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Mass measurements and studies for the r process at IGISOL

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Outline

1) Introduction
2) How to measure masses?
3) Recent results from mass measurements at JYFLTRAP
4) How to produce heavy neutron-rich nuclei for r-process studies?
5) Summary and conclusions

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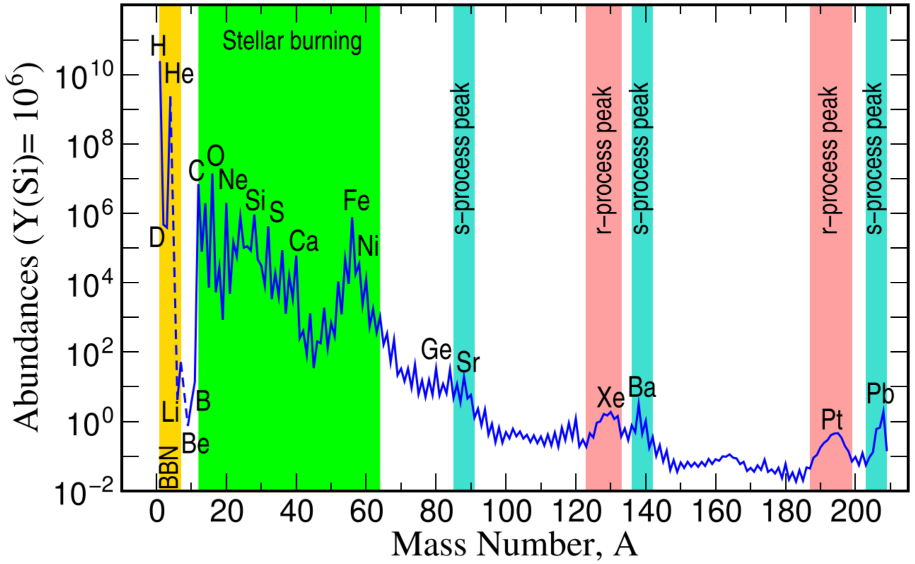
1. Introduction

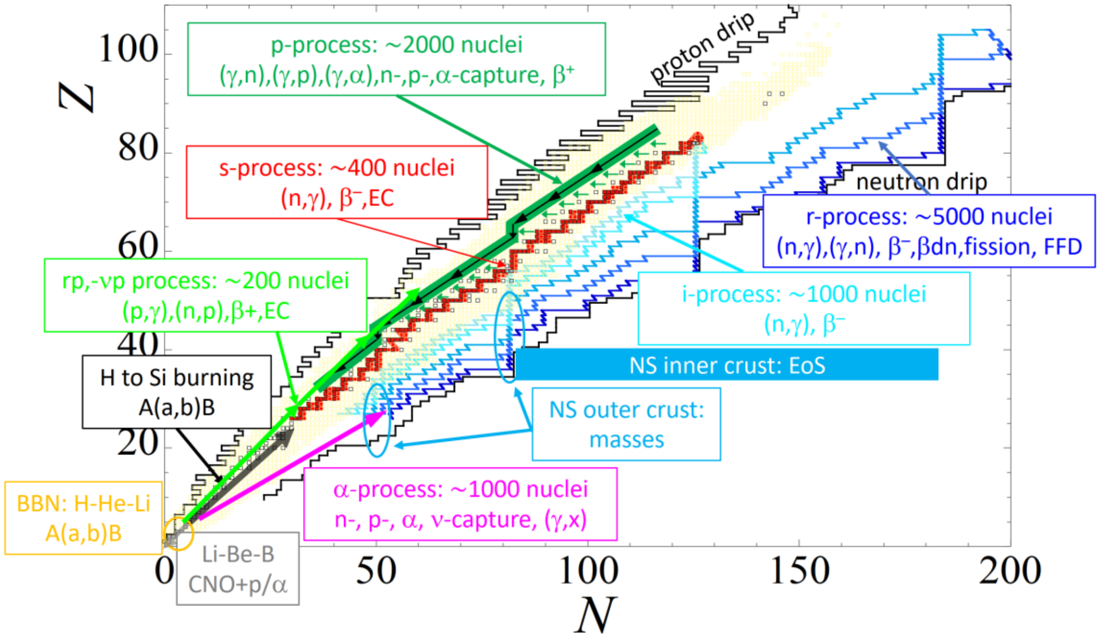
Rapid neutron capture process (r process)

- How are the heavy elements formed?
  - Rapid neutron capture process responsible for around 50% of heavy-element abundances



Cowan et al., Rev. Mod. Phys. 93 (2021) 015002

r process proceeds along neutron-rich nuclei



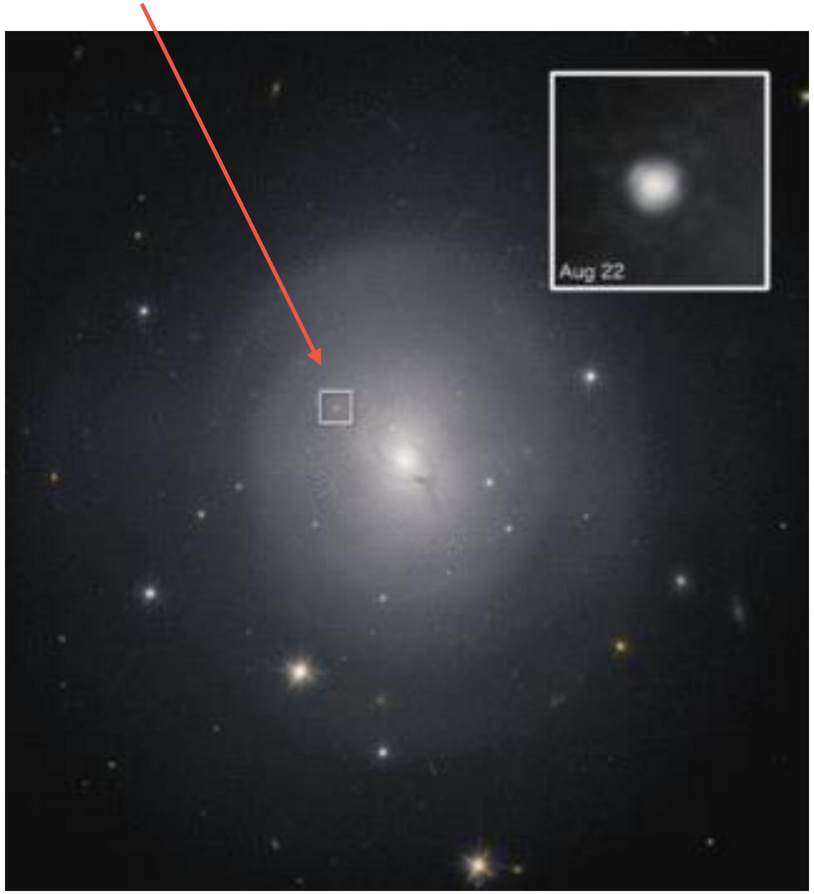
Arnould and Goriely, PPNP 112 (2020) 103766

Where does the r process take place?

- Neutron-star mergers
  - Evidence from GW170817 and its kilonova!
- Other sites?
  - Neutron-star black hole mergers
  - Neutrino-driven winds from core-collapse supernovae
  - Magnetorotational supernovae with jets
  - Collapsars ....

r-process calculations using different astrophysical trajectories needed to constrain the sites and interpret observations

Kilonova from GW170817 neutron-star merger



Credit: NASA and ESA

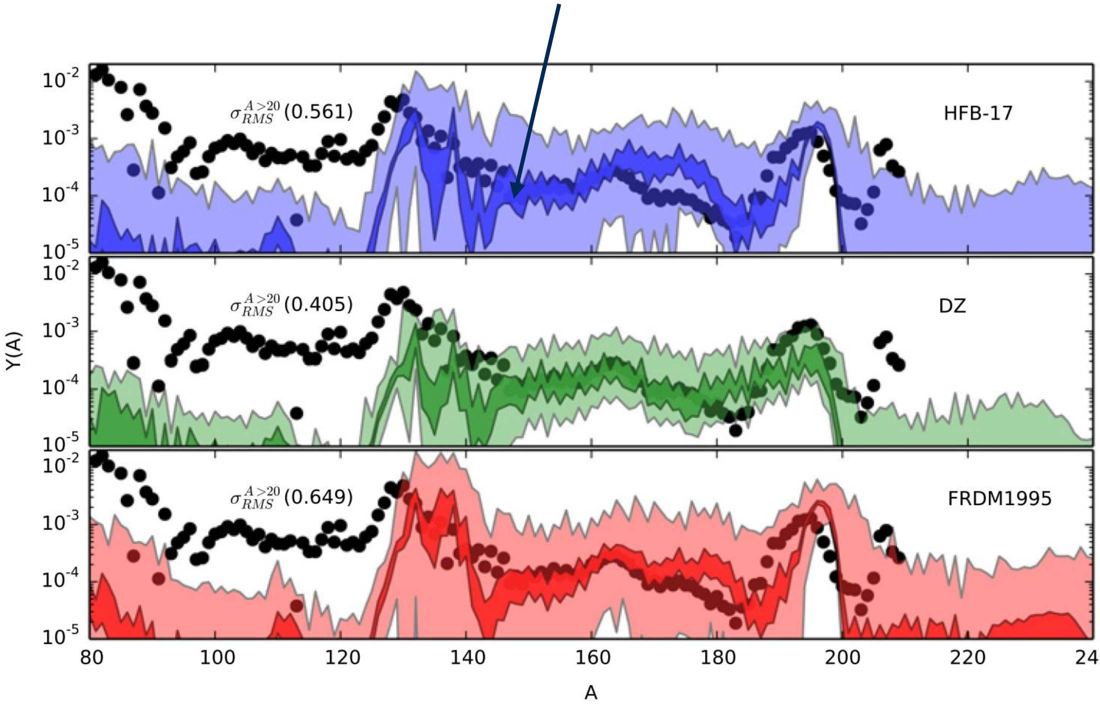
Why nuclear masses are important for the r process?

- Masses have an impact, e.g., on:
  - Neutron-capture (n,γ) and their reverse photodisintegration (γ,n) rates via neutron-separation energies :
    $S_n(Z,N) = [-M(Z,N) + M(Z,N-1) + M_n]c^2$
  - Beta-decay rates and beta-delayed neutron emission via the Q values
    (if not already experimentally known)

    → Impact on final abundances
- Masses determine the energy consumed/released in the decays and reactions (Q values)

    → Kilonova lightcurves

Hypothetical 100 keV uncertainty



M. Mumpower et al., PPNP 86 (2016) 86

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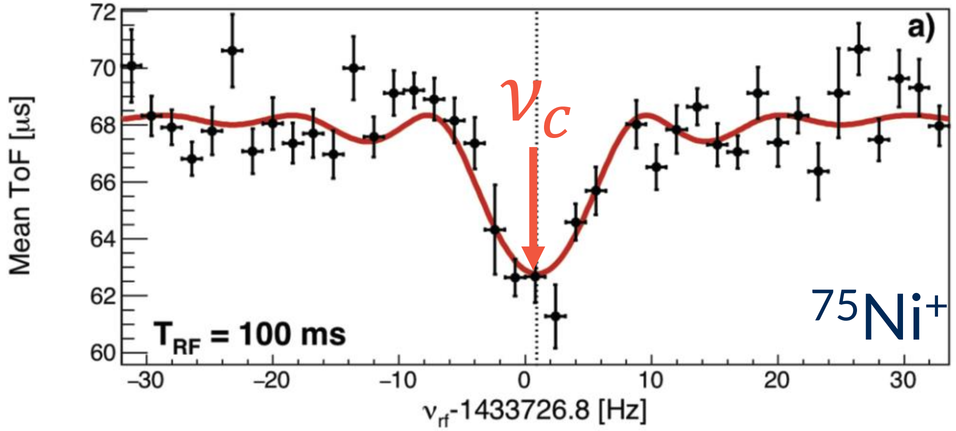
2. How to measure masses of exotic isotopes?

How to precisely measure masses of exotic isotopes?

- Nuclear masses can be derived from atomic masses
- Penning trap mass spectrometry offers the most precise way to determine atomic masses:
  - Determine the cyclotron frequency ν_c of an ion with charge **q** and mass **m** in a magnetic field **B**:

$$\boxed{\nu_c = \nu_- + \nu_+ = \frac{1}{2\pi}\frac{qB}{m}}$$

- Example of a Time-of-Flight Ion Cyclotron Resonance (TOF-ICR) from JYFLTRAP:



S. Giraud et al., Phys. Lett. B 833 (2022) 137309

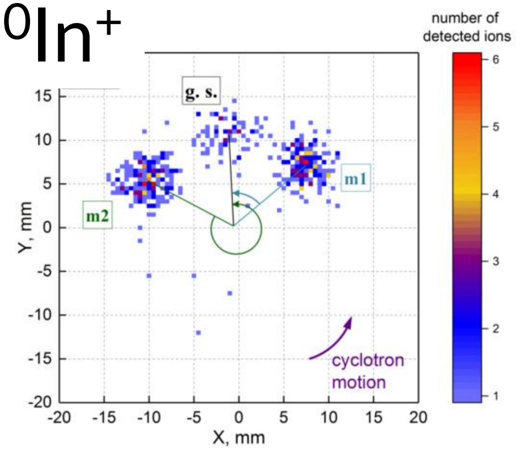
- B field determined by performing a similar measurement with ^{84}Kr$^+$ ions with well-known mass.

Newer method: Phase-Imaging Ion Cyclotron Resonance technique (PI-ICR)

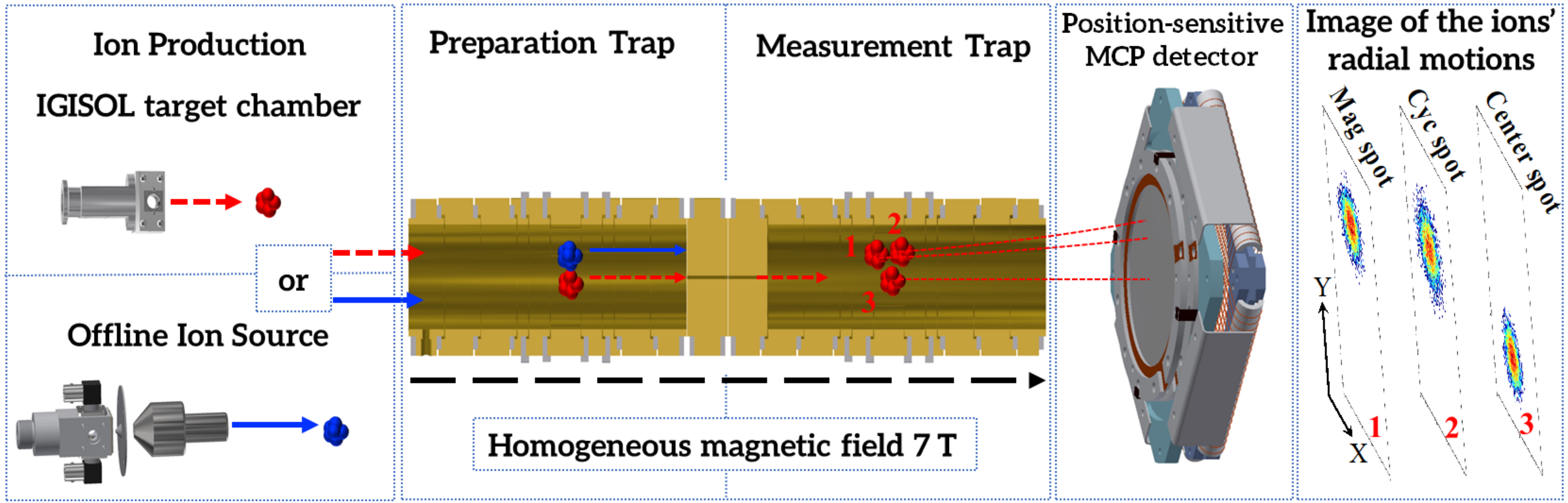
- $\nu_c = \nu_- + \nu_+ = \frac{1}{2\pi}\frac{qB}{m}$
- Determine the radial frequencies $\boldsymbol{\nu_-}$ and $\boldsymbol{\nu_+}$ from their accumulated phases $\boldsymbol{\varphi}$ in time **t** : $\nu_\pm = \frac{\varphi_\pm + 2\pi n_\pm}{2\pi t}$

Every ion counts
Better precision and higher resolving power than TOF-ICR!

$^{130}\mathrm{In}^+$



D.A. Nesterenko et al., PLB 808 (2020) 135642



PI-ICR: S. Eliseev et al., PRL 110, 082501 (2013), Appl. Phys. B (2014) 114:107–128.
PI-ICR at JYFLTRAP: D.A. Nesterenko et al., Eur. Phys. J. A 54, 154 (2018); Eur. Phys. J. A 57, 302 (2021).

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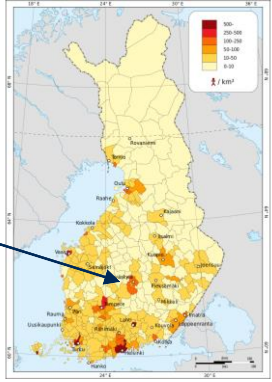
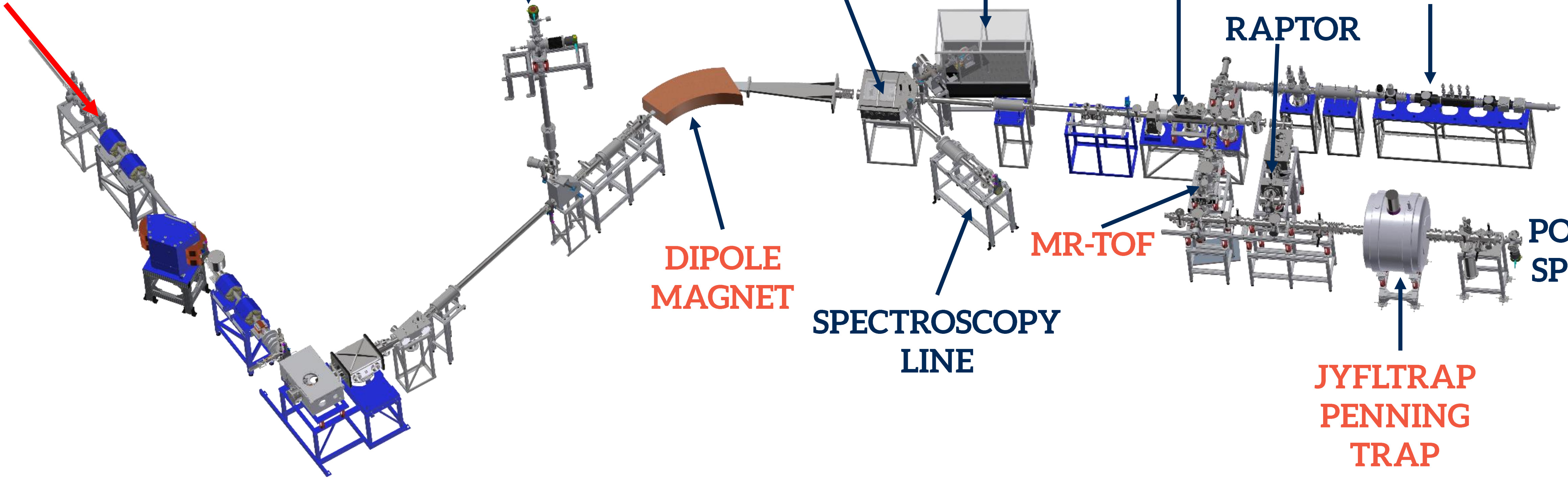
3. Recent results from JYFLTRAP

JYFLTRAP at the IGISOL facility in the JYFL Accelerator Laboratory, University of Jyväskylä





BEAM FROM CYCLOTRON

OFFLINE ION SOURCE STATION

SWITCHYARD

CS ATOM TRAP

COOLER-BUNCHER

COLLINEAR LASER SPEC. LINE

RAPTOR

DIPOLE MAGNET

SPECTROSCOPY LINE

MR-TOF

POST-TRAP SPECTROSCOPY

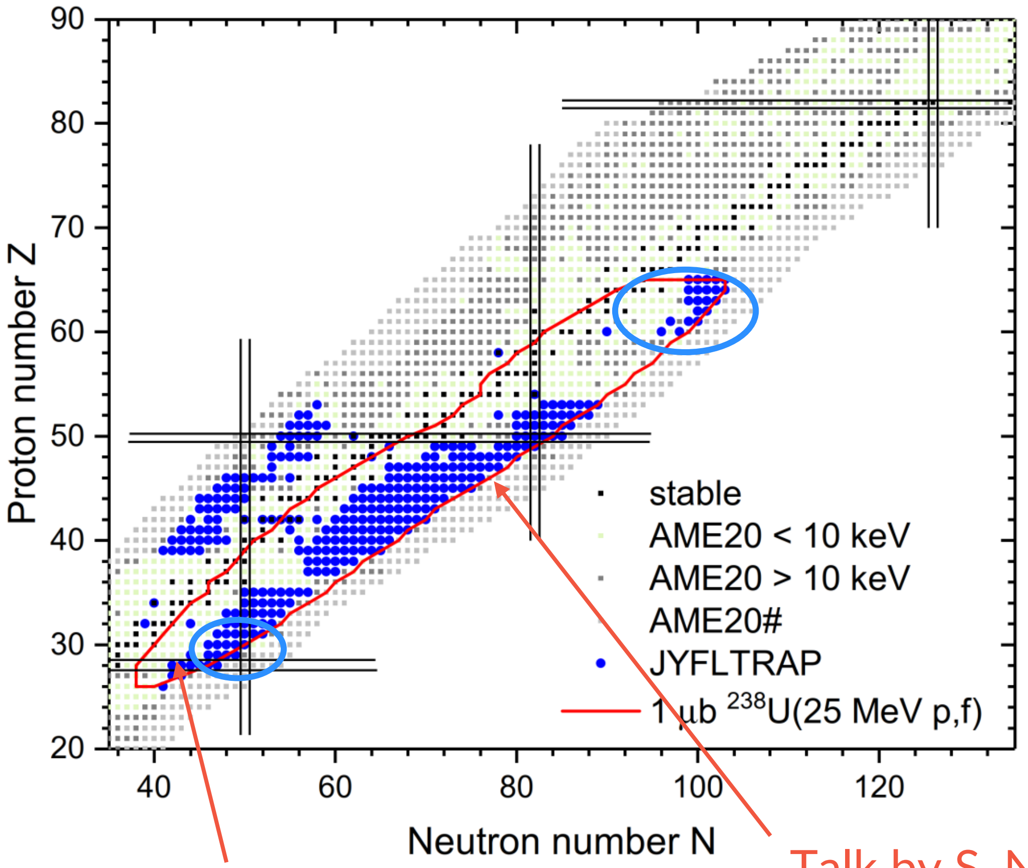
JYFLTRAP PENNING TRAP

TARGET CHAMBER

- Fast and universal ion guide technique

J. Ärje, J. Äystö et al., PRL 54 (1985) 99

Measured nuclei at JYFLTRAP



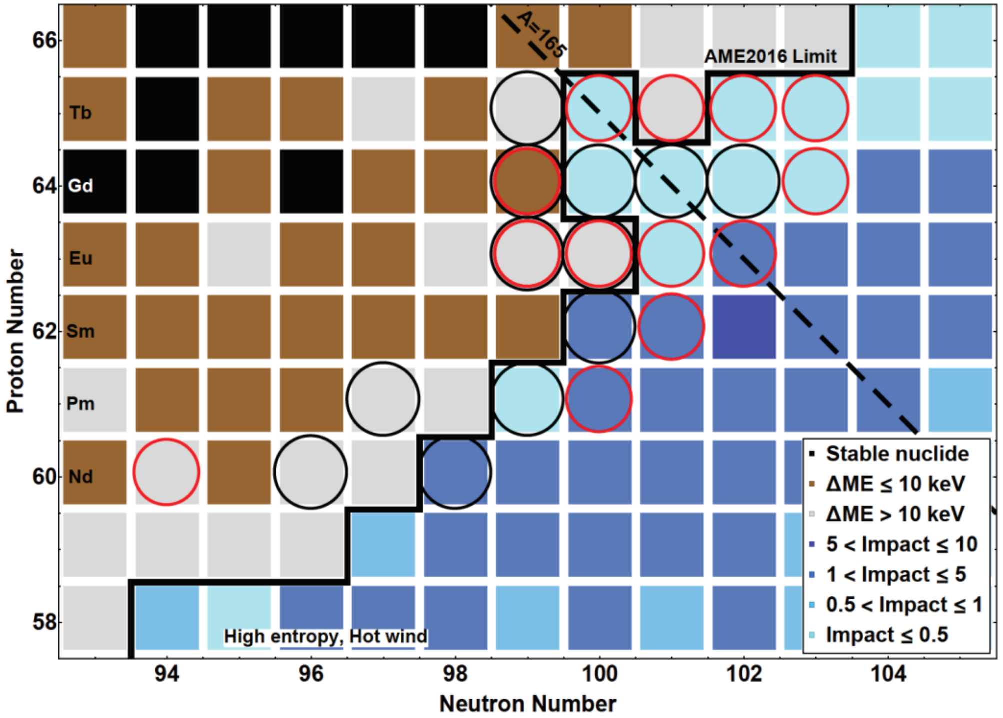
Talk by L. Canete:
Thu 8.9. at 10:00

Talk by S. Nikas:
Tue 17:00

- Around 400 atomic masses measured, including more than 50 isomeric states
- Mass-excess precisions typically < 10 keV
- Focus on this talk:
  - Rare-earth region
  - ^{78}Ni region
  - Rh isotopes

Mass measurements in the rare-earth region

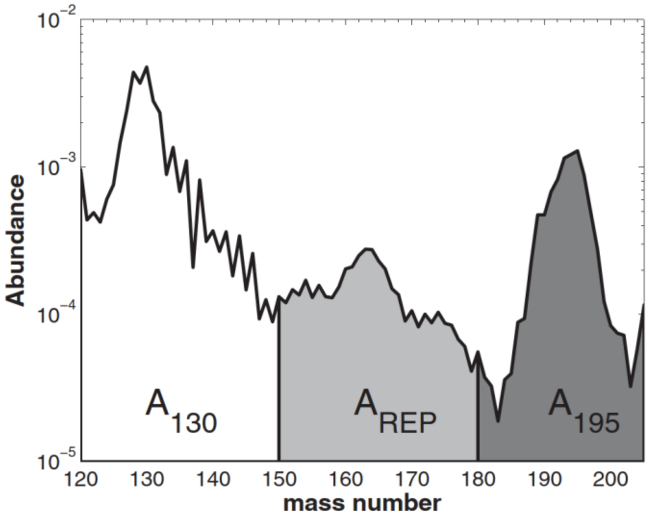
- Two measurement campaigns with JYFLTRAP at IGISOL
- Measured masses for:
  - 22 ground states
  - 2 isomers
- 14 cases measured for the first time
- In collaboration with Univ. of Notre Dame



M. Vilén et al., PRL 120 (2018) 262701
M. Vilén et al., PRC 101 (2020) 034312

Motivation: Origin of the rare-earth abundance peak?

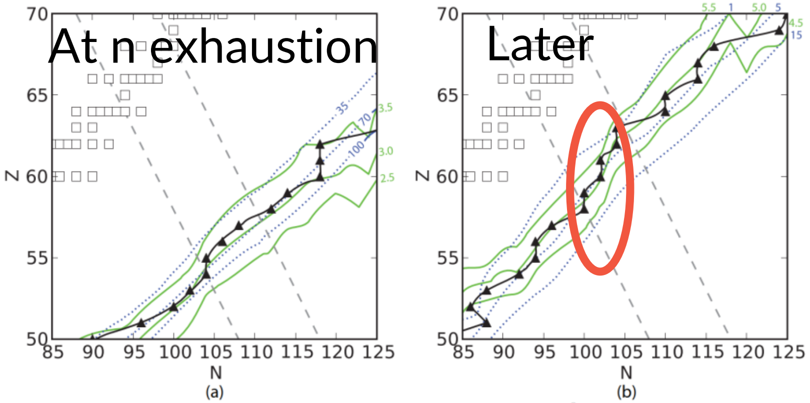
- Rare-earth abundance peak (REP) of the r process at around A=165



M. Mumpower et al., PRC 86 (2012) 035803

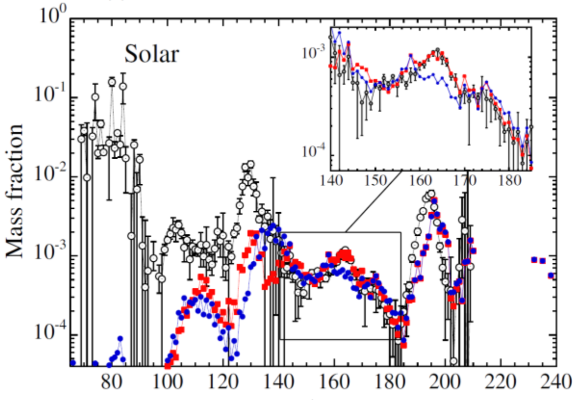
- Caused by a kink in neutron-separation energies?

R. Surman et al., PRL 79 (1997) 1809.
M. Mumpower et al., PRC 85 (2012) 045801



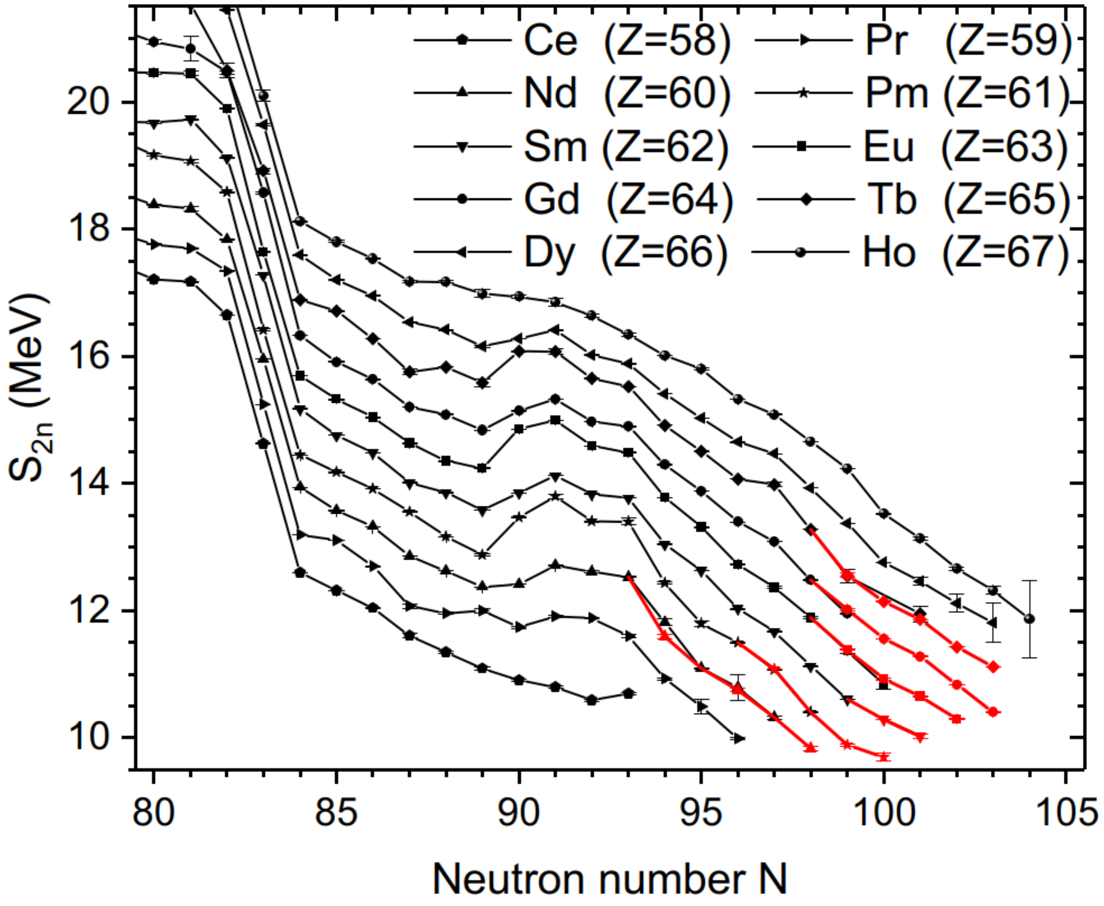
- Or fission?

Goriely et al., PRL 111 (2013) 242502



Two-neutron separation energies

- No kink observed in two-neutron separation energies S_{2n}
  - Red points: including new JYFLTRAP masses
- But the midshell N=104 not yet reached...

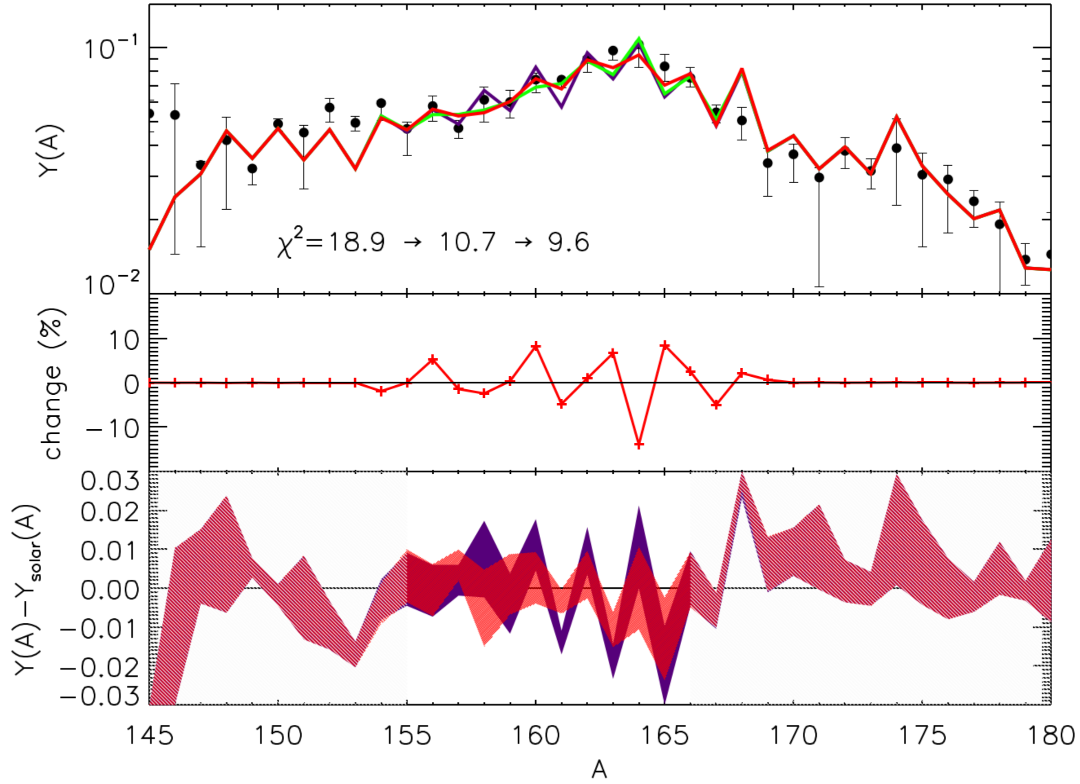


M. Vilén et al., PRC 101 (2020) 034312

Impact on the r-process calculations

- Assumed:
  - Merger with two 1.35M_{solar} neutron stars
  - $Y_e = 0.016$, initial $s/k_B \sim 8$
- Changes up to 25% observed!
- Better agreement with the r-process abundances
- Mainly due to revised neutron-capture rates calculated using TALYS

Purple: AME16+FRDM12
Green: AME16+JYFL'18
Red: AME16 + JYFL'18+JYFL'20

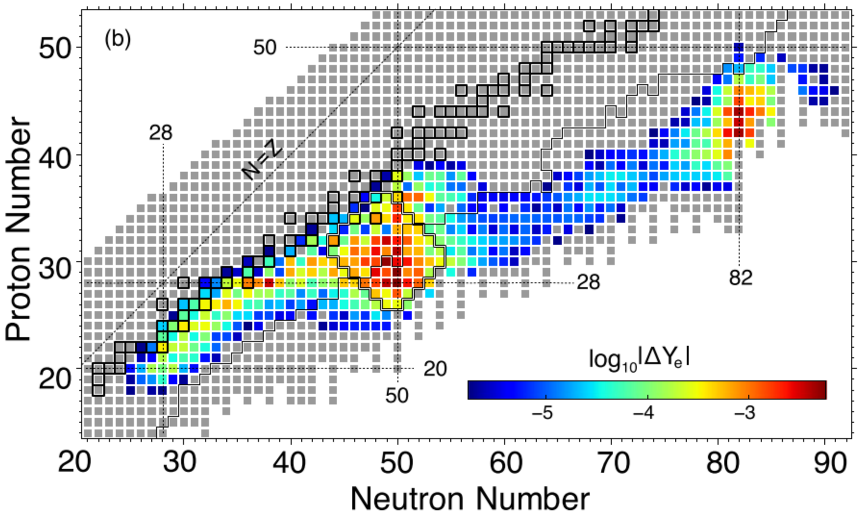


M. Vilén et al., PRC 101 (2020) 034312

^{78}Ni region and impact of electron captures on the core collapse?

- ^{74,75}Ni, ^{76,77,78}Cu and ^{79}Zn measured with JYFLTRAP
- ^{74,75}Ni measured for the first time
  - found to be around 180-250 keV less bound than predicted in AME2020
- Isomeric states in ^{76}Cu and ^{79}Zn also measured
- Nuclei relevant for the first r process peak (S. Nikas)

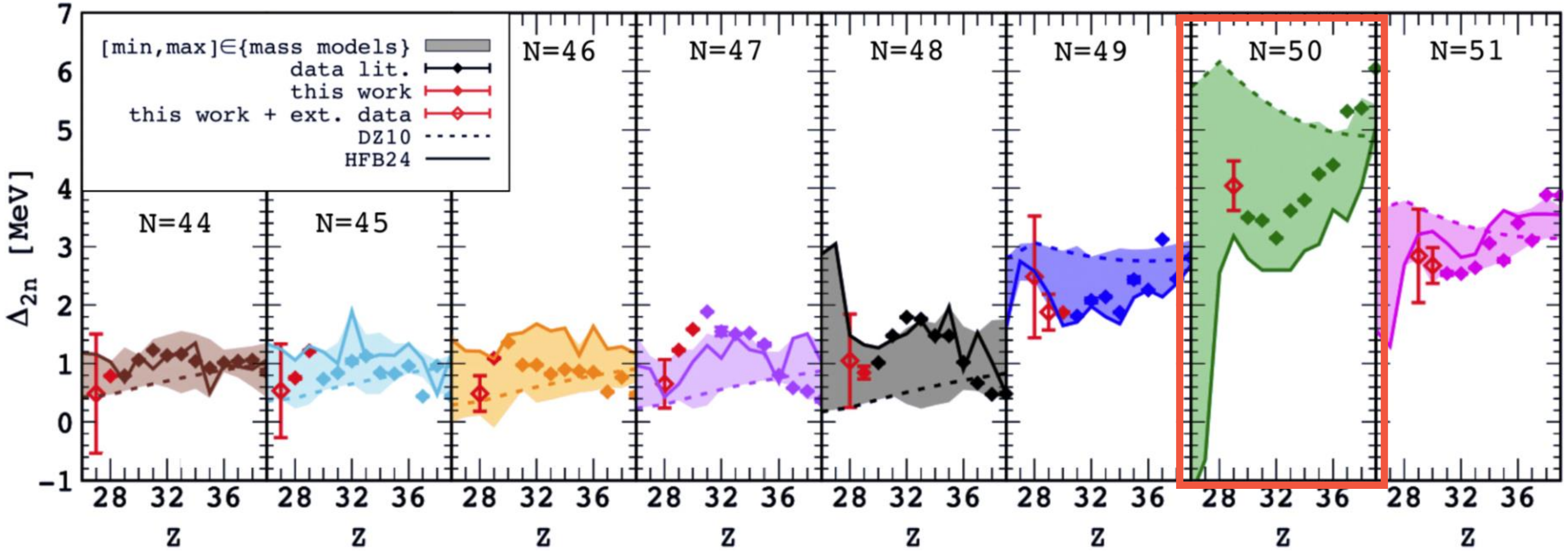
- Nuclei close to N=50 crucial for electron captures during the core collapse
  - Cooling via neutrino emission
  - Reduce electron degeneracy pressure
    → Mass of the inert core
    → Peak neutrino luminosity



Sullivan et al., ApJ 816 (2016) 44

Impact on the empirical two-neutron shell gap

- N = 50 empirical shell gap is weakly reinforced as Z = 28 is approached, in agreement with the doubly magic behavior of ^{78}Ni
- Experimental values closer to HFB-24 than DZ10
- HFB-24 predicts a weaker N=50 shell closure than DZ10



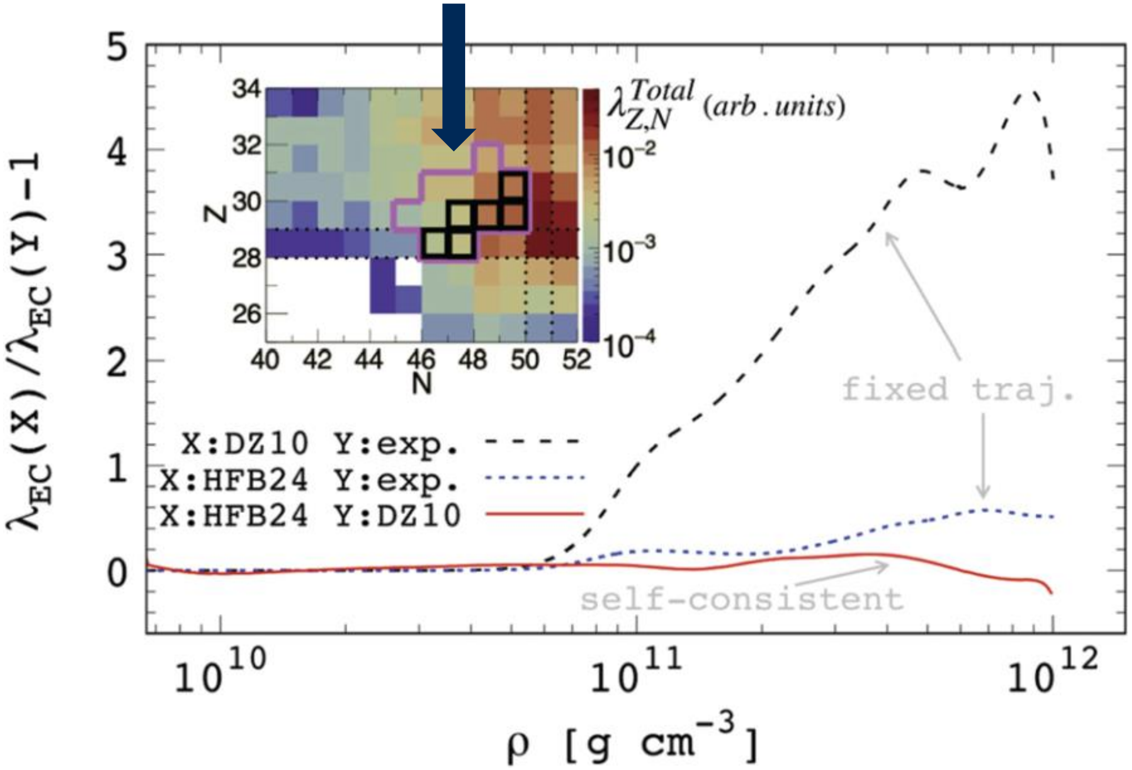
S. Giraud et al., Phys. Lett. B 833 (2022) 137309

Colourful band: range of mass models (DZ10, DZ28, FRDM12, HFB-24, WS4, KTUY05)

Impact on core-collapse supernova?

- Nuclei close to N~50 highest impact→ need Q_{EC} values (masses) for the rates
- Impact depends also on the used astrophysical trajectory
- Masses provide an important first step for more accurate calculations

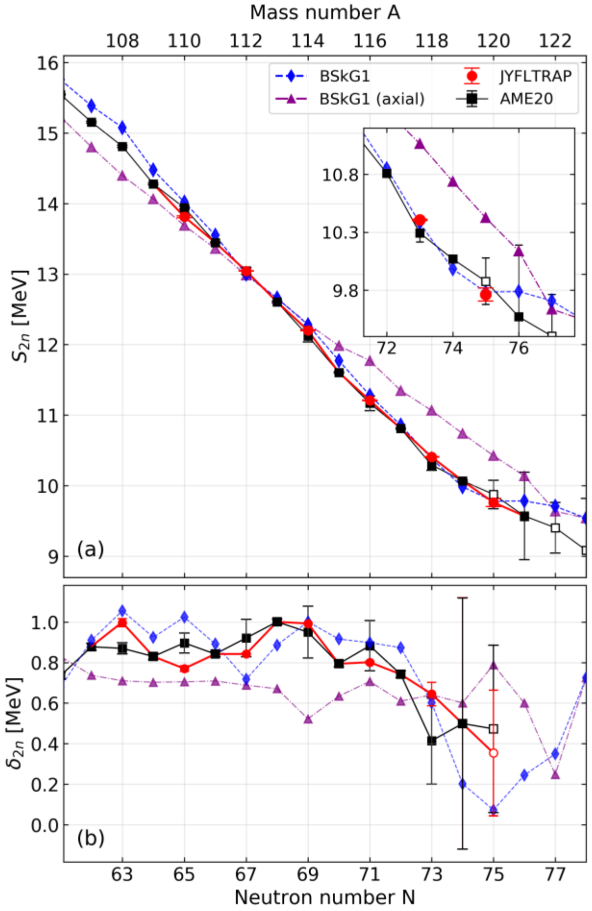
Determined key Q_{EC} values!



S. Giraud et al., Phys. Lett. B 833 (2022) 137309

Rh isotopes – testing the nuclear mass models

- Campaign on neutron-rich Rh isotopes with PI-ICR at JYFLTRAP
- Ground and isomeric states resolved and precisely measured for the first time
- Important for benchmarking nuclear mass models, in particular the role of triaxiality in the A~110 region
  - Large fraction of r-process nuclei will remain experimentally inaccessible→ need mass models for the calculations



M. Hukkanen, W. Ryssens et al., to be submitted

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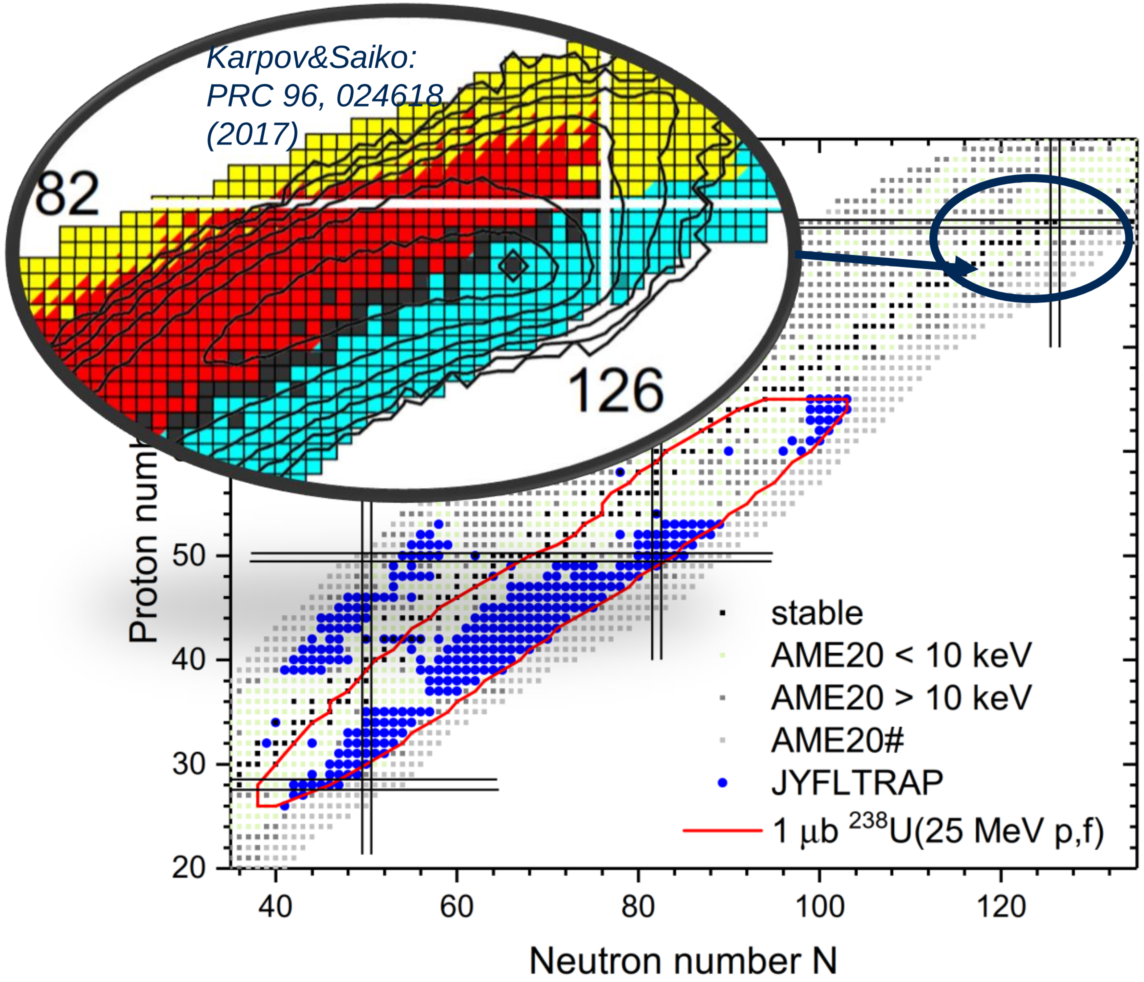
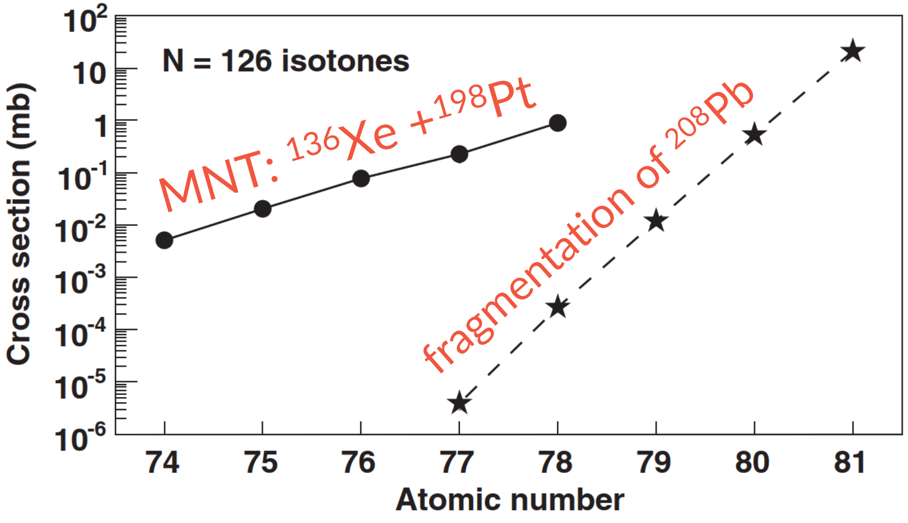
4. How to produce heavier neutron-rich nuclei?

Multinucleon-transfer reactions to reach nuclei beyond the fission fragment region?



Karpov&Saiko: PRC 96, 024618 (2017)

- Multinucleon-transfer (MNT) reactions a promising method to produce heavy neutron-rich nuclei close to N=126

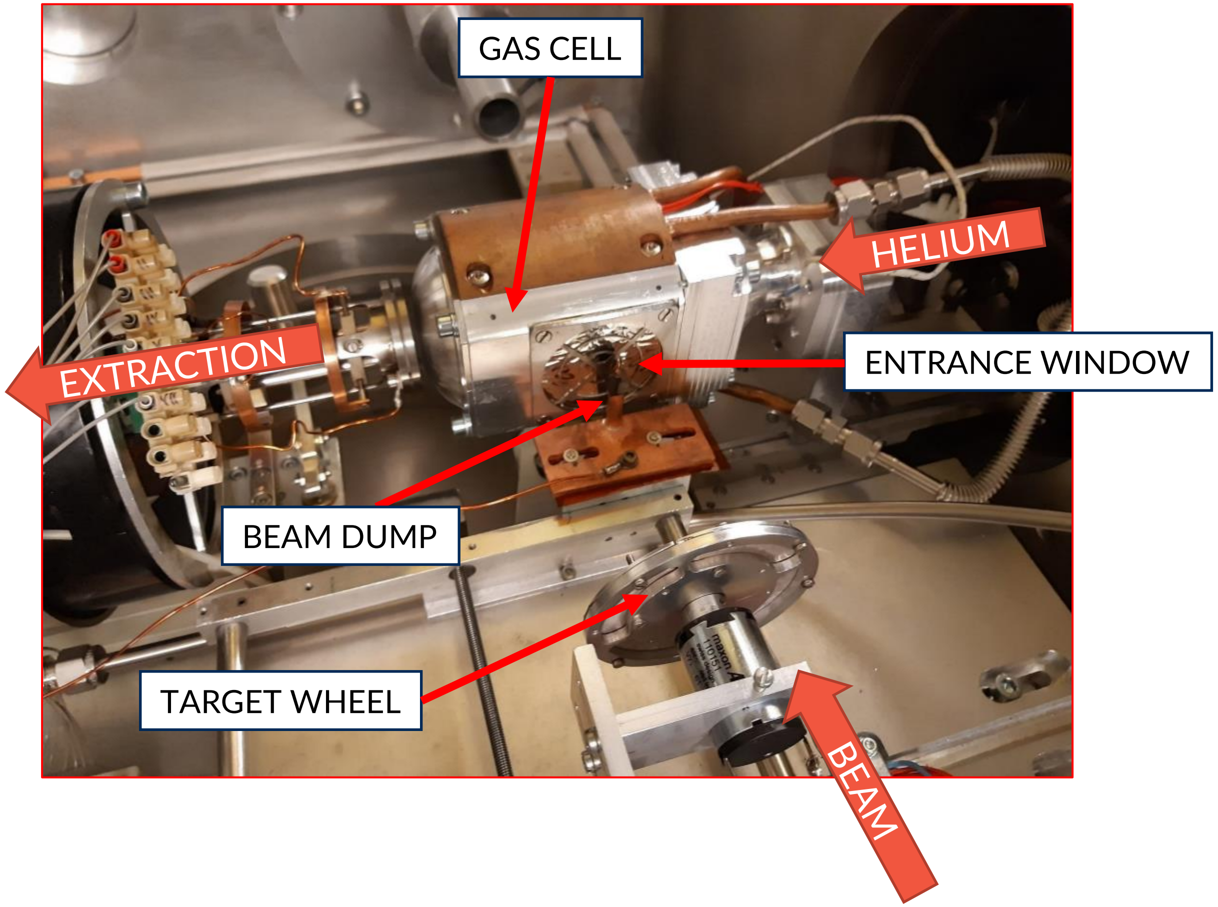


Watanabe et al., PRL 115, 172503 (2015)

MNT project at IGISOL

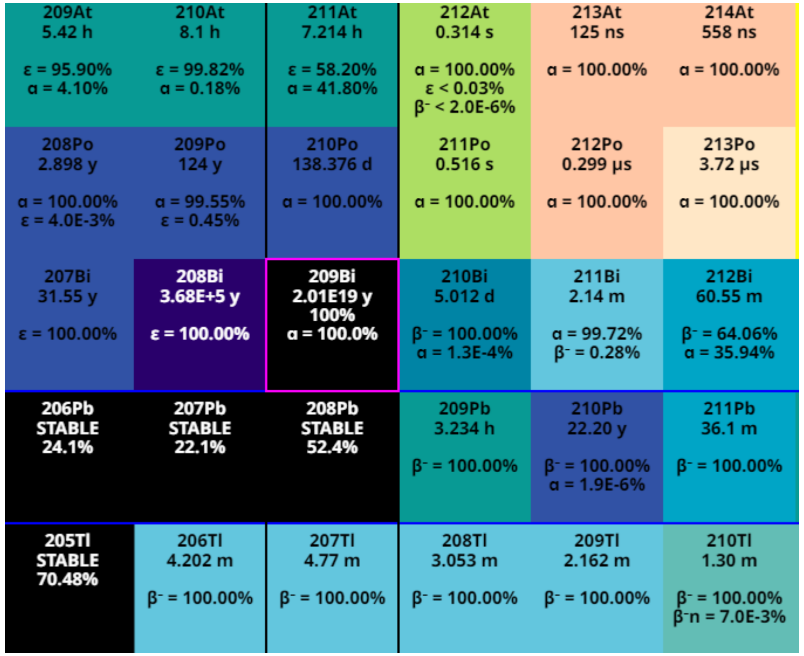
- First proof-of-principle experiments in 2019
  - using the existing HIGISOL gas cell and its target platform
  - designed for heavy-ion fusion evaporation reactions, not optimal for MNT reactions

European Research Council
Established by the European Commission



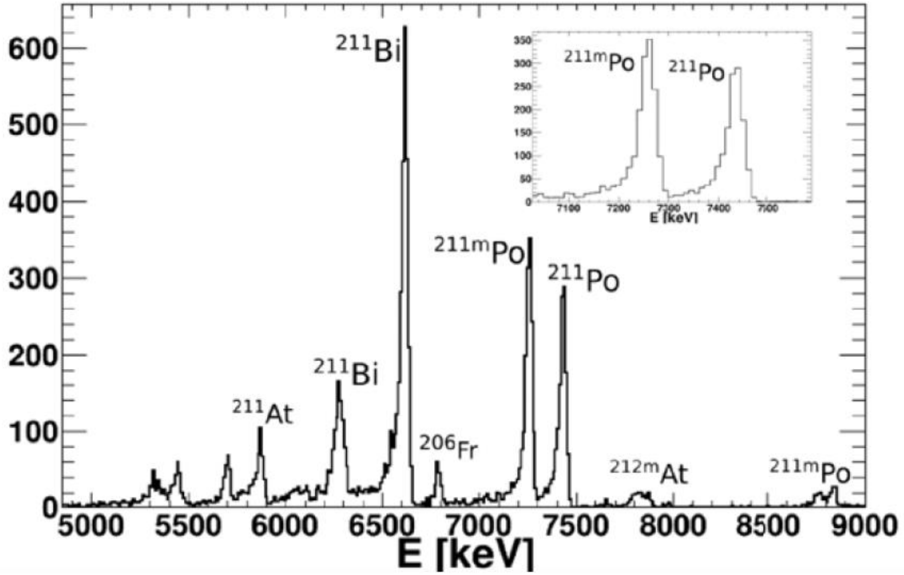
Test reaction with the HIGISOL gas cell: 945 MeV ^{136}Xe on ^{209}Bi target

- 10 pnA of ^{136}Xe at 945 MeV
- ^{209}Bi target, thickness 5µm



209At 5.42 h ε = 95.90% α = 4.10%	210At 8.1 h ε = 99.82% α = 0.18%	211At 7.214 h ε = 58.20% α = 41.80%	212At 0.314 s α = 100.00% ε < 0.03% β^- < 2.0E-6%	213At 125 ns α = 100.00%	214At 558 ns α = 100.00%
208Po 2.898 y α = 100.00% ε = 4.0E-3%	209Po 124 y α = 99.55% ε = 0.45%	210Po 138.376 d α = 100.00%	211Po 0.516 s α = 100.00%	212Po 0.299 µs α = 100.00%	213Po 3.72 µs α = 100.00%
207Bi 31.55 y ε = 100.00%	208Bi 3.68E+5 y ε = 100.00%	209Bi 2.01E19 y 100% α = 100.0%	210Bi 5.012 d β^- = 100.00% α = 1.3E-4%	211Bi 2.14 m α = 99.72% β^- = 0.28%	212Bi 60.55 m β^- = 64.06% α = 35.94%
206Pb STABLE 24.1%	207Pb STABLE 22.1%	208Pb STABLE 52.4%	209Pb 3.234 h β^- = 100.00%	210Pb 22.20 y β^- = 100.00% α = 1.9E-6%	211Pb 36.1 m β^- = 100.00%
205Tl STABLE 70.48%	206Tl 4.202 m β^- = 100.00%	207Tl 4.77 m β^- = 100.00%	208Tl 3.053 m β^- = 100.00%	209Tl 2.162 m β^- = 100.00%	210Tl 1.30 m β^- = 100.00% β^-n = 7.0E-3%

- Alpha particles detected at switchyard → successful production and transportation

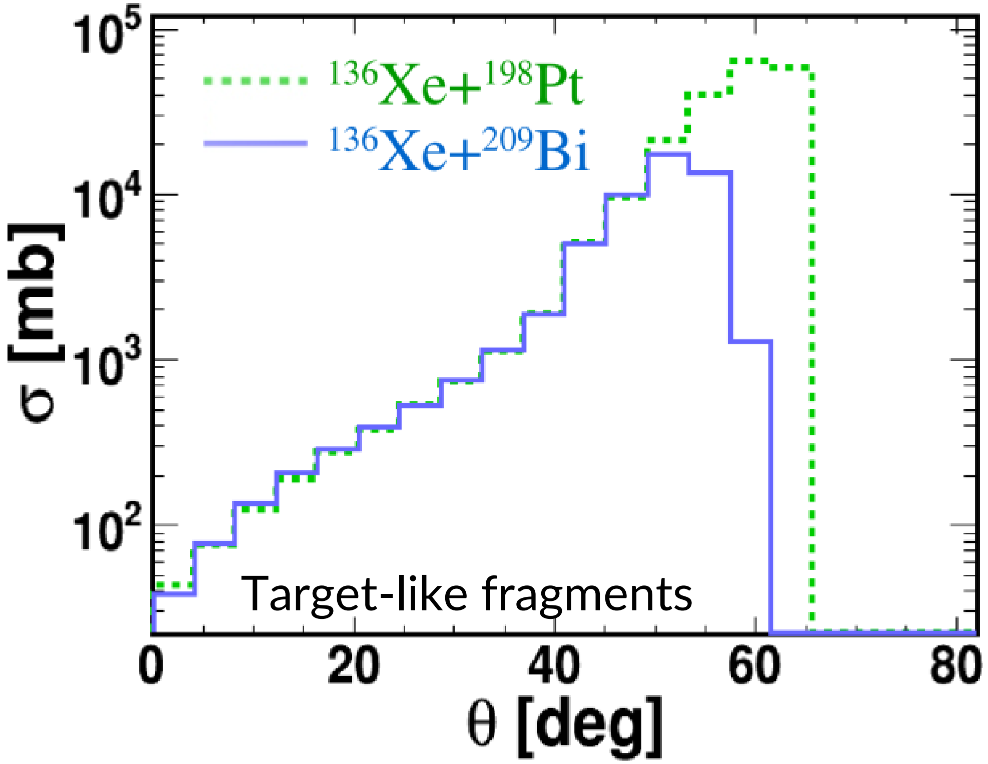


T. Dickel, AK, et al., J. Phys.: Conf. Ser. 1668 (2020) 012012

Proof-of-principle experiment successful at IGISOL!

MNT cross sections and simulations

- MNT reaction cross sections peak at angles around 40-60 degrees
  - HIGISOL gas cell designed for heavy-ion fusion evaporation reactions for which products at small angles
  - **Need a dedicated gas cell with a larger entrance window and target closer to the gas cell!**

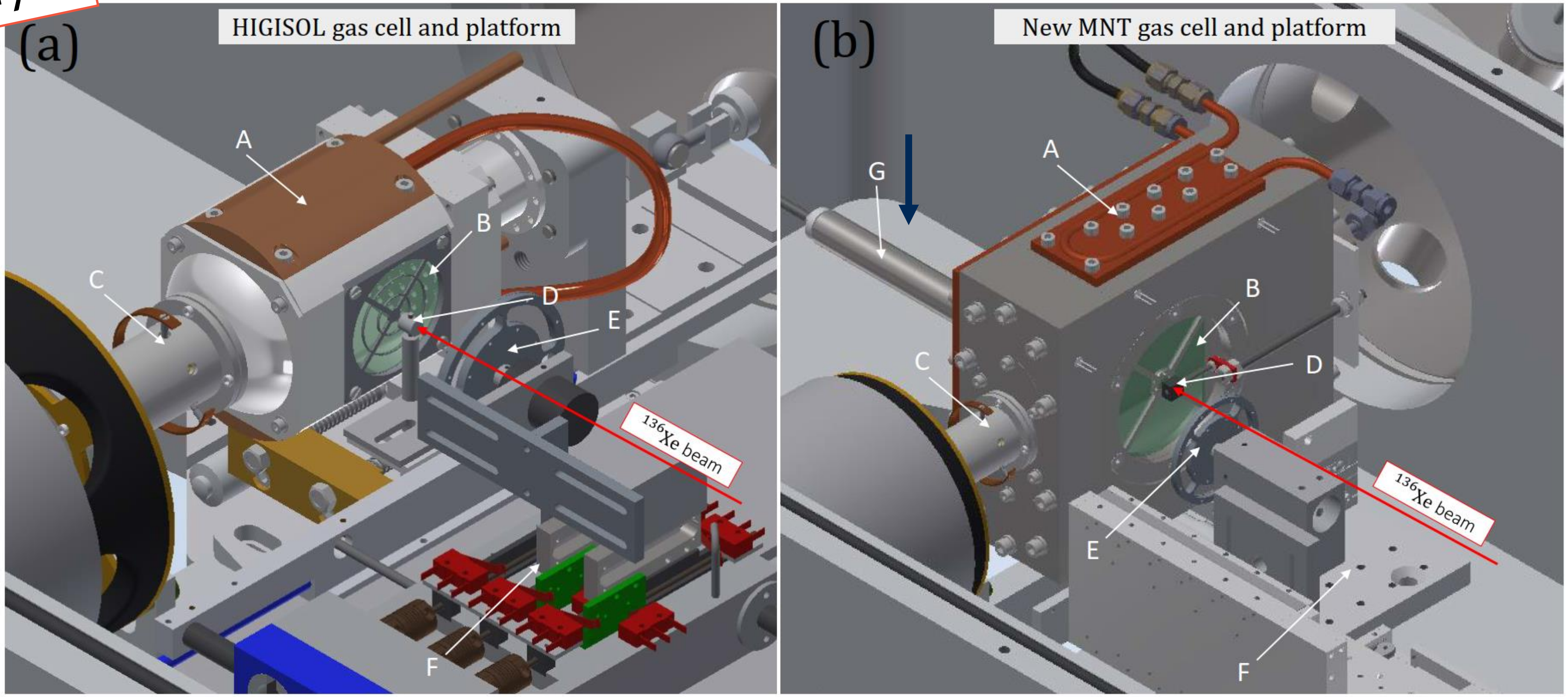


A. Spataru et al., Acta Phys. Pol. B 51 (2020) 817

New gas cell for the MNT reactions

See Poster #76
by A. Zadvornaya!

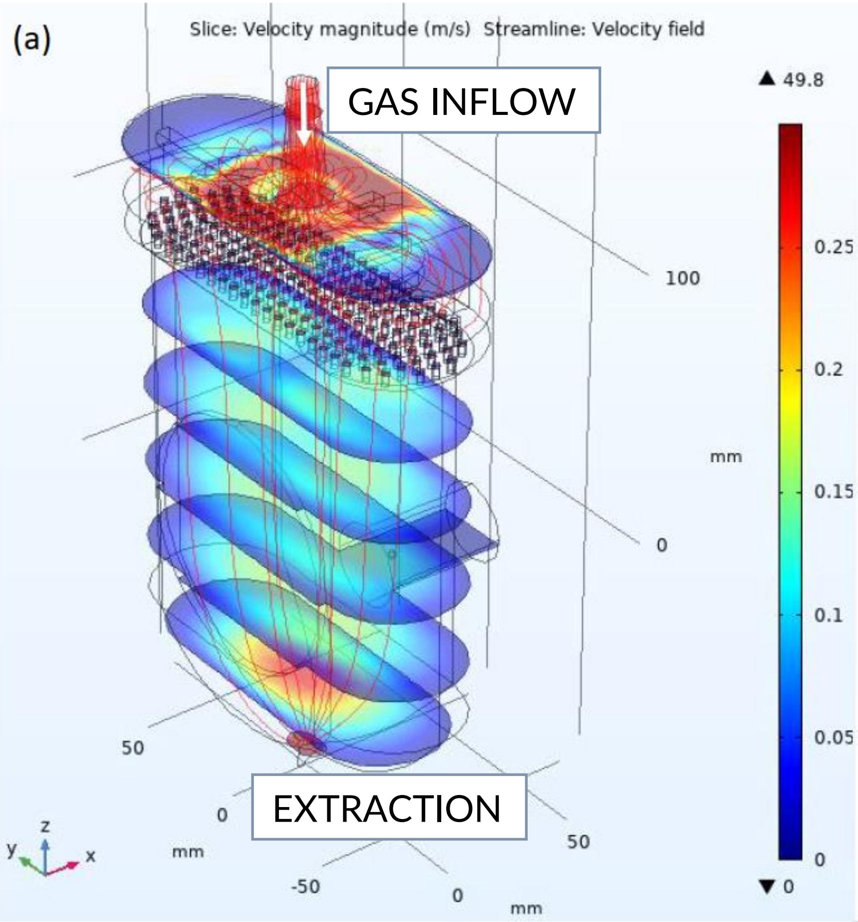
Taller gas cell with larger entrance window. Gas cell optimised for the gas flow.



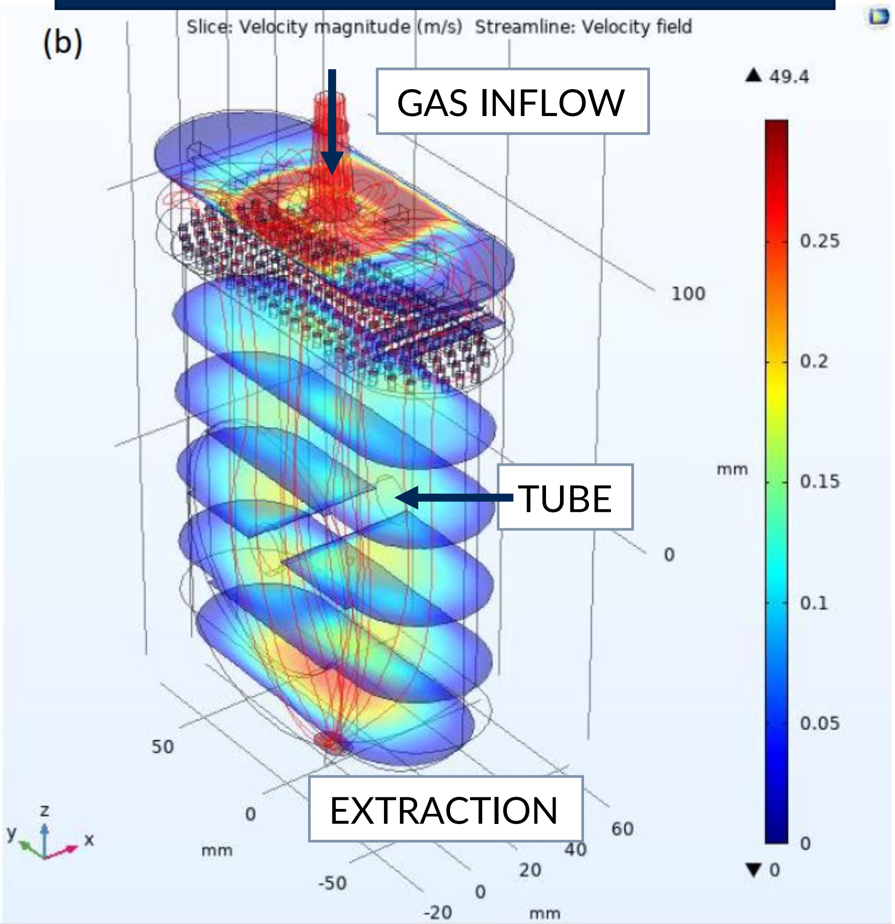
Two configurations of the new gas cell

Comsol Multiphysics simulations, A. Zadvornaya et al., to be submitted

(a) Beam dump in front of the gas cell



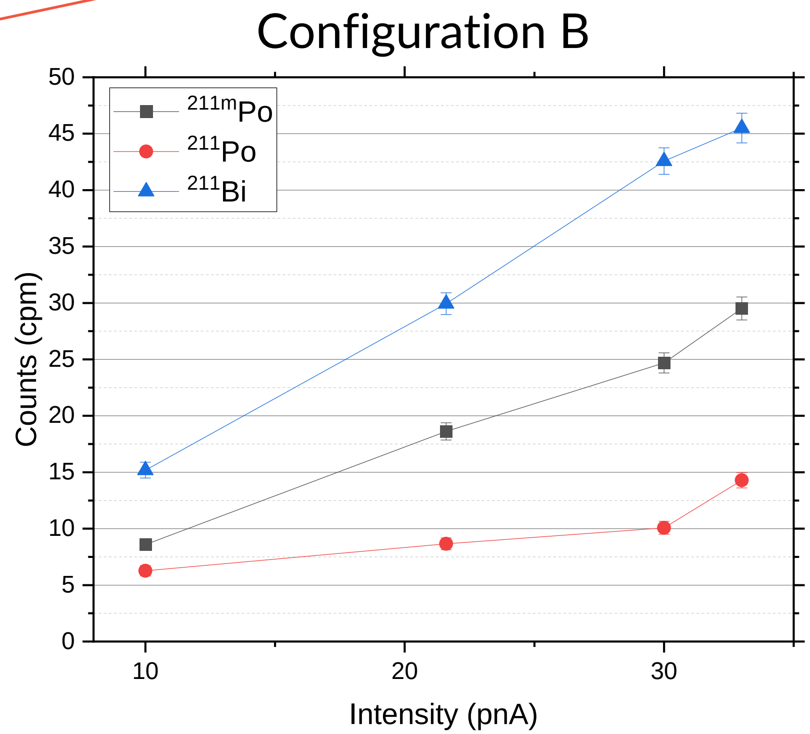
(b) Beam dump behind the gas cell (tube through the cell)



Online experiments

- Saturation obtained with around 30 pnA using configuration A
  - Primary beam scattering into the gas cell and creating plasma?
- Configuration B:
  - Much better and stable performance with the beam dump behind the gas cell
  - No saturation at 30 pnA
  - → higher intensities in future?
  - Possibility to add a degrader foil on the entrance window

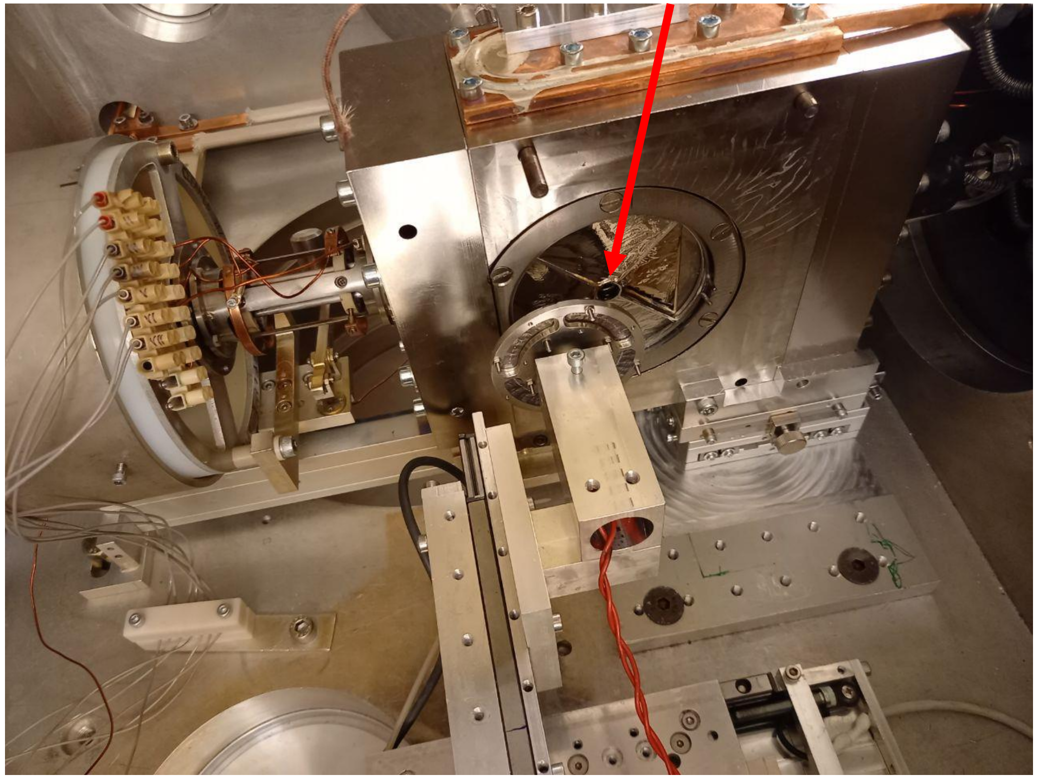
See Poster #76 by A. Zadvornaya!



Summarising MNT project at IGISOL

- New gas cell working but still needs more systematic tests
- Goal: ^{136}Xe + ^{198}Pt
- So far the focus has been on target-like fragments
  - How about projectile-like fragments, e.g. lighter neutron-rich nuclei?

Configuration B. Beamtube through the gas cell.



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5. Summary and outlook

Summary and outlook

- JYFLTRAP Penning trap widely used for:
  - mass measurements – also isomeric states (→ excitation energy for the isomer)
  - post-trap decay spectroscopy with isomerically clean beams (not discussed today)
  - isomeric yield ratios in fission (not discussed today)
- More accurate mass values and excitation energies determined for dozens neutron-rich nuclei and isomers with JYFLTRAP recently
- New MNT gas cell built and commissioned at IGISOL→ production of neutron-rich nuclei beyond the fission fragment region → new nuclei to be measured

Acknowledgements

Thanks to all collaborators and the IGISOL Group!

erc

European Research Council

Established by the European Commission

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INSTITUT FRANÇAIS

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SUOMEN TIEDESEURA THE FINNISH SOCIETY OF SCIENCES AND LETTERS

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