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UNIVERSITY OF JYVÄSKYLÄ

Studies for nuclear structure and astrophysics with the JYFLTRAP Penning trap

Anu Kankainen
Email: anu.kankainen@jyu.fi
University of Jyväskylä

Outline

1. JYFL Accelerator laboratory and the IGISOL facility
2. Why and how to measure atomic masses?
3. Results from mass measurements with JYFLTRAP
4. Decay spectroscopy at IGISOL
5. Summary and outlook

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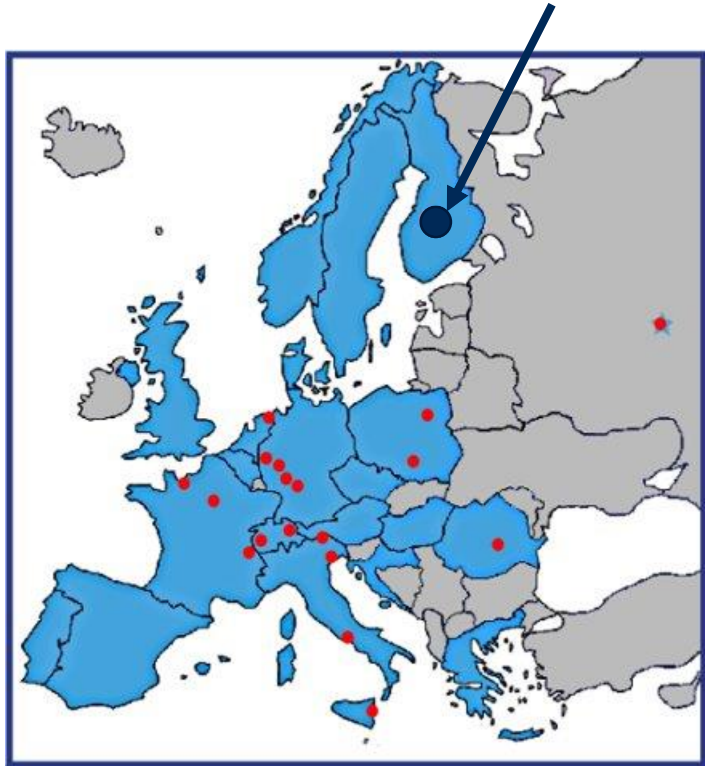
JYFL Accelerator laboratory and the IGISOL facility

JYFL Accelerator Laboratory at the Department of Physics, University of Jyväskylä

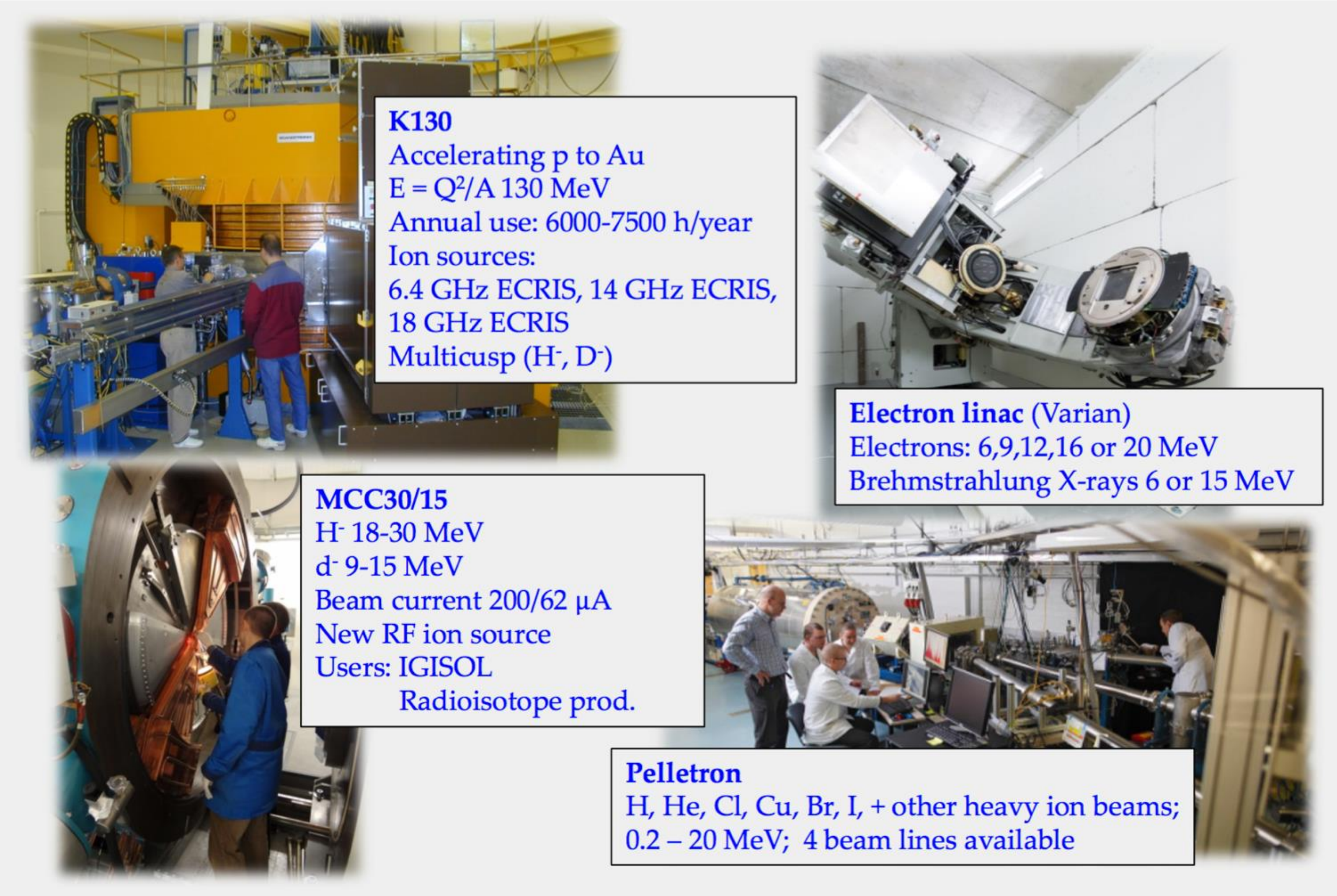


● From North to South:
JYFL (Jyväskylä, Finland), **JINR** (Dubna,Russia),
KVI-CART (Groningen, The Netherlands), **HIL** (Warsaw, Poland),
GANIL (Caen, France), **COSY** (Jülich, Germany), **ELSA** (Bonn, Germany),
MAMI (Mainz, Germany), **GSI** (Darmstadt, Germany), **ALTO** (Orsay, France),
CCB (IFJ, PAN Kraków, Poland), **ILL** (Grenoble,France),
CERN (Genève, Switzerland), **PSI** (Villingen, Switzerland),
ECT* (Trento, Italy), **LNL-INFN** (Legnaro, Italy), **IFIN-HH** (Bucharest, Romania),
LNF-INFN (Frascati, Italy), **LNS-INFN** (Catania, Italy)

- Core research fields:
  - Fundamental Nuclear Science and Applications
  - Accelerator-Based Materials Science and Cultural Heritage
  - Radiation Effects in Electronics
  - Commercial Services
- Over 6000 h (about 250 days) of beamtime/year
- Two open calls for scientific proposals per year
  - 15th March and 15th September
  - Evaluated by an international panel of independent experts (PAC)

@jyflacclab

Accelerators at JYFL



K130
Accelerating p to Au
E = Q^2/A 130 MeV
Annual use: 6000-7500 h/year
Ion sources:
6.4 GHz ECRIS, 14 GHz ECRIS, 18 GHz ECRIS
Multicusp (H^-, D^-)

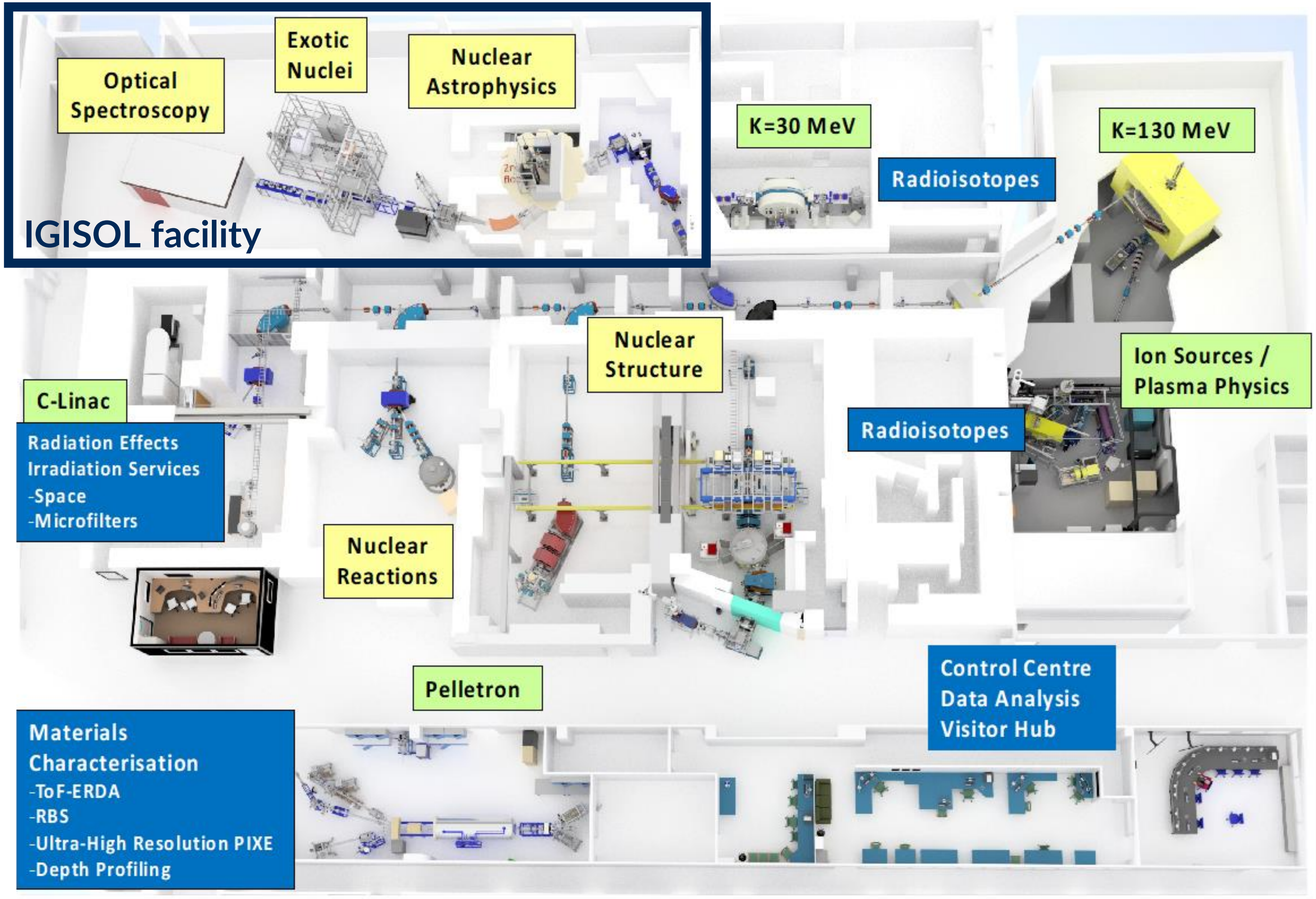
Electron linac (Varian)
Electrons: 6,9,12,16 or 20 MeV
Brehmstrahlung X-rays 6 or 15 MeV

MCC30/15
H^- 18-30 MeV
d^- 9-15 MeV
Beam current 200/62 µA
New RF ion source
Users: IGISOL
Radioisotope prod.

Pelletron
H, He, Cl, Cu, Br, I, + other heavy ion beams;
0.2 – 20 MeV; 4 beam lines available

+ Academy of Finland funding to purchase a new 3 MV tandem accelerator

JYFL Accelerator Laboratory

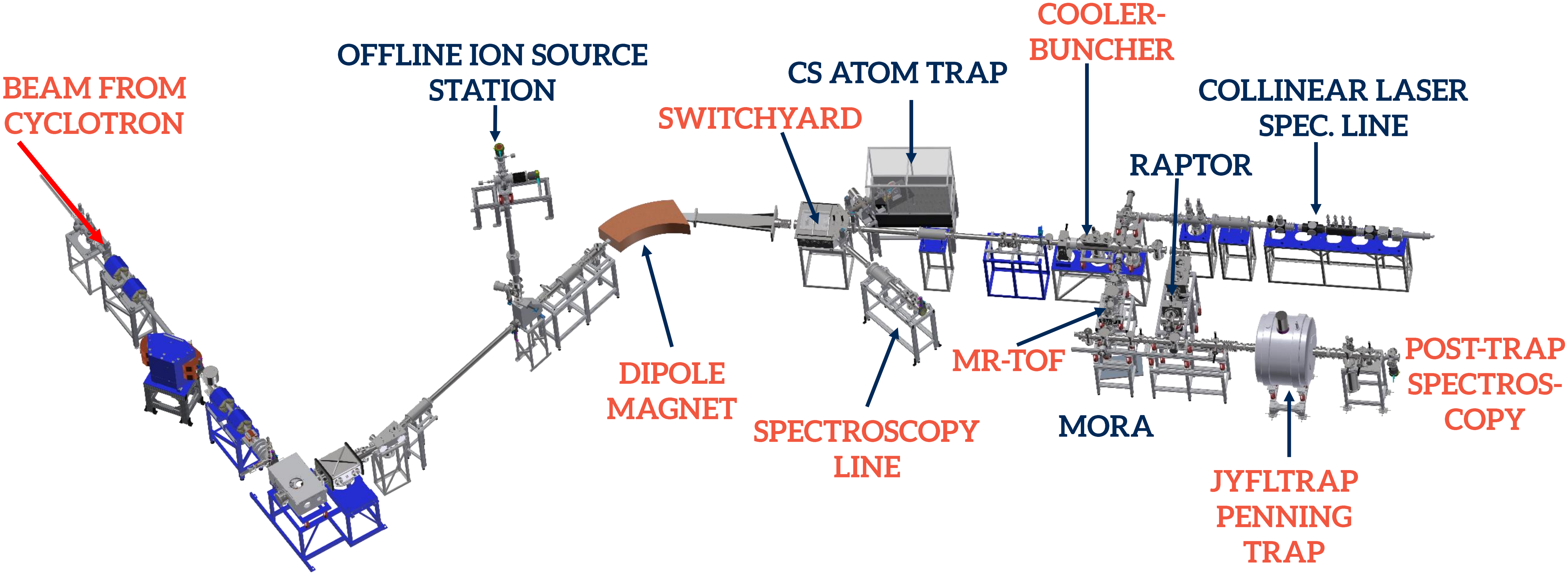


Radiation Effects
Irradiation Services
- Space
- Microfilters

Materials Characterisation
- ToF-ERDA
- RBS
- Ultra-High Resolution PIXE
- Depth Profiling

Control Centre
Data Analysis
Visitor Hub

Ion Guide Isotope Separator On-Line (IGISOL)

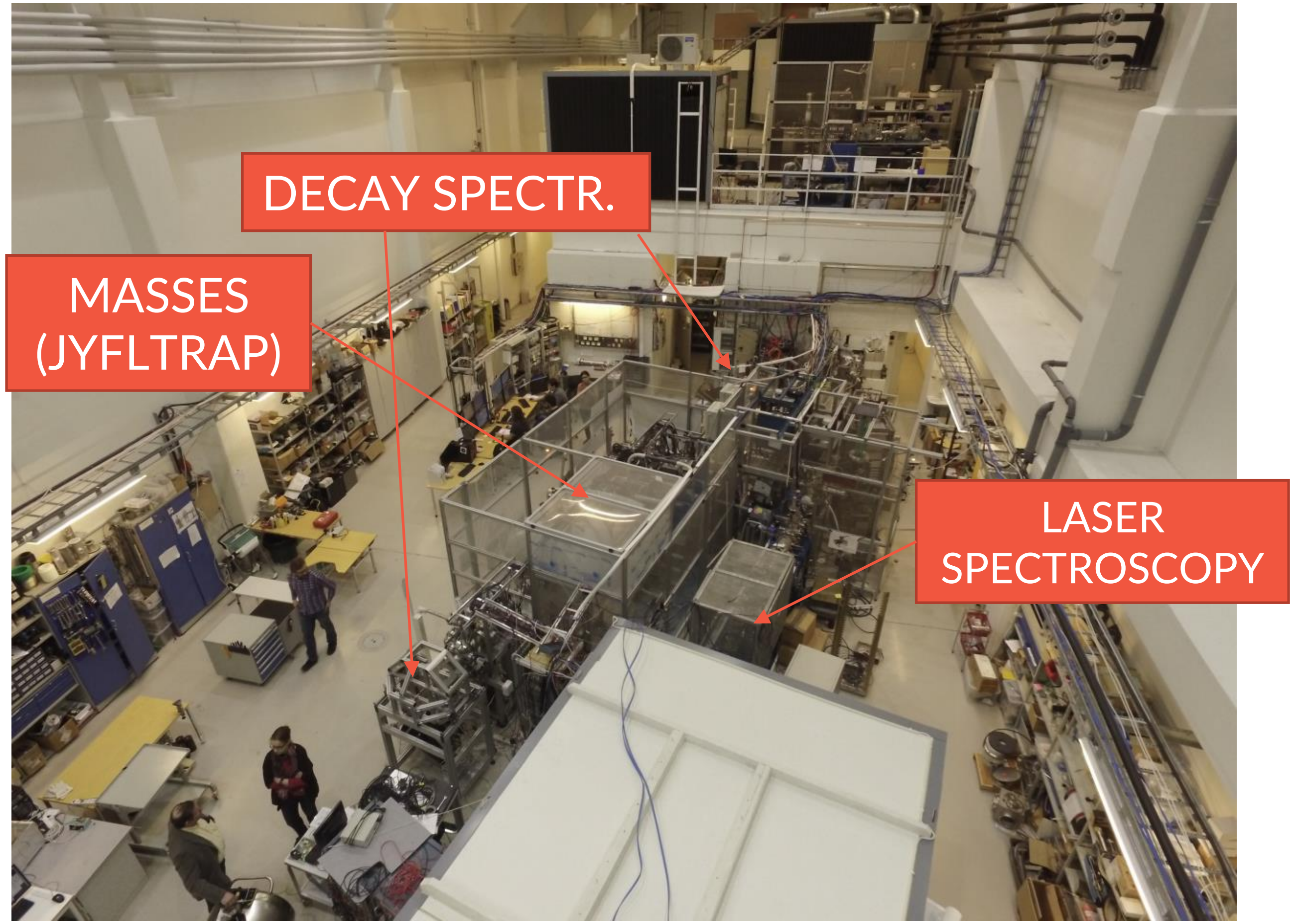


TARGET CHAMBER

- Fast and universal ion guide technique

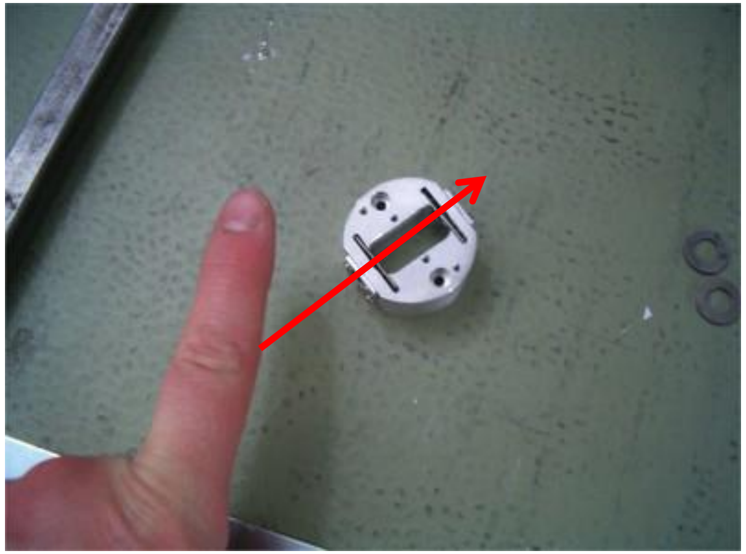
J. Ärje, J. Äystö et al., PRL 54 (1985) 99

IGISOL hall

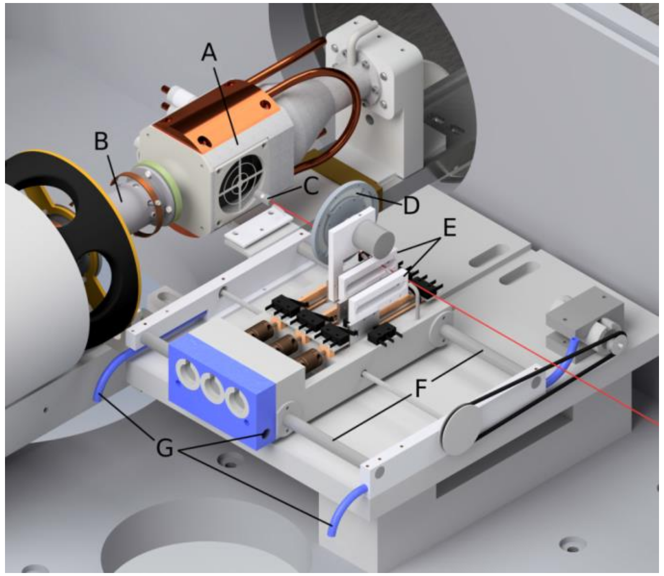


Production of neutron-deficient nuclei at IGISOL

- Light-ion ion guide
  - Fusion evaporation reactions with proton (or other light ion) beams



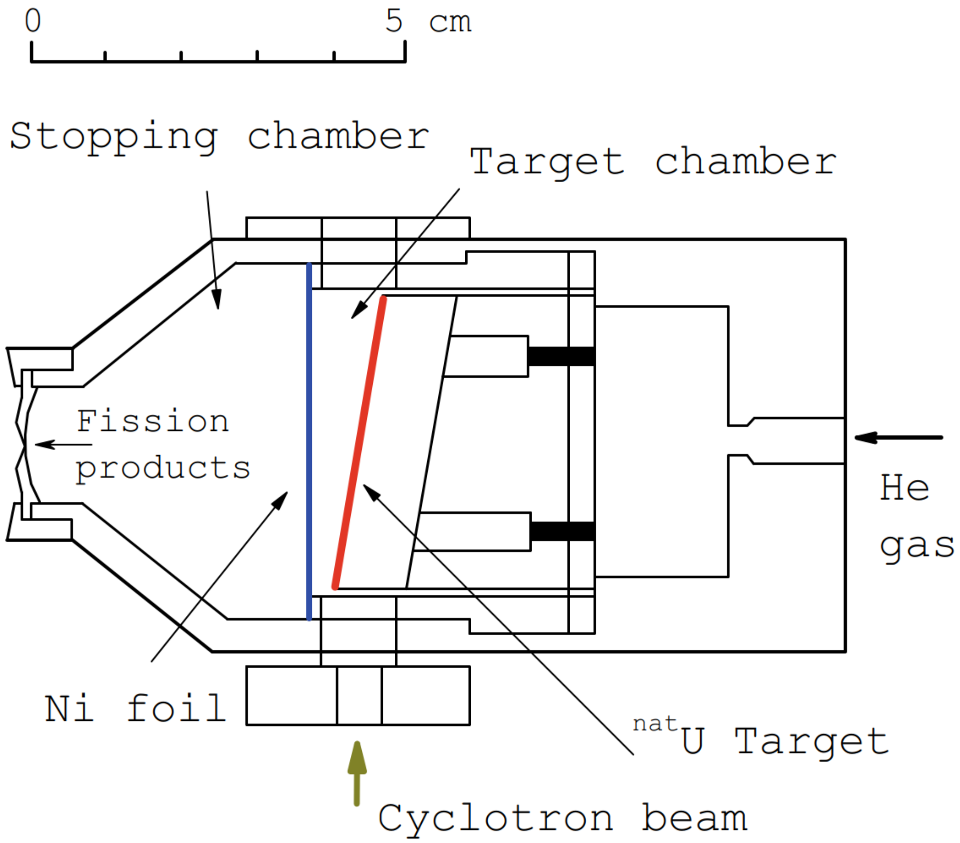
- Heavy-ion ion guide (HIGISOL)
  - Fusion evaporation reactions with heavy-ion beams (e.g. ^{36}Ar, ^{40}Ca,..)



M. Vilén et al., PRC 100 (2019) 054333

Production of neutron-rich nuclei at IGISOL

- Proton-induced fission on uranium or thorium
  - 25 or 30 MeV protons
  - 15 mg/cm^2 thick target
  - 250-300 mbar helium
- Chemically insensitive and fast ion-guide method
- No separate ion source needed

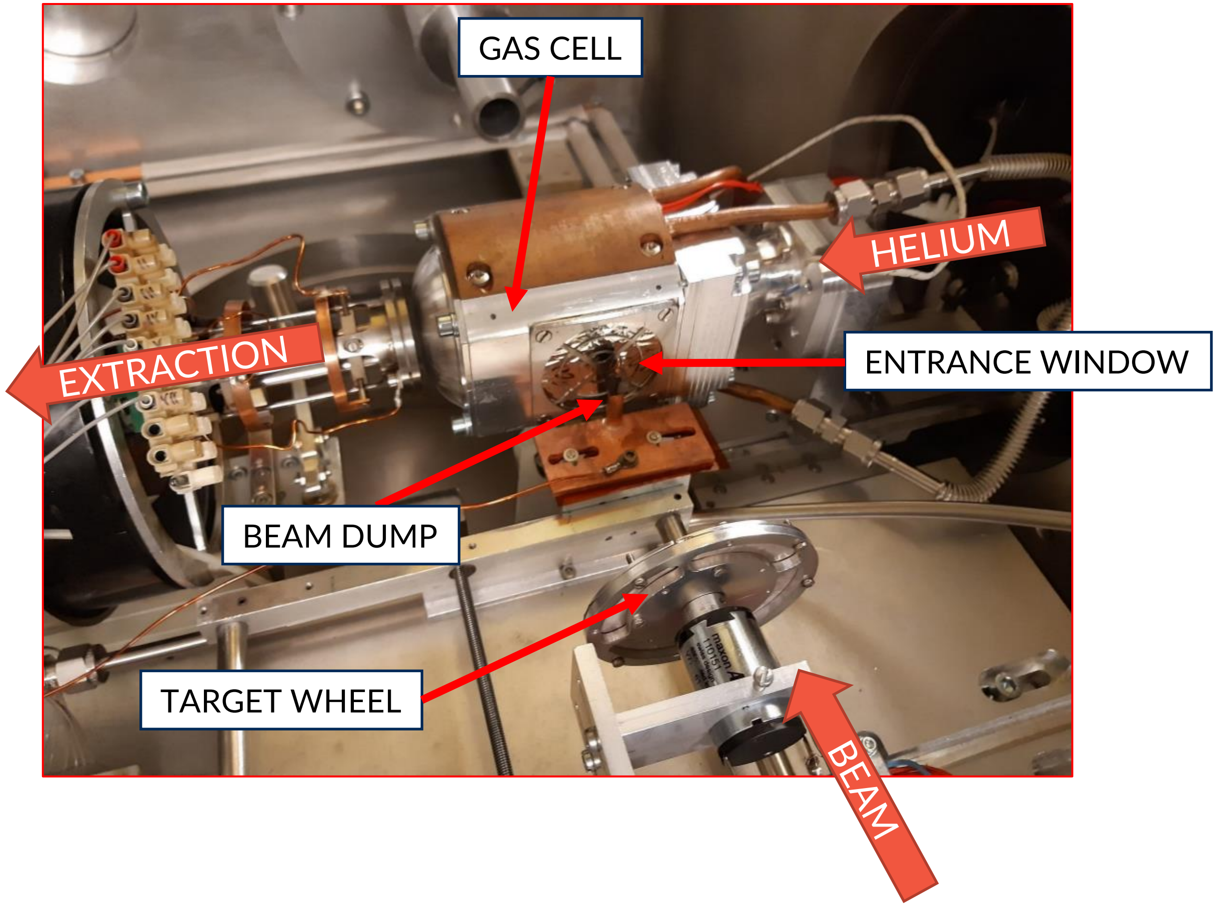


A. Al-Adili et al., Eur. Phys. J. A 51 (2015) 59

Multi-nucleon transfer reactions at IGISOL

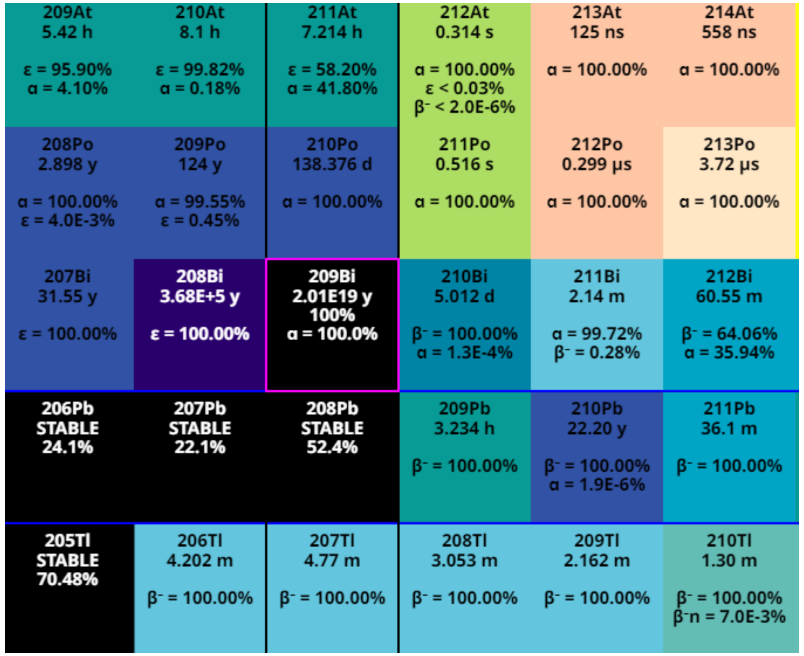
- Goal: produce neutron-rich beyond the fission fragment region
- First proof-of-principle experiments in 2019
  - using the existing HIGISOL gas cell and its target platform

European Research Council
Established by the European Commission



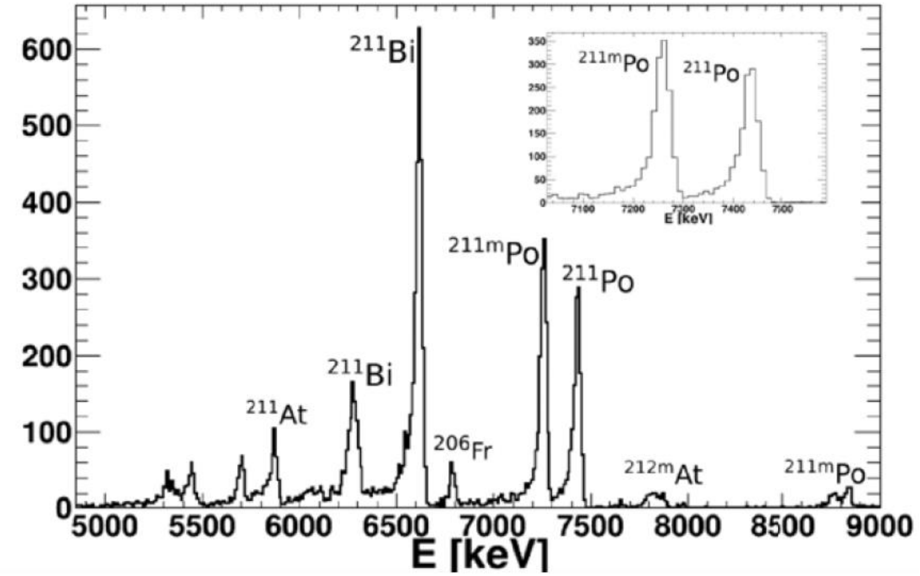
Test MNT experiment with the HIGISOL gas cell: 945 MeV ^{136}Xe on ^{209}Bi target

- 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 012012

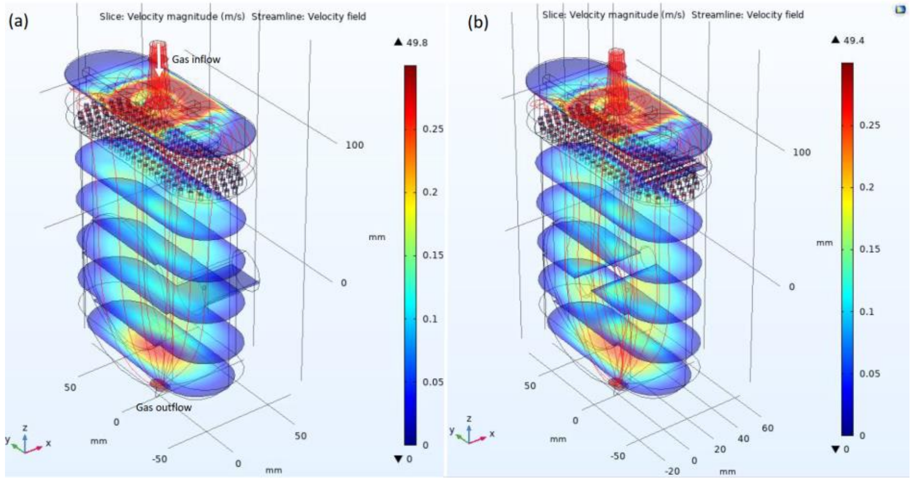
→ Proof-of-principle experiment successful at IGISOL! Design a new gas cell for MNT reactions.

New MNT gas cell and platform

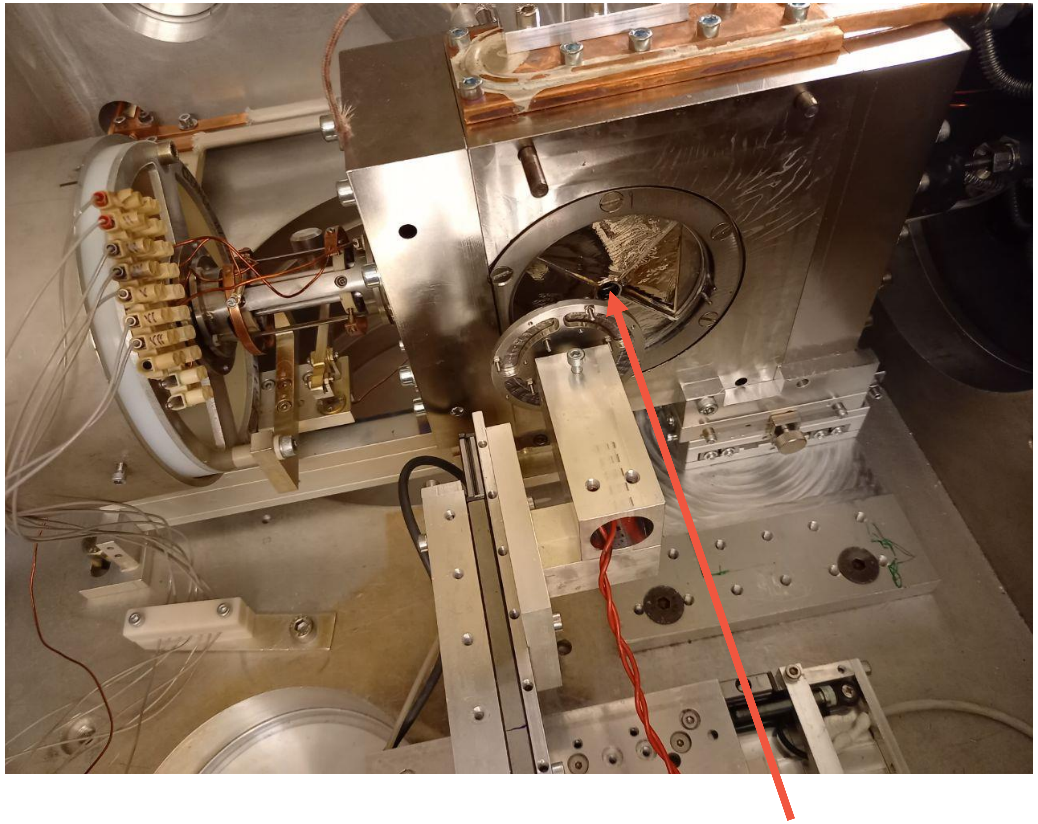
- Two versions of the new gas cell simulated and designed

A) Beam stopped before the gas cell

B) Beam stopped after the gas cell (beamtube)



Configuration B. Beamtube through the gas cell.



Configuration B better based on test experiments

Why and how to measure masses?

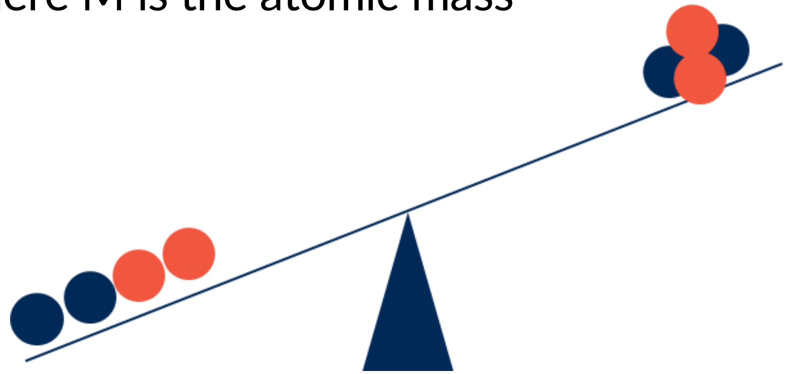
Why nuclear masses are important?

- Almost entire atomic mass in the nucleus
- Nucleus weighs less than its constituents

→ NUCLEAR BINDING ENERGY

$$B(Z,N) = \left[Z \cdot M(\,^{1}H) + N \cdot M_n - M(Z,N)\right]c^2$$

where M is the atomic mass



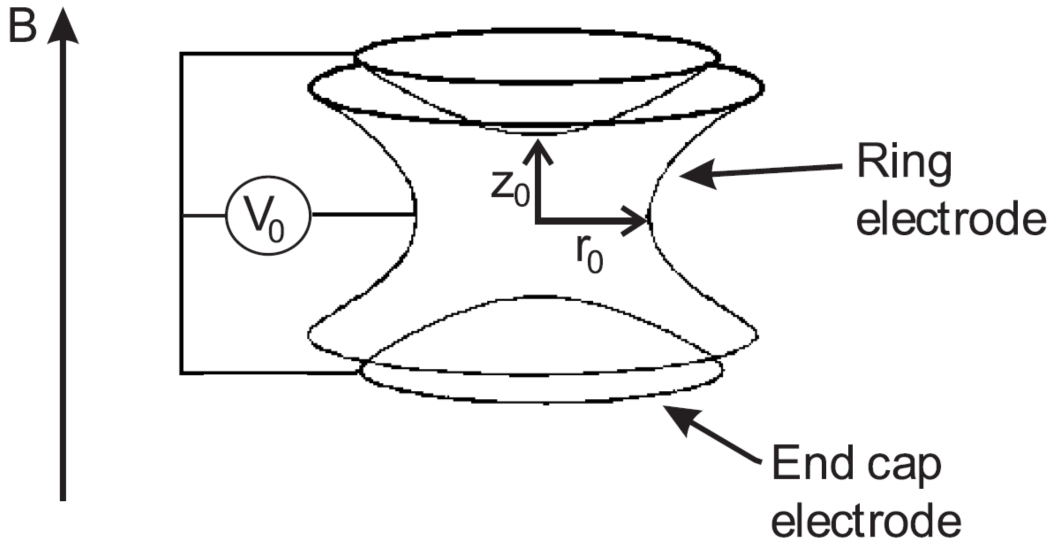
- High-precision atomic mass measurements provide information on nuclear binding energies important e.g. for
  - nuclear structure
  - nuclear astrophysics
  - fundamental physics
- Direct measurements of decay and reaction Q values, e.g.
  - Ultra-low beta-decay/EC Q values for neutrino physics
  - Superallowed or mirror beta decay Q-values
- Direct measurements of isomeric excitation energies
  - Beta-decaying isomers difficult to determine via other methods

Penning trap mass spectrometer

- First Penning trap by Hans Georg Dehmelt
  - Nobel Prize in Physics in 1989
- Strong magnetic field

  → radial (r) confinement
- Weak quadrupolar electrostatic potential

  → axial (z) confinement



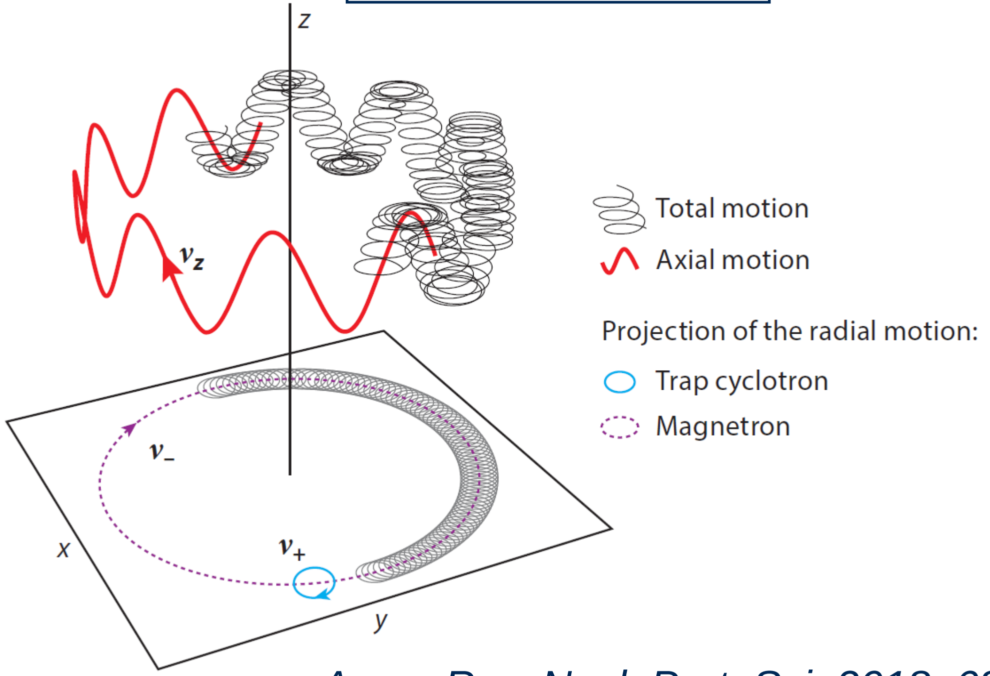
Three eigenmotions in the trap

- Electric and magnetic fields
  → three eigenmotions:
  - Slow magnetron ν_-
  - Fast cyclotron ν_+
  - Axial ν_z
- Invariance theorem:
  - $\nu_c^2 = \nu_-^2 + \nu_+^2 + \nu_z^2$

  Brown&Gabrielse, Phys. Rev. A 25 (1982) 2423;Int. J. Mass Spectrom. 279 (2009) 107
- Radial sideband frequency:
  - $\nu_c = \nu_- + \nu_+$

- Ion's cyclotron frequency:

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

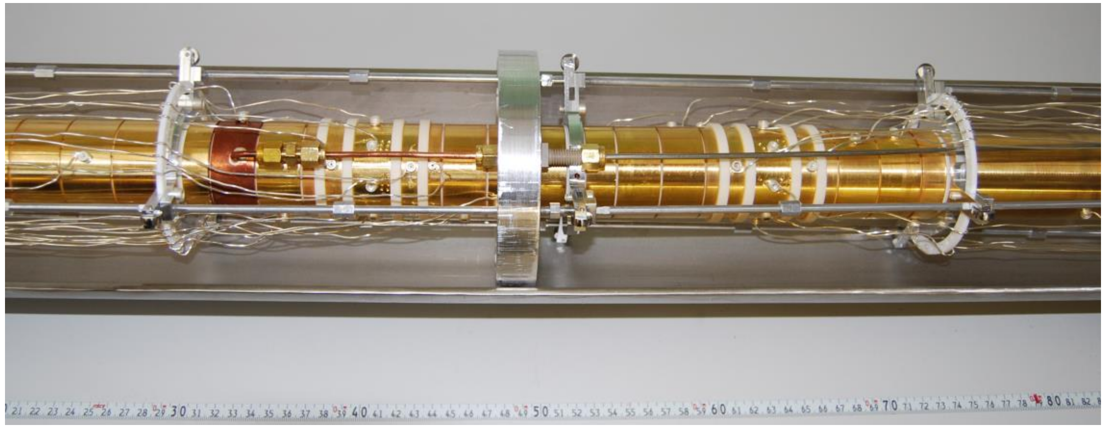


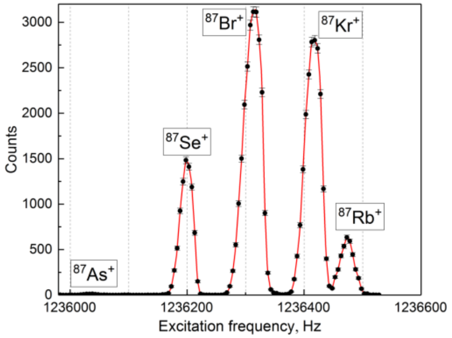
Annu. Rev. Nucl. Part. Sci. 2018. 68:45–74

JYFLTRAP double Penning trap

- 7 T superconducting solenoid
- 1st trap: select and prepare the ions of interest for mass measurements
- 2nd trap: actual mass measurements

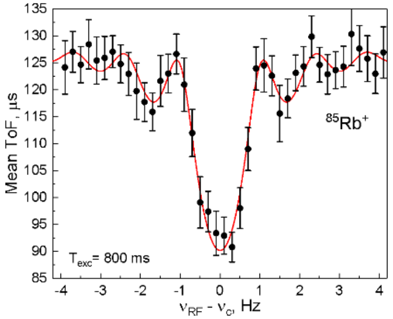
1. PREPARATION TRAP **2. MEASUREMENT TRAP**





Mass-selective buffer-gas cooling technique

G. Savard et al.,
Phys. Lett. A 158, 247 (1991)

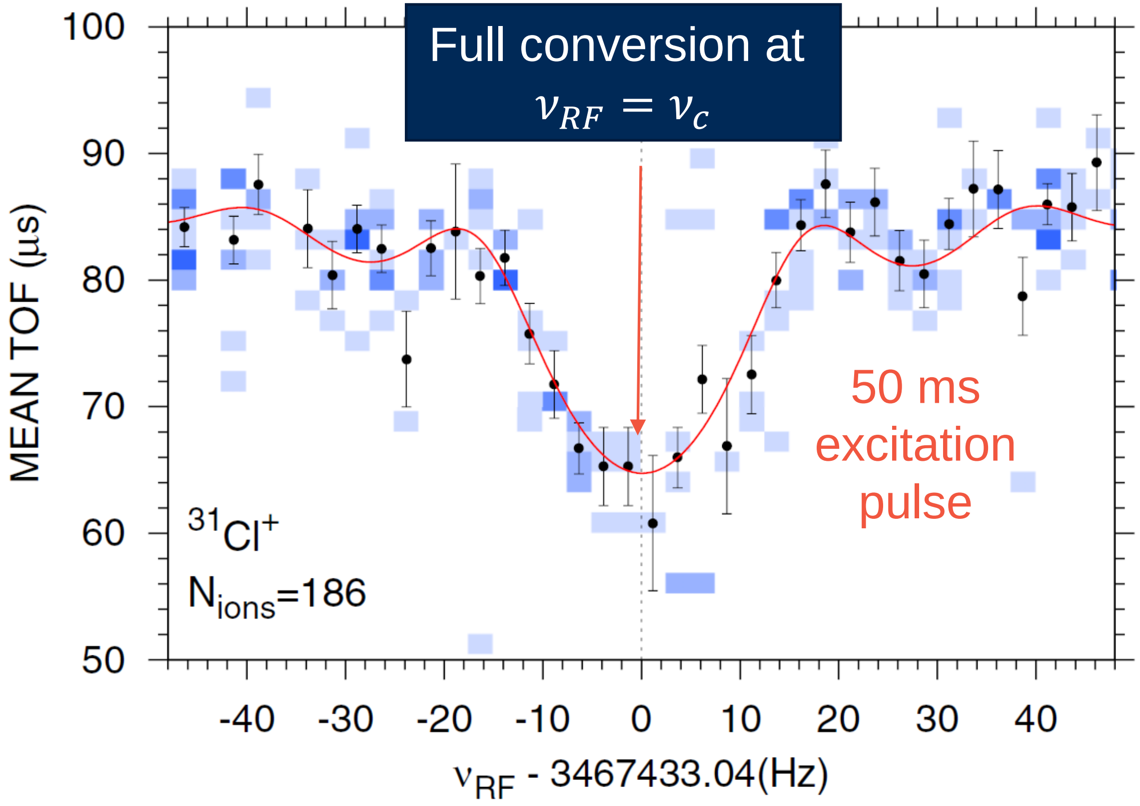


Time-of-Flight Ion Cyclotron Resonance technique (TOF-ICR)

M. König et al. Int. J. Mass Spectrom. Ion Process. 142, 95 (1995)

TOF-ICR technique

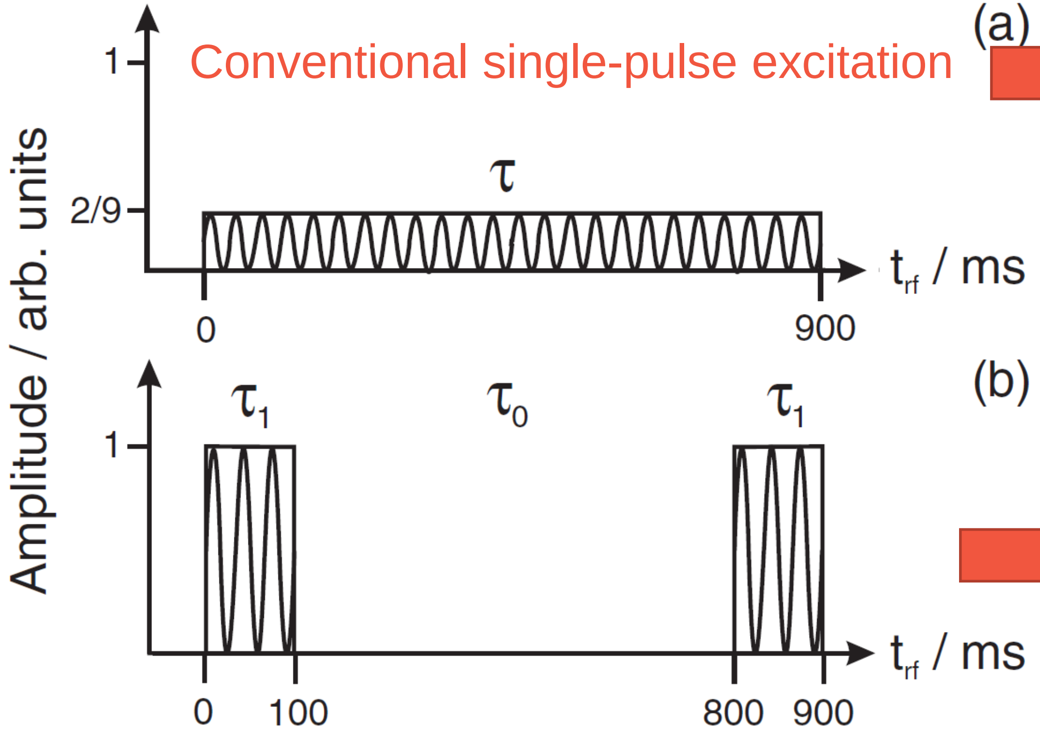
- Initial slow magnetron motion ν_- converted to fast cyclotron motion via quadrupolar excitation at the sideband frequency $\nu_c = \nu_- + \nu_+$
  - Radial energy increases
  - Fastest ions at full conversion



A. Kankainen et al., PRC 93, 041304(R) (2016)

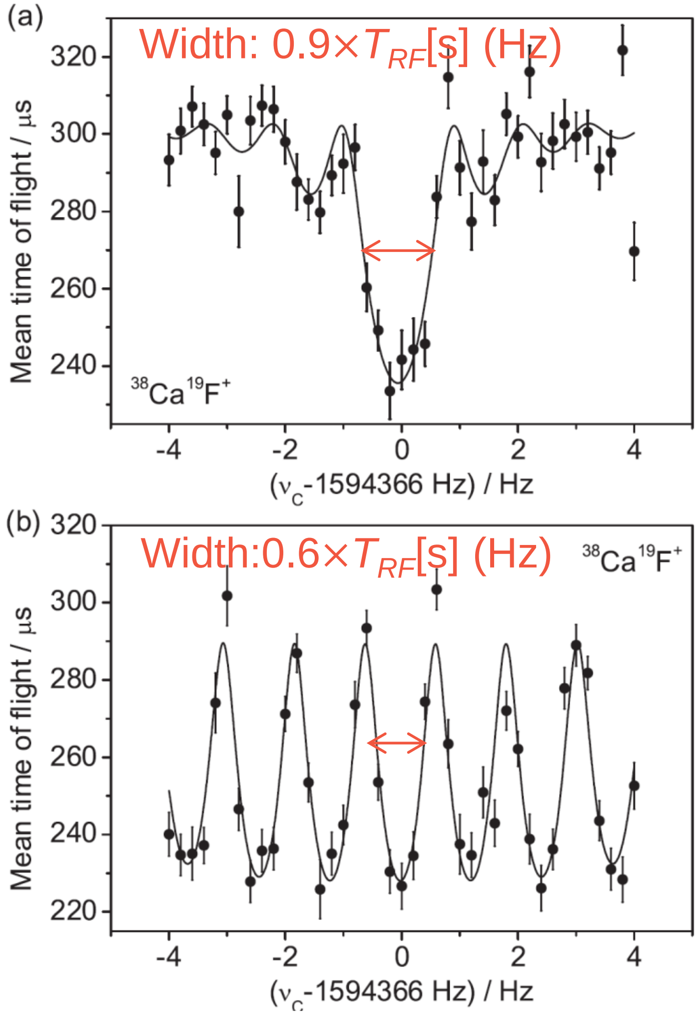
”Ramsey-type” excitation: higher precision with several deeper minima

George et al., PRL 98, 162501 (2007),
Int. J. Mass Spectrom. 264, 110 (2007).
M. Kretzschmar, Int. J. Mass Spectrom. 264, 122 (2007)



Conventional single-pulse excitation

”Ramsey-type” excitation pattern



Width: 0.9×T_{RF}[s] (Hz)

900 ms

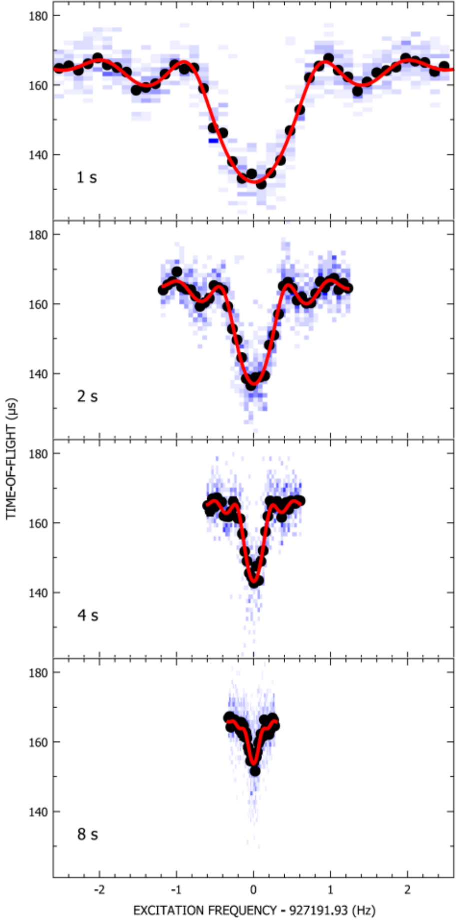
Width:0.6×T_{RF}[s] (Hz)

100 ms (On)
- 700 ms (Off)
-100 ms (On)

Precision depends on the excitation time

$$\Delta\nu(FWHM) \approx \frac{0.8}{T_{RF}}$$

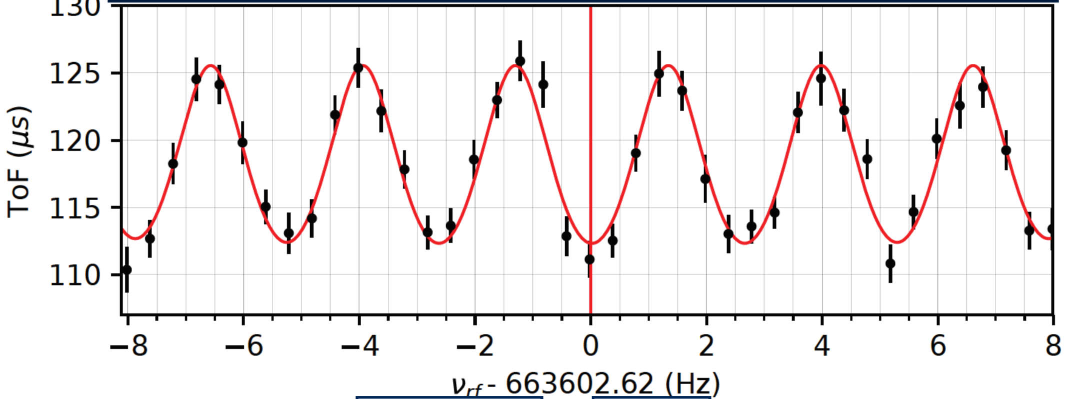
BETTER RESOLVING POWER

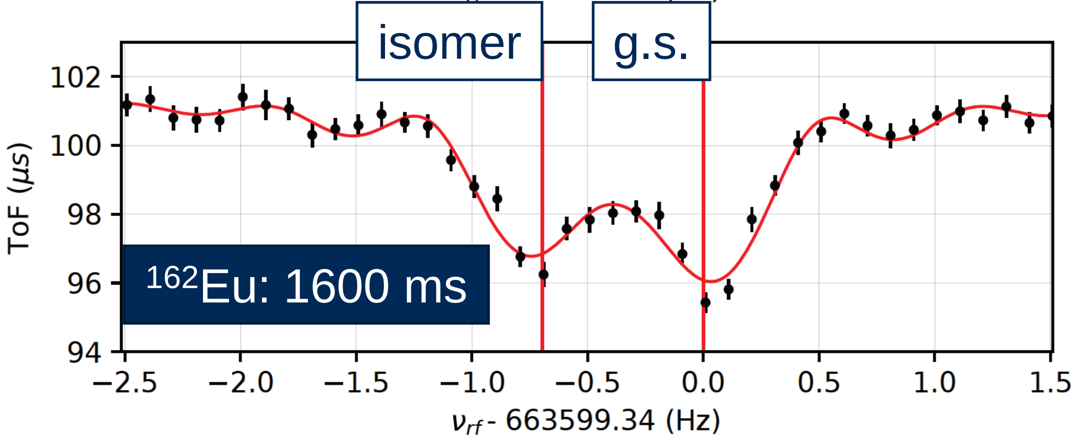


Eronen et al., *PPNP 91 (2016) 259*

Looks like a single state but is a mixture!

^{162}Eu: 25-350-25 ms (On-Off-On)





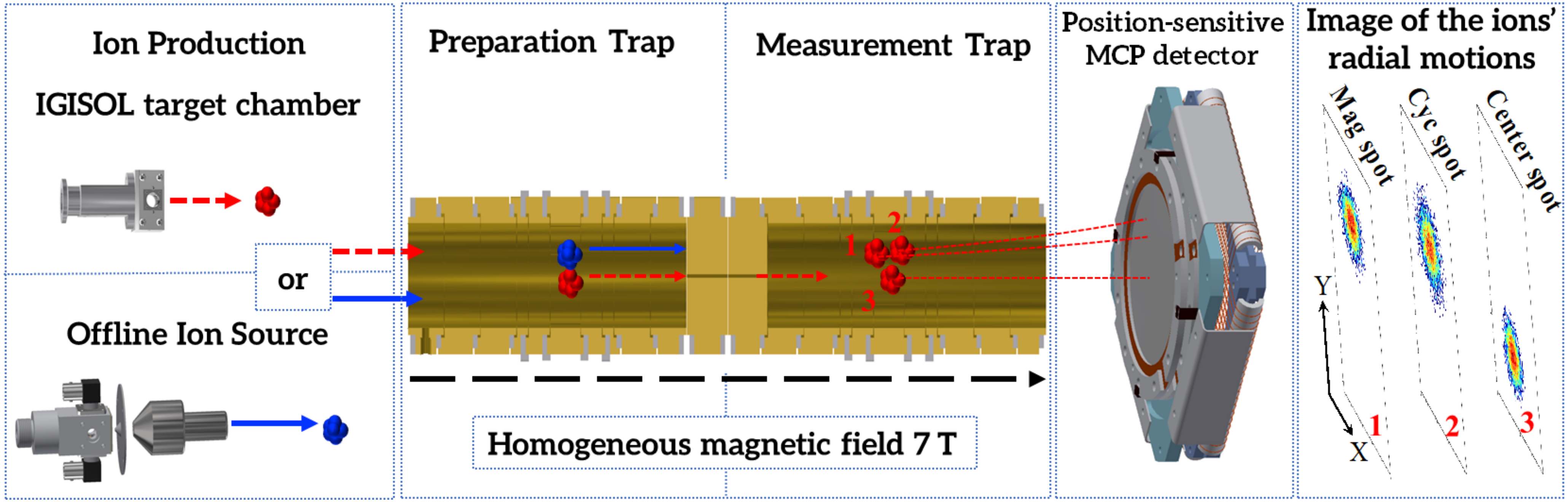
PI-ICR technique: motion projected on the detector (magnification)

Cyclotron frequency: $\nu_c = \nu_- + \nu_+ = \frac{1}{2\pi}\frac{qB}{m}$

Radial frequencies from their accumulated phases φ

in time t : $\nu_- = \frac{\varphi_- + 2\pi n_-}{2\pi t}$ and $\nu_+ = \frac{\varphi_+ + 2\pi n_+}{2\pi t}$

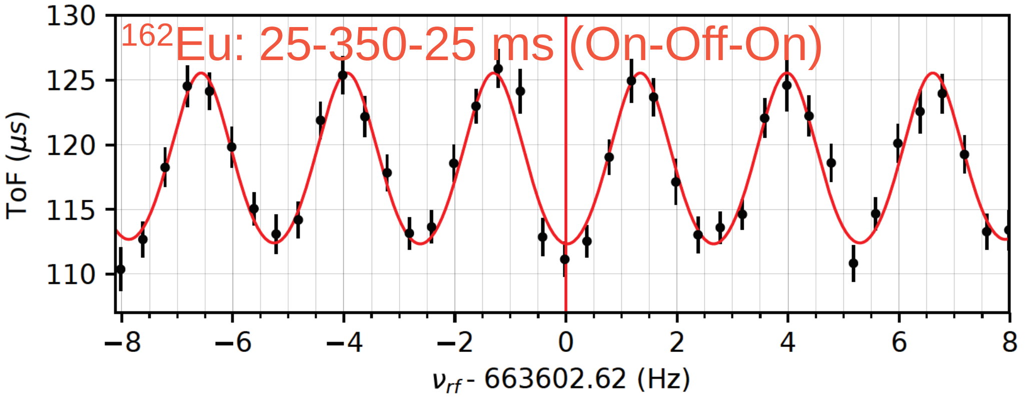
Every ion counts
Better precision than TOF-ICR
Higher resolving power than TOF-ICR

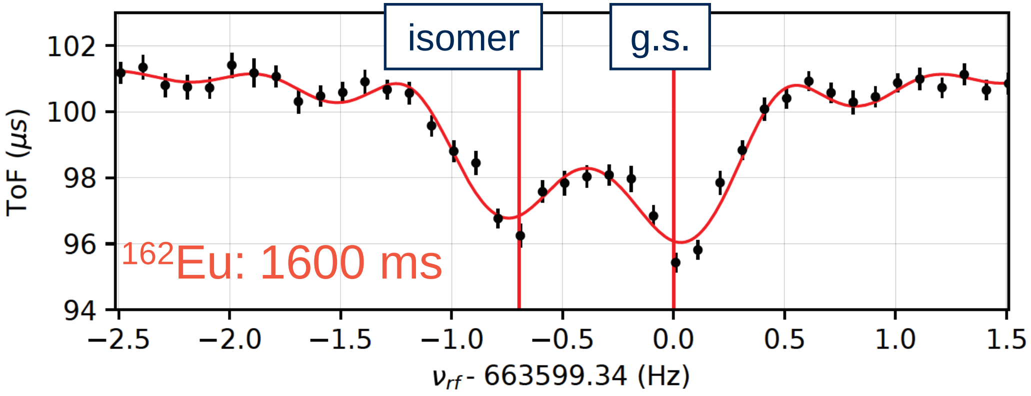


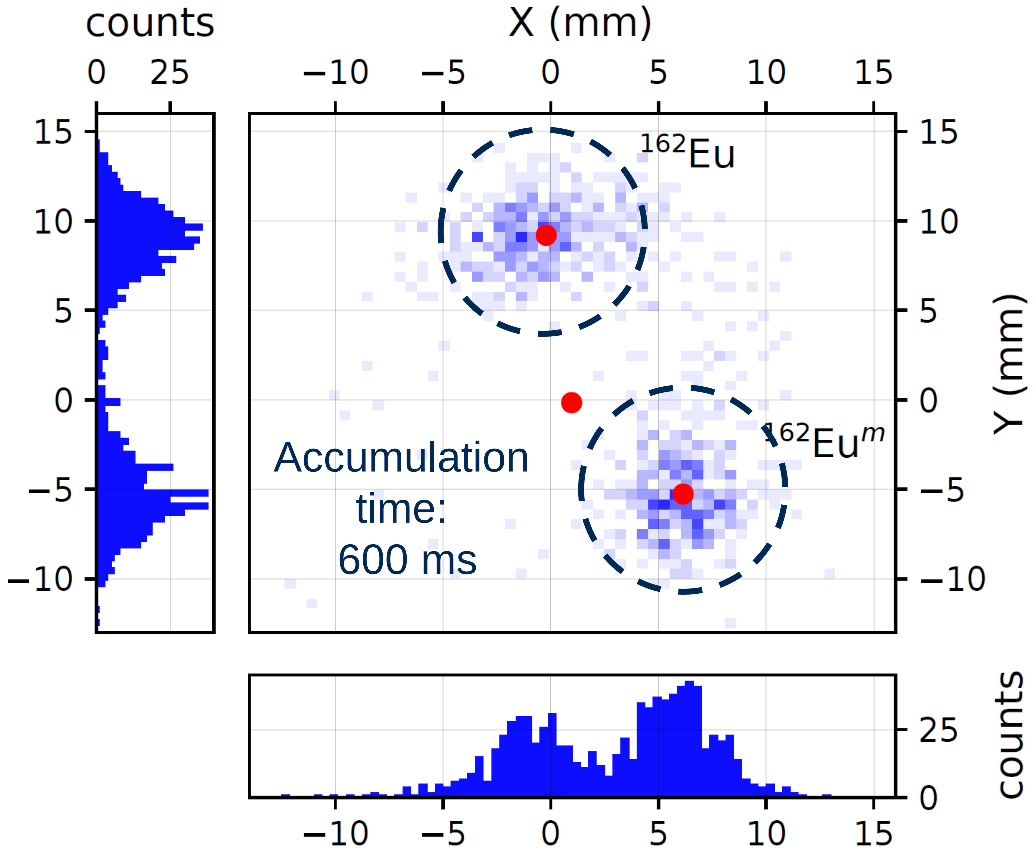
PI-ICR: S. Eliseev et al., PRL 110, 082501 (2013), Appl. Phys. B (2014) 114:107–128.
PI-ICR at JYFLTRAP: D.A. Nesterenko et al., Eur. Phys. J. A 54, 154 (2018); Eur. Phys. J. A 57, 302 (2021).

PI-ICR technique at JYFLTRAP

- Commissioned in 2018: D.A Nesterenko et al., EPJA 54 (2018) 154.
- Systematics studies: D.A: Nesterenko et al., EPJA 57 (2021) 302.







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

Reference ions for the magnetic field B

- Similar measurement done with a reference ion which is already known with a high precision
- Frequency ratio $r = \frac{\nu_c^{ref}}{\nu_c}$
- Typical reference ions:
  - $^{39}K^+$ (δm/m~1.3E-10)
  - $^{85,87}Rb^+$ (δm/m~5.9E-11)
  - $^{133}Cs^+$ (δm/m~6.8E-11)
  - Ideally: ^{12}C or its clusters!

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

mass

$$\boxed{m = \frac{\nu_c^{ref}}{\nu_c}\left(m_{ref} - m_e\right) + m_e}$$

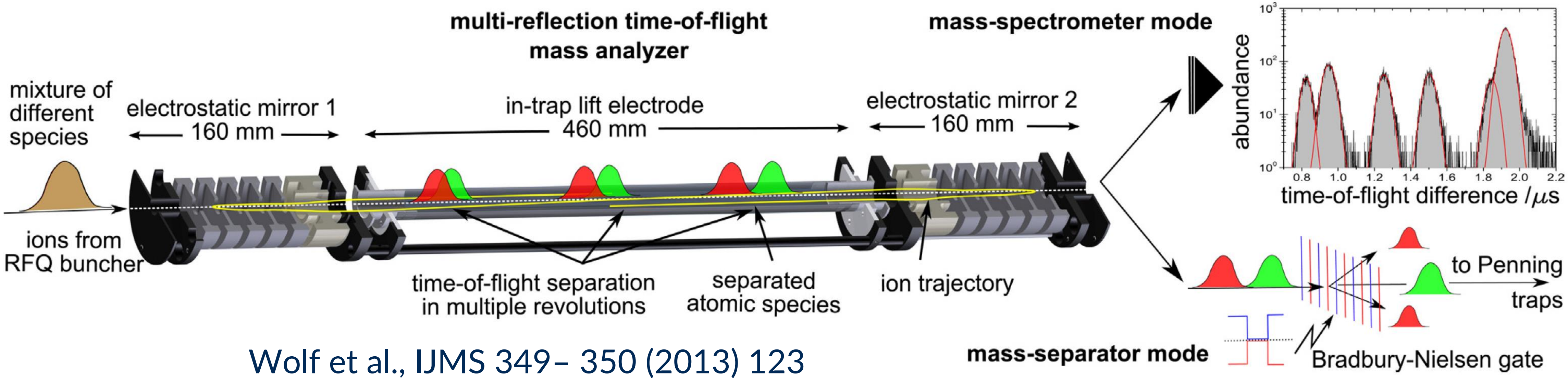
Multi-Reflection Time-of-Flight Mass Separator/Spectrometer (MR-TOF)

- Idea: Wollnik and Przewloka, Int. J. Mass. Spectrom. Ion Proc. 96 (1990) 267

$$\boxed{E_{kin} = qV = \frac{1}{2}mv^2}$$

same flight path →

$$\boxed{t_{obs} = a\sqrt{\frac{m}{q}} + b}$$



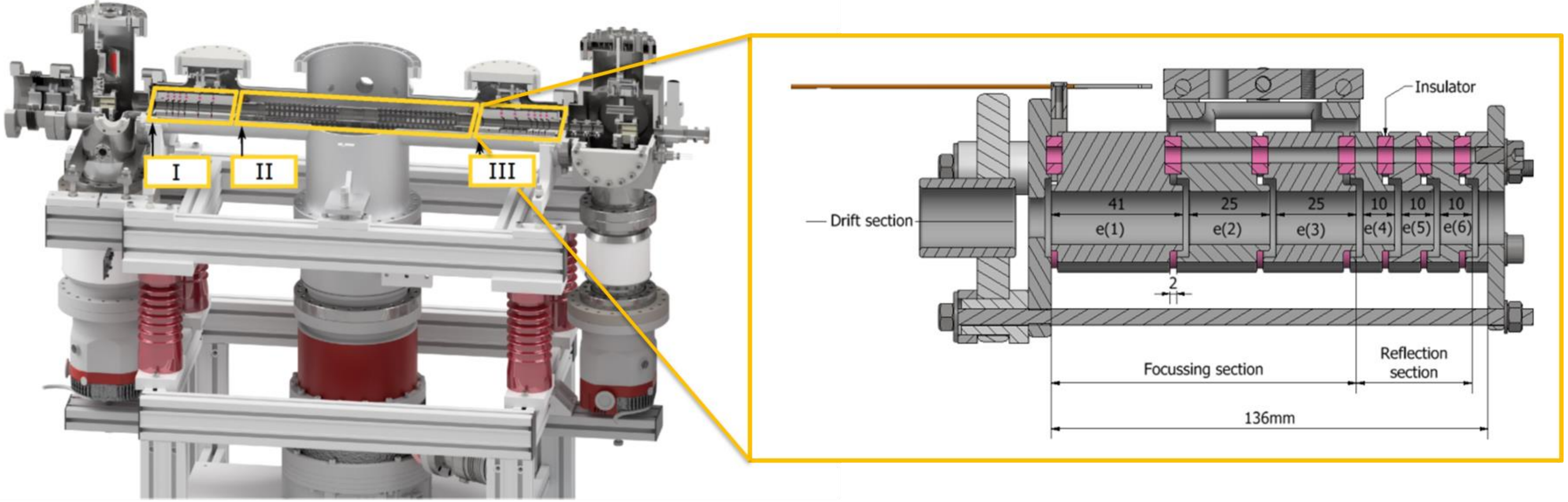
Wolf et al., IJMS 349– 350 (2013) 123

MR-TOF at IGISOL

- Mirror electrodes (I and III)
- Drift tube (II)
- Mass resolving power

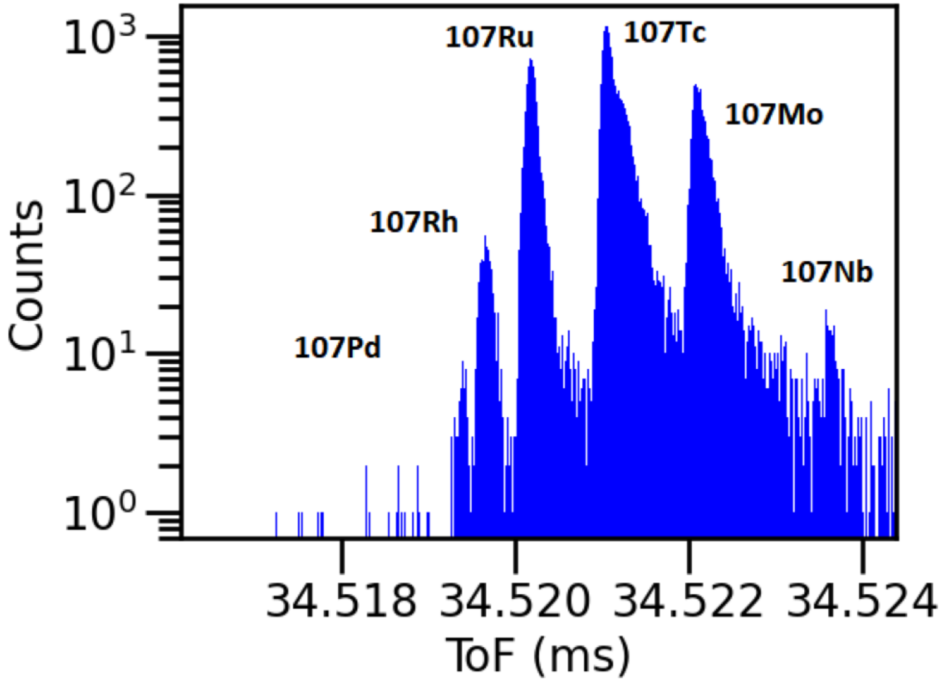
$$R = \frac{m}{\Delta m} = \frac{t}{2\Delta t} \sim 200\,000$$

- Located after RFQ cooler-buncher, before JYFLTRAP
- Fast beam purification for mass measurements and decay spectroscopy
- Fast mass measurements with MR-TOF



MR-TOF: online commissioning 2022

- Fission fragments at A=107



V. Virtanen, PhD thesis work

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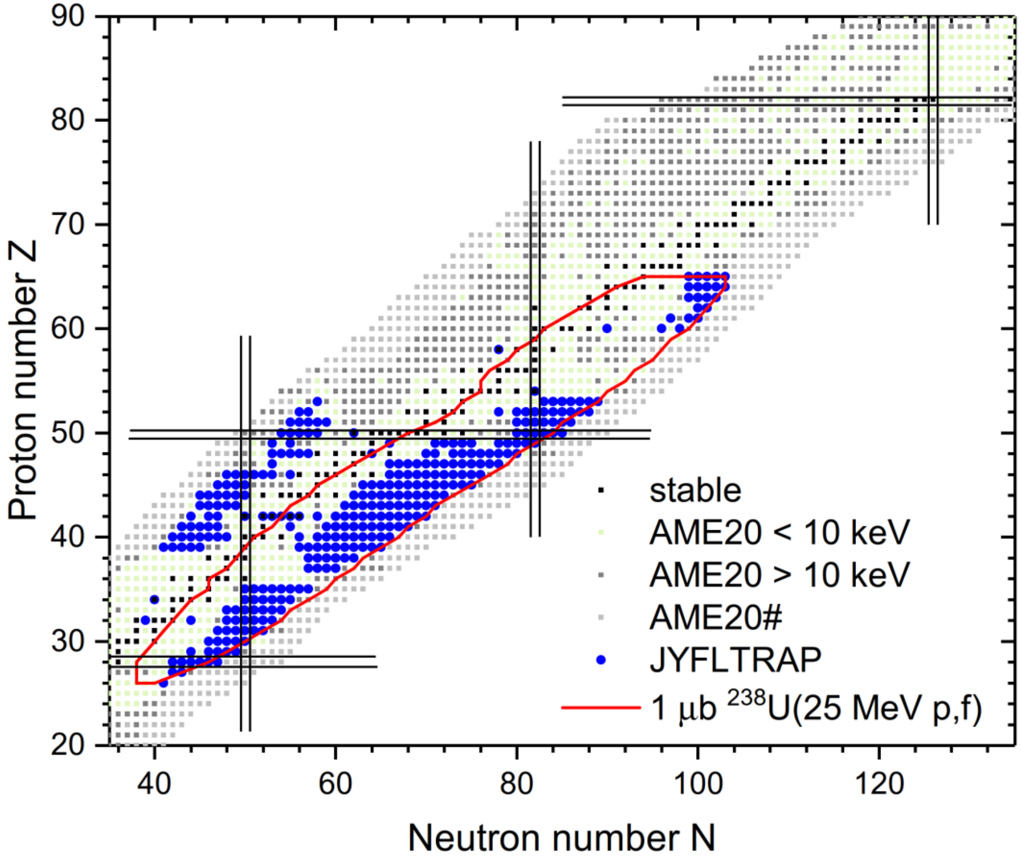
Results of mass measurements at JYFLTRAP

JYFLTRAP mass measurements



- Around 400 atomic masses measured, including more than 50 isomeric states
- Precisions in mass-excess values typically < 10 keV

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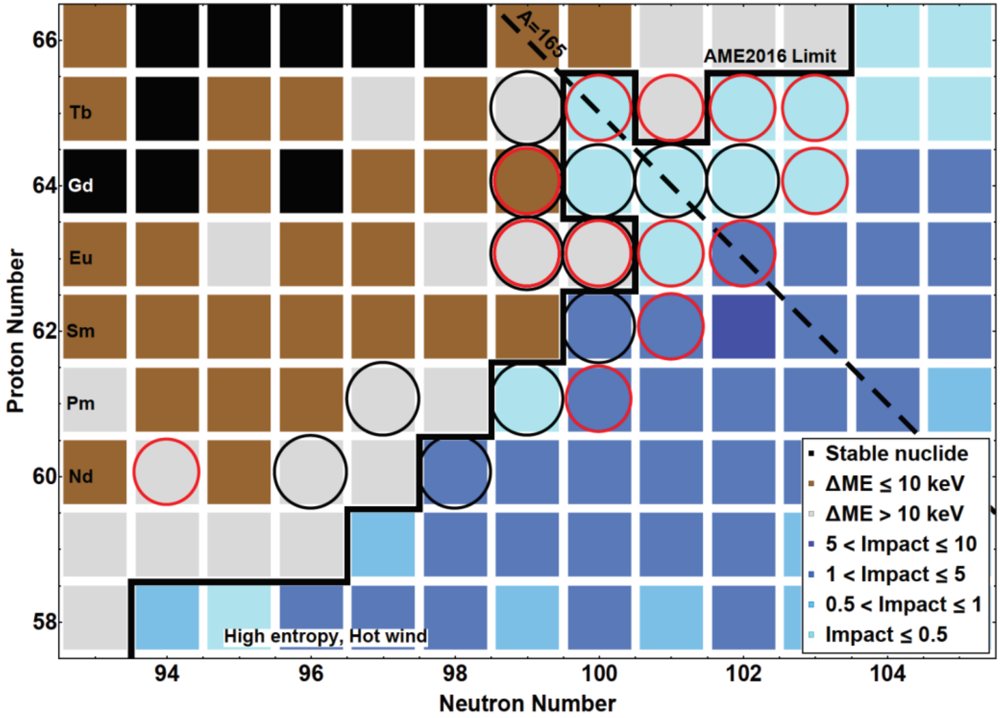
Neutron-rich rare-earth isotopes

Mass measurements in the rare-earth region

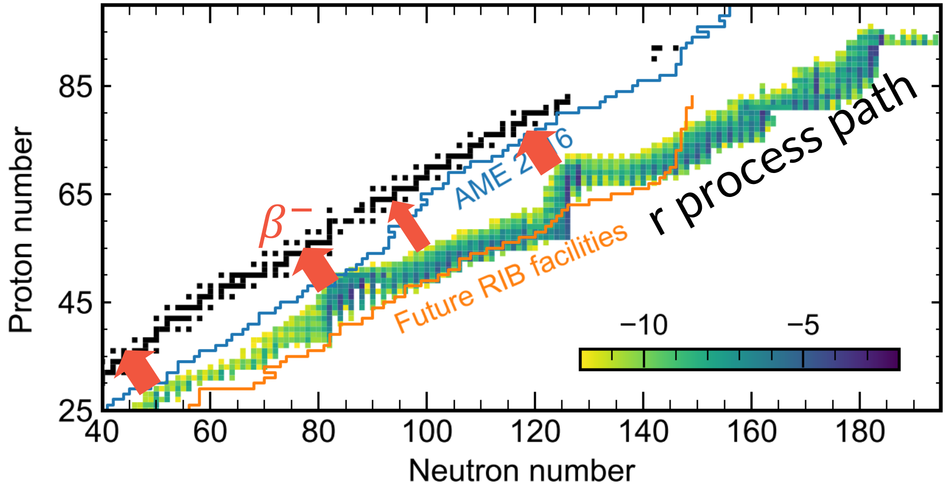
- Two measurement campaigns at IGISOL
- With JYFLTRAP, measured masses for:
  - 22 ground states
  - 2 isomers
- 14 cases measured for the first time



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

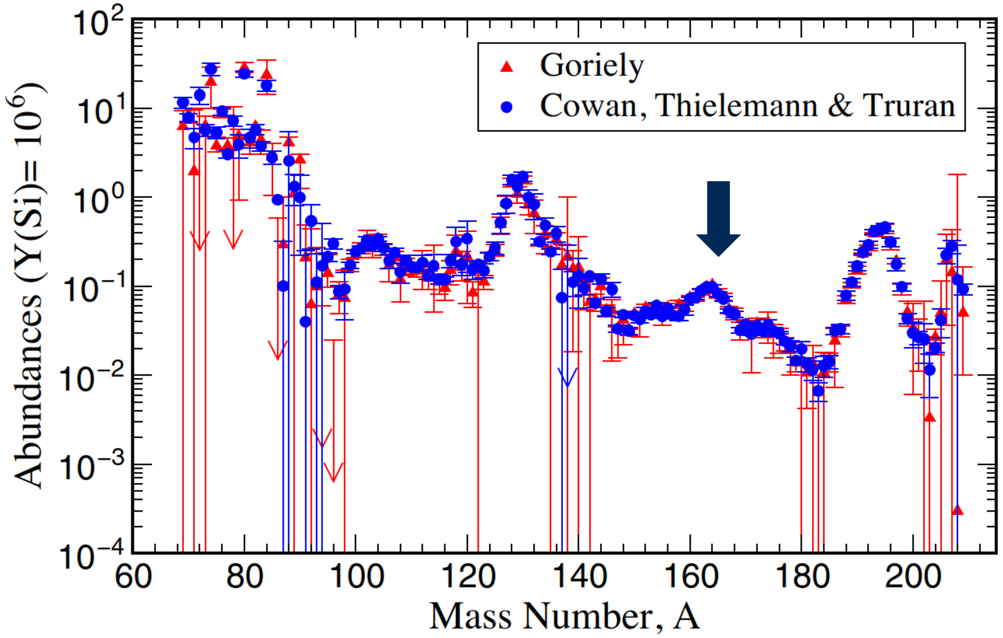
Motivation: rare-earth abundance peak in the r process

- Rapid neutron capture process (r process):
  - proceeds far from stability via neutron captures and beta decays
  - eventually beta decay to stable nuclides
  - nuclear masses a key input



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

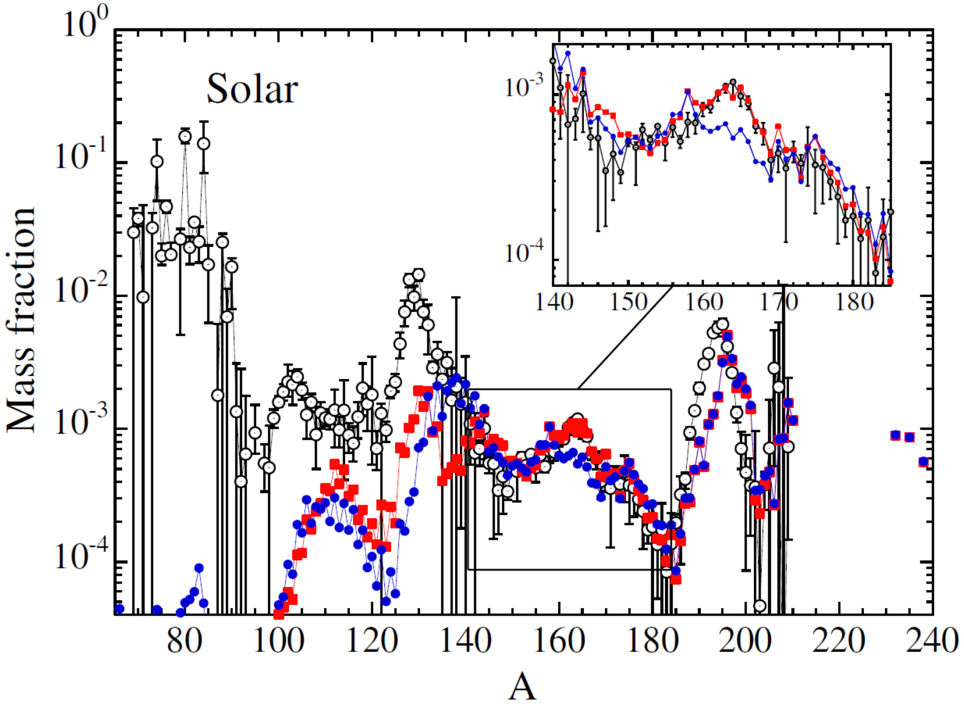
- Main abundance peaks at A~80, 130, 195
  - Related to closed neutron shells at N=50, 82 and 126
- Smaller rare-earth abundance peak at A~165



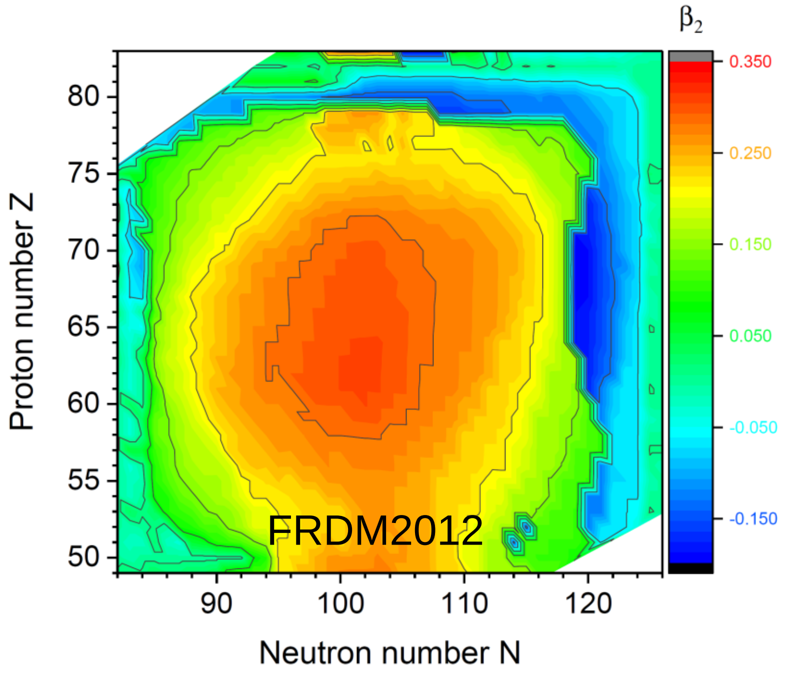
Cowan et al., Rev. Mod. Phys. 93 (2021) 015002

Origin of the rare-earth abundance peak?

- Fission cycling with doubly asymmetric fission model (SPY)?
  - Goriely et al., PRL 111 (2013) 242502



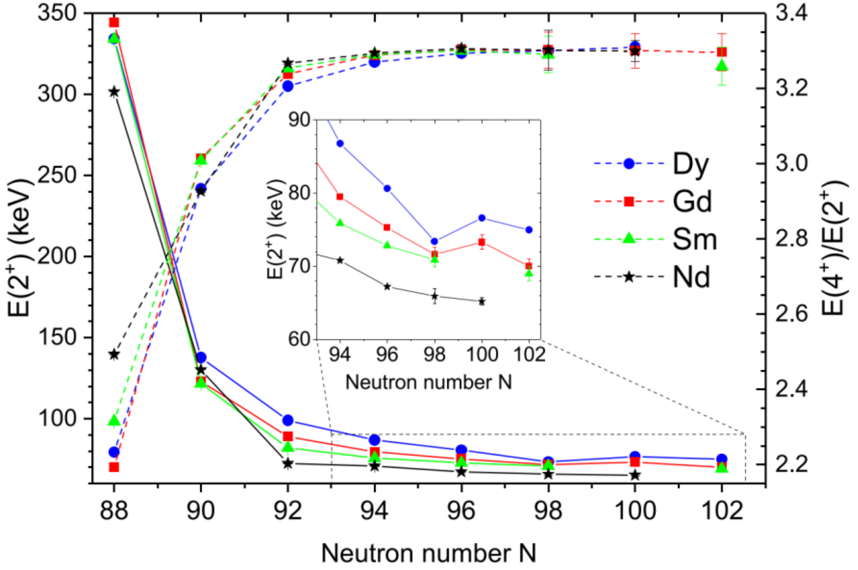
- Deformation funneling the flow toward stability?
  - Surman et al., PRL 79 (1997) 1809; Mumpower et al., PRC 85 (2012) 045801; PPNP 86 (2016) 86

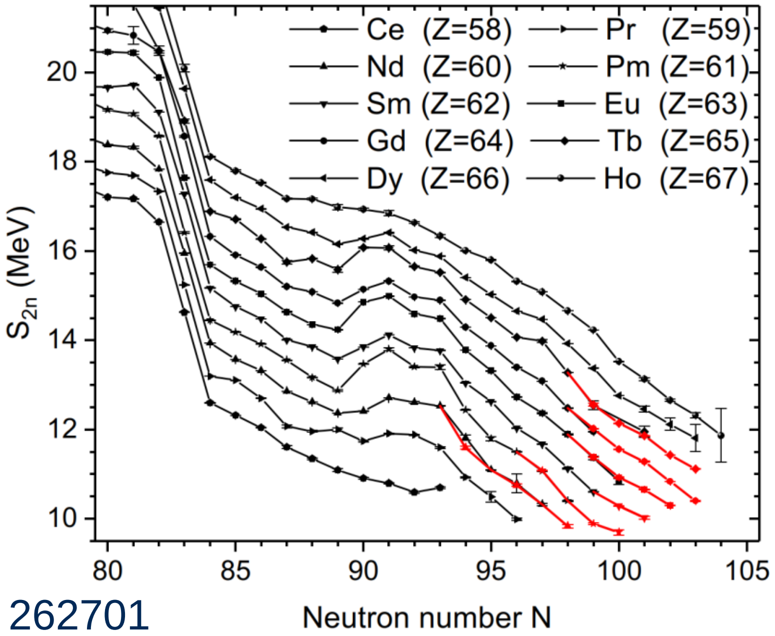


Nuclear structure

- Earlier work (gamma spectroscopy):
  - Onset of deformation at N~89
  - Decrease in 2^+ excitation energies
  - $E(4^+)/E(2^+)$ ratio increases→ rigid rotor
  - Small kink at N=100→ subshell closure?

- Is this seen in two-neutron separation energies?
  - Onset of deformation at N~89? Yes.
  - Small kink at N~100? No clear change.





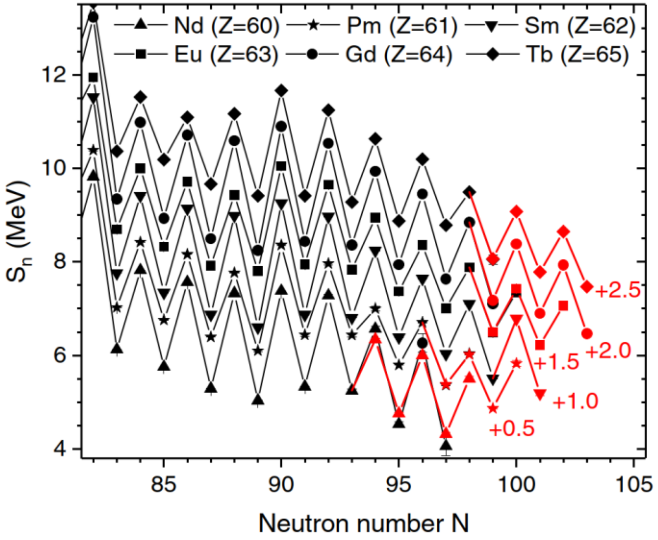
RED:
JYFLTRAP

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

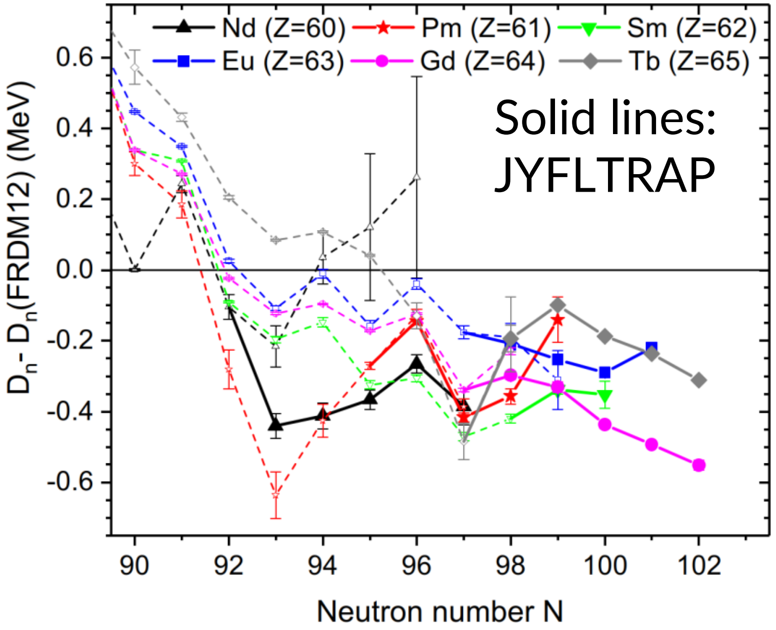
Reduced neutron pairing

- Odd-even staggering in neutron separation energies
- Neutron pairing energy metric

$D_n(N) = (-1)^{N+1}[S_n(Z,N+1) - S_n(Z,N)] = 2\Delta^3(N)$



Neutron pairing gets weaker than predicted by FRDM12 (and other theoretical models) when moving toward the midshell at N=104

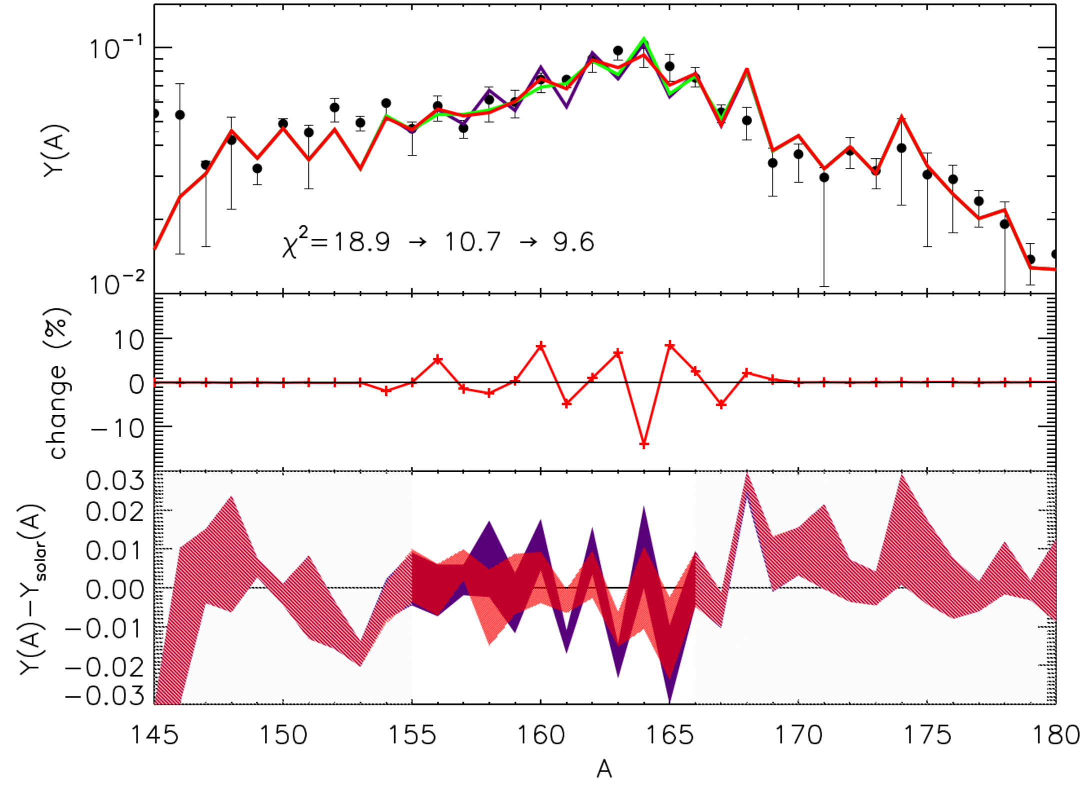


M. Vilén et al., PRC 101 (2020) 034312

Impact on the r-process calculations

- Assumed:
  - Merger with two 1.35Msolar neutron stars
  - Y_e = 0.016, initial $s/k_B \sim 8$
- Changes up to 25% observed!
- 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

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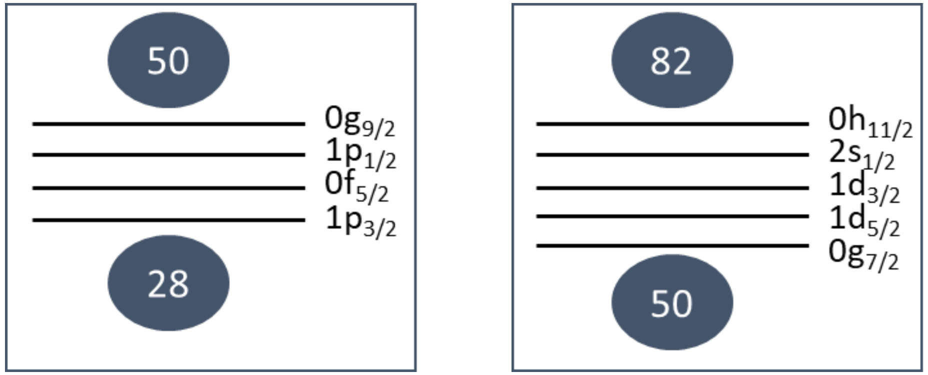
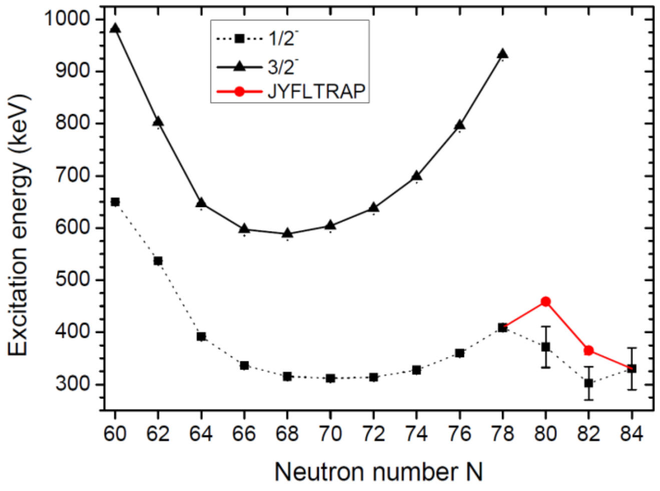
Isomeric states in ^{128}In and ^{130}In

Neutron-rich indium (Z=49) isotopes

- Isomeric states very common in indium isotopes
  - High- and low-j shells
  - Ideal for testing e.g. shell-model predictions
  - Relevance for the r process



- Earlier studies on odd-A In at JYFLTRAP:
  - $1/2^-$ isomers in ^{129,131}In (proton hole in the $1p_{1/2}$ shell)

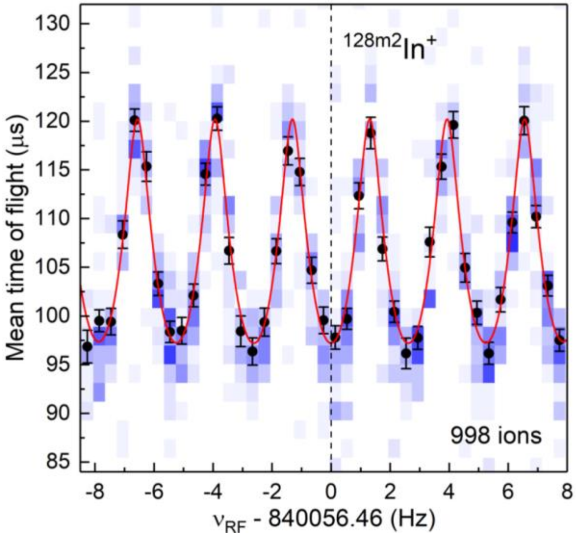


A. Kankainen et al., PRC 87, 024307 (2013)

Odd-odd indium isotopes

- More complicated than the odd-A isotopes
- Campaign of measurements at JYFLTRAP during the recent years
- 30 MeV protons + natural uranium target at IGISOL
- Here: focus on ^{128}In and ^{130}In

- **^{128}In: measured at JYFLTRAP:**
  - Ground state (3)+
  - First isomeric state (8-) at 285.1(25) keV
  - New isomeric state at 1797.6(20) keV!



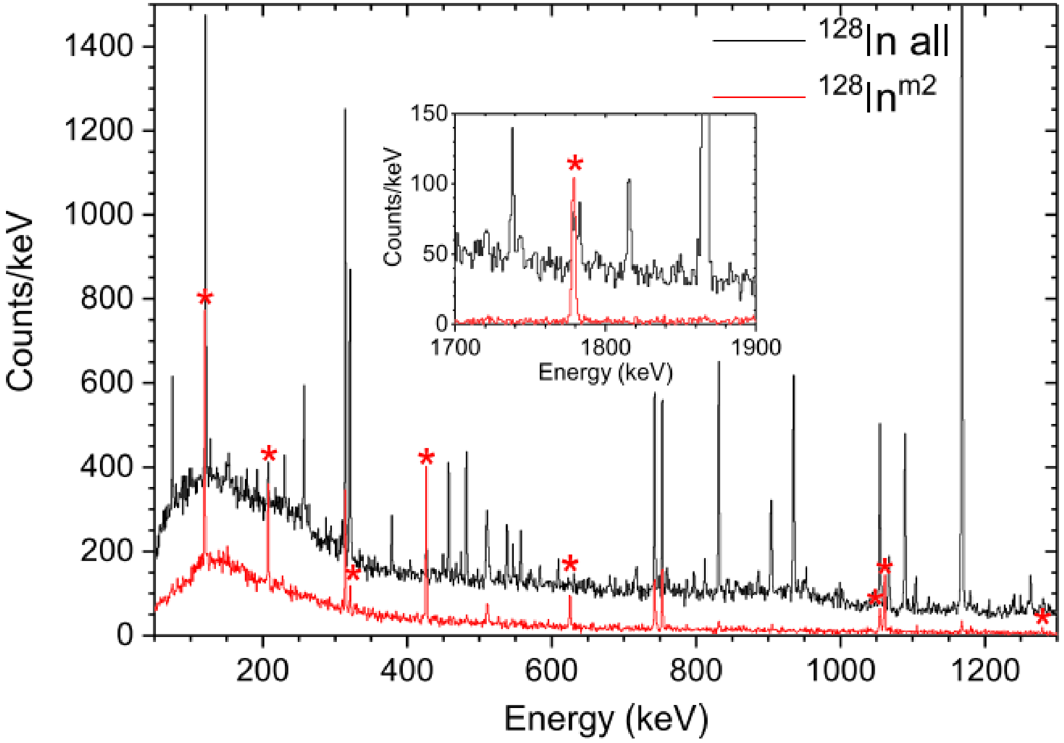
D.A. Nesterenko et al., Phys. Lett. B 808, 135642 (2020)

What is this new isomer? Post-trap decay spectroscopy

- Selected the isomeric-state ions to the post-trap decay spectroscopy station (scintillator, two coaxial Ge and a BeGE)
- Spectrum collected by selecting the new isomer (in red):
  - the new isomer has to populate the (15^-) 220(30) ns isomer in ^{128}Sn either directly or indirectly

    Pietri et al., Phys. Rev. C 83 (2011) 044328;
    Iskra et al., Phys. Rev. C 89 (2014) 044324
- Half-life not determined but estimated to be longer than 300 ms based on the length of the used trap cycle

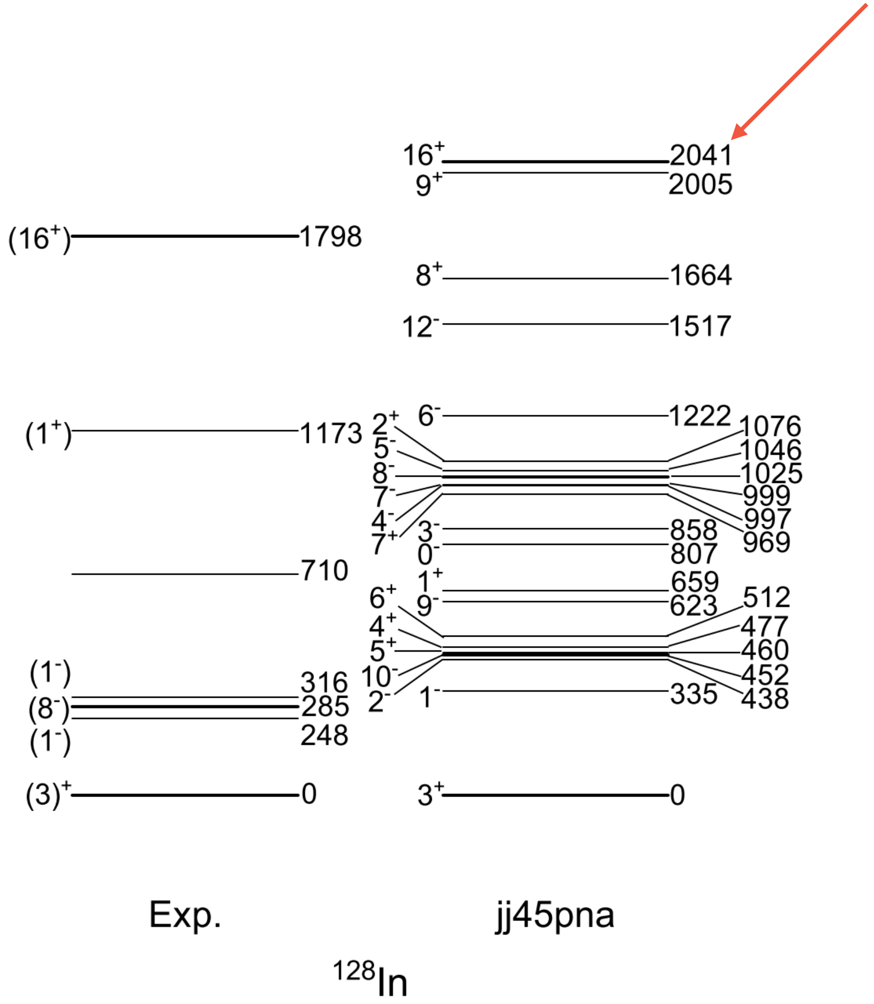
Beta-gated gamma spectrum



D.A. Nesterenko et al., Phys. Lett. B 808, 135642 (2020)

Shell-model calculations for $^{128}\mathrm{In}^{m2}$

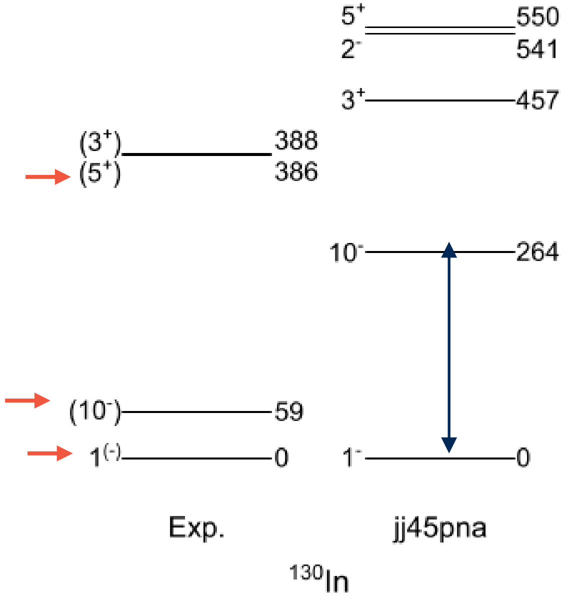
- Valence space:
  protons: $1p_{3/2}$, $0f_{5/2}$, $1p_{1/2}$, $0g_{9/2}$,
  neutrons: $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$, $0h_{11/2}$
- NuShellX@MSU
- Effective interaction jj45pna
- Shell-model predicts that the new isomer is 16^+
  - No other spin-trap states at around 2 MeV
  - 92% $\left(\pi 0g_{9/2}\right)^{-1} \otimes \left(\nu 1d_{3/2}^{-1} 0h_{11/2}^{-2}\right)$
- Systematics of isomers in N=79 isotones ^{129}Sn, ^{130}Sb and ^{131}Te also supports the assignment

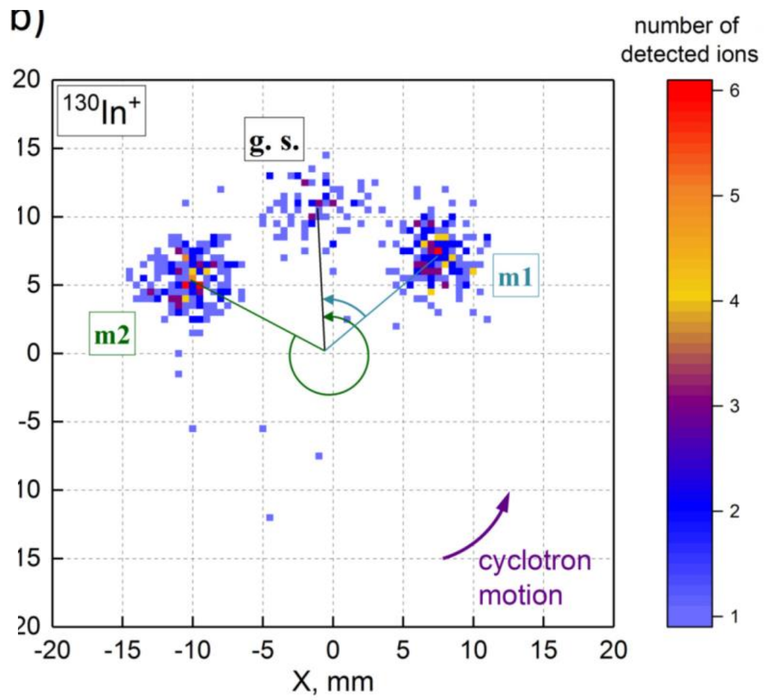


D.A. Nesterenko et al., Phys. Lett. B 808, 135642 (2020)

Isomeric states in ^{130}In (Z=49, N=81)

- $1^{(-)}$ ground state: 47(22) keV lower than in Babcock et al., Phys. Rev. C 97 (2018) 024312
  - $(\pi 0g_{9/2}^{-1}) \otimes (\nu 0h_{11/2}^{-1}) \approx$ 80%, $(\pi p_{3/2}^{-1}) \otimes (\nu 1d_{5/2}^{-1}) \approx$ 8%, and $(\pi 1p_{1/2}^{-1}) \otimes (\nu 2s_{1/2}^{-1}) \approx$ 6%
- 10^- isomer at 59(9) keV:
  - $(\pi 0g_{9/2}^{-1}) \otimes (\nu 0h_{11/2}^{-1})$
  - Shell model predicts a much higher energy
- (5^+) isomer at 385.5(50) keV:
  - confirmed to be below the (3+) state at 388.3(2) keV





D.A. Nesterenko et al., Phys. Lett. B 808, 135642 (2020)

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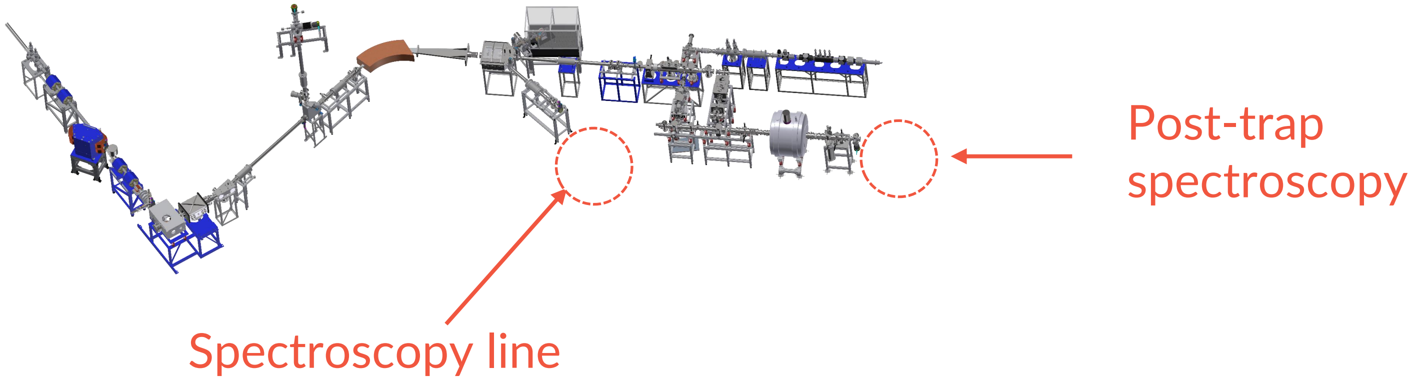
Decay spectroscopy at IGISOL

Decay spectroscopy at IGISOL

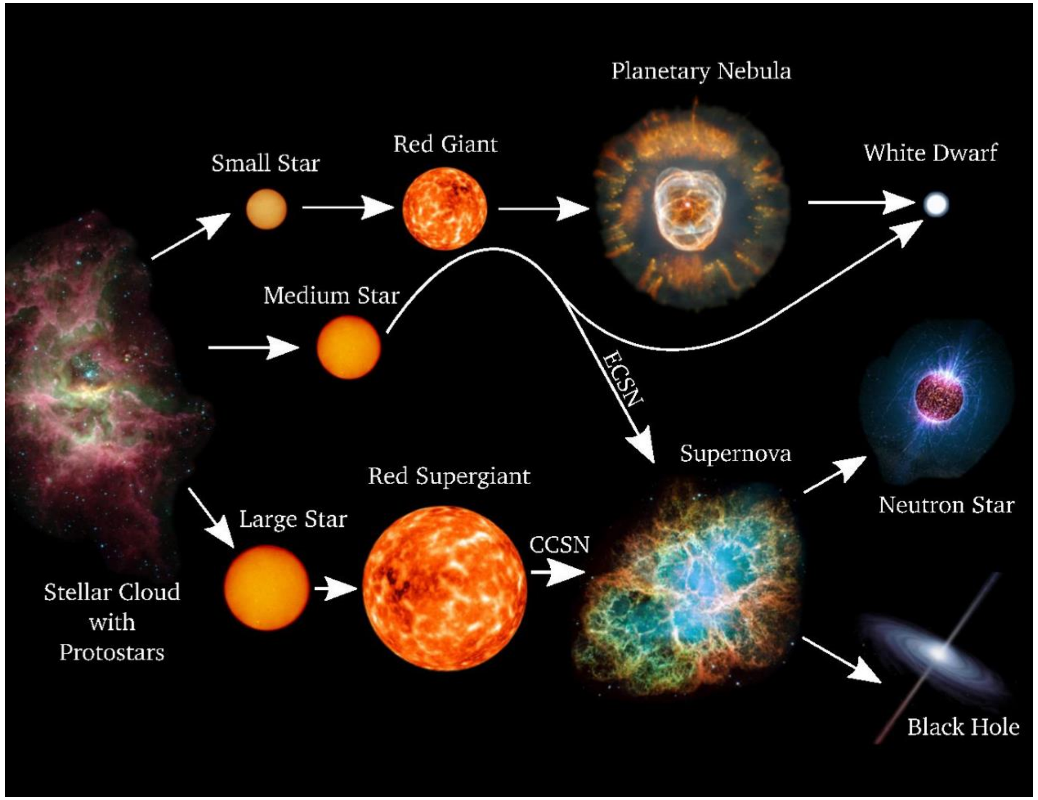
- Spectroscopy line
  - Continuous beam
  - Mass number A (mass-to-charge ratio m/q, mainly singly charged ions)

- Post-trap spectroscopy
  - Ion bunches extracted every ~100 ms
  - Isotopically or even isomerically pure beams



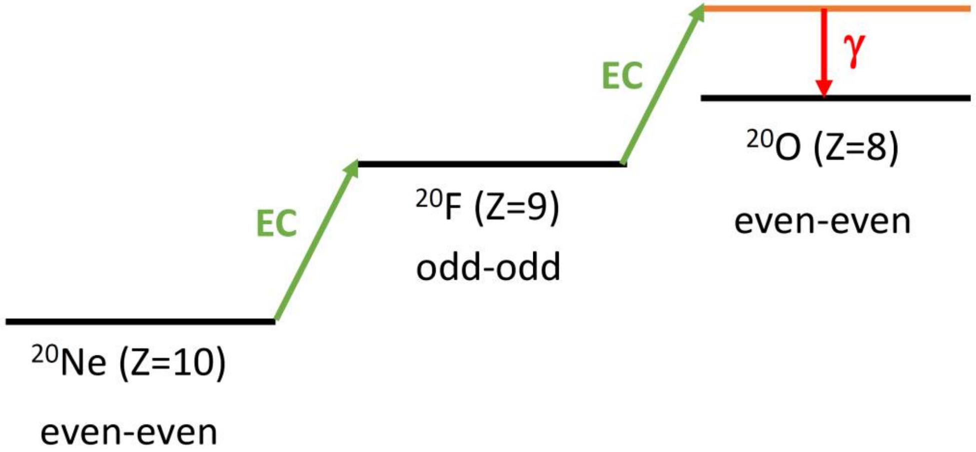
Beta decay of ^{20}F at the spectroscopy line

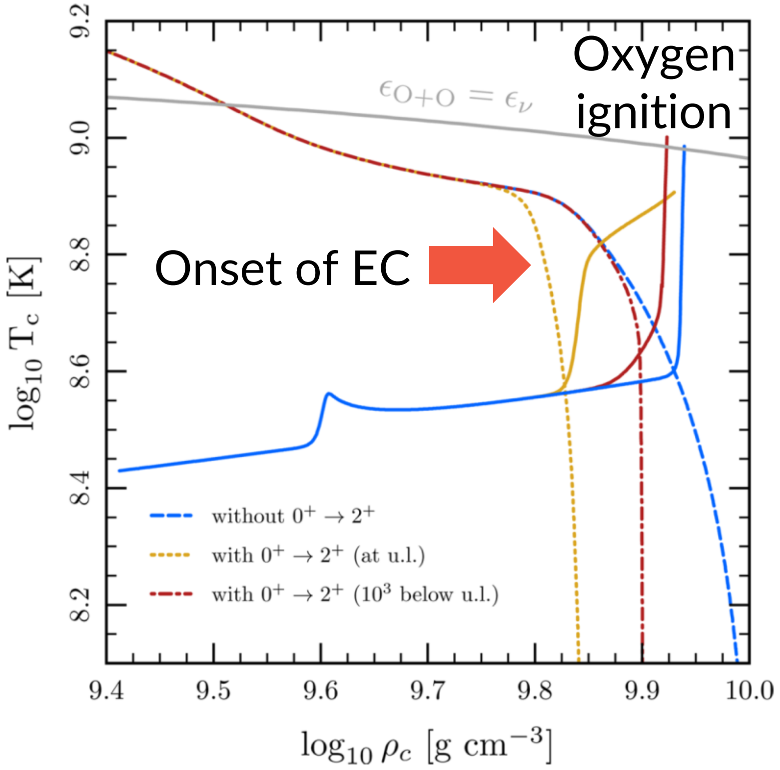
- Motivation: fate of intermediate-mas stars (8-10 solar masses):
  - Thermonuclear explosion or electron-capture supernova?
- The birth and death rate of intermediate-mass stars similar to the rate of all stars heavier than 10 solar masses
  - contribution to the galactic chemical evolution potentially significant



Electron captures on ^{20}Ne crucial

- Study EC on ^{20}Ne via its inverse reaction, beta decay of ^{20}F!

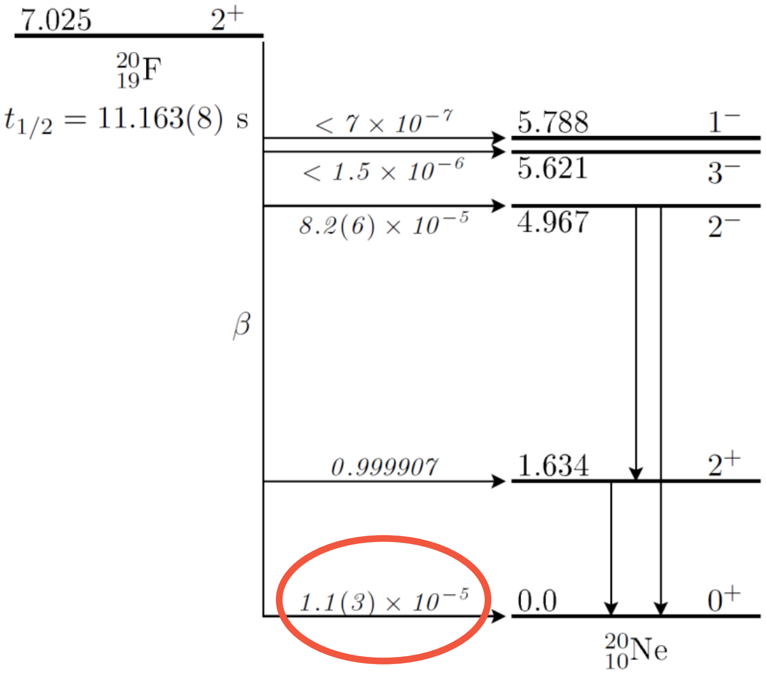




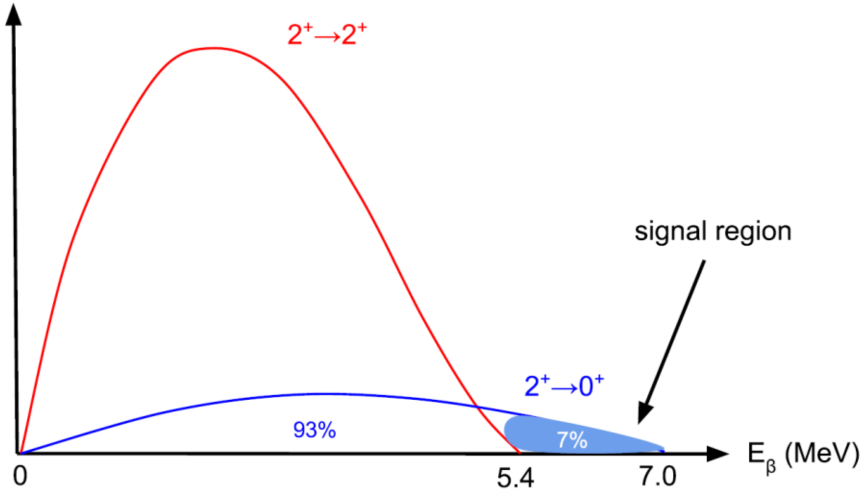
*J. Schwab et al., MNRAS **453**, 1910–1927 (2015)*

Study via inverse reaction: beta decay of ^{20}F

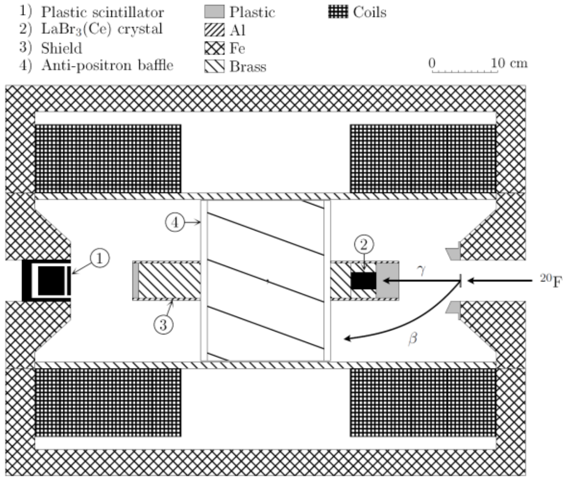
- Challenge: ground-state to ground-state beta decay second-forbidden non-unique
  - Previously: only an experimental upper limit: Calaprice & Alburger: PRC 17 (1978) 730



- How to avoid beta-gamma summing?



First measurement at IGISOL

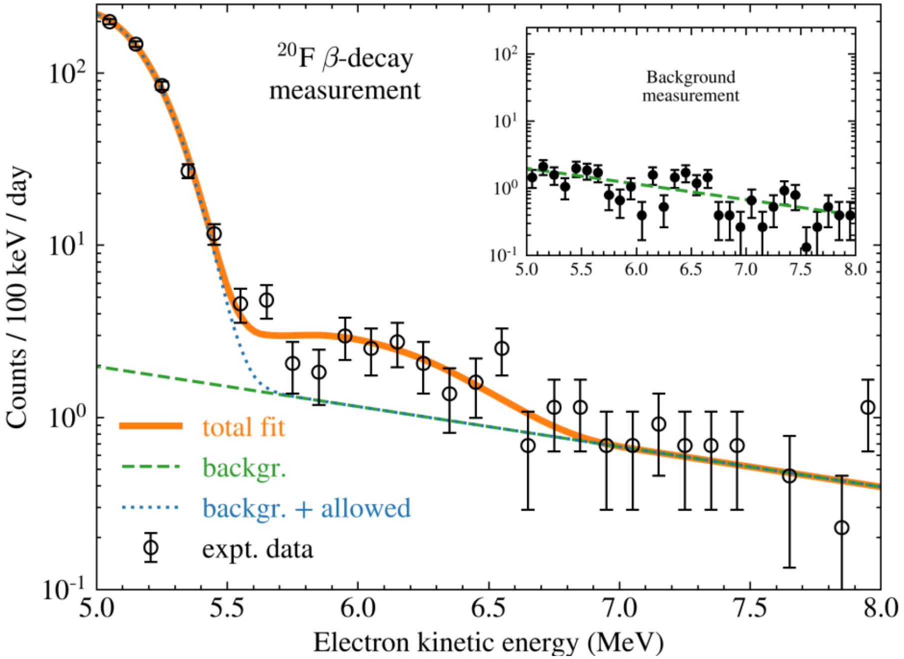


O.S. Kirsebom, M. Hukkanen, A. Kankainen et al., Phys. Rev. C 100, 065805 (2019)

- ^{19}F(d,p)^{20}F reaction with 6 MeV d at IGISOL
- ~11 kHz implantation rate
- Scionix plastic scintillator for electrons
- $LaBr_3$ for detecting 1.6 MeV gammas (normalization)
- Magnetic electron transporter to guide the electrons (β^- particles)→ avoid $\beta-\gamma$ summing

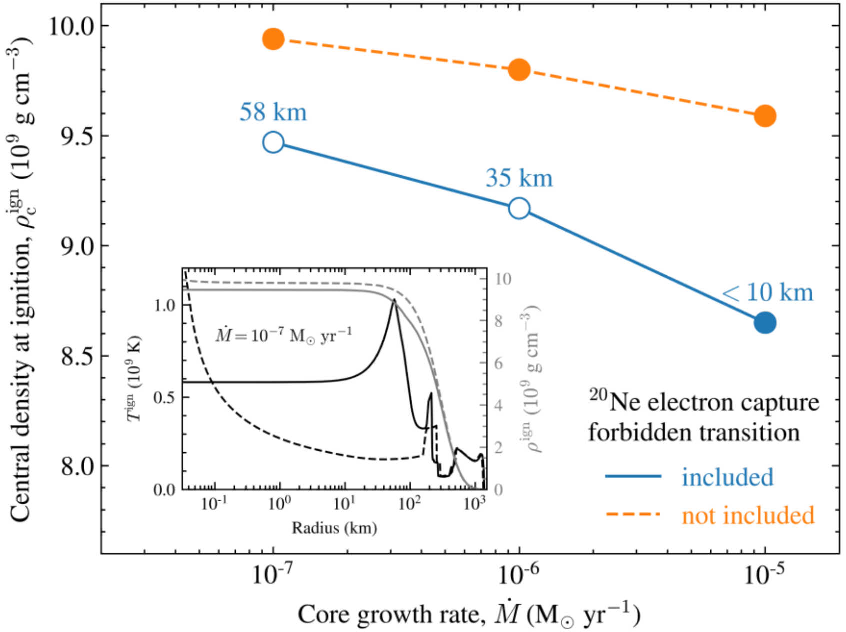
Result

- Beta-decay branch [0.41(11)× 10^{-5}] and transition strength [log ft=10.89(11)] exceptionally large



O. Kirsebom et al., PRL 123 (2019) 262701

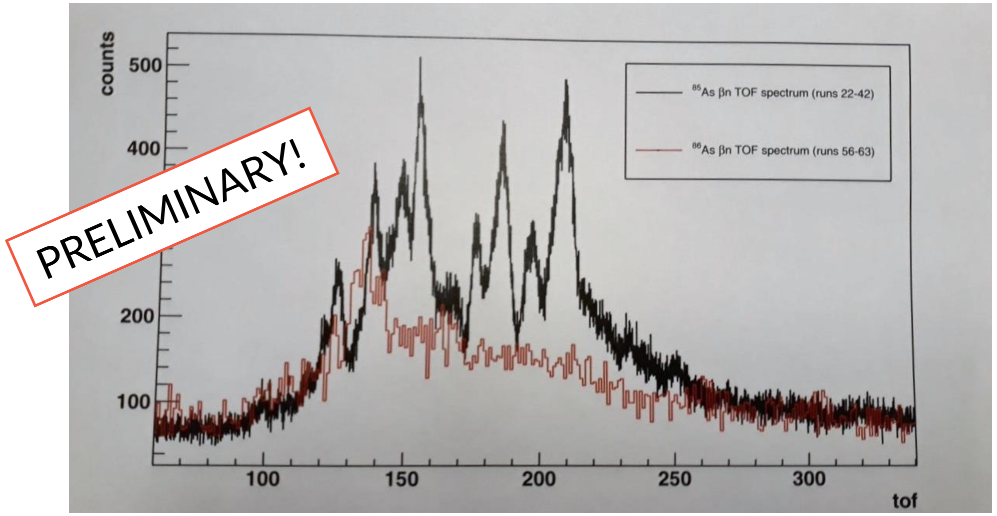
- Star is (partially) disrupted by a thermonuclear explosion rather than collapsing to form a neutron star



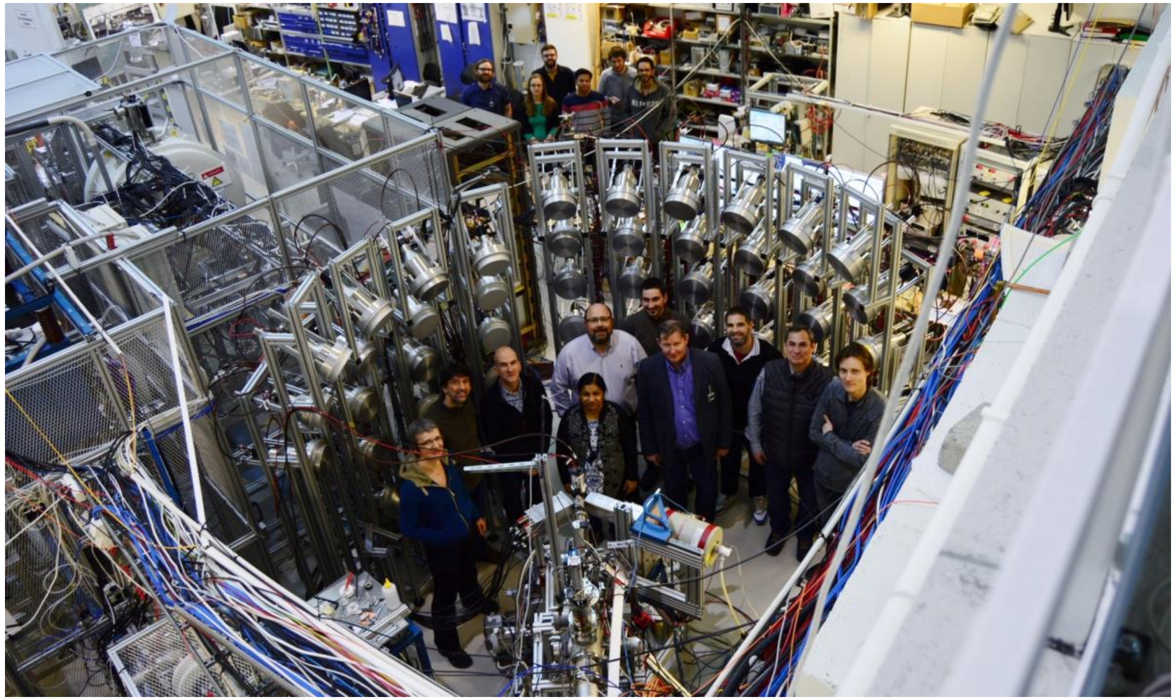
O. Kirsebom et al., PRL 123 (2019) 262701

Beta-delayed neutrons with MONSTER at spectrosopy line

- MONSTER designed for HISPEC/DESPEC experiment of NUSTAR@FAIR
- Commissioning at IGISOL March 2019 with beta decays of ^{85,86}As
- 48 liquid scintillator detector modules (full version 100 modules)

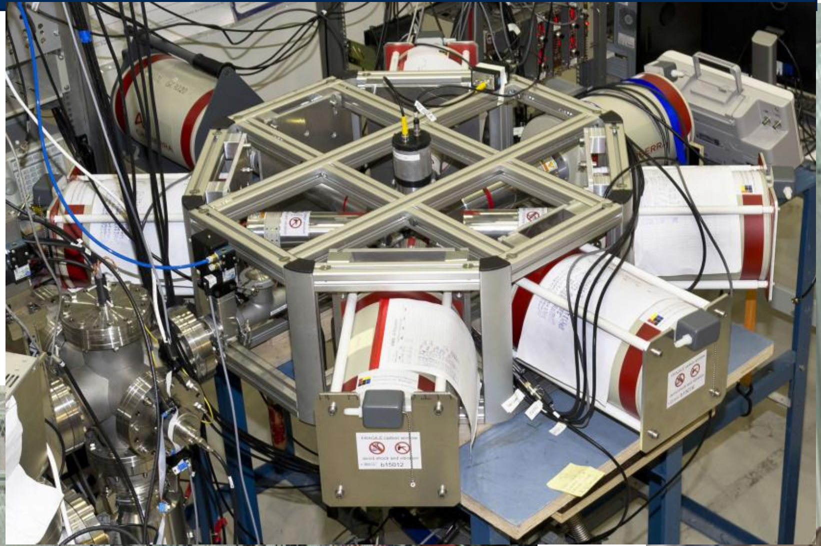


PRELIMINARY!

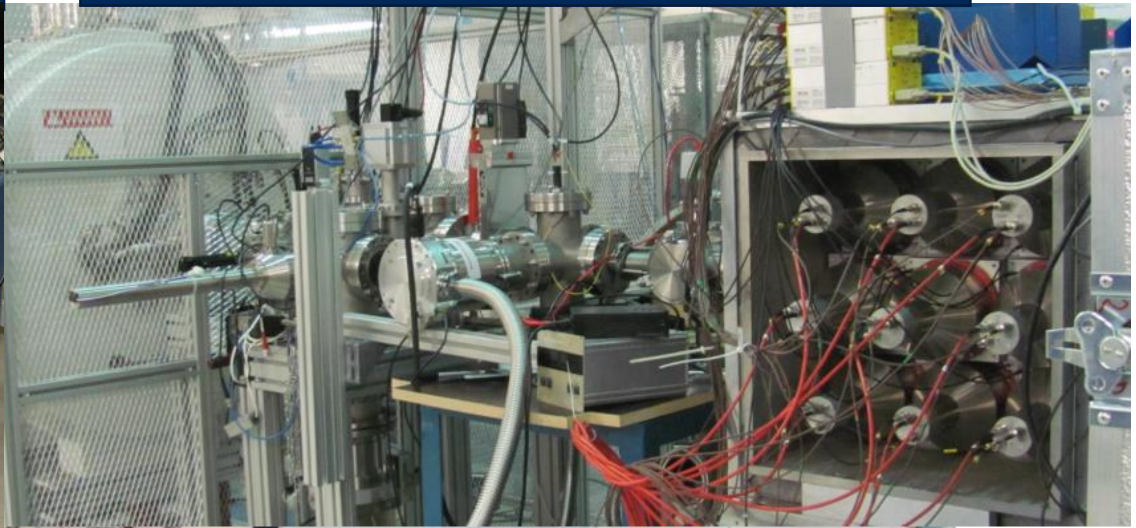


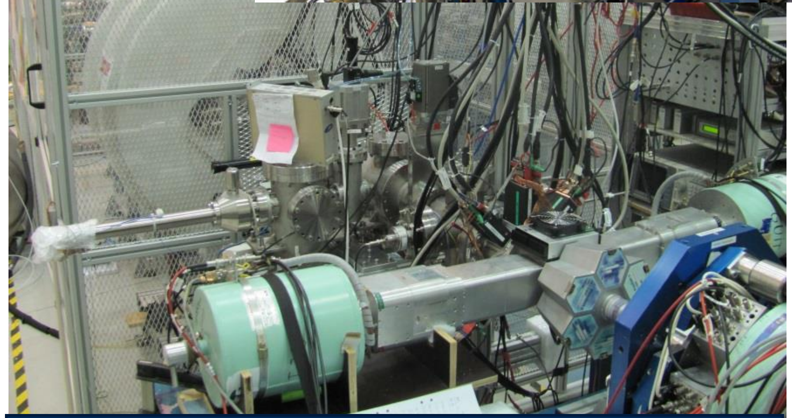
Post-trap decay spectroscopy at IGISOL

BEGE array (University of Warsaw)



DTAS (total absorption decay spectroscopy)



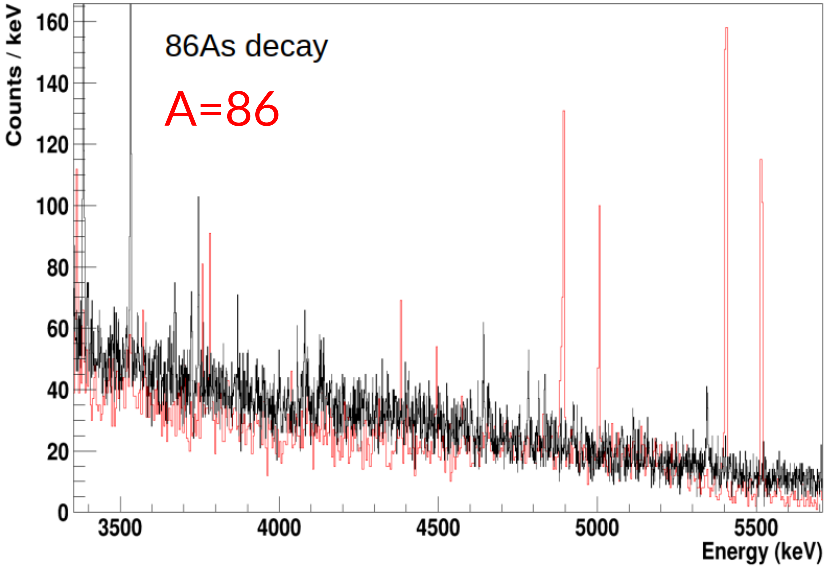


TASISpec (Lund-GSI)

BELEN-48 for beta-delayed neutrons

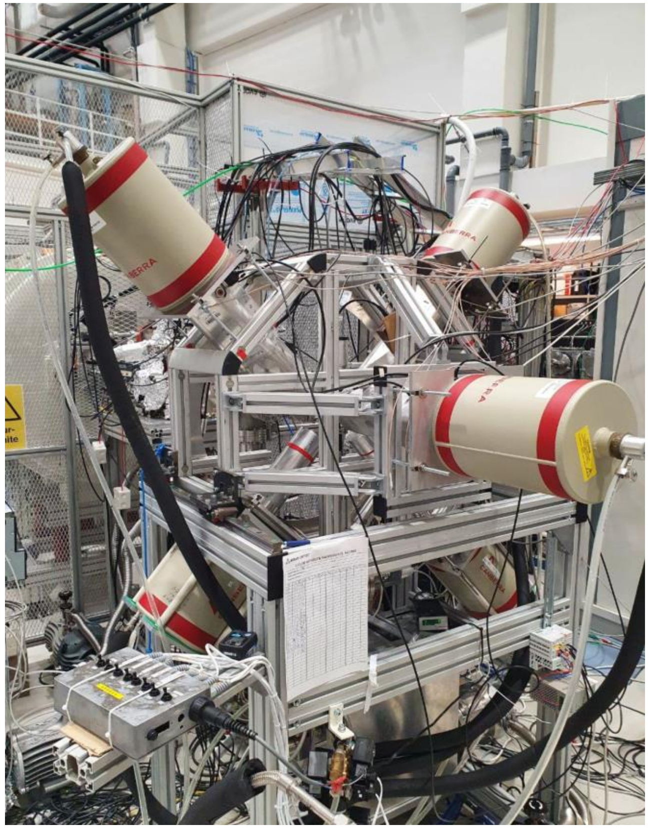
Beta decay of ^{86}As at the post-trap setup

- ^{86}As selected with JYFLTRAP
- Focused on beta-delayed gamma rays
- Three Clovers (IFIN-HH), two 70% coaxial Ge
- Several new transitions observed
- Unambigous identification of ^{86}As(βn) gammas



Lama Al Ayoubi, PhD thesis work

Experimental setup March 2022



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Summary and outlook

Summary and outlook

- IGISOL offers versatile opportunities to study both neutron-deficient and neutron-rich nuclei
- Research areas:
  - High-precision mass measurements for fundamental physics, nuclear structure and nuclear astrophysics
  - Decay spectroscopy, even with isomerically pure beams
  - Laser spectroscopy
  - Fission yield studies
  - Fundamental physics (MORA experiment, ^{135}Cs atom trap)
- Dozens of isomeric states measured with the PI-ICR technique at JYFLTRAP
- MR-TOF commissioned online
- JYFL PAC: next call deadline 15th September 2022!

Acknowledgements

Thanks to all collaborators and the IGISOL Group!

European Research Council
Established by the European Commission

ACADEMY OF FINLAND

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This work has been supported by the Academy of Finland under grants No. 275389, 284516, 312544 and the Finnish Centre of Excellence Programme 2012-2017 (Nuclear and Accelerator Based Physics Research at JYFL). This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 771036 (ERC CoG MAIDEN).