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Mass measurements and the rare-earth r-process peak

Anu Kankainen

Introduction

Credit: Credit: NASA/JPL-Caltech/S. Stolovy (SSC/Caltech)

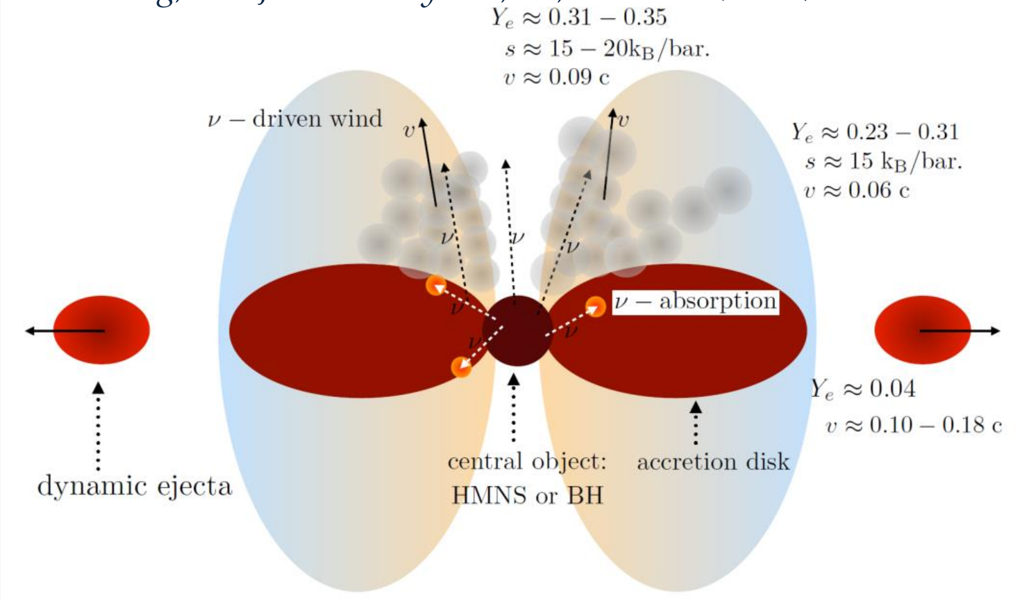
The rapid neutron capture process

Note: Talk by Gabriel Martinez-Pinedo yesterday

- Origin of around half of the elements heavier than iron
- Neutron-star mergers as the astrophysical site: GW170817 *ApJL 848, L12 (2017)*
- Multimessenger observations – accurate nuclear data needed for calculations

Prompt/dynamic ejecta
- Very neutron-rich
- Fission cycling

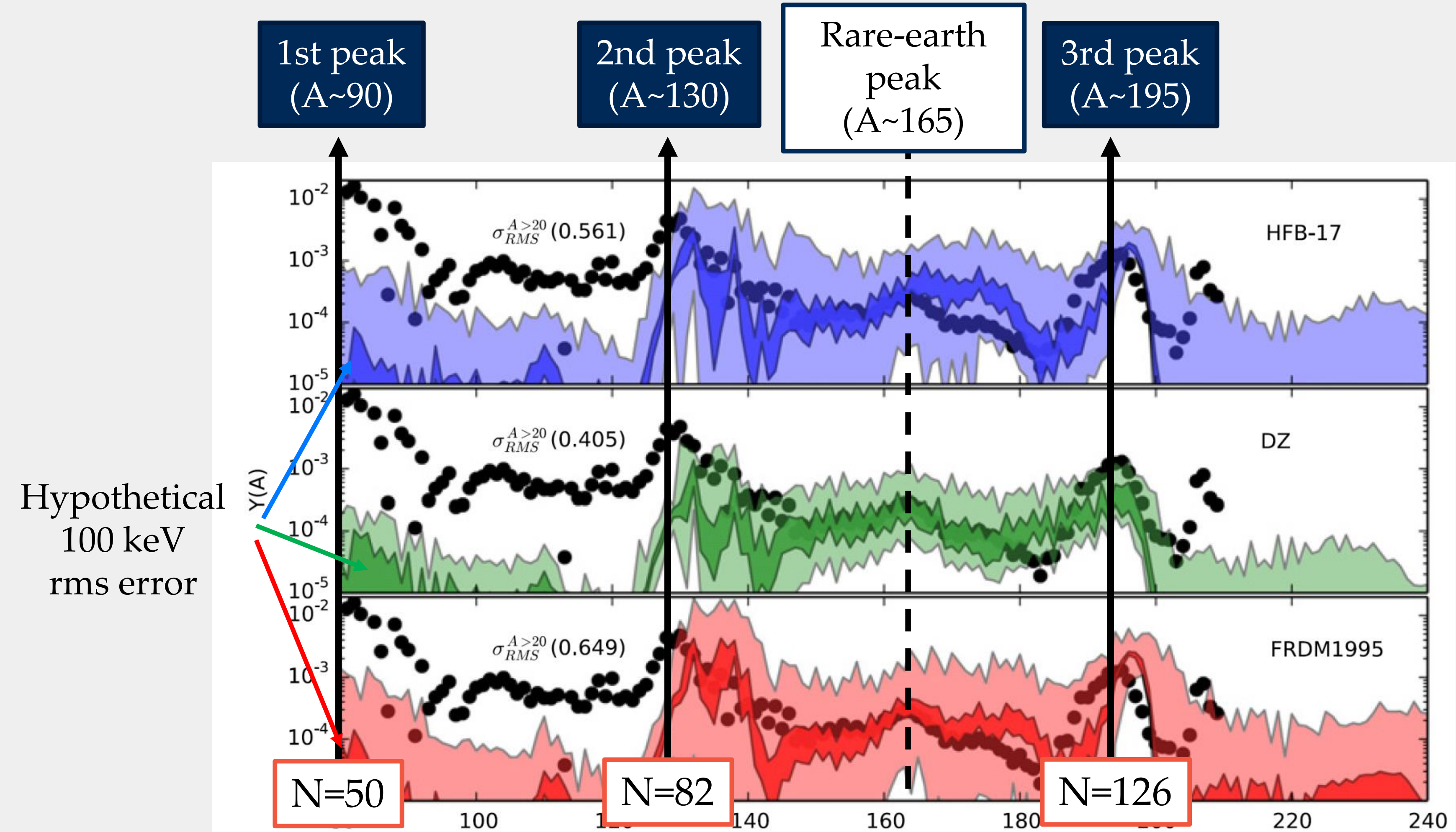
S. Rosswog, Int. J. Mod. Phys. D, 24, 1530012 (2015)



Disk ejecta
- Less neutron-rich
- Fission not so dominant

See also: *Rosswog et al., Class. Quantum Grav. 34 (2017) 104001*
Just et al., MNRAS 448 (2015) 541
Mendoza-Temis et al., PRC 92 (2015) 055805

The r process abundances



Main (A>120) r process, hot trajectory[A]

M.R. Mumpower et al. ,
Progr. Part. Nucl. Phys. 86 (2016) 86

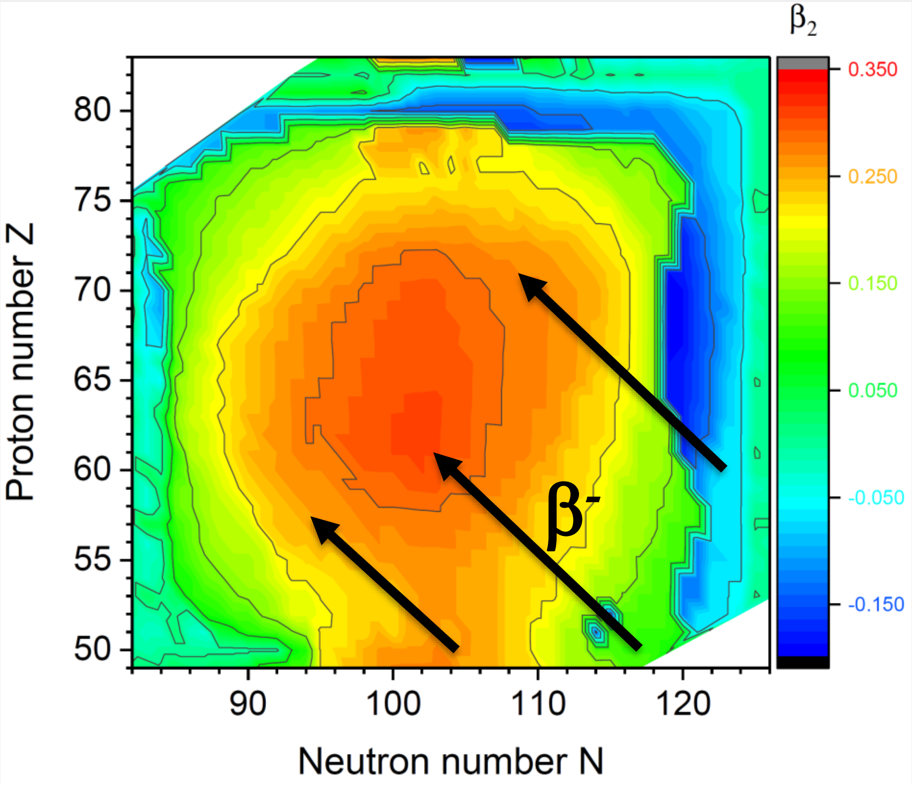
Formation of the rare-earth abundance peak

Deformation (kink in S_n values) funneling material flow to A~165?

- At later stages of the r process
- No (n,γ)-(γ,n) equilibrium
- Experimentally reachable nuclei

R. Surman et al., PRL 79 (1997) 1809.
M. Mumpower et al., PRC 85 (2012) 045801.
M. Mumpower et al., PPNP 86 (2016) 86.

FRDM2012. *P. Möller et al., ADNDT 109-110, 1(2016)*

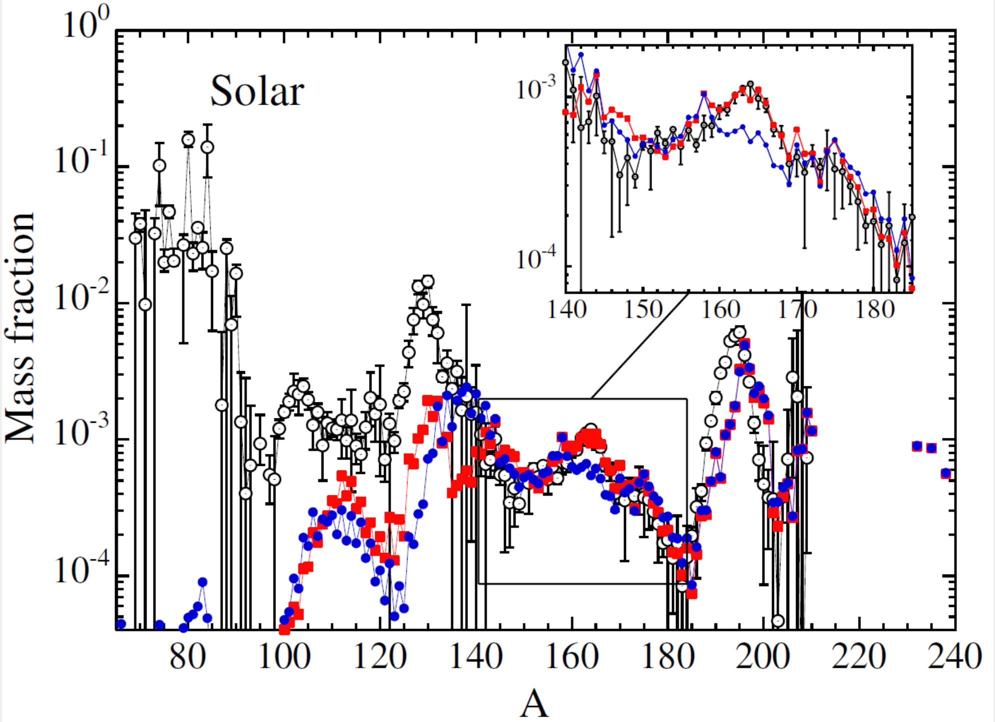


Formation of the rare-earth abundance peak

Via fission cycling from neutron-rich nuclei around A~278 but difficult to test experimentally…

Red:
double asymmetric distributions with the new scission point model SPY

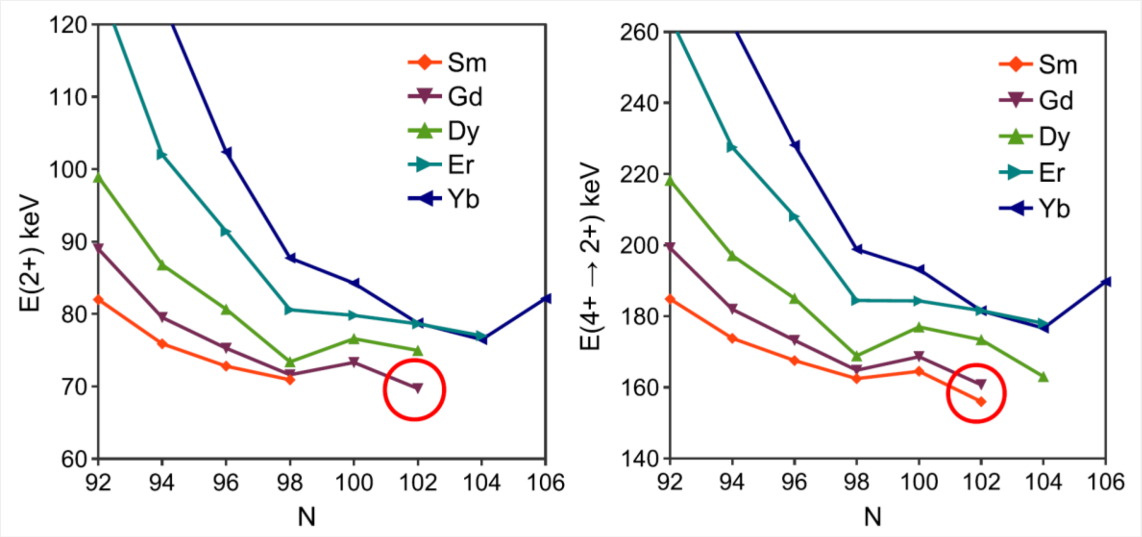
Blue:
symmetric distributions (GEF 2013)



S. Goriely et al., PRL 111 (2013) 242502

Nuclear structure motivation

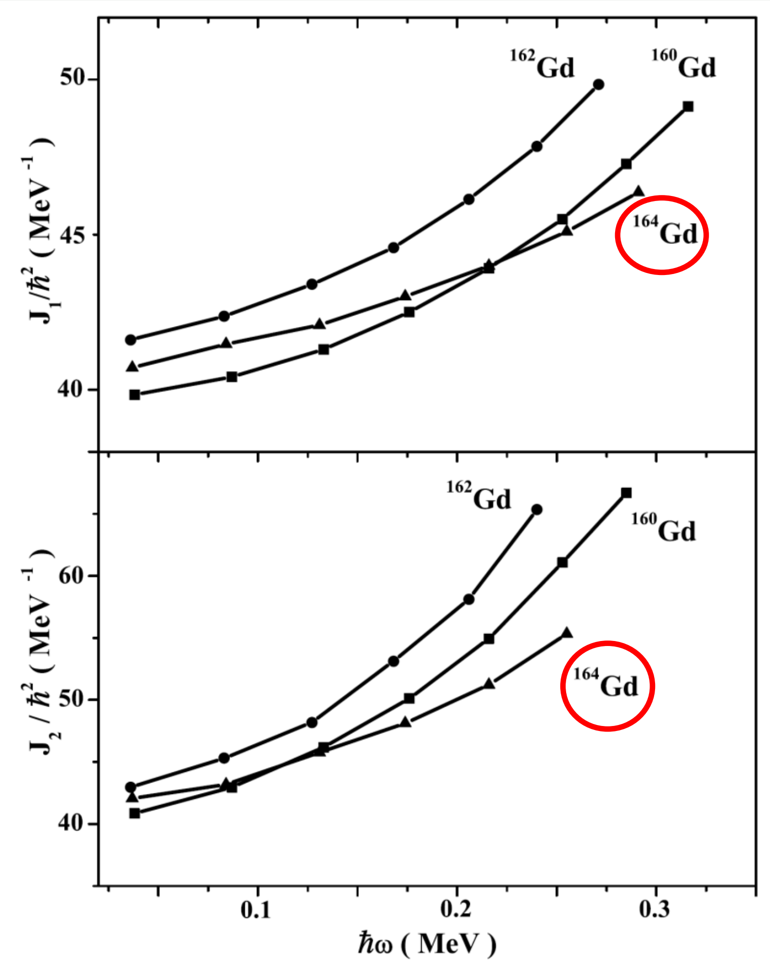
The rare-earth region located in the midshell between N=82 and N=126 also interesting for nuclear structure



Z. Patel et al., PRL 113 (2014) 262502

- EURICA at RIKEN
- Local maximum at N=100
- Deformed shell closure at N=100?
- Also suggested by mean-field calculations
  L. Satpathy and S. Patra, Nucl. Phys. A 722, (2003) C24 & J. Phys. G 30 (2004) 771.

Nuclear structure motivation



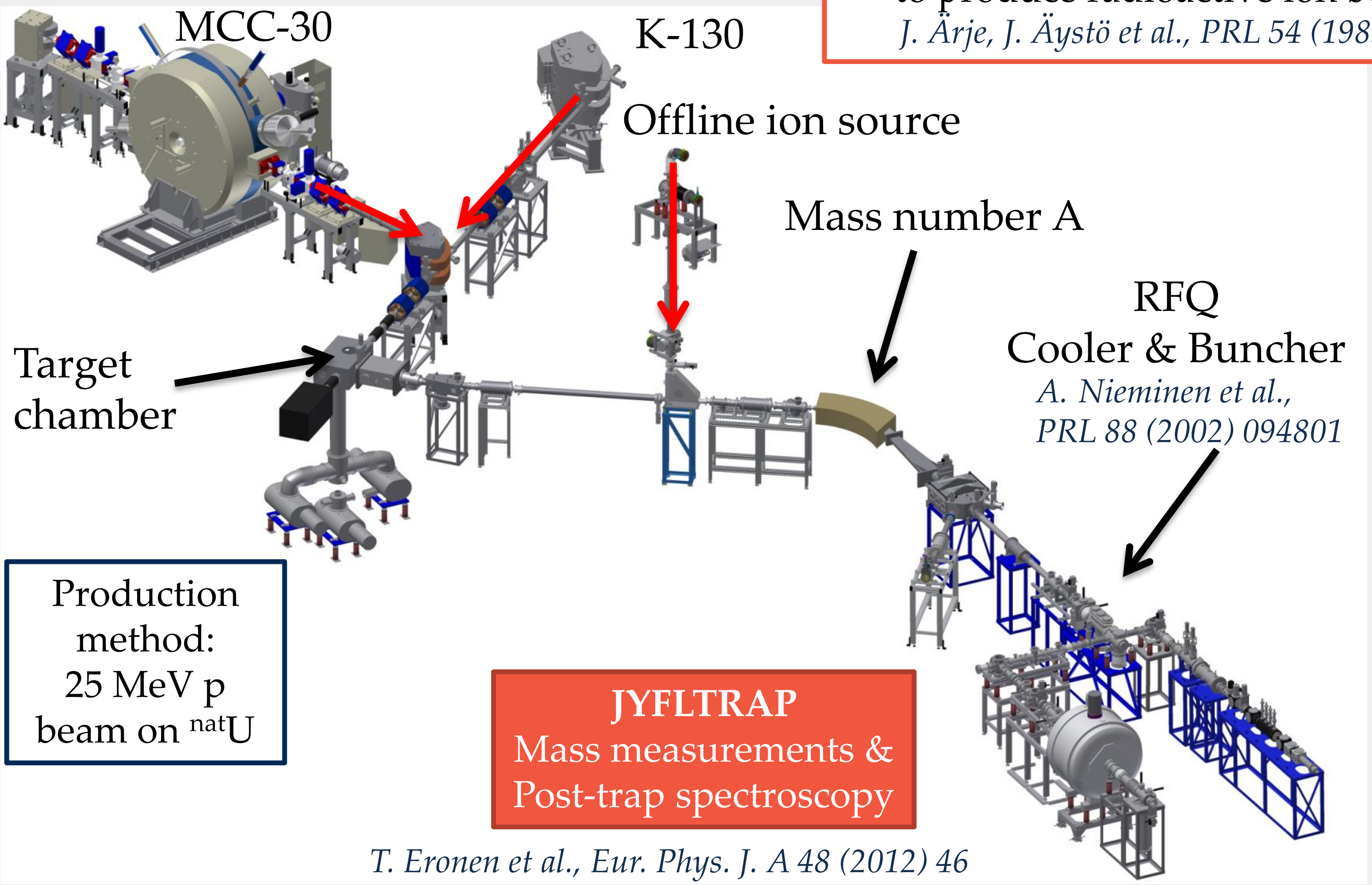
Jones et al, Eur. Phys. J. A 25 (2005) 467

- Gammasphere and ^{252}Cf source
- ^{164}Gd (N=100) more rigid than ^{160,162}Gd
- Less stretching (less increase with increasing $\hbar\omega$)

Mass measurements with JYFLTRAP at IGISOL

IGISOL facility at JYFL

IGISOL - a fast and universal method to produce radioactive ion beams
J. Ärje, J. Äystö et al., PRL 54 (1985) 99

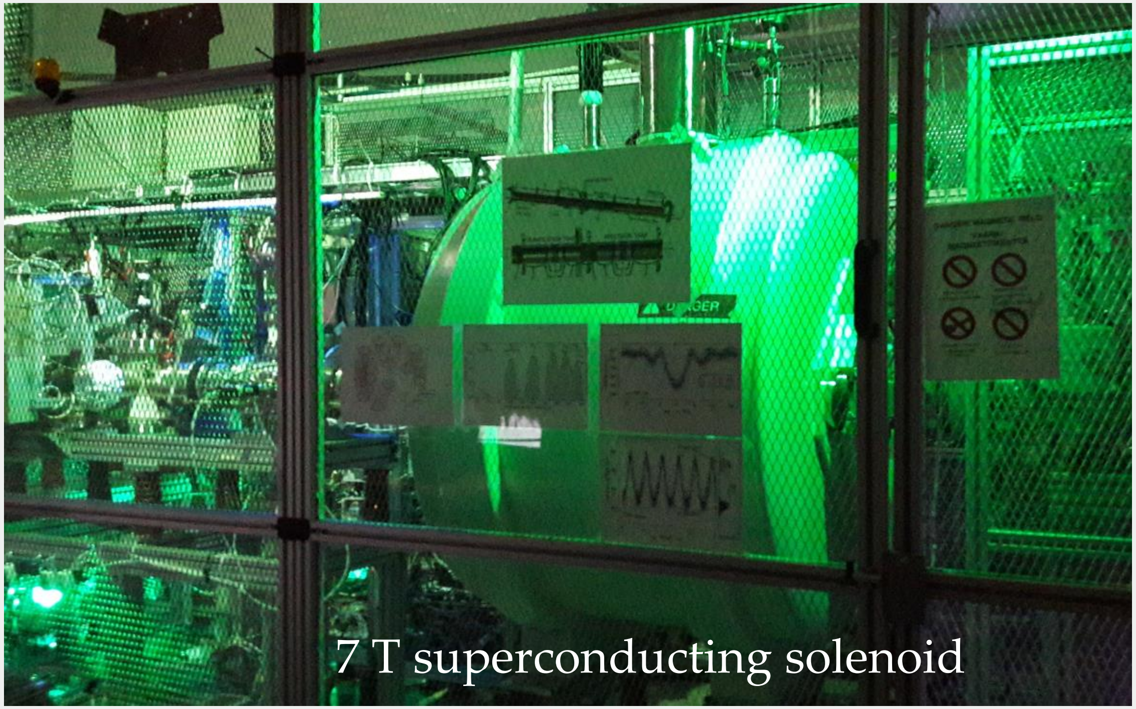


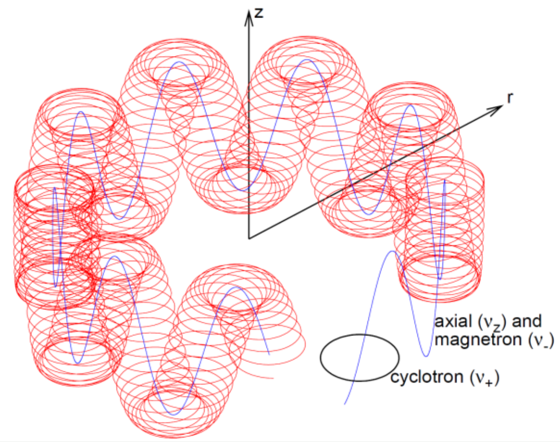
Production method:
25 MeV p beam on ^{nat}U

JYFLTRAP
Mass measurements & Post-trap spectroscopy

T. Eronen et al., Eur. Phys. J. A 48 (2012) 46

JYFLTRAP Penning trap





Ion's cyclotron resonance frequency:

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

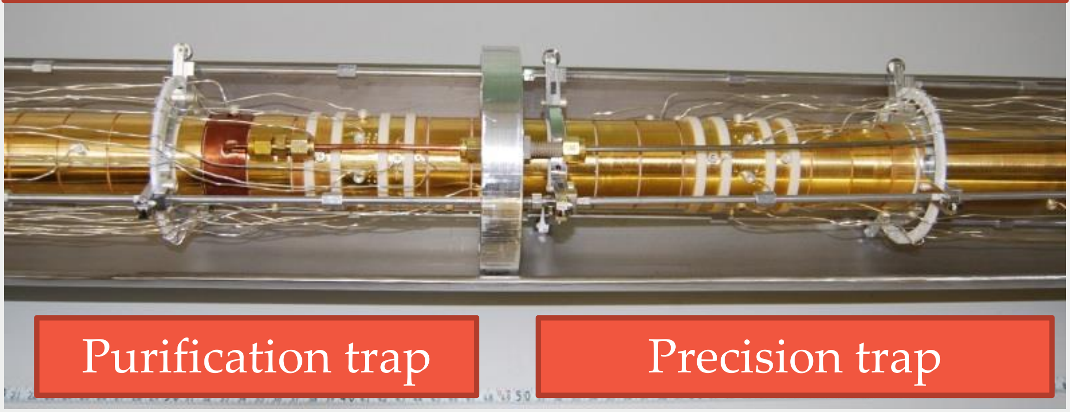
B determined using a reference ion with a well-known mass:

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

Used reference ions: $^{136}Xe^+$, $^{158}Gd^+$, $^{163}Dy^+$, and $^{171}Yb^+$

Measurements at JYFLTRAP

JYFLTRAP – a cylindrical double Penning trap



Purification trap

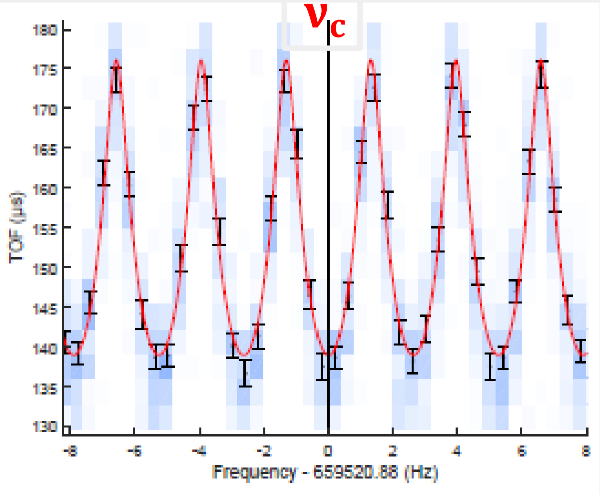
Mass-selective buffer-gas cooling technique
G. Savard et al., Phys. Lett. A 158 (1991) 247

Precision trap

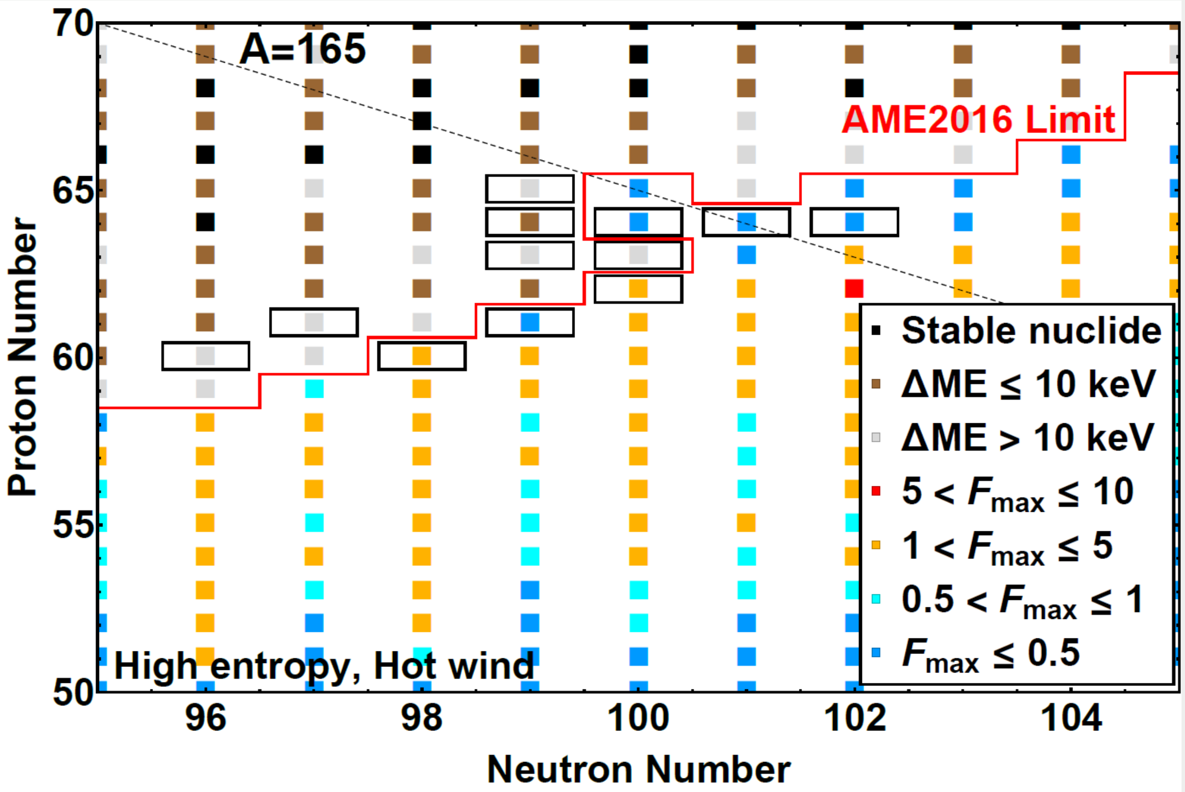
Time-of-Flight Ion Cyclotron Resonance (TOF-ICR) technique
M. König et al., Int. J. Mass Spectr. Ion Proc. 142 (1991) 95

Select the ion of interest, e.g. $^{163}Eu^+$ → Determine ν_c

TOF-ICR for $^{163}Eu^+$



Measured isotopes



Measured nuclides:

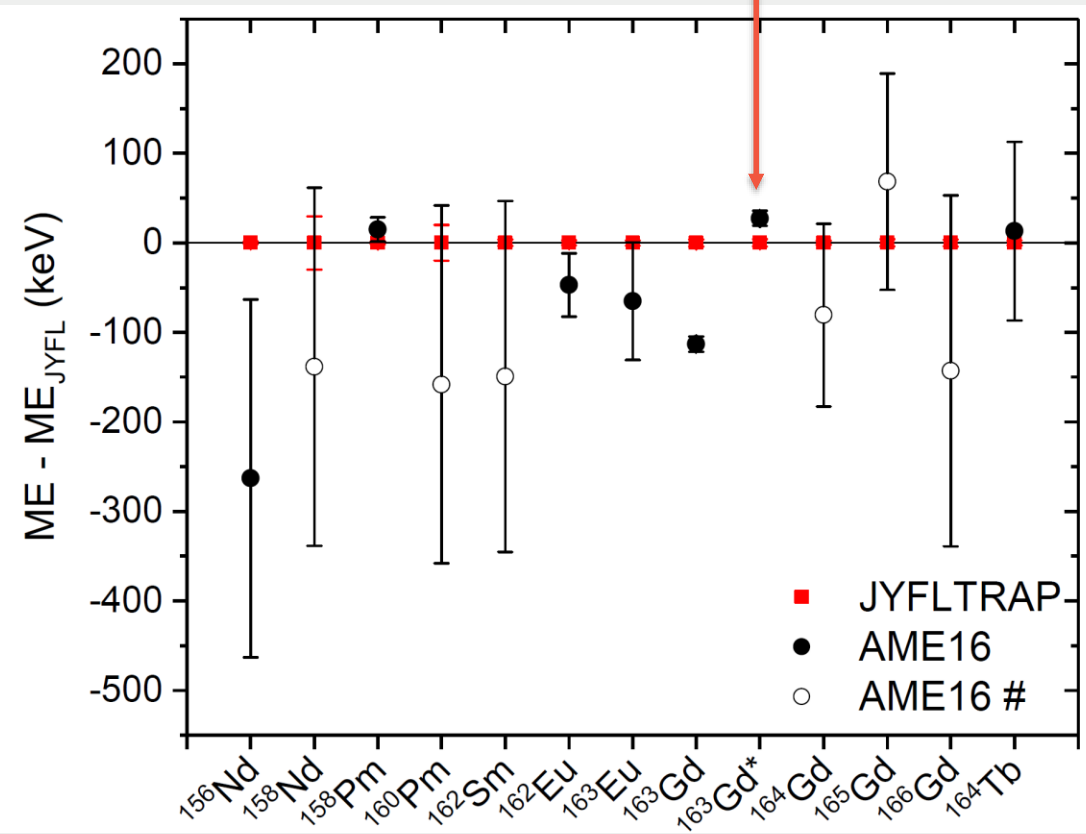
- ^{156,158}Nd (Z=60)
- ^{158,160}Pm (Z=61)
- ^{162}Sm (Z=62)
- ^{162,163}Eu (Z=63)
- $^{163\text{-}166}$Gd (Z=64)
- ^{164}Tb (Z=65)

6 isotopes measured for the first time!

Results

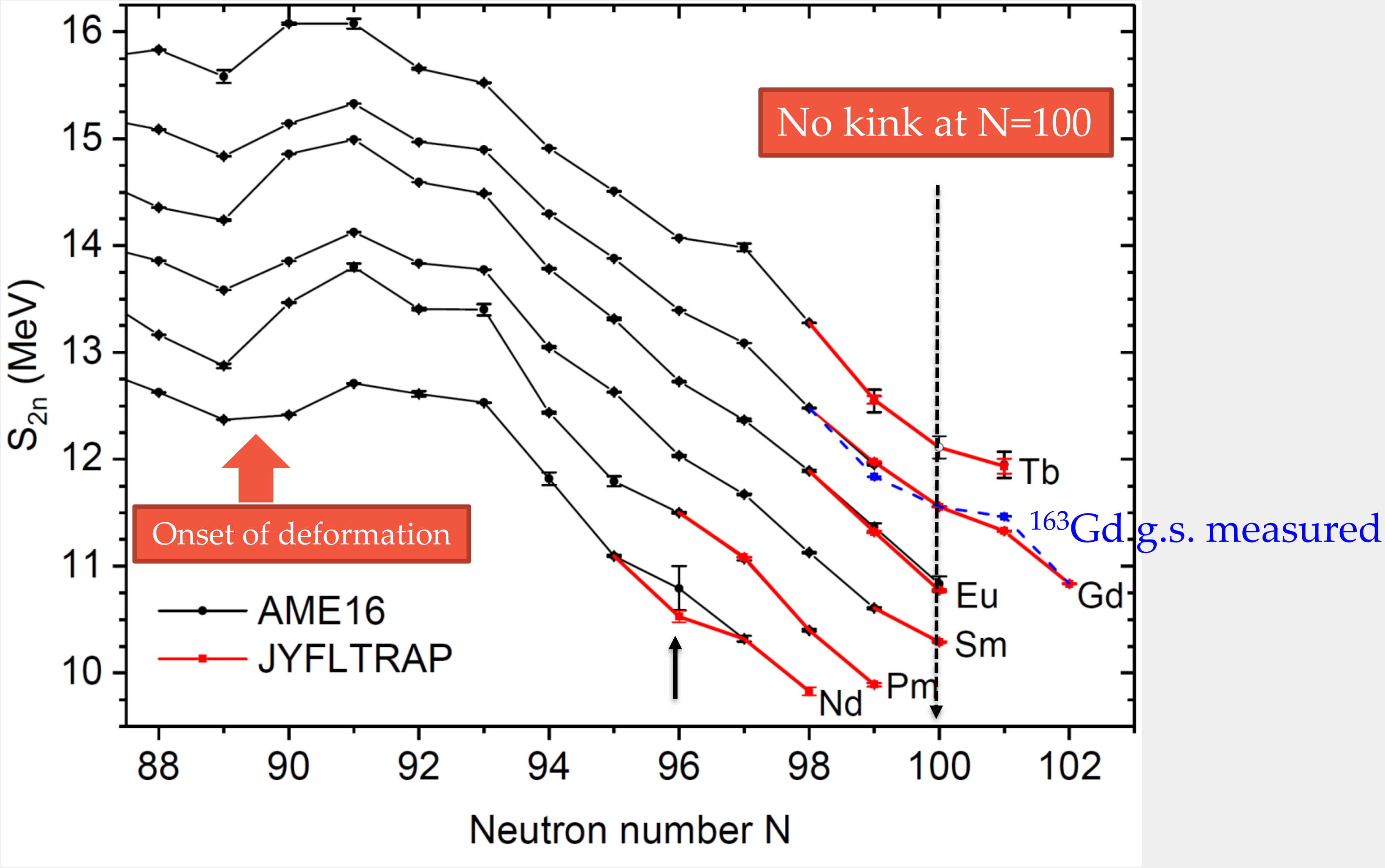
Mass-excess values

Corrected with
E_x=137.8 keV



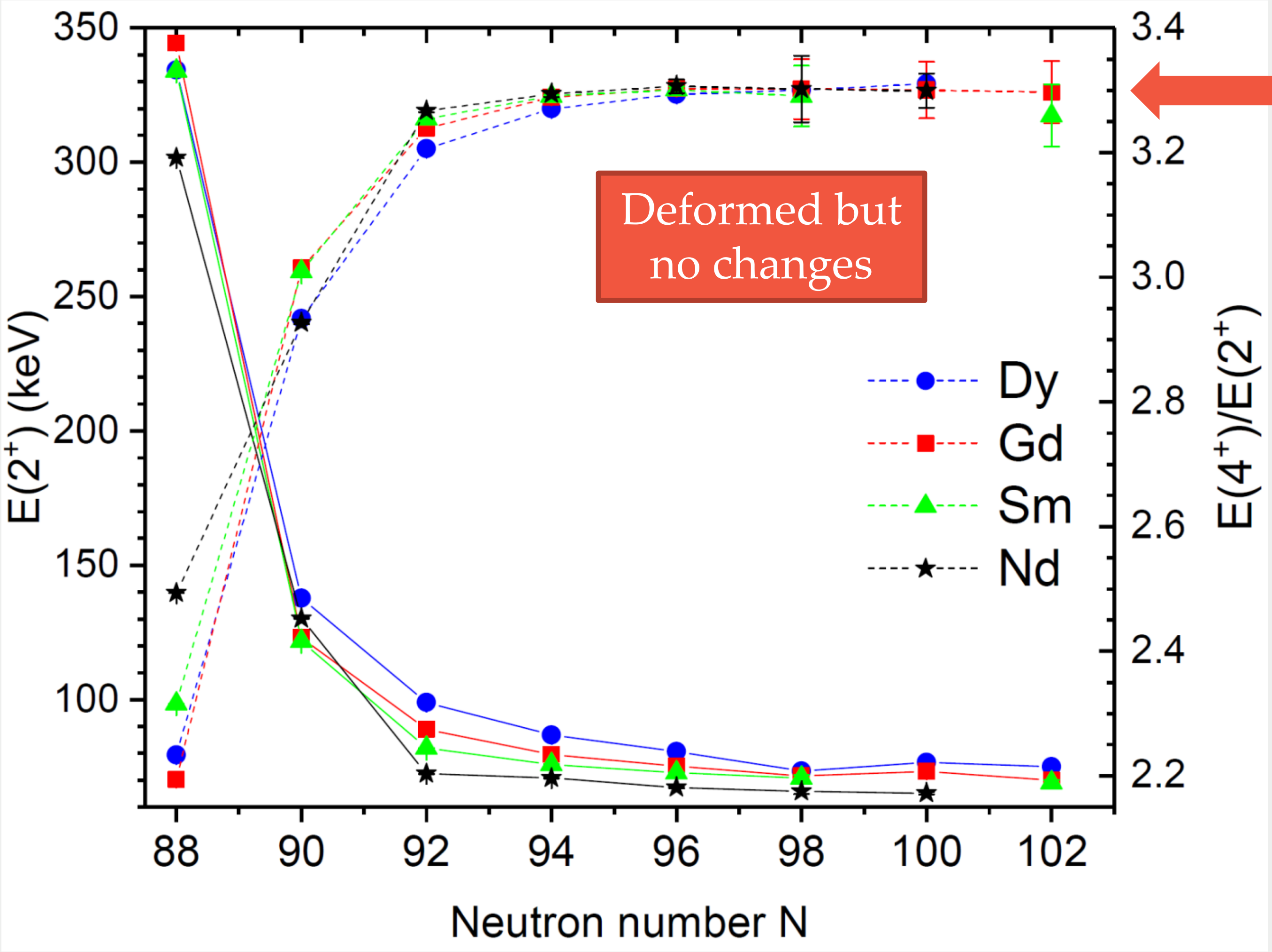
- Extrapolated masses typically too low
- **^{156}Nd:** based on a β-decay experiment *[M. Shibata et al., ENAM2001 Proceedings, p. 479]* but estimated to be 70 keV too low based on the mass surface in AME16
- **^{163}Gd:** measured with the Canadian Penning Trap (CPT) at CARIBU but: known isomeric state at 137.8 keV *[H. Hayashi et al., NIMA 747, 41 (2014)]*

Two-neutron separation energies S_{2n}



M. Vilén et al., arXiv:1801.08940v3 [nucl-ex]

Comparison to $E(2^+)$ and $E(4^+)/E(2^+)$



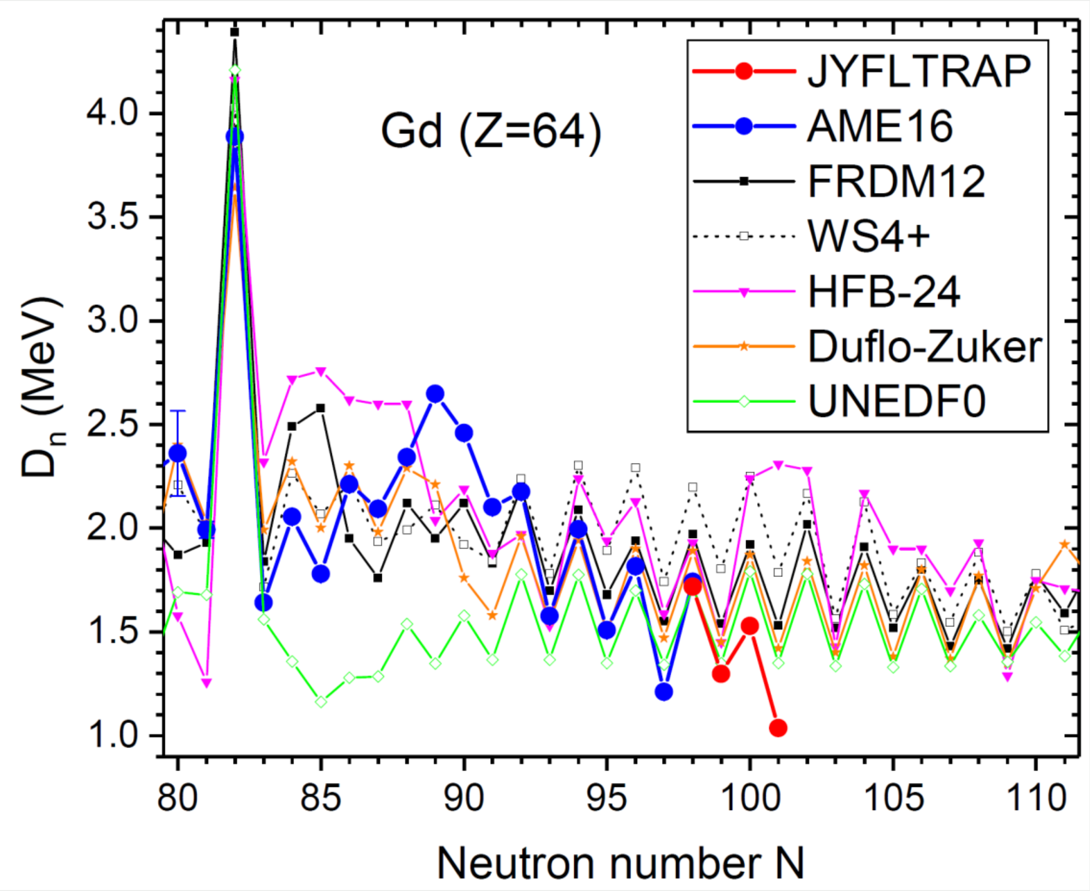
$E(4^+)/E(2^+)\sim3.3$
rigid rotor

Neutron pairing metric D_n for Gd

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

- a sensitive probe for structural changes

Empirical neutron pairing gap or odd-even staggering parameter



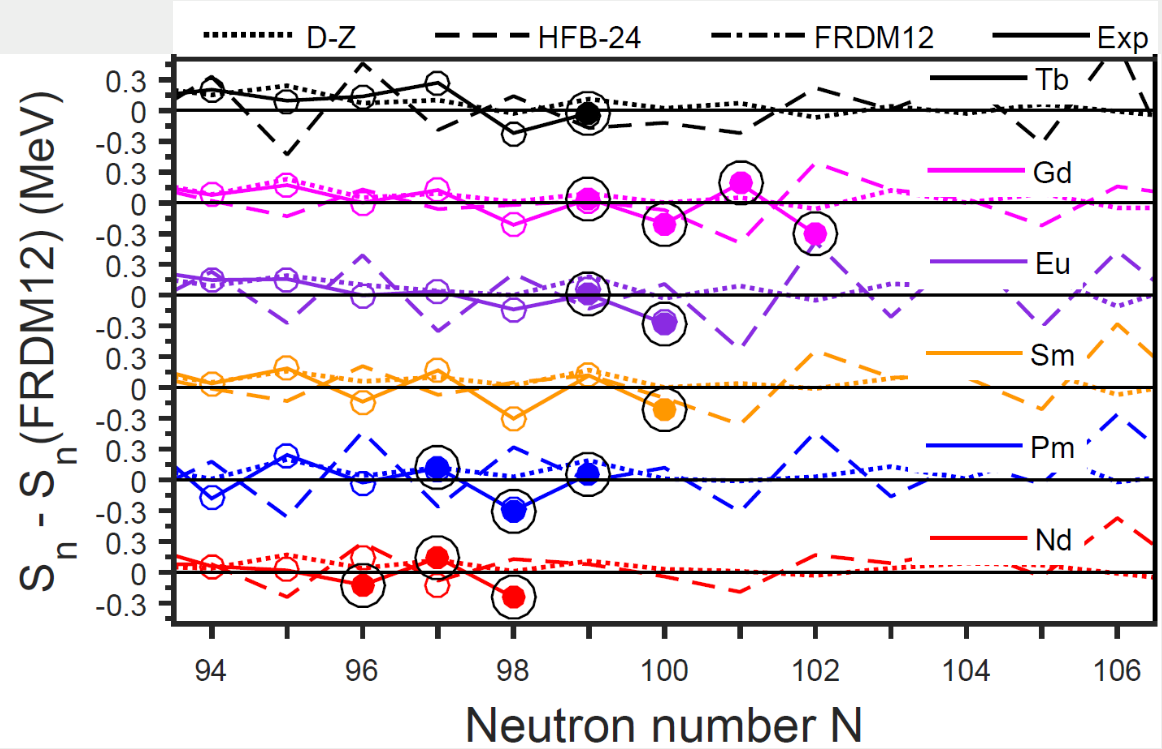
M. Vilén et al., arXiv:1801.08940v3 [nucl-ex]

Experimental **neutron pairing weaker** than predicted by theoretical models when approaching the midshell!

Also increased δV_{pn}
- talk by Burcu Cakirli on proxy SU(3) yesterday

Neutron separation energies S_n

Relevant for r-process calculations
(neutron capture rates and photodisintegration)

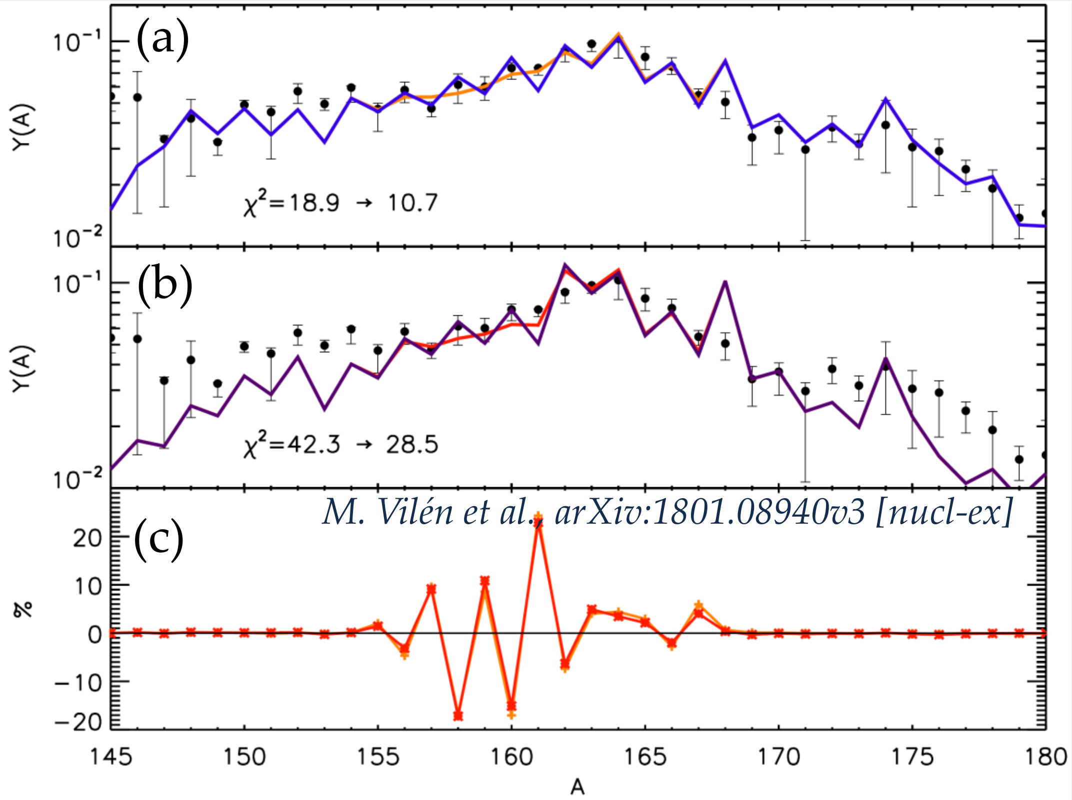


Less odd-even staggering:

- Lower for N= 96,98,100,102
- Higher for N=97,99,101

Impact on the r-process calculations

New S_n values result in smoother calculated abundance distributions and in a better agreement with the observed pattern



(a) Merger with two $1.35M_{solar}$ neutron stars. (Y_e = 0.016, initial s/kB ~ 8)
Prompt, dynamic ejecta.

(b) A low-entropy, hot wind (Y_e = 0.15 , s/kB = 10)
Accretion disk winds.

Changes up to 25% observed. Mainly due to revised neutron capture rates

Baseline: AME16 exp. + FRDM12
Neutron-capture rates: TALYS

Summary and outlook

Summary:
- 12 neutron-rich rare-earth isotopes measured with JYFLTRAP
- 6 nuclides measured for the first time
- No evidence for the N=100 subshell closure
- Reduced neutron pairing compared to theoretical models
- Smoother calculated r-process abundance distributions

Outlook:
- PI-ICR technique at JYFLTRAP:

Dr Dmitrii Nesterenko (Talk on Friday!)

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www.jyu.fi/igisol
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3 postdoctoral positions at IGISOL!

ERC Consolidator Grant 2017
MAIDEN (Masses, Isomers and Decay studies for Elemental Nucleosynthesis

erc
European Research Council
Established by the European Commission

Project starts 1st June 2018

Seeking for post docs to work on:

- Mass measurements (JYFLTRAP+MR-TOF)
- Decay spectroscopy of neutron-rich nuclei
- Development and testing multinucleon-transfer ion guide at IGISOL

Learn more and how to apply: http://dlvr.it/QDGKP9
For any questions, contact: anu.kankainen@jyu.fi