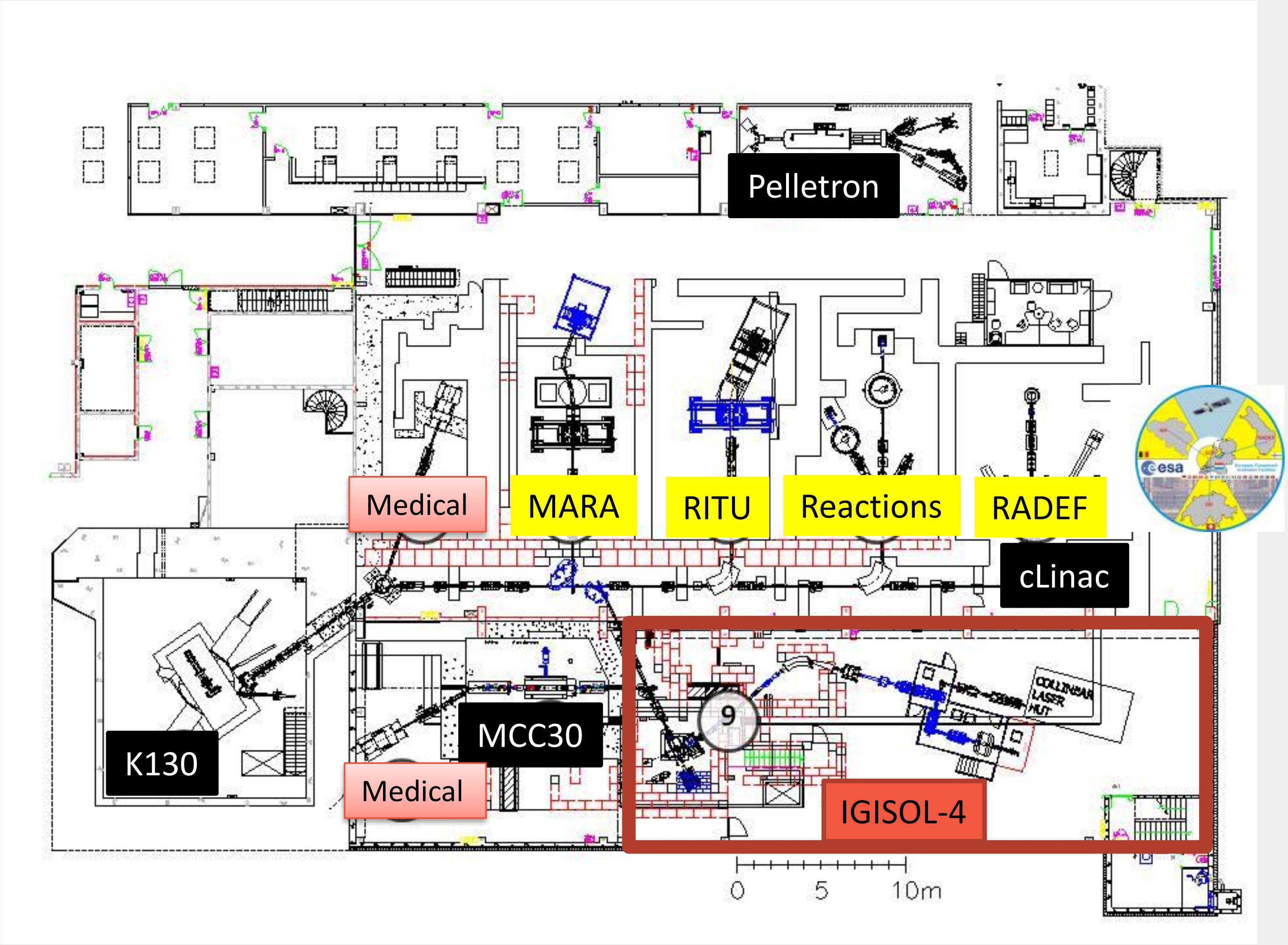
JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Nuclear structure studies at IGISOL

Anu Kankainen

Academy of Finland Research Fellow

IGISOL at JYFL

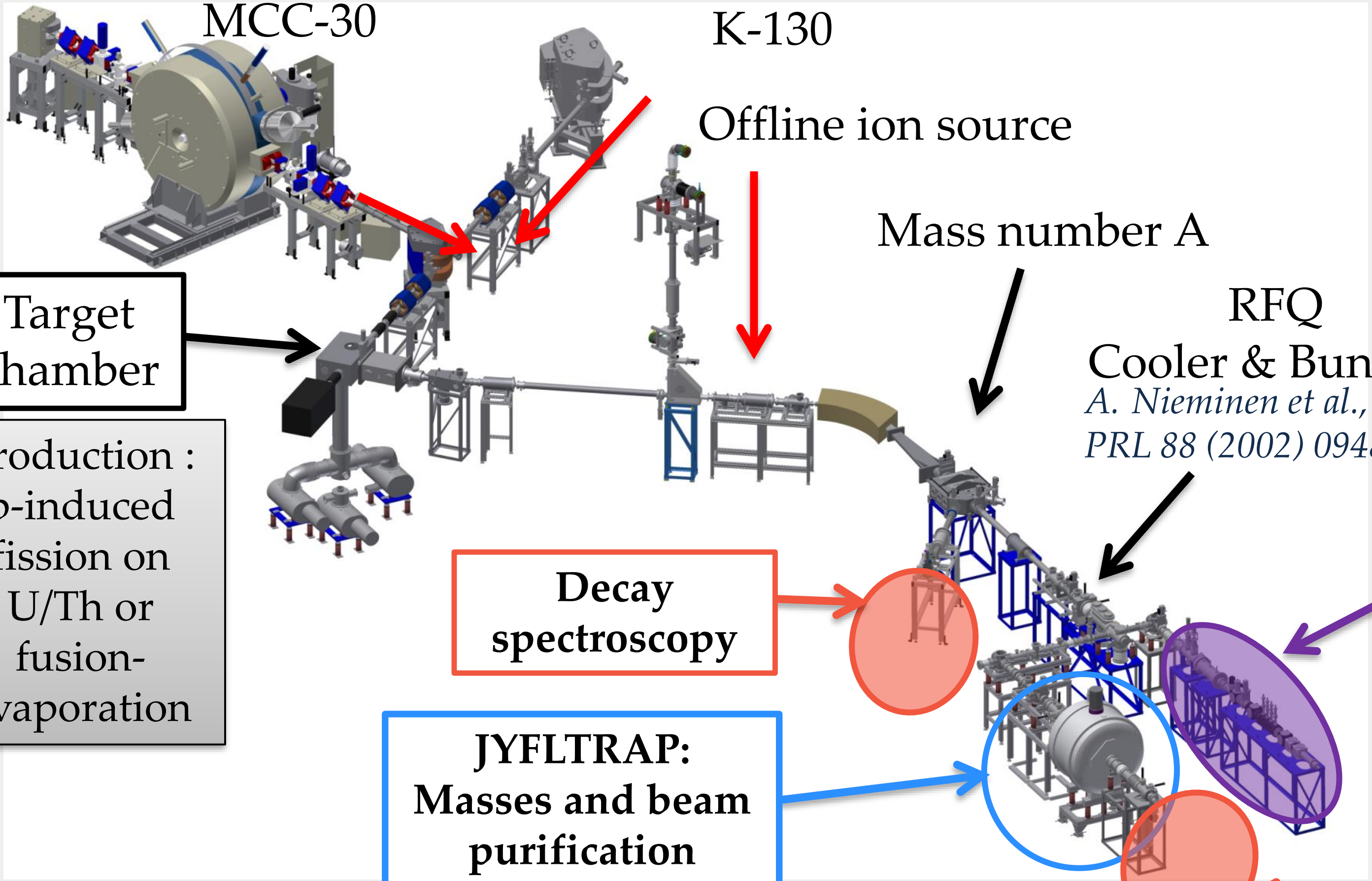


IGISOL (Ion Guide Isotope Separator On-Line)

IGISOL - a fast and universal method to produce radioactive beams

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

IGISOL-4: *I.D. Moore et al., Nucl. Instrum. Meth. B 317 (2013) 208*



RFQ
Cooler & Buncher

A. Nieminen et al.,
PRL 88 (2002) 094801

Target chamber

Production :
p-induced fission on U/Th or fusion-evaporation

Decay spectroscopy

Laser spectroscopy

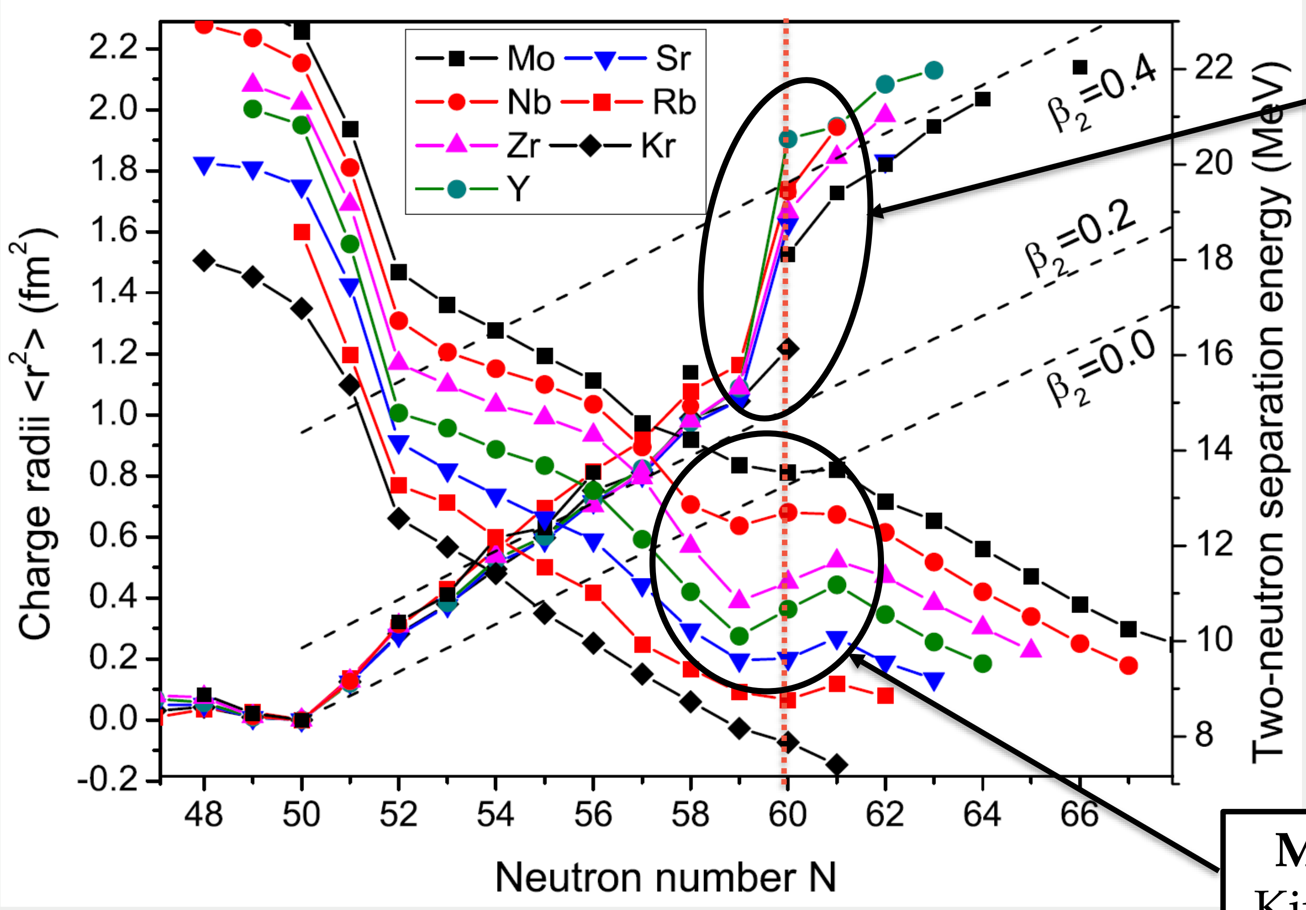
JYFLTRAP: Masses and beam purification

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

Post-trap decay spectroscopy

Complementary methods, example: onset of deformation at N=60

A. Kankainen, J. Äystö, A. Jokinen,
J. Phys. G: Nucl. Part. Phys. 39 (2012) 093101.



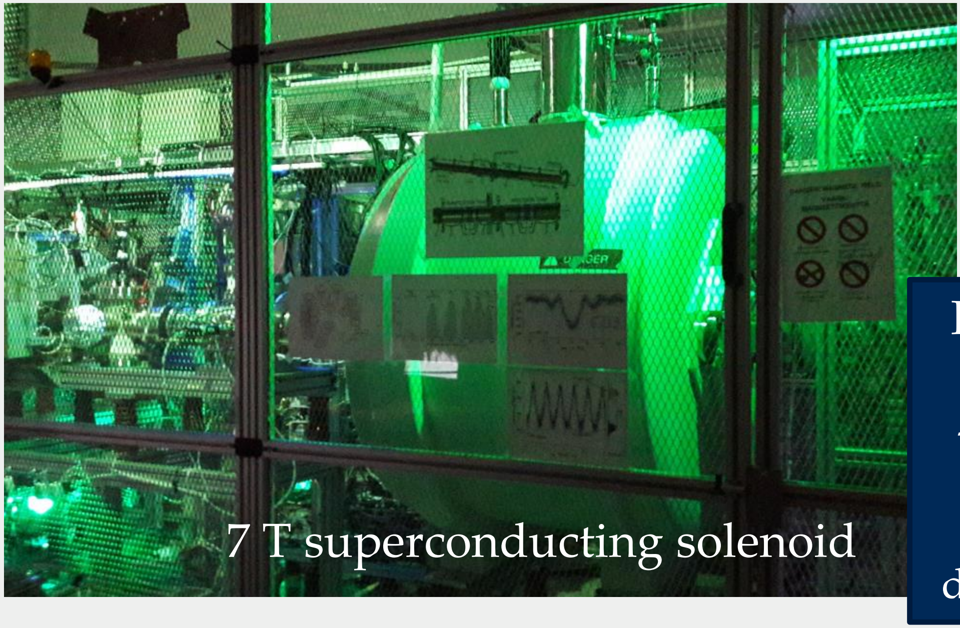
Laser spectroscopy: Increase in the root-mean square charge radii

For a review on laser spectroscopy: P. Campbell et al. , PPNP 86 (2016) 127

Mass measurements: Kink in the S_{2n} energies

Precision mass measurements with the JYFLTRAP Penning trap

JYFLTRAP mass measurements


7 T superconducting solenoid

PURIFICATION TRAP
- select the ions of interest for mass measurements or decay spectroscopy

PRECISION TRAP
- mass measurements using TOF-ICR (time of flight ion cyclotron resonance) or PI-ICR (phase-imaging ICR) techniques

Ion's cyclotron resonance frequency:

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

B determined using a reference ion:

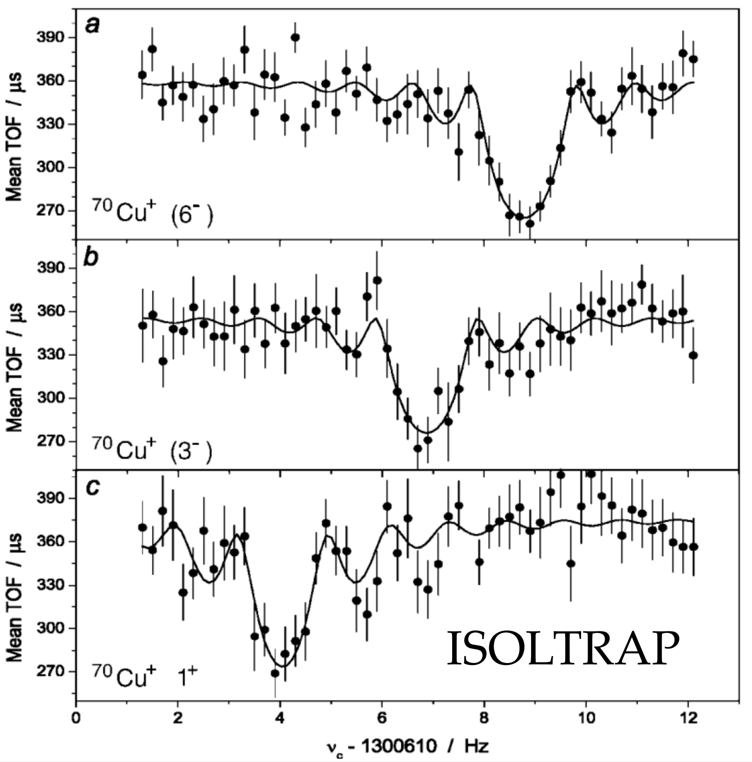
$$m = \frac{\nu_c{}^{ref}}{\nu_c}\left(m_{ref} - m_e\right) + m_e$$

Two different methods

TOF-ICR
- ν_c determined from the time-of-flight spectrum

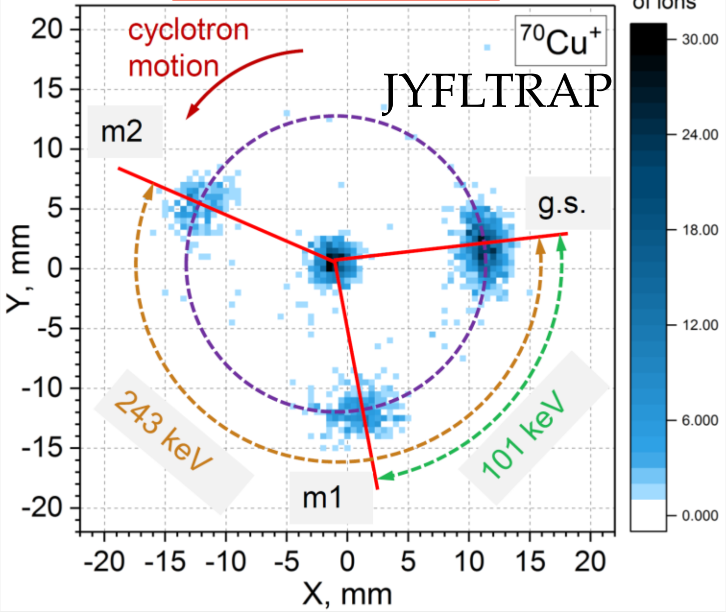
PI-ICR
- ν_c determined from the phase ϕ of the ions after a phase accumulation time t

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



Roosbroeck et al., PRL 92, 112501 (2004)

T_{RF} = 900 ms+ 3000 ms for cleaning

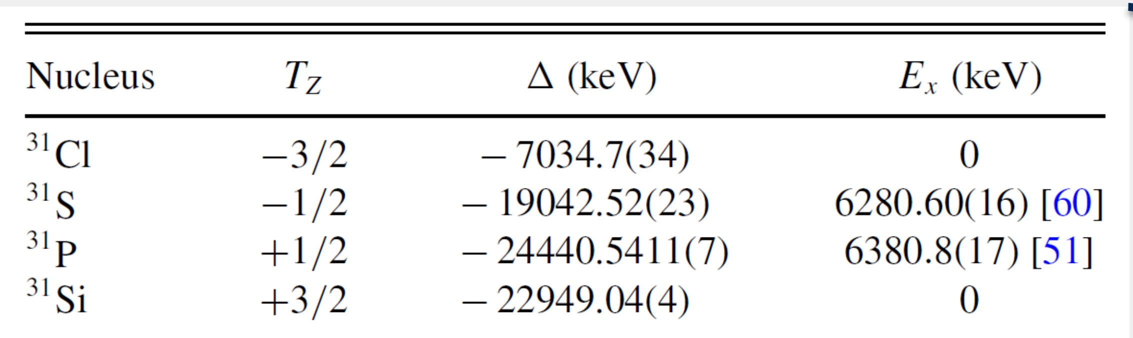


100 ms accumulation time

Mass measurements of neutron-deficient nuclides for isospin symmetry

Breakdown of IMME for T=3/2 at A=31

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

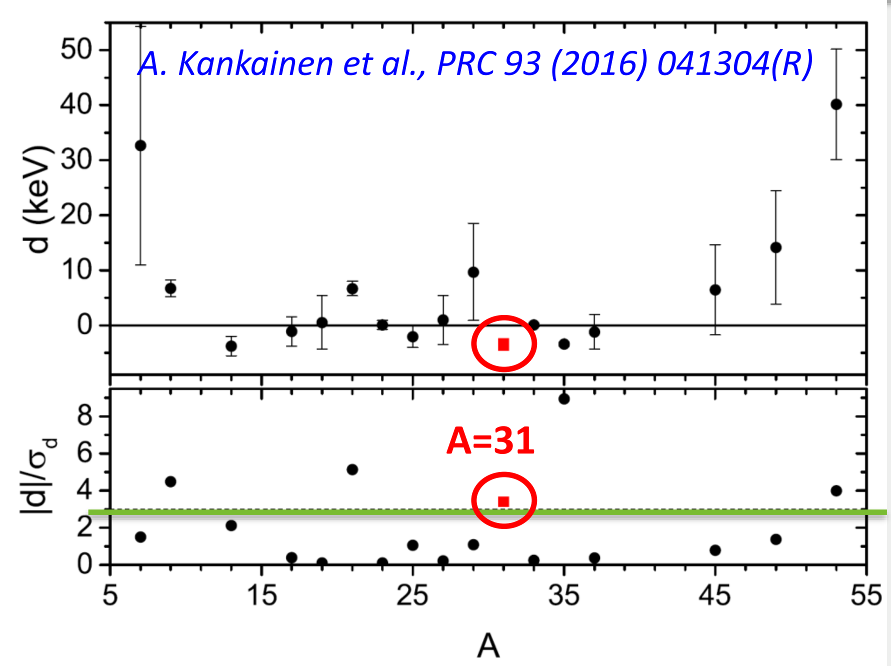


Nucleus	T_Z	Δ (keV)	E_x (keV)
^{31}Cl	−3/2	− 7034.7(34)	0
^{31}S	−1/2	− 19042.52(23)	6280.60(16) [60]
^{31}P	+1/2	− 24440.5411(7)	6380.8(17) [51]
^{31}Si	+3/2	− 22949.04(4)	0

Quadratic IMME fit fails with $\chi^2/n=11.6$!

Cubic coefficient:
$d = -3.5(11)$ keV

Compare: with ^{31}Cl mass from AME12: $\chi^2/n=0.08$

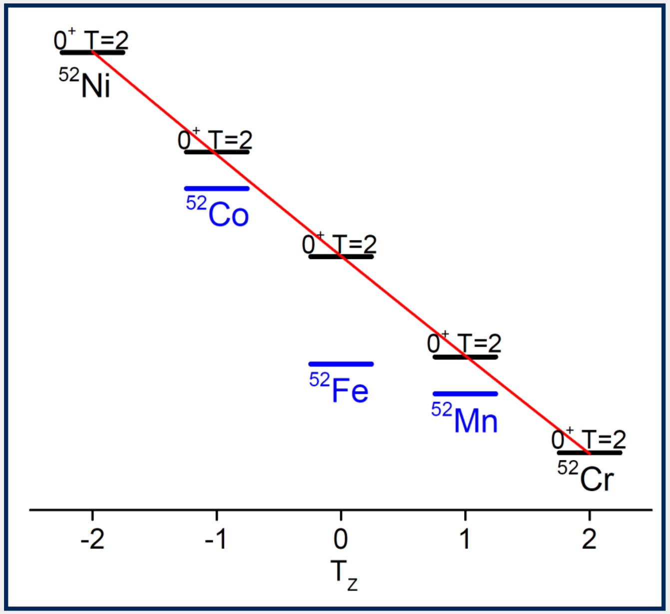


The breakdown valid also with the new E_x(IAS) from
Bennett et al., PRL 116 (2016) 102502:
$\chi^2/n = 16.2$ for the quadratic IMME
d = −4.3(11) keV

Explanation: Isospin mixing in ^{31}P (mixing in ^{31}S not enough)?
Bennett et al., PRC 93, 064310 (2016)

IMME for T=2 at A=52

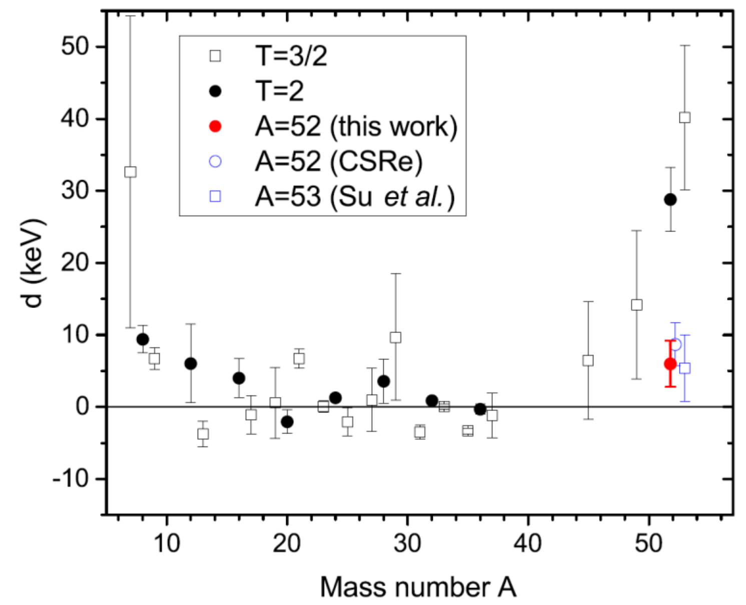
Measured with JYFLTRAP:
- ✓ ^{52}Co, ^{52}Co^{m}
- ✓ ^{52}Fe, ^{52}Fe^{m}
- ✓ ^{52}Mn



JYFLTRAP ^{52}Co (g.s. and isomer) 1-3σ higher than the CSRe storage-ring results
X. Xu et al., PRL 117, 182503 (2016)

Cubic coefficients d:

JYFLTRAP:	d = 6.0(32) keV
CSRe:	d = 5.8(42) keV
CSRe+JYFLTRAP for ^{52}Fe and ^{52}Mn:	d = 8.7(30) keV

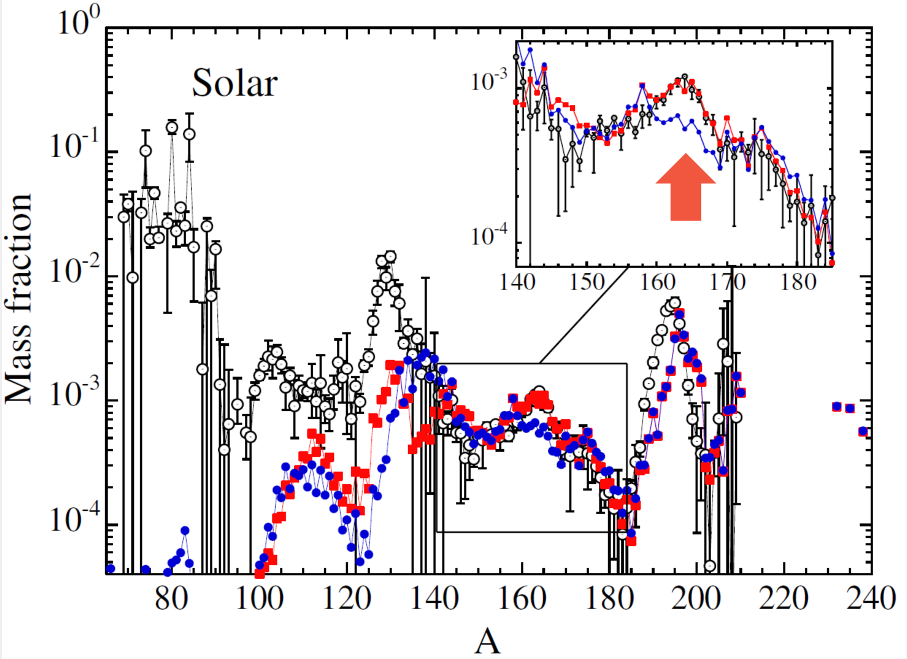


D.A. Nesterenko, AK et al.,
J. Phys. G: Nucl. Part. Phys. 44 (2017) 065103

Mass measurements of neutron-rich rare-earth isotopes

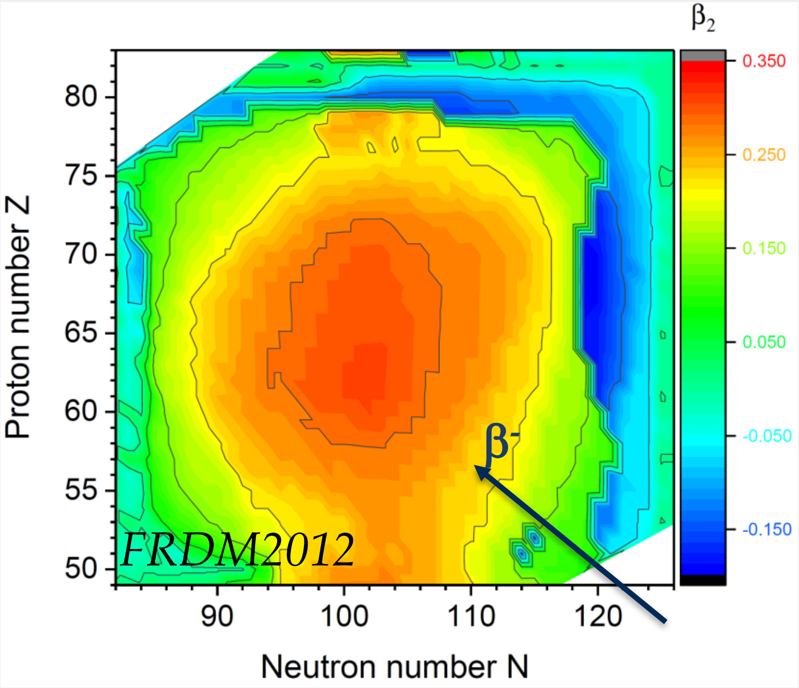
Formation of the rare-earth abundance peak in the r process

FISSION RECYCLING?



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

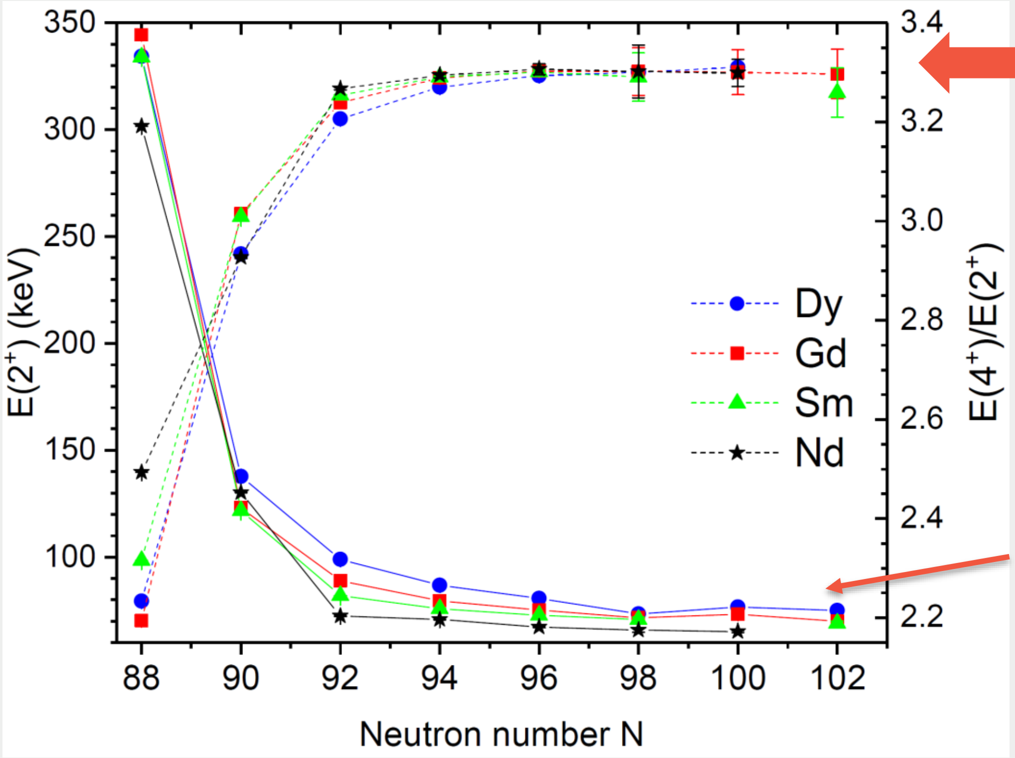
DEFORMATION FUNNELING THE FLOW?



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

Possible subshell closure at N=100?

Predicted by HF calculations in
S. K. Ghorui et al., PRC 85 (2012) 064327



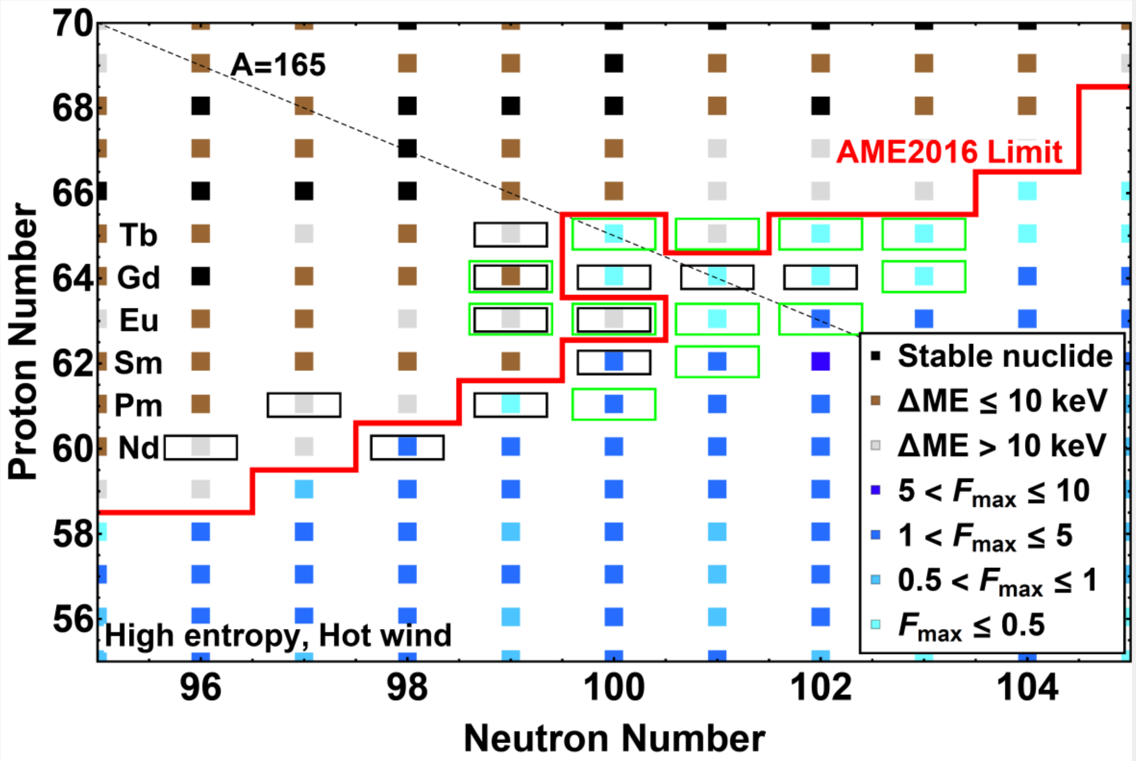
$E(4^+)/E(2^+)$~3.3
rigid rotor

^{164}Sm and ^{166}Gd N=102 isotones with EURICA at RIKEN

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

Measured nuclides

Mass measurements of 21 rare-earth isotopes
Campaign I: *M. Vilén et al., PRL 120, 262701 (2018)*
Campaign II: *manuscript in preparation*

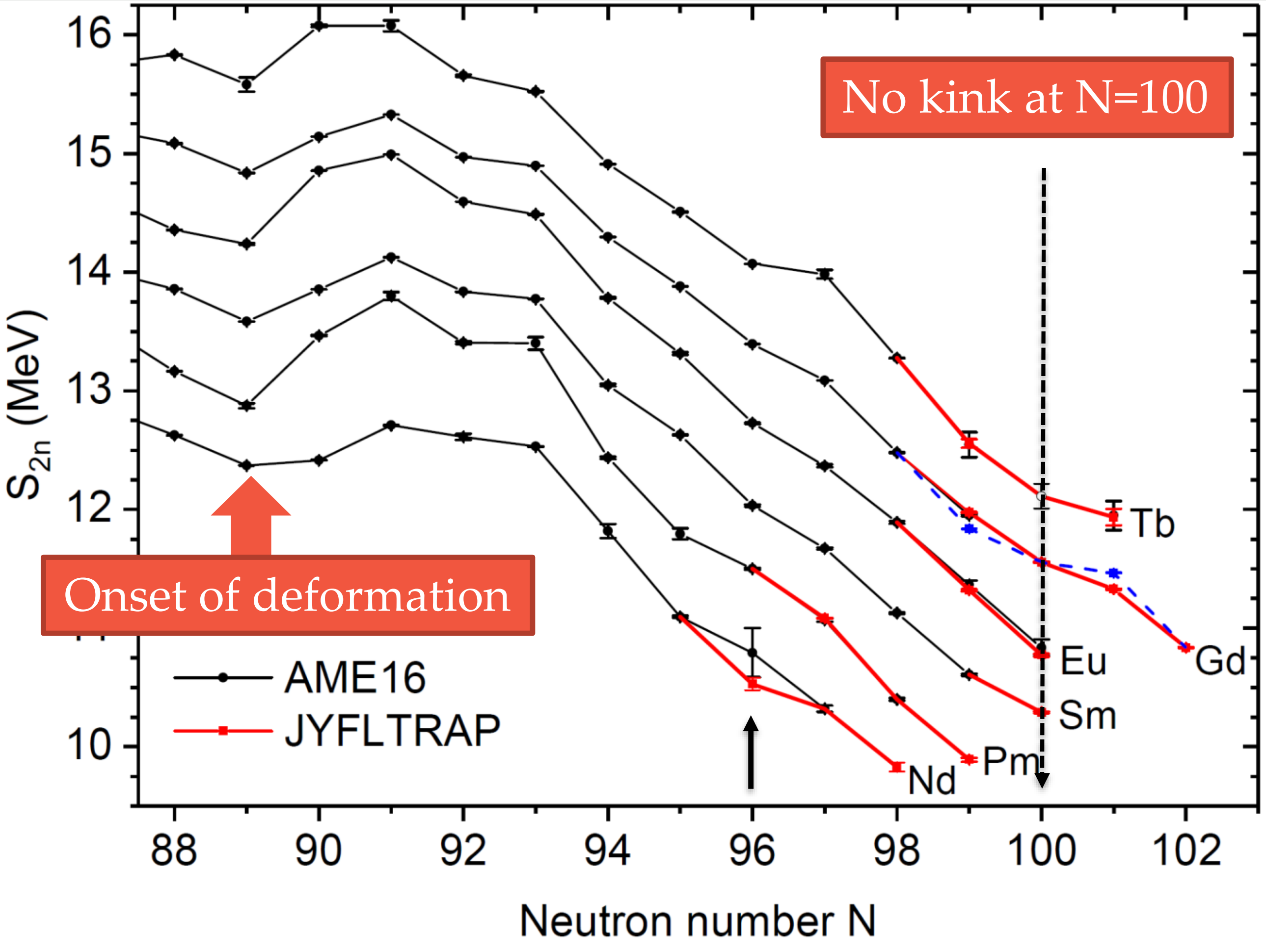


European Research Council
Established by the European Commission

Part of my
ERC Consolidator
Grant MAIDEN
(MAsses, Isomers and
Decay studies for
Elemental
Nucleosynthesis)

Two-neutron separation energies S_{2n}

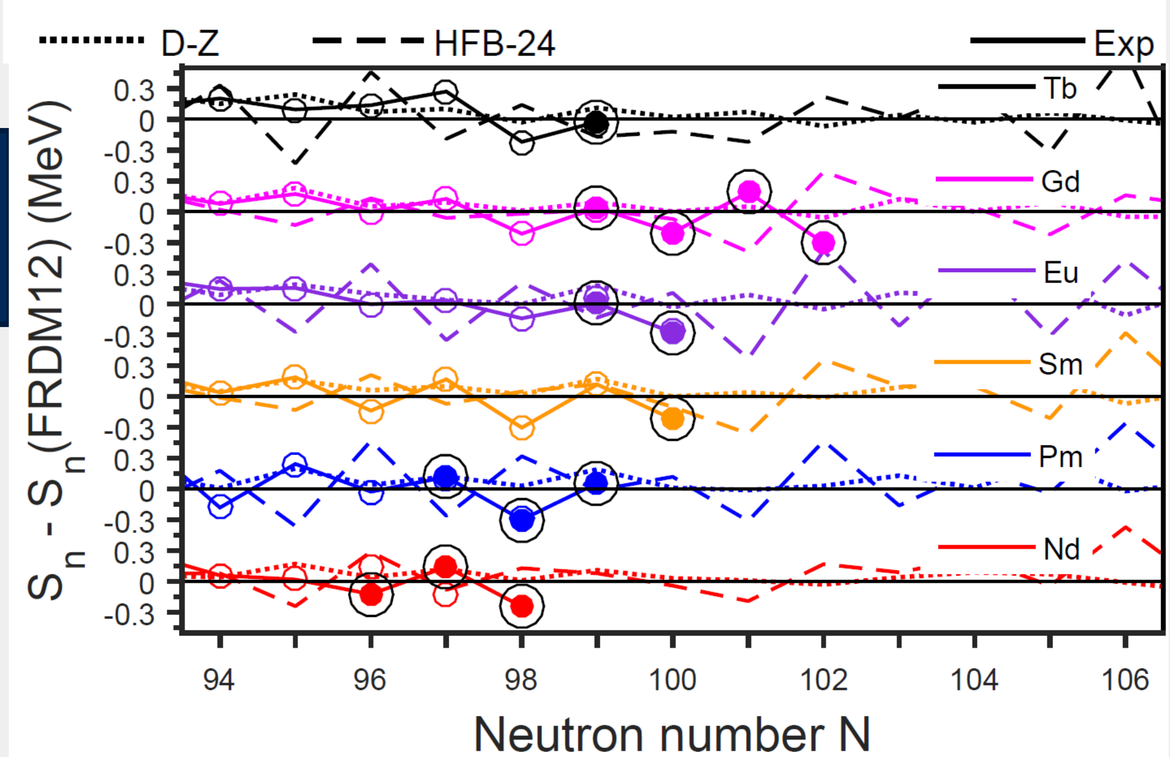
M. Vilén et al., PRL 120, 262701 (2018)



Neutron separation energies S_n

Less odd-even staggering than predicted by the models

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

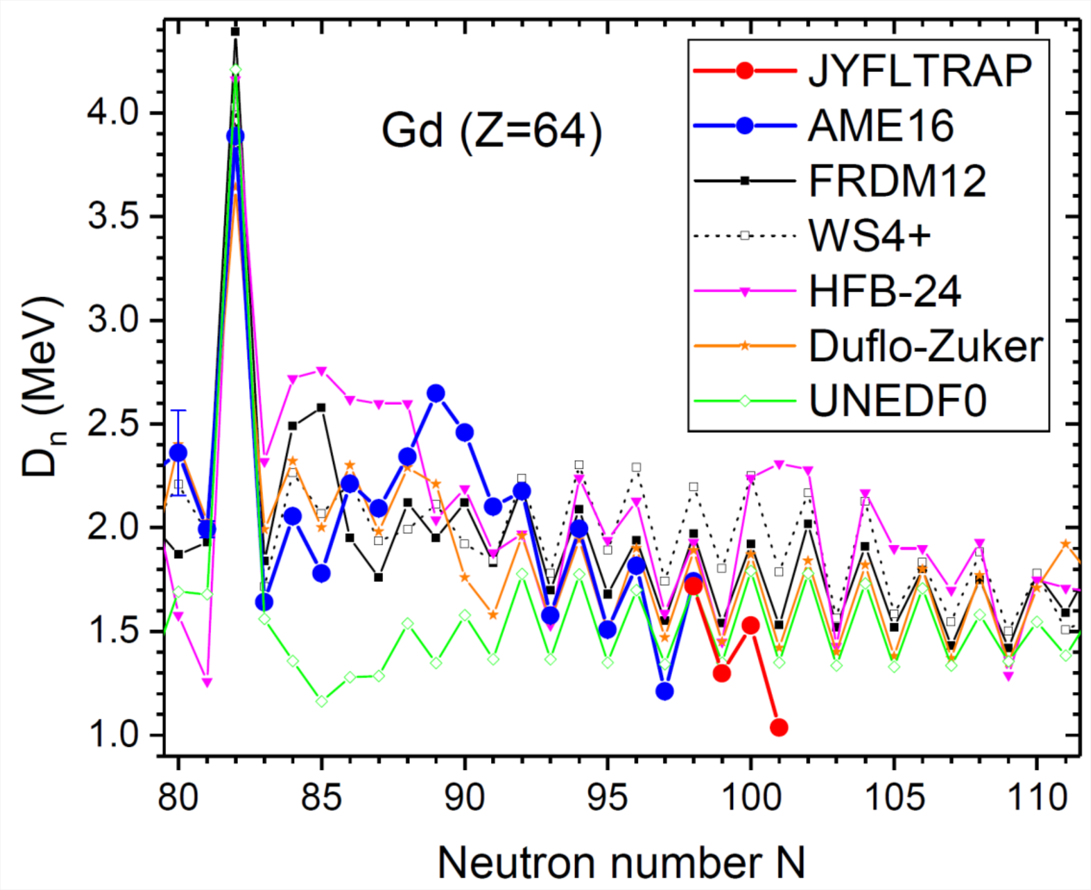


Important inputs for the r process!

Neutron pairing metrics D_n

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

Empirical neutron pairing gap a.k.a. odd-even staggering parameter

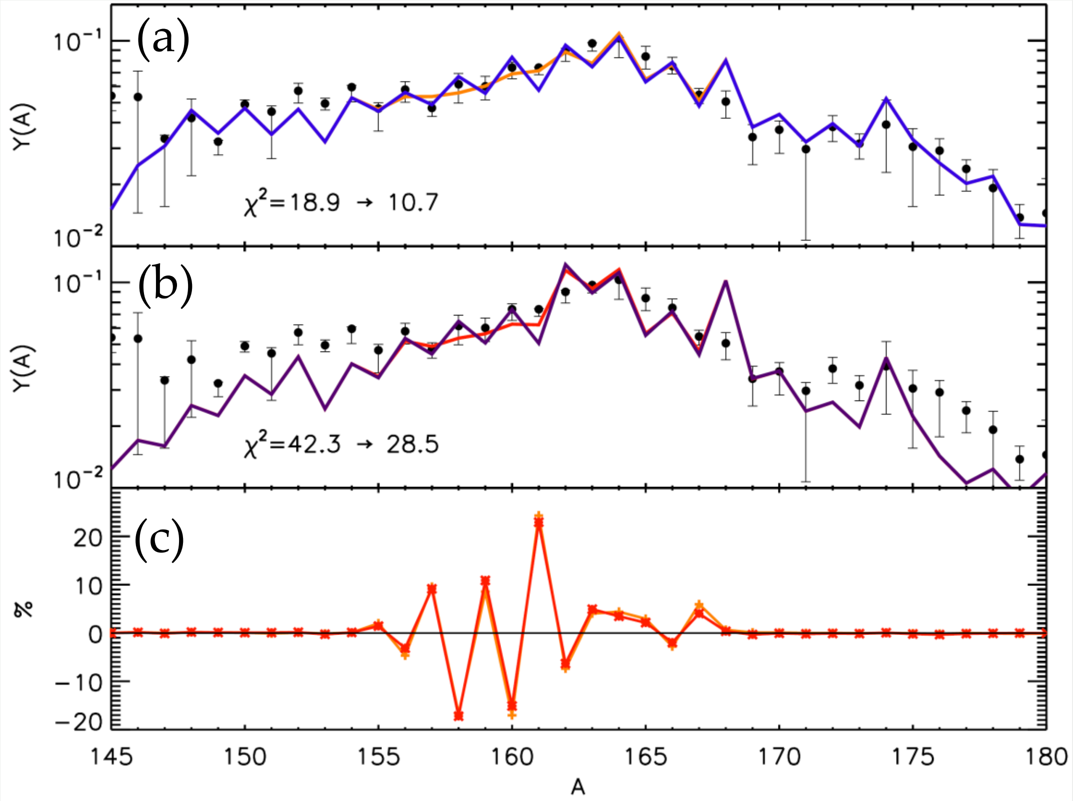


M. Vilén et al., PRL 120, 262701 (2018)

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

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 $s/k_B \sim 8$)

(b) A low-entropy, hot wind ($Y_e = 0.15$, $s/k_B = 10$)

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

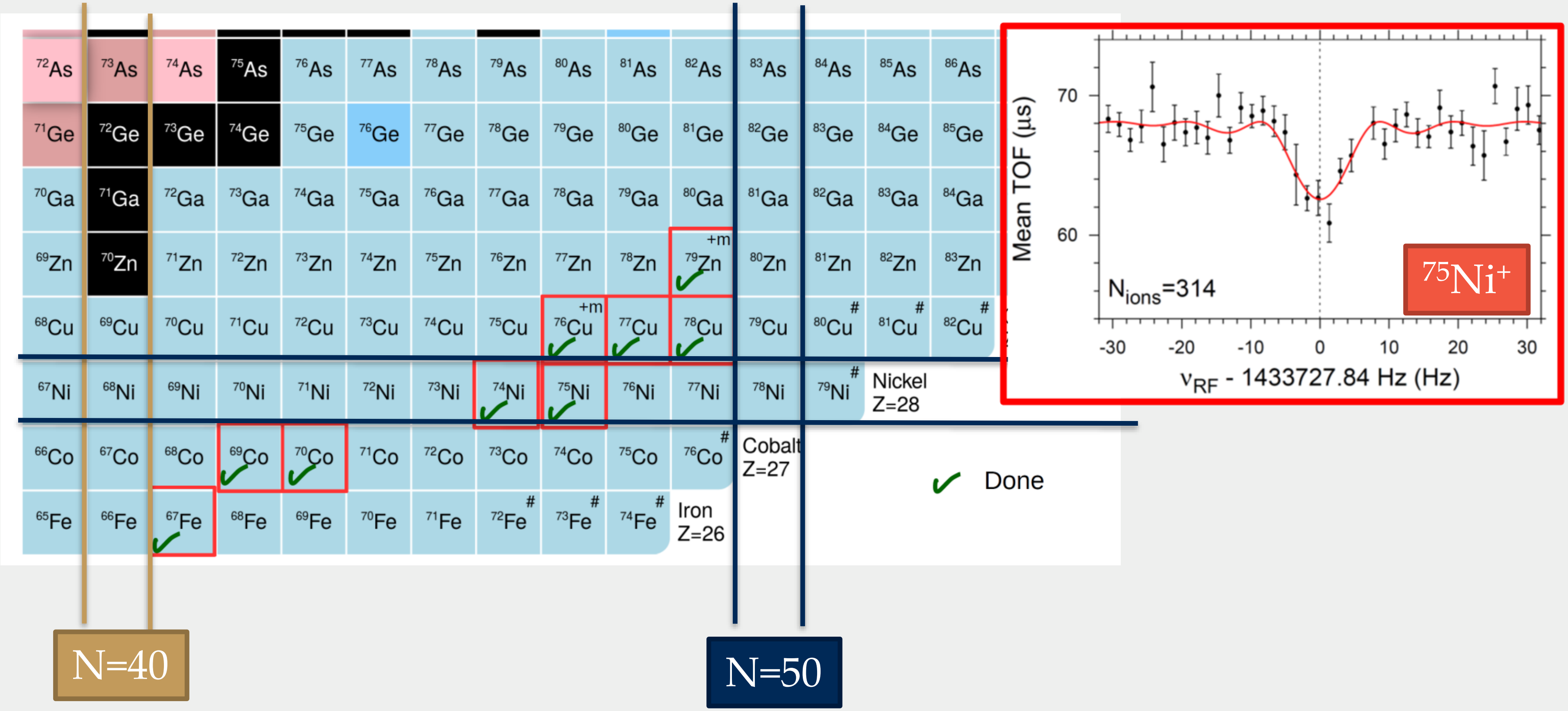
Baseline: AME16 exp. + FRDM12
Neutron-capture rates: TALYS

Mass measurements close to ^{78}Ni: isomeric states

Mass measurements close to N=40 and N=50 at JYFLTRAP

Measured several new isotopes close to N=40 and N=50 at JYFLTRAP

L.C. Canete, S. Giraud, A. Kankainen, B. Bastin et al., in preparation

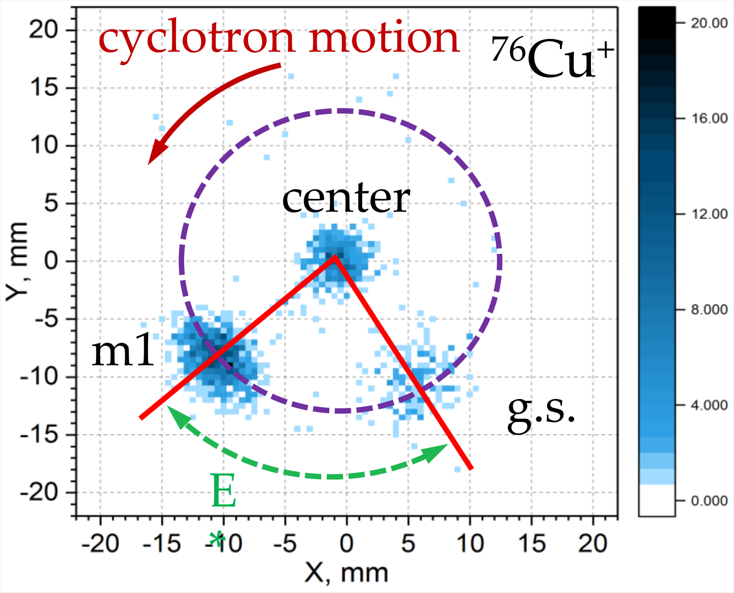


^{72}As	^{73}As	^{74}As	^{75}As	^{76}As	^{77}As	^{78}As	^{79}As	^{80}As	^{81}As	^{82}As	^{83}As	^{84}As	^{85}As	^{86}As
^{71}Ge	^{72}Ge	^{73}Ge	^{74}Ge	^{75}Ge	^{76}Ge	^{77}Ge	^{78}Ge	^{79}Ge	^{80}Ge	^{81}Ge	^{82}Ge	^{83}Ge	^{84}Ge	^{85}Ge
^{70}Ga	^{71}Ga	^{72}Ga	^{73}Ga	^{74}Ga	^{75}Ga	^{76}Ga	^{77}Ga	^{78}Ga	^{79}Ga	^{80}Ga	^{81}Ga	^{82}Ga	^{83}Ga	^{84}Ga
^{69}Zn	^{70}Zn	^{71}Zn	^{72}Zn	^{73}Zn	^{74}Zn	^{75}Zn	^{76}Zn	^{77}Zn	^{78}Zn	+m ^{79}Zn ✓	^{80}Zn	^{81}Zn	^{82}Zn	^{83}Zn
^{68}Cu	^{69}Cu	^{70}Cu	^{71}Cu	^{72}Cu	^{73}Cu	^{74}Cu	^{75}Cu	+m ^{76}Cu ✓	^{77}Cu ✓	^{78}Cu ✓	^{79}Cu	# ^{80}Cu	# ^{81}Cu	# ^{82}Cu
^{67}Ni	^{68}Ni	^{69}Ni	^{70}Ni	^{71}Ni	^{72}Ni	^{73}Ni	^{74}Ni ✓	^{75}Ni ✓	^{76}Ni	^{77}Ni	^{78}Ni	# ^{79}Ni	Nickel Z=28	
^{66}Co	^{67}Co	^{68}Co	^{69}Co ✓	^{70}Co ✓	^{71}Co	^{72}Co	^{73}Co	^{74}Co	^{75}Co	# ^{76}Co	Cobalt Z=27			
^{65}Fe	^{66}Fe	^{67}Fe ✓	^{68}Fe	^{69}Fe	^{70}Fe	^{71}Fe	# ^{72}Fe	# ^{73}Fe	# ^{74}Fe	Iron Z=26				

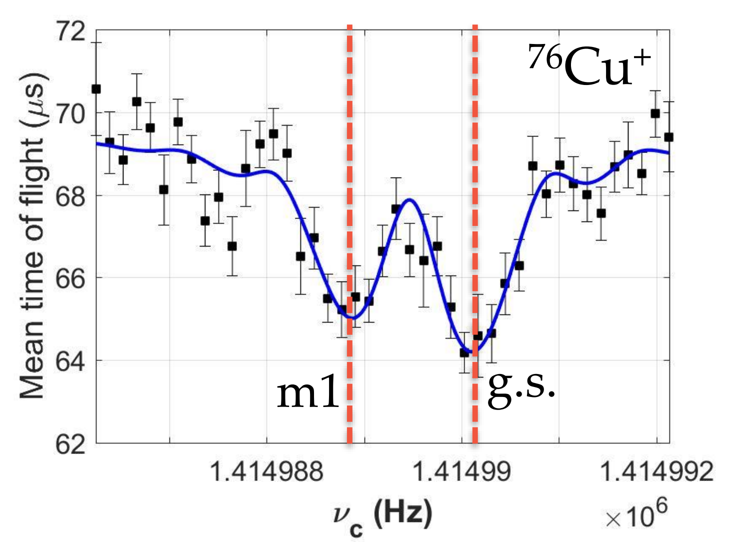
✓ Done

Isomeric states probed via mass measurements

JYFLTRAP: PI-ICR, t_{acc} = 200 ms



JYFLTRAP: TOF-ICR, T_{RF} = 1120 ms



J^π = (1,3) $T_{1/2}$ = 1.27(30) s

E* = 0#(200#) keV

NUBASE
2016

?

J^π = (3,4) $T_{1/2}$ = 637.7(55) ms

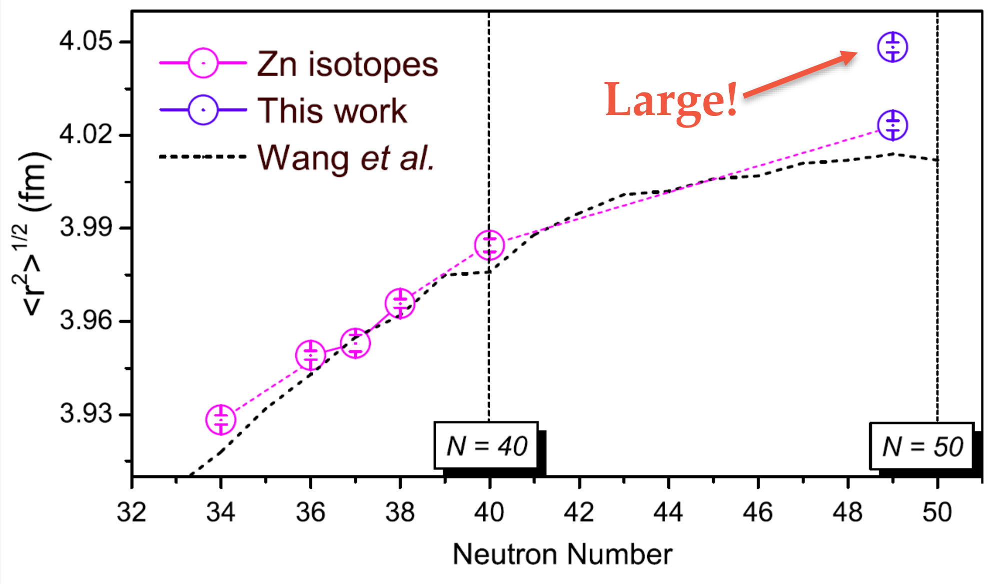
ME = -50976(7) keV

Two half-lives (TRISTAN):
J. A. Winger et al, PRC 42, 954 (1990).

Mass of ^{76}Cu (ISOLTRAP):
C. Guenaut et al., PRC 75, 044303 (2007);
A. Welker et al., PRL 119, 192502 (2017).

Shape coexistence: $^{79}\mathrm{Zn}^{m}$ ($1/2^{+}$)

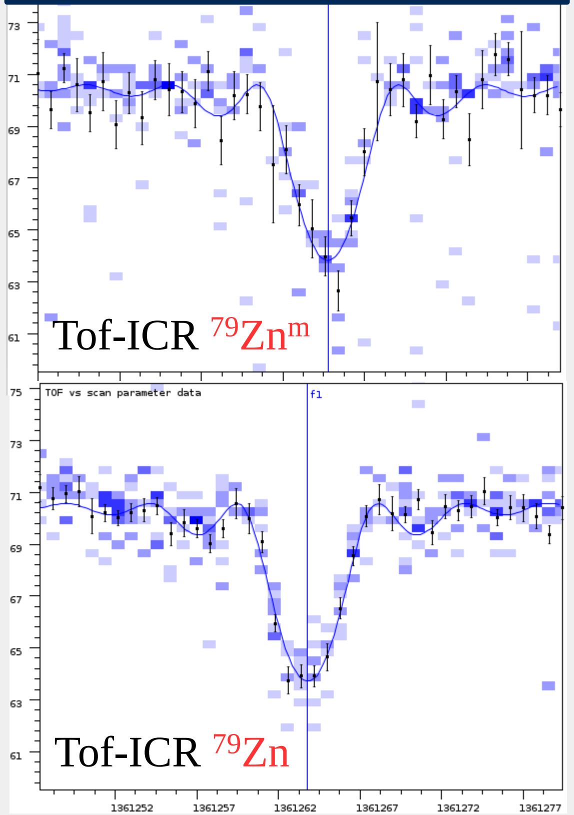
Collinear laser spectroscopy at ISOLDE



X. F. Yang et al. PRL 116, 182502 (2016)

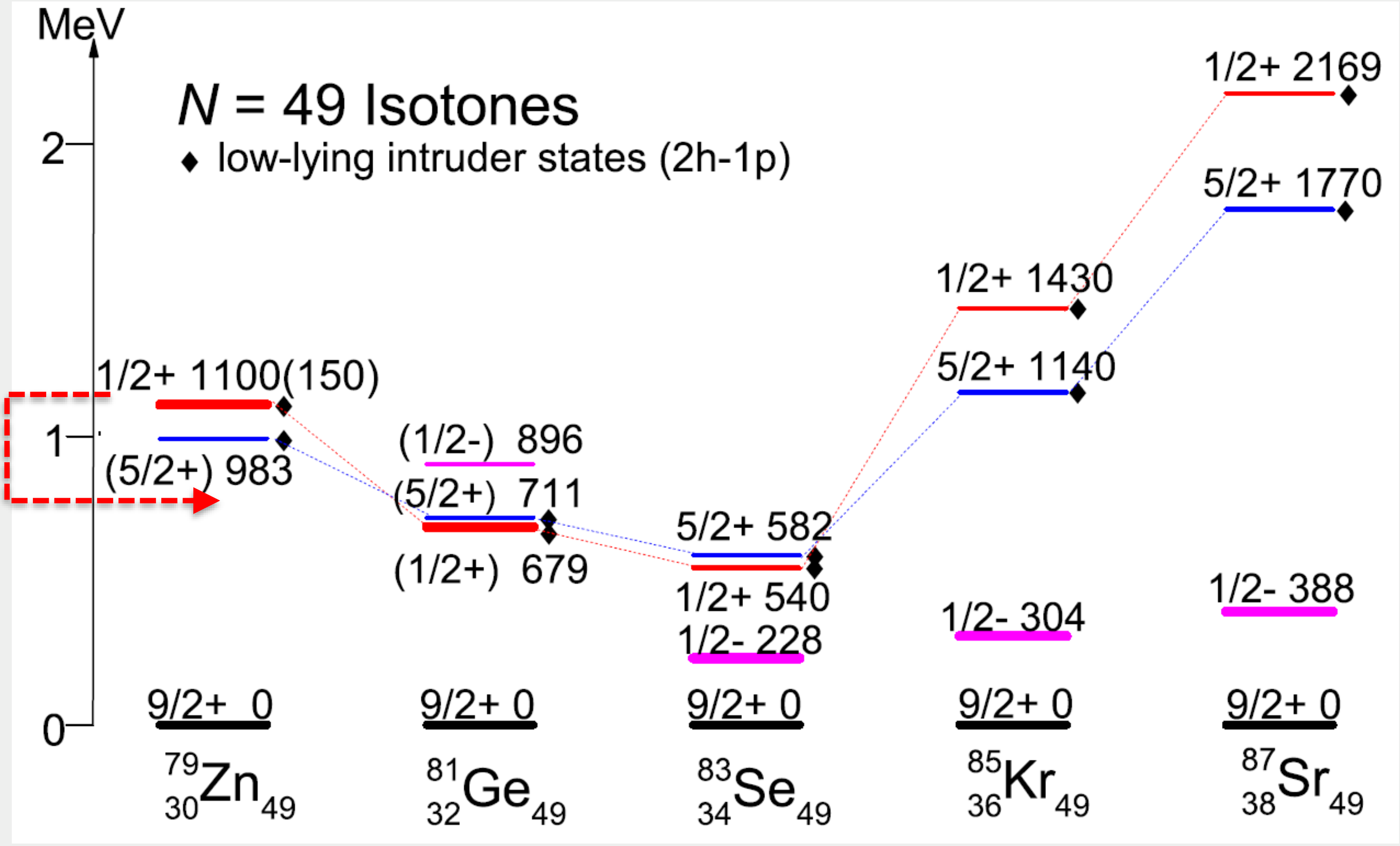
JYFLTRAP:

$$E_x = [m(^{79}Zn^{m}) - m(^{79}Zn)]c^2$$



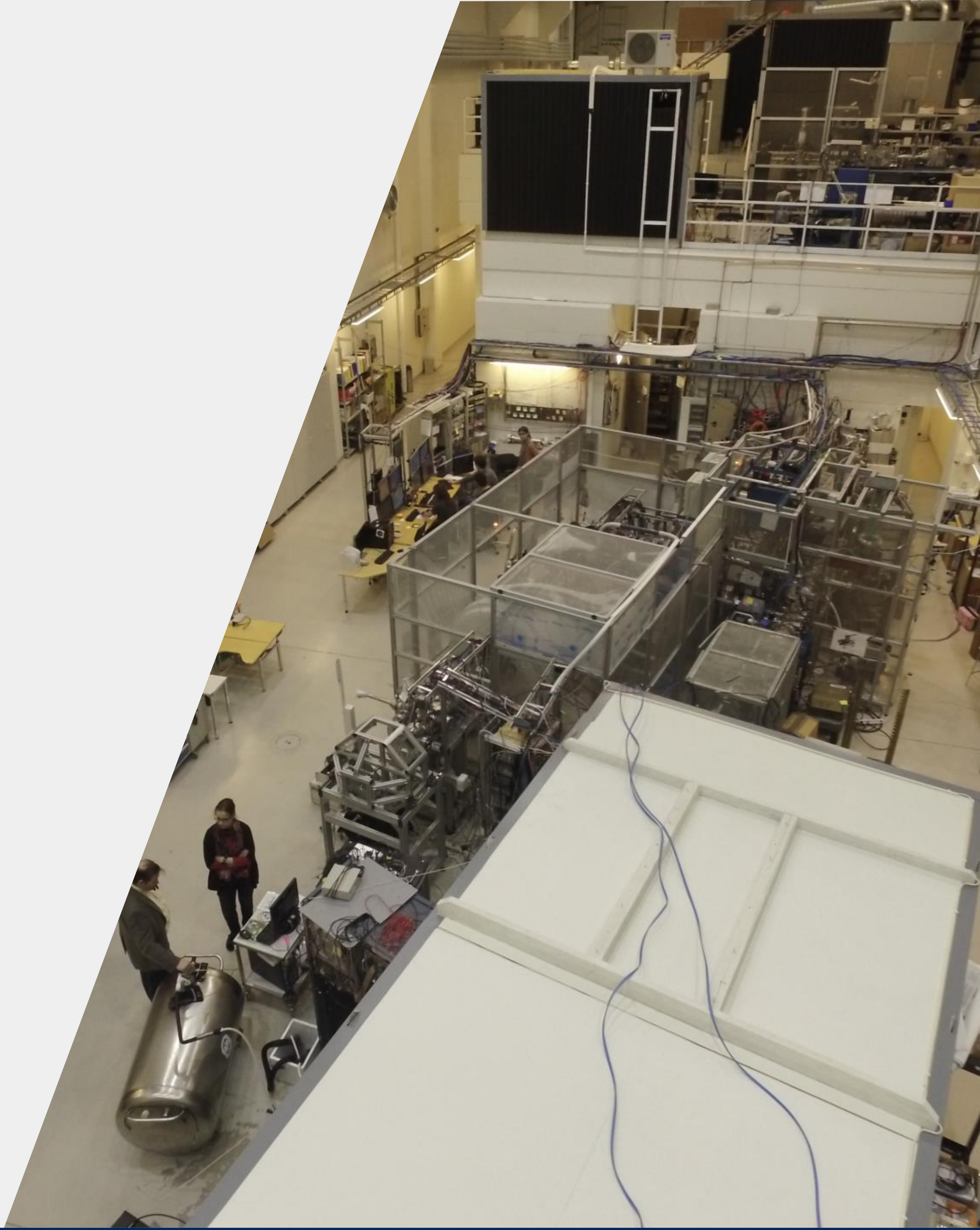
Systematics of N=49 isotones

Shell evolution when moving further away from stability



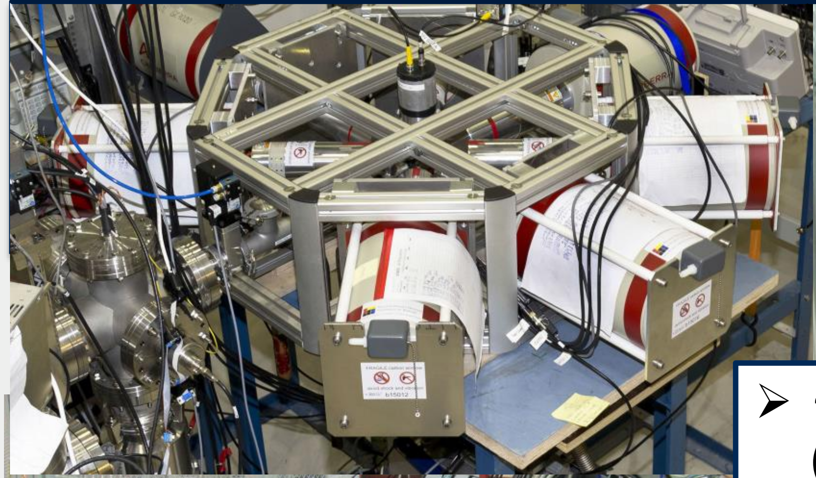
X. F. Yang et al., PRL 116, 182502 (2016)

Outlook



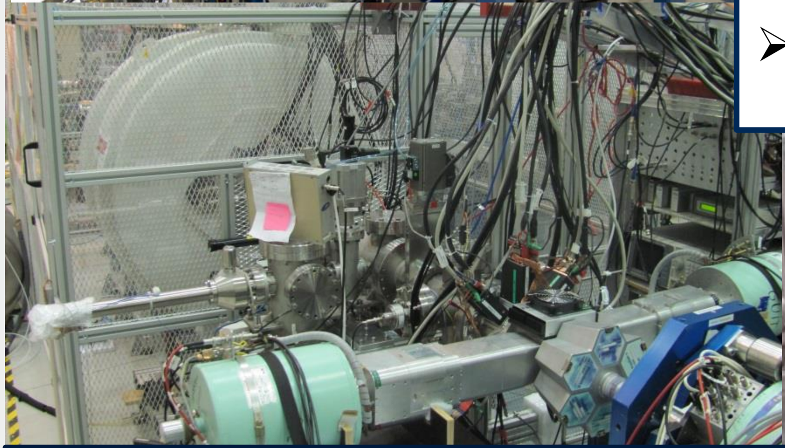
Several decay spectroscopy experiments at IGISOL

BEGE array (Univ. of Warsaw)

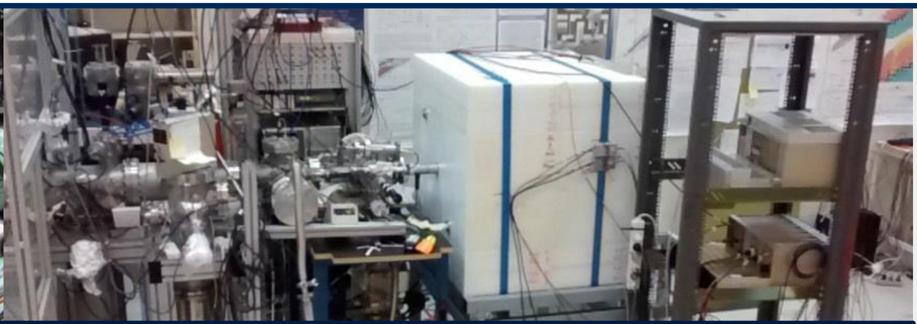


DTAS (total absorption decay spectroscopy)

- γ emission from neutron-unbound states (^{87,88}Br and ^{94}Rb) *J.L. Tain et al., PRL 115 (2015) 062502*
- ^{136}Sb, one of the heaviest $\beta 2n$ emitters studied *R. Caballero-Folch et al., PRC 98, 034310 (2018)*



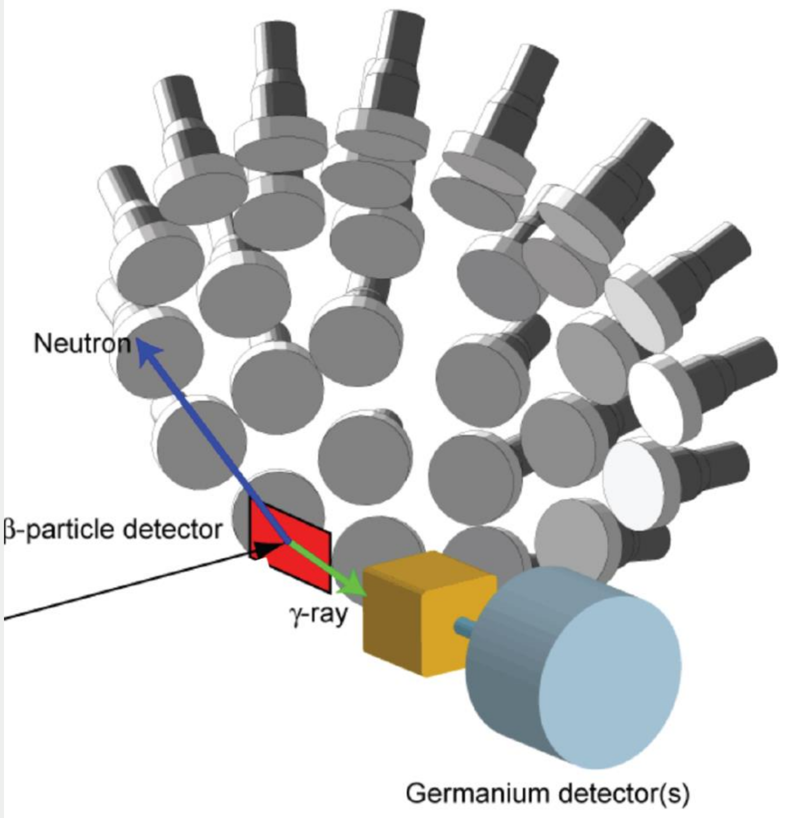
TASISpec (Lund-GSI)



BELEN-48 for beta-delayed neutrons

MONSTER (MOdular Neutron SpectromeTER) NuSTAR@FAIR

Beta-delayed neutron spectroscopy based on time of flight



T. Martínez et al., Nuclear Data Sheets 120 (2014) 78

- 8 modules at IGISOL
- Liquid scintillator detector
- Gamma-neutron separation from pulse shape
- First online tests at IGISOL in Feb 2019 using ^{85}As (P_n= 59.4(24)%)

Acknowledgments

IGISOL
Univ. of Jyväskylä
O. Beliuskina, L. Canete, C. Delafosse, T. Eronen, R. de Groote, A. Jokinen, I.D. Moore, D.A. Nesterenko, H. Penttilä, I. Pohjalainen, S. Rinta-Antila, A. de Roubin, M. Vilén, A. Zadvornaya, J. Äystö
and all the collaborators related to the discussed experiments!

UNIVERSITY OF JYVÄSKYLÄ

ACADEMY OF FINLAND

erc
European Research Council
Established by the European Commission

ERC CoG MAIDEN

INSTITUT FRANÇAIS
FINLANDE

SOCIETAS SCIENTIARUM FENNICA - FINSKA VETENSKAPS-SOCIETETEN
SUOMEN TIEDESEURA THE FINNISH SOCIETY OF SCIENCES AND LETTERS

This work has been supported by the Academy of Finland under grants No. 275389 and 284516, 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).