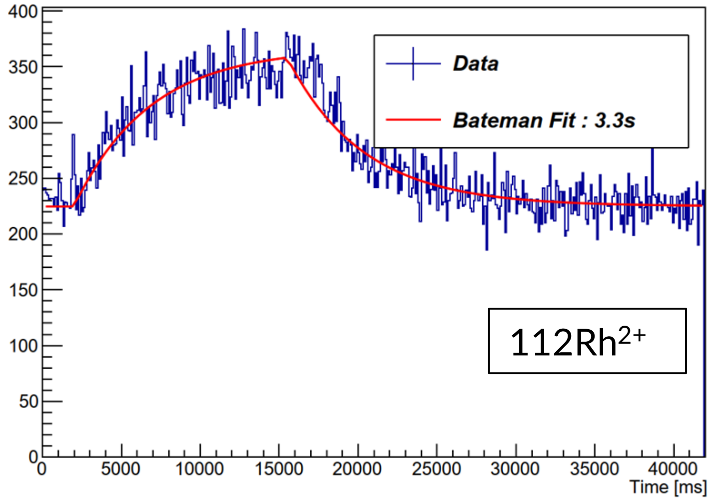
- Proton-induced fission at 25 MeV produces mainly the isomeric state of ^{112}Rh at IGISOL.
- The ground state of ^{112}Rh was measured via in-trap decay of ^{112}Ru (leading to charge state 2^+ of ^{112}Rh)
- Half-life measurements with a Si detector after the trap was used to further confirm the measured states

State	E_x [keV] NUBASE2016	$T_{1/2}$ [s] NUBASE2016
g.s.		3.4 (0.4)
m.	340 (70)	6.73 (0.15)



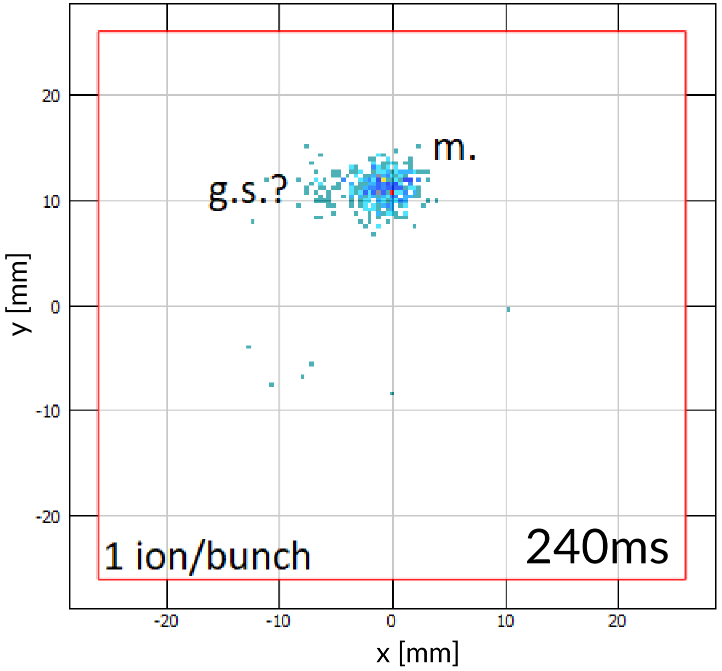


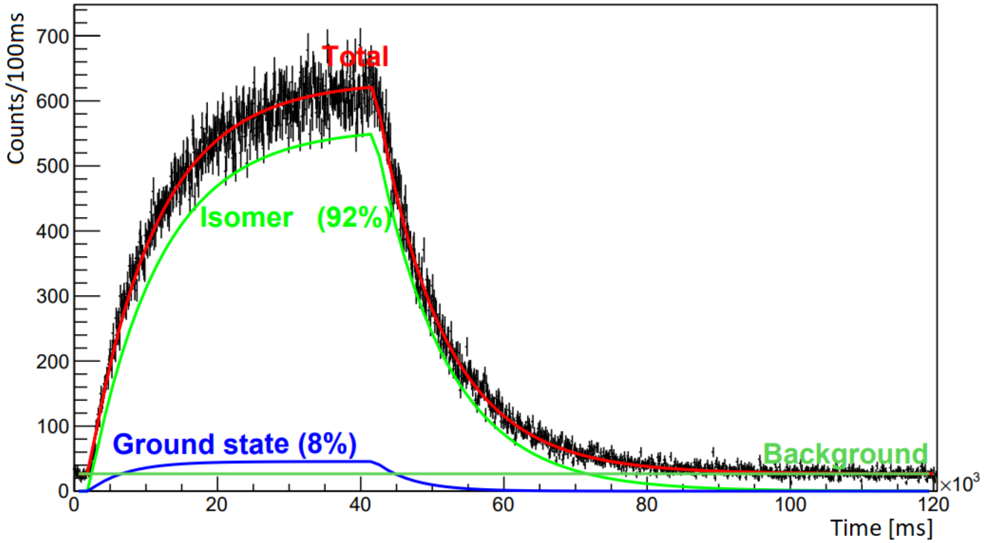


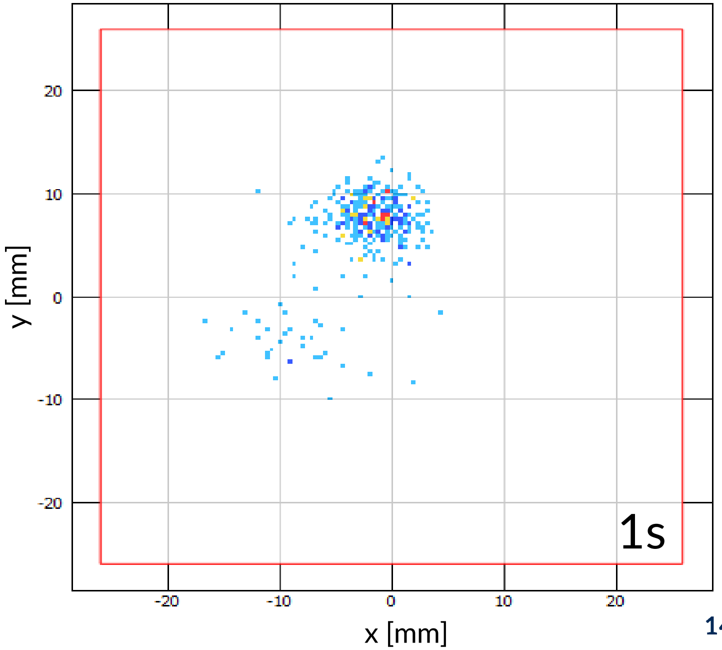


^{112}Rh case - fission

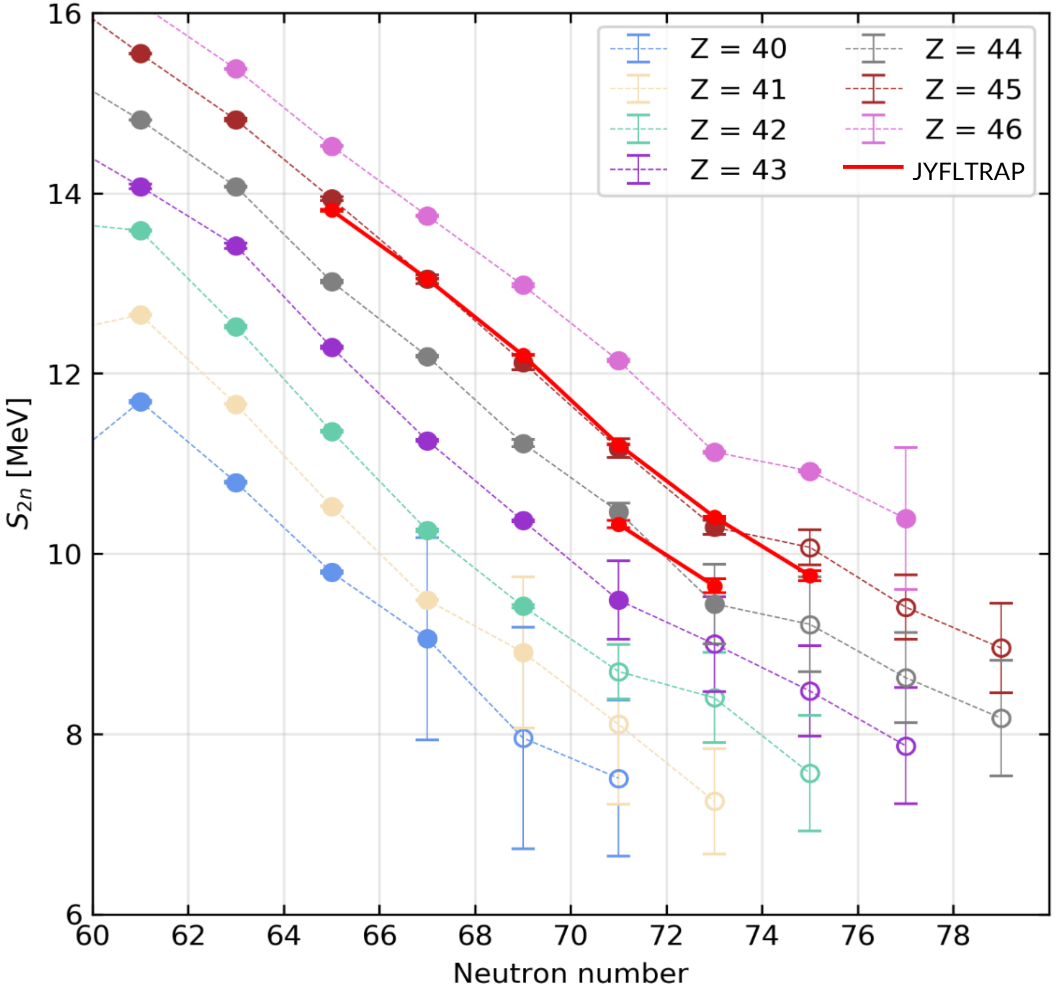
- Upon closer inspection we noticed that there are two states produced through fission, but the energy difference between the states is very low (30-40 keV).
- We made another measurement with 1s phase accumulation time to separate these two states.
- The measurement with 1s phase accumulation time confirmed the two states that were seen with 240 ms accumulation time



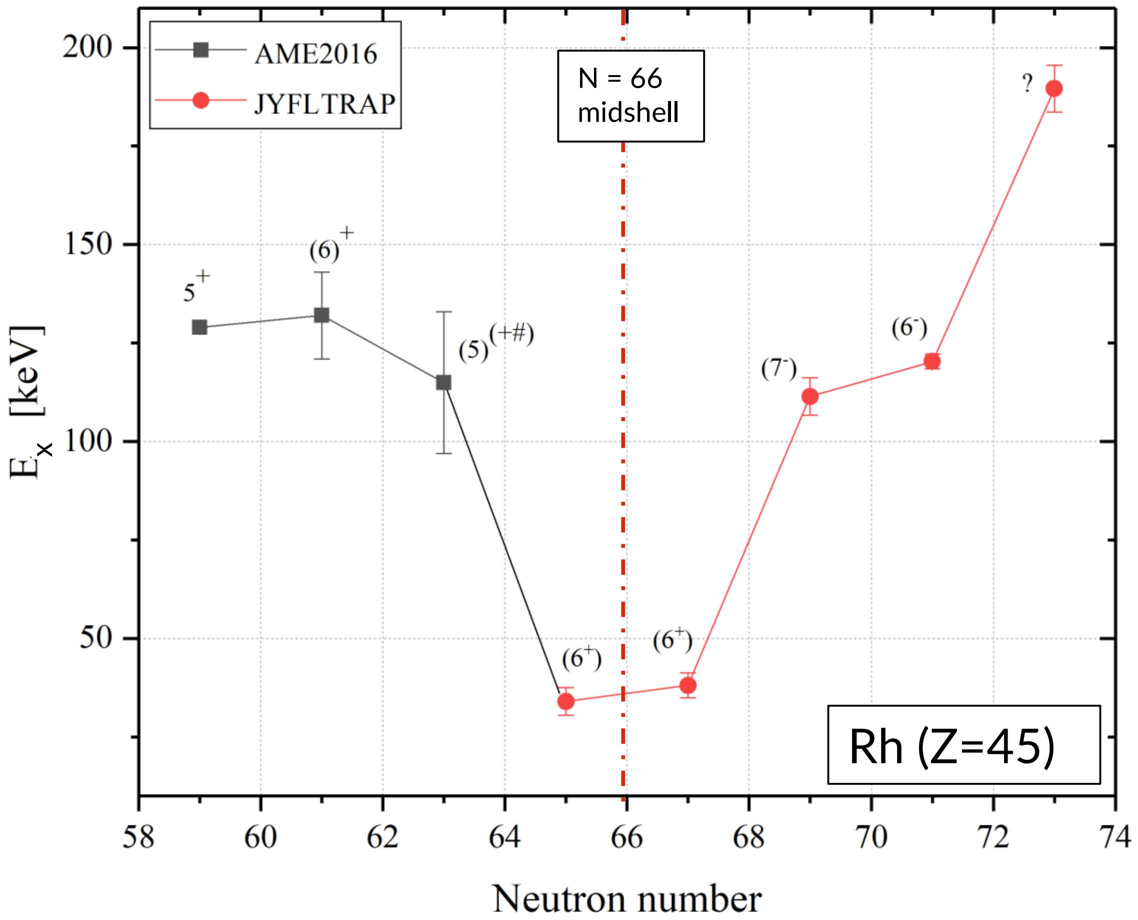




Two neutron separation energies and isomeric states



The colored lines (except red) indicate the AME2016 values while the red line indicates the JYFLTRAP measurements of ruthenium isotopes at Z = 44 and rhodium isotopes at Z = 45.

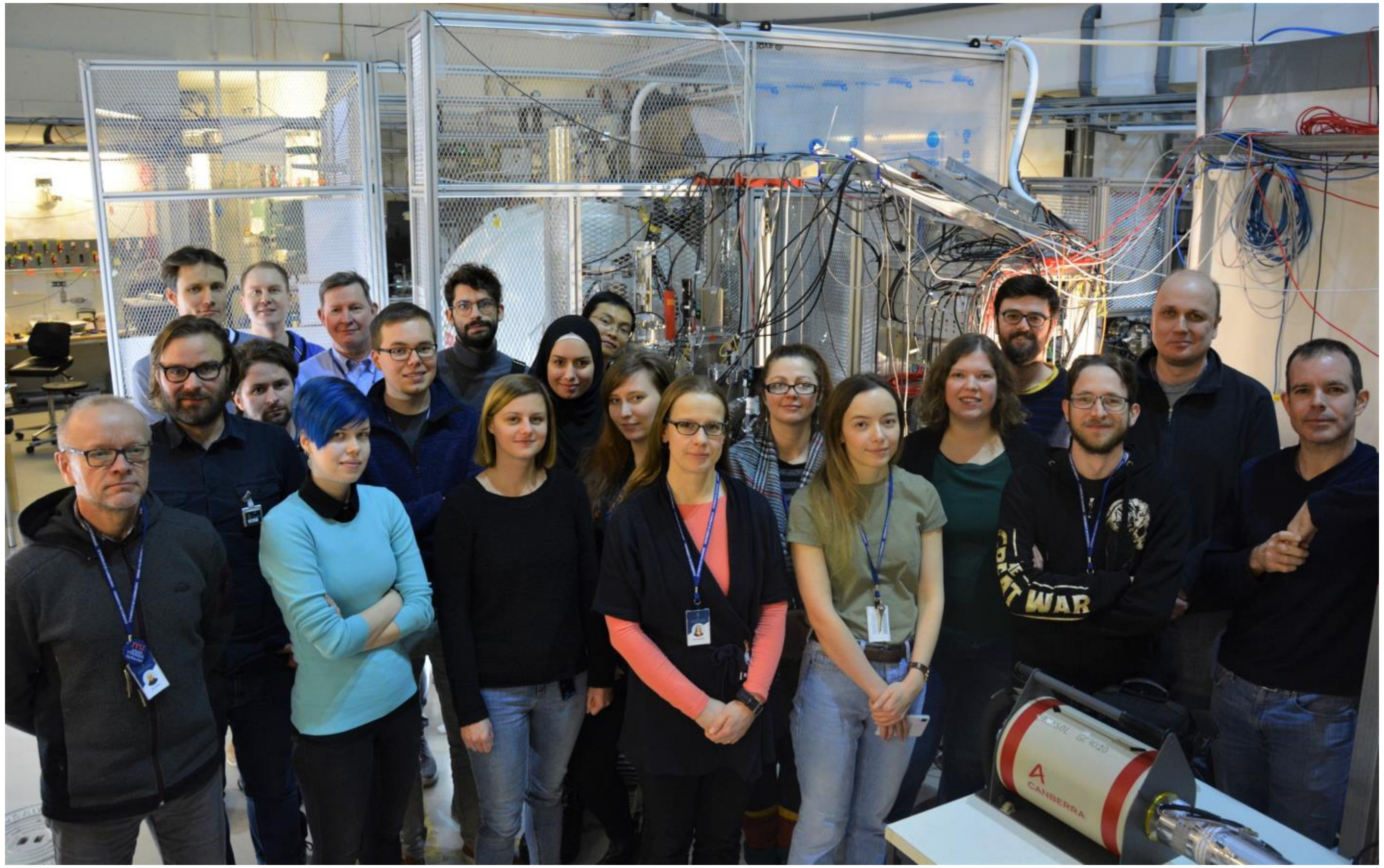


The values plotted in black are from NUBASE2016 when values plotted in red are from our experiment. The spin-parties are from NUBASE2016.

Summary

- The refractory region elements have been studied extensively at IGISOL over the years. In this experiment the studies were extended to reach even more neutron-rich elements. Part of the region previosuly studied was revisited to explore the separation of isomeric states with the PI-ICR technique.
- 14 ground-state masses and 7 isomeric states were measured, several of which were measured for the first time. The precision of multiple masses was improved utilizing the PI-ICR and TOF-ICR techniques at the JYFLTRAP Penning trap.
- Analysis is being finalised and a publication is under preparation.
- We are working with theorists for the nuclear structure studies and possible effects of the r-process simulations.
- We still have 2 days of beamtime left!

Thank you for your attention!



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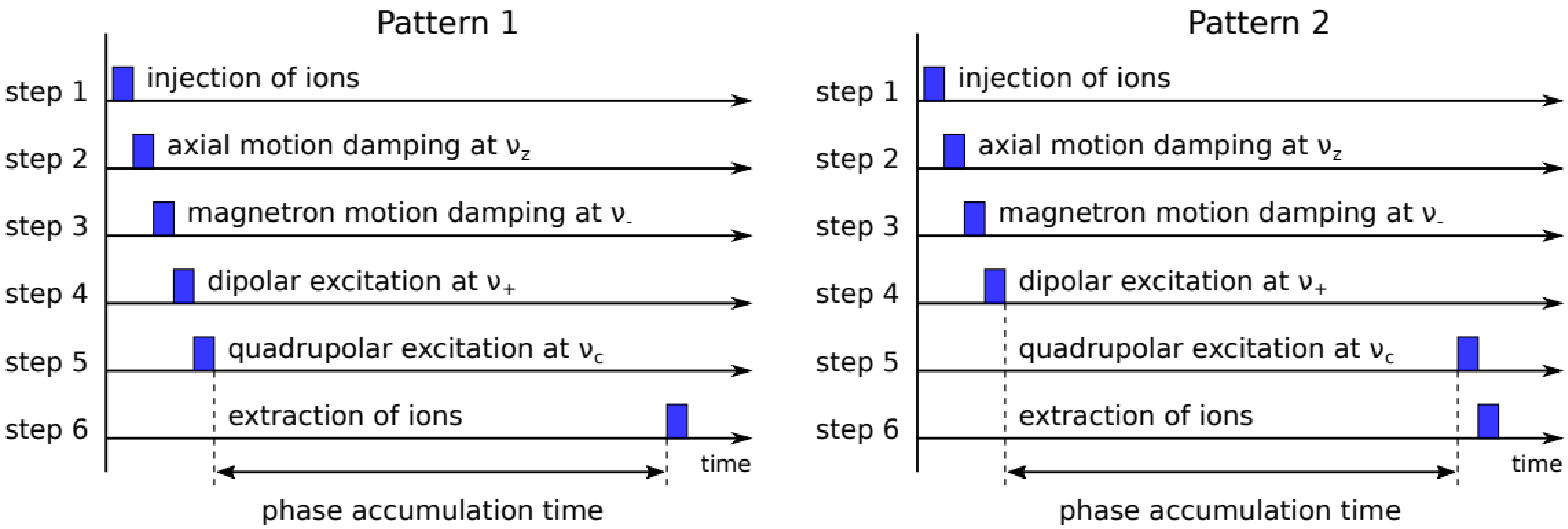
Timing pattern of the PI-ICR



M. Vilen, thesis (2019)