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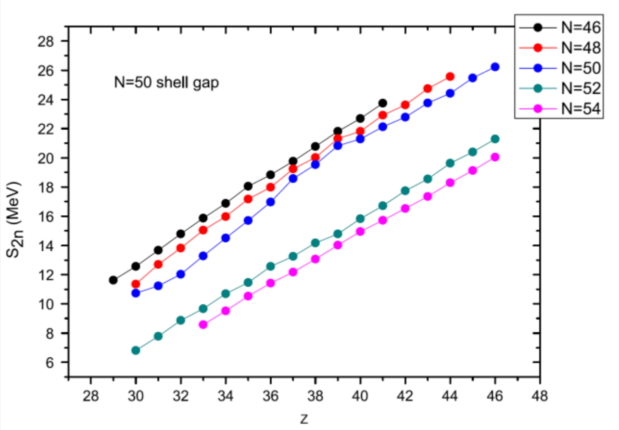
UNIVERSITY OF JYVÄSKYLÄ

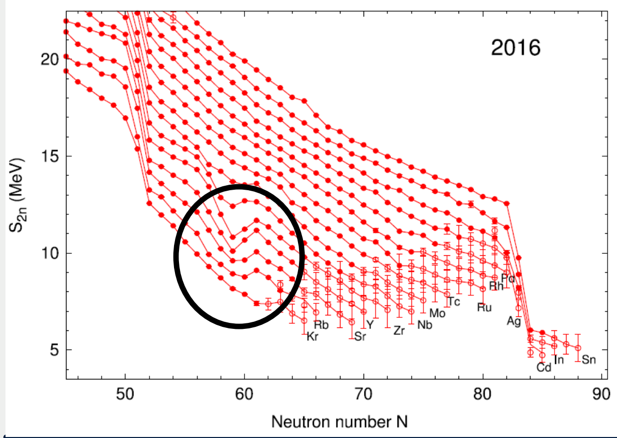
Nuclear structure studies via precision mass measurements

Anu Kankainen

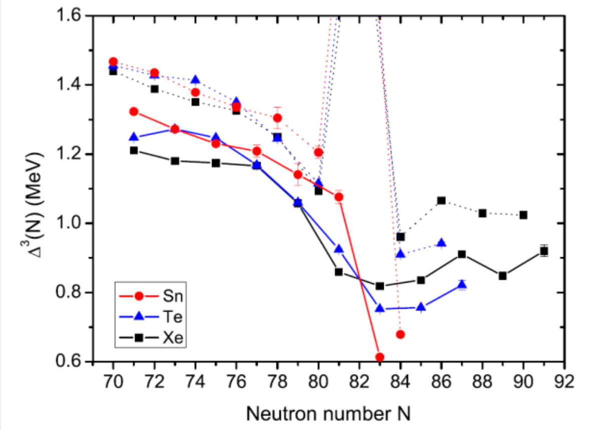
Nuclear structure via mass measurements



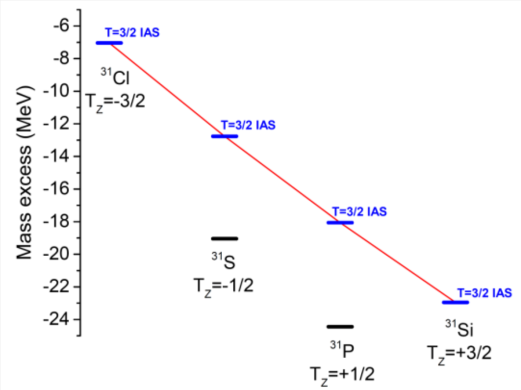
Evolution of shell gaps



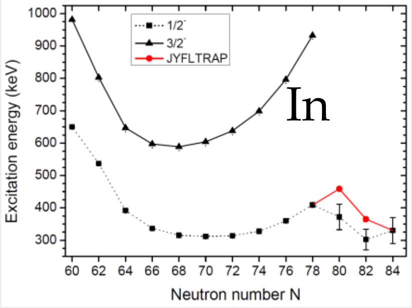
Onset of deformation



Nucleon pairing energies

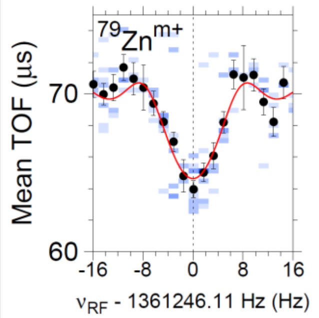


IMME, isospin symmetry



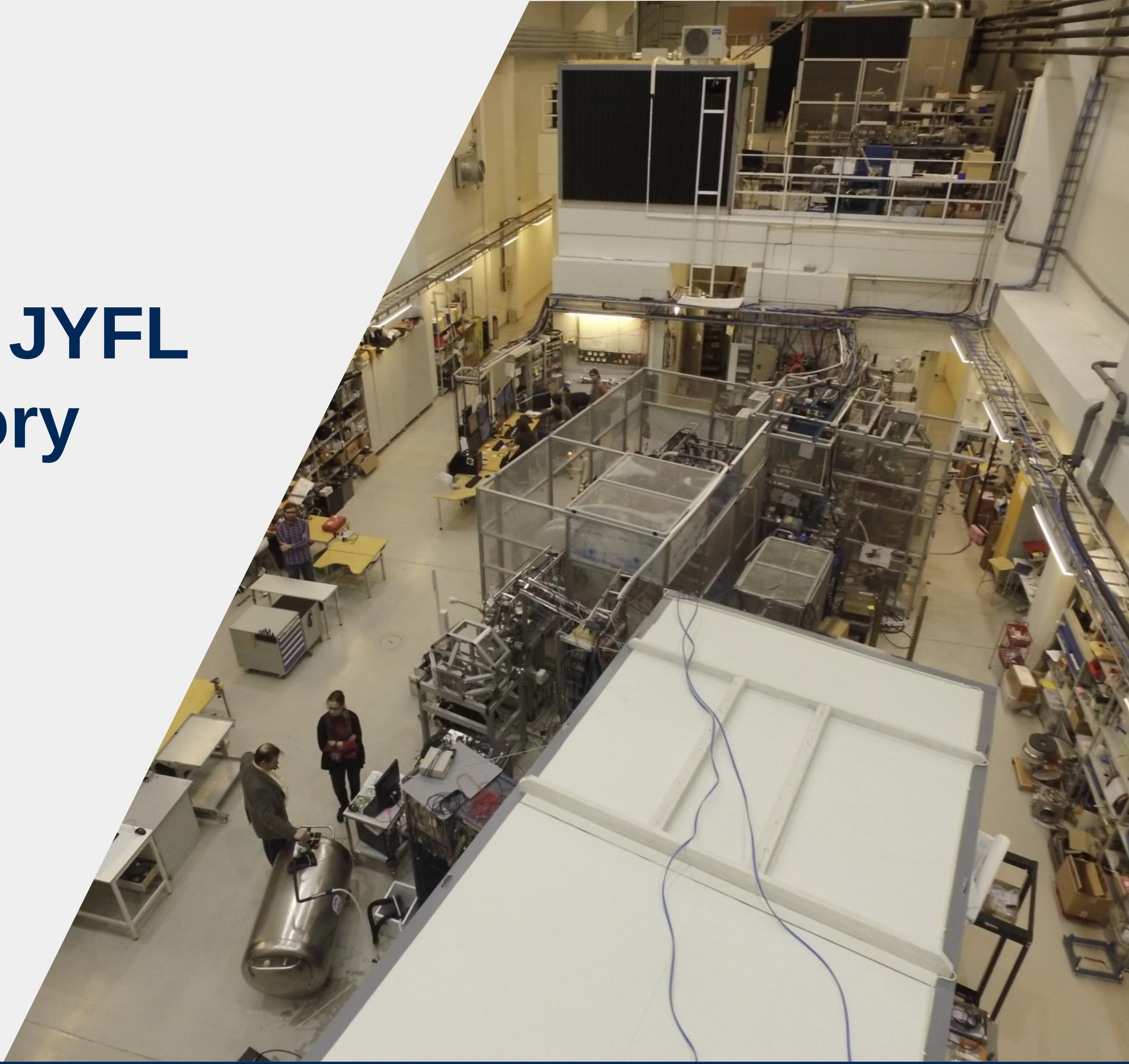
ISOMERS

Single-particle energies

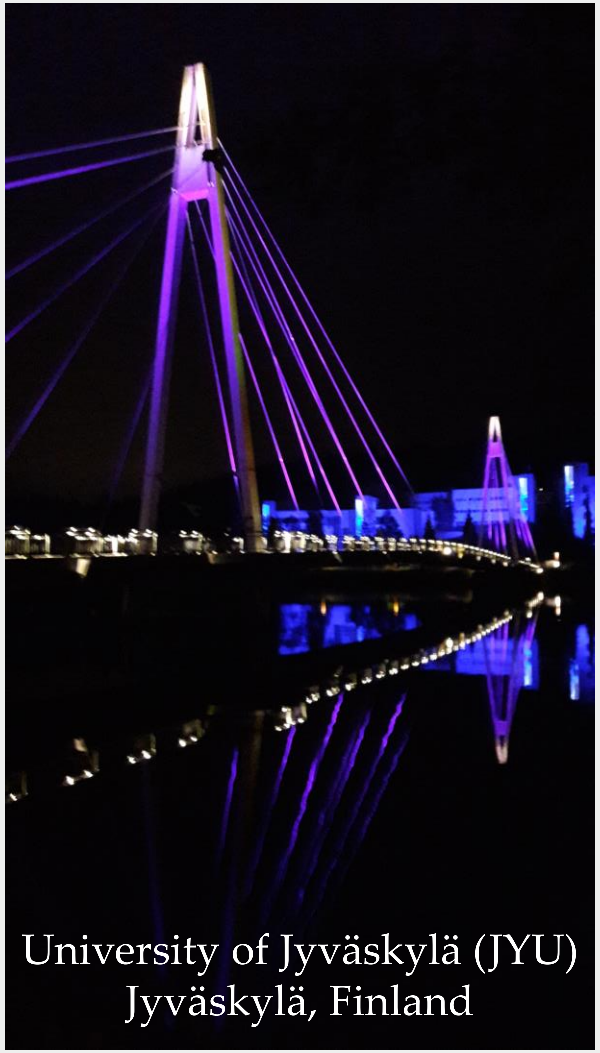


Shape coexistence

IGISOL facility in the JYFL Accelerator Laboratory



JYFL Accelerator Laboratory



FOUR ACCELERATORS

K-130 CYCLOTRON

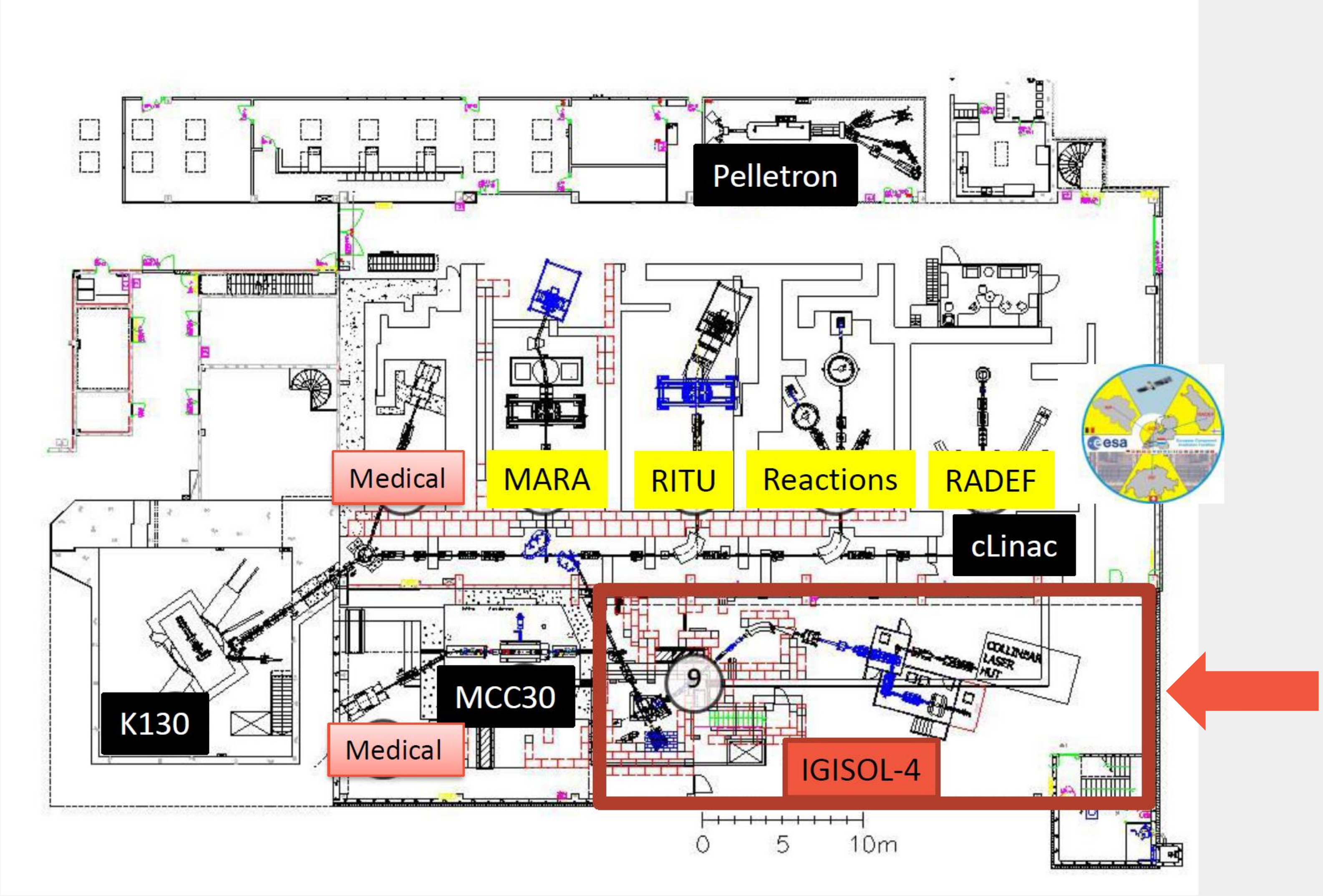
MCC-30/15 CYCLOTRON

1.7 MV PELLETRON

VARIAN cLINAC2100

@jyflacclab

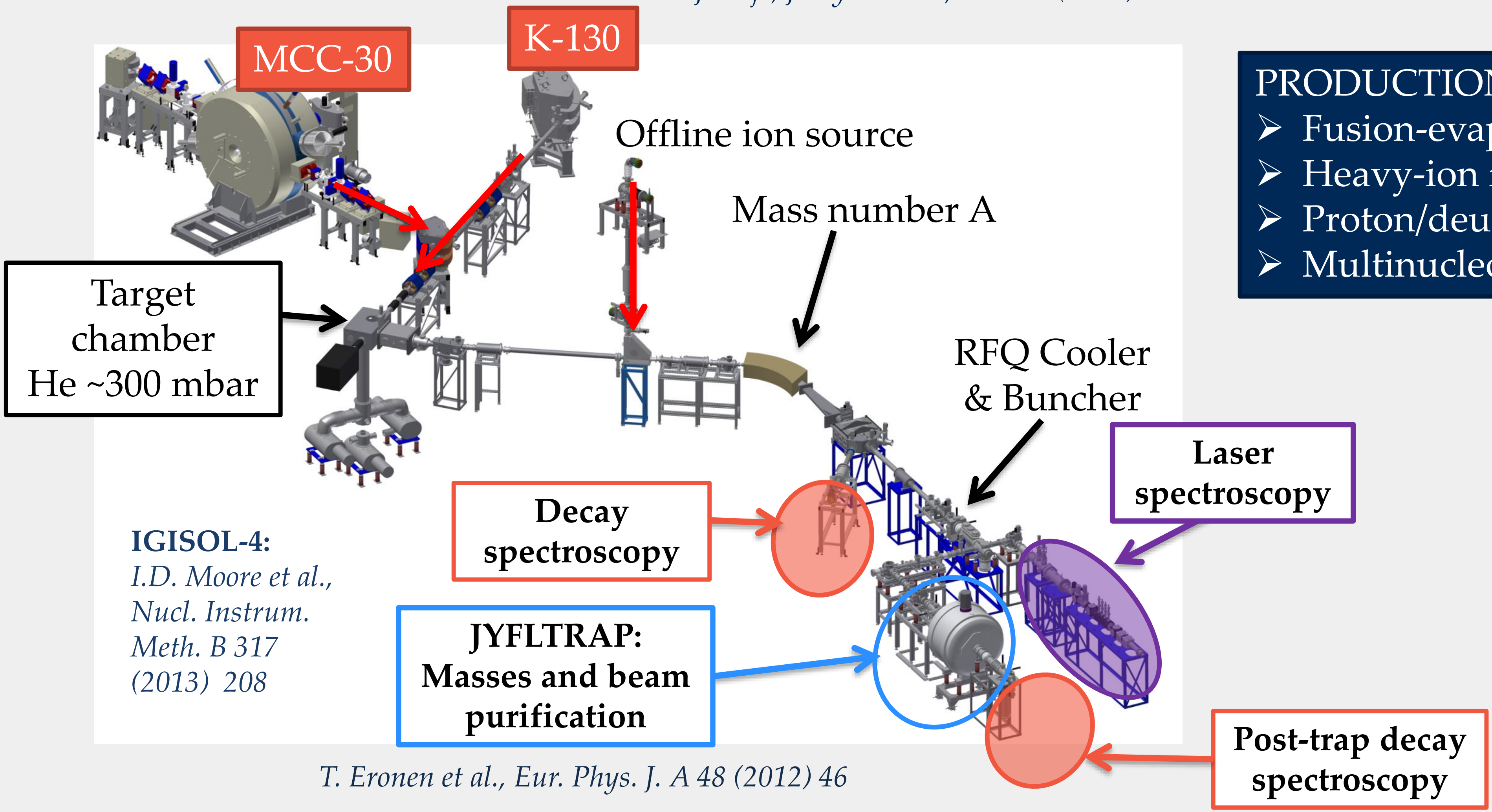
IGISOL facility at JYFL Accelerator Laboratory



IGISOL (Ion Guide Separator On-Line)

- a fast and universal method to produce radioactive beams

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

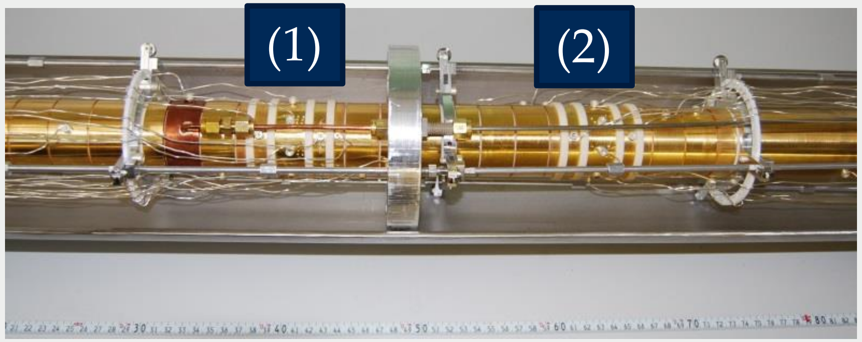


IGISOL-4:
I.D. Moore et al., Nucl. Instrum. Meth. B 317 (2013) 208

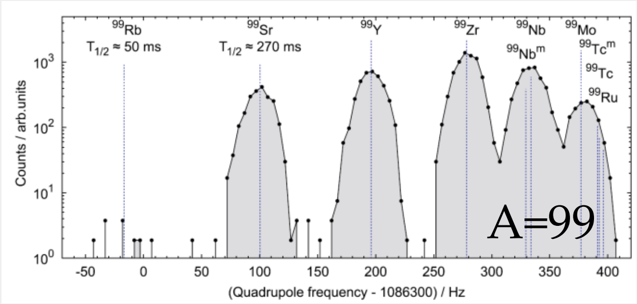
T. Eronen et al., Eur. Phys. J. A 48 (2012) 46

PRODUCTION METHODS:
- Fusion-evaporation
- Heavy-ion fusion-evaporation
- Proton/deuteron-induced fission
- Multinucleon transfer (in progr.)

JYFLTRAP –
a cylindrical double Penning trap at IGISOL



(1) PURIFICATION TRAP
- Selecting the ions

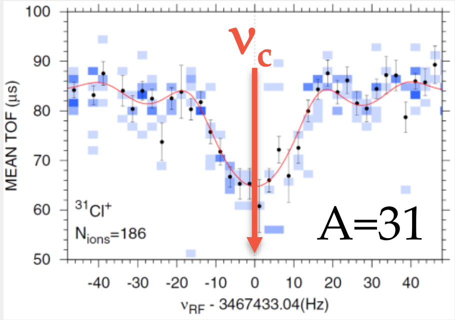


Mass-selective buffer gas cooling technique
Savard et al., Phys. Lett. A 158, 247 (1991)

Ion's cyclotron resonance frequency:

B with a reference ion:

(2) PRECISION TRAP
- Mass measurements



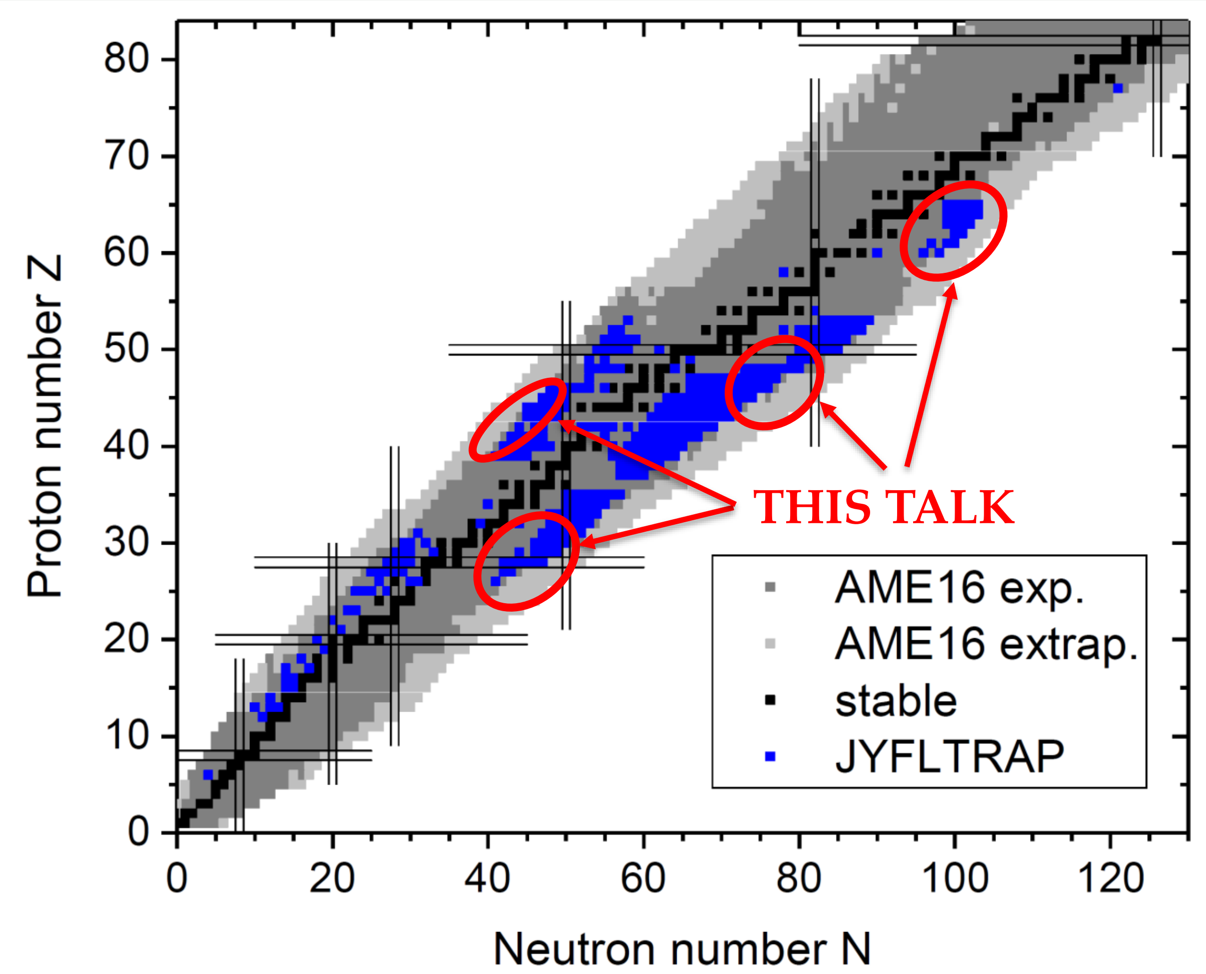
Time-of-Flight Ion Cyclotron Resonance (TOF-ICR) technique
M. König et al., Int. J. Mass Spectrom. Ion Proc. 142, 95 (1995)

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

mass

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

Nuclides measured with JYFLTRAP



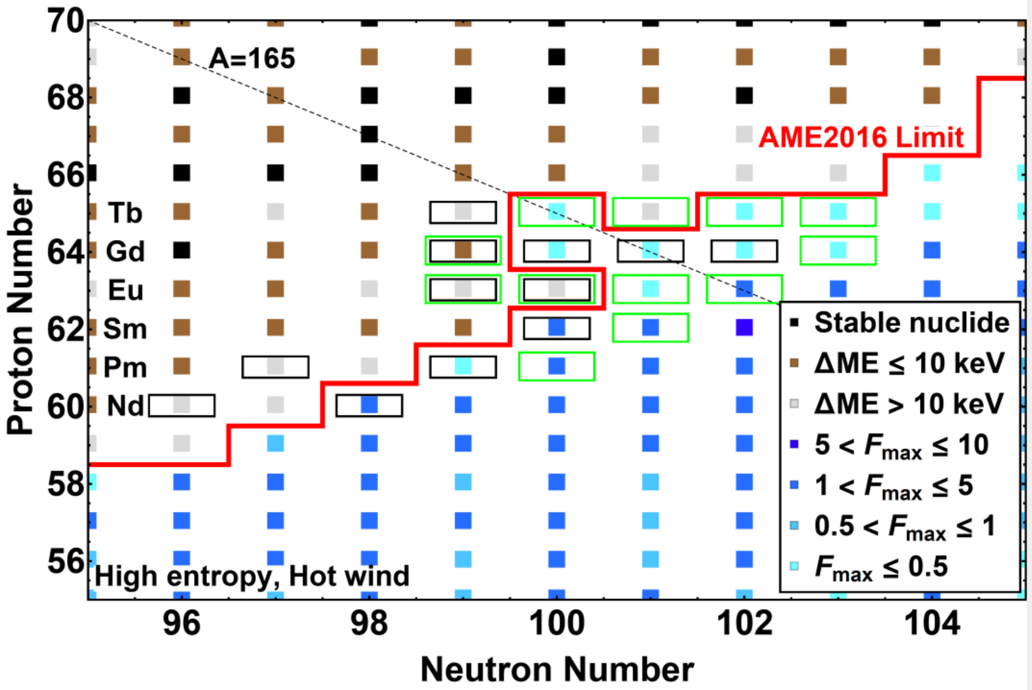
JYFLTRAP:

- Over 340 nuclides measured
  - ~100 neutron-deficient
  - ~220 neutron-rich
  - ~20 stable
- More than 50 isomeric states
- Typical precisions: ~10 ppb

Neutron-rich rare-earth isotopes

Neutron-rich rare-earth isotopes

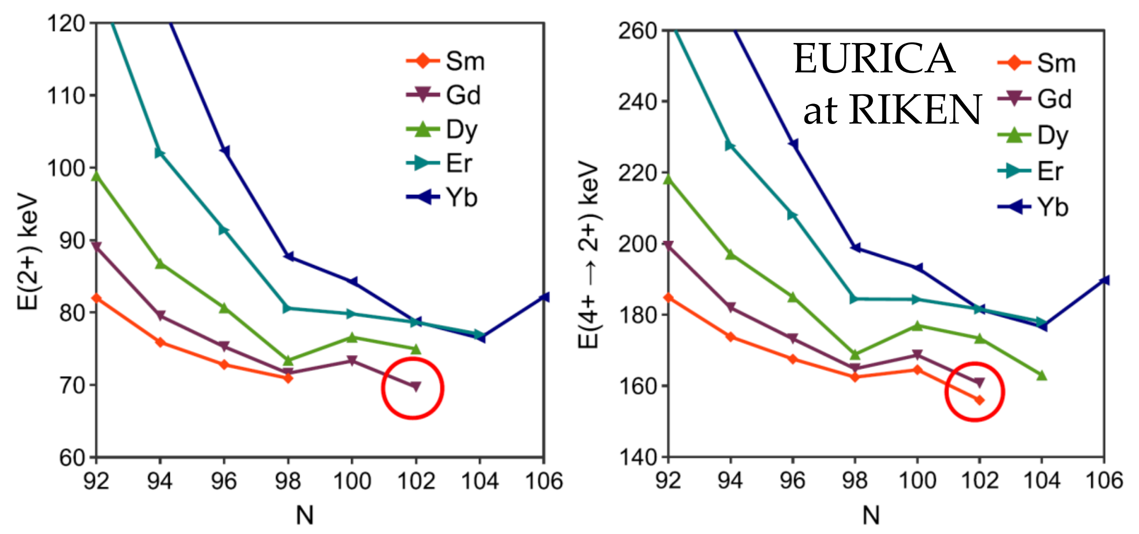
- 21 rare-earth isotopes measured
- 14 masses measured for the first time
- Mainly TOF-ICR, recently also PI-ICR
- Campaign I: *M. Vilén et al., PRL 120, 262701 (2018)*
- Campaign II: *in preparation*



Motivated by the rare-earth abundance peak in the astrophysical r process

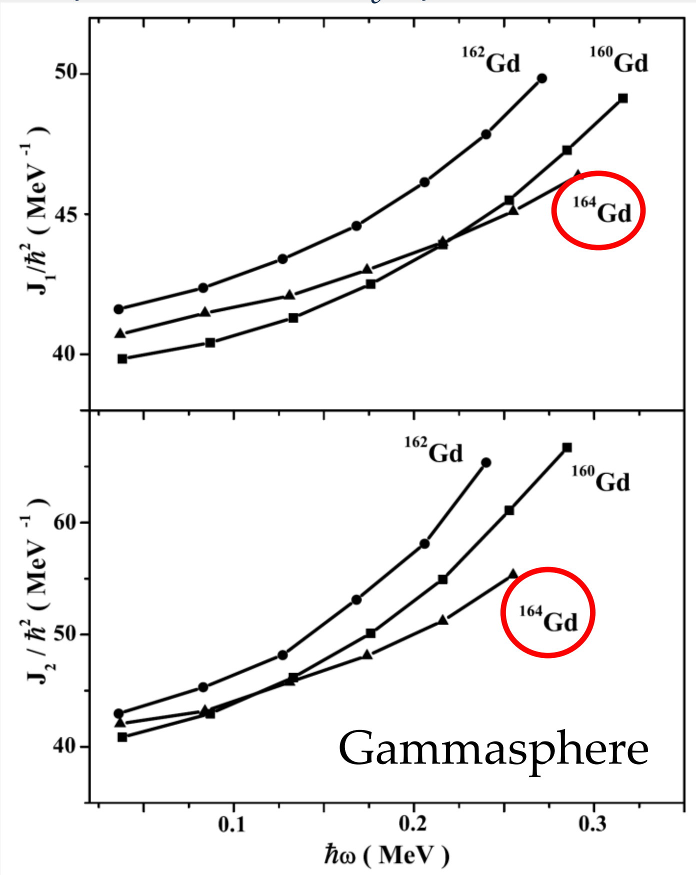
Nuclear structure motivation: N=100?

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



Local maximum at N=100 - deformed shell closure?
Suggested by mean-field calculations [*L. Satpathy and S. Patra, Nucl. Phys. A 722, (2003) C24 & J. Phys. G 30 (2004) 771*]

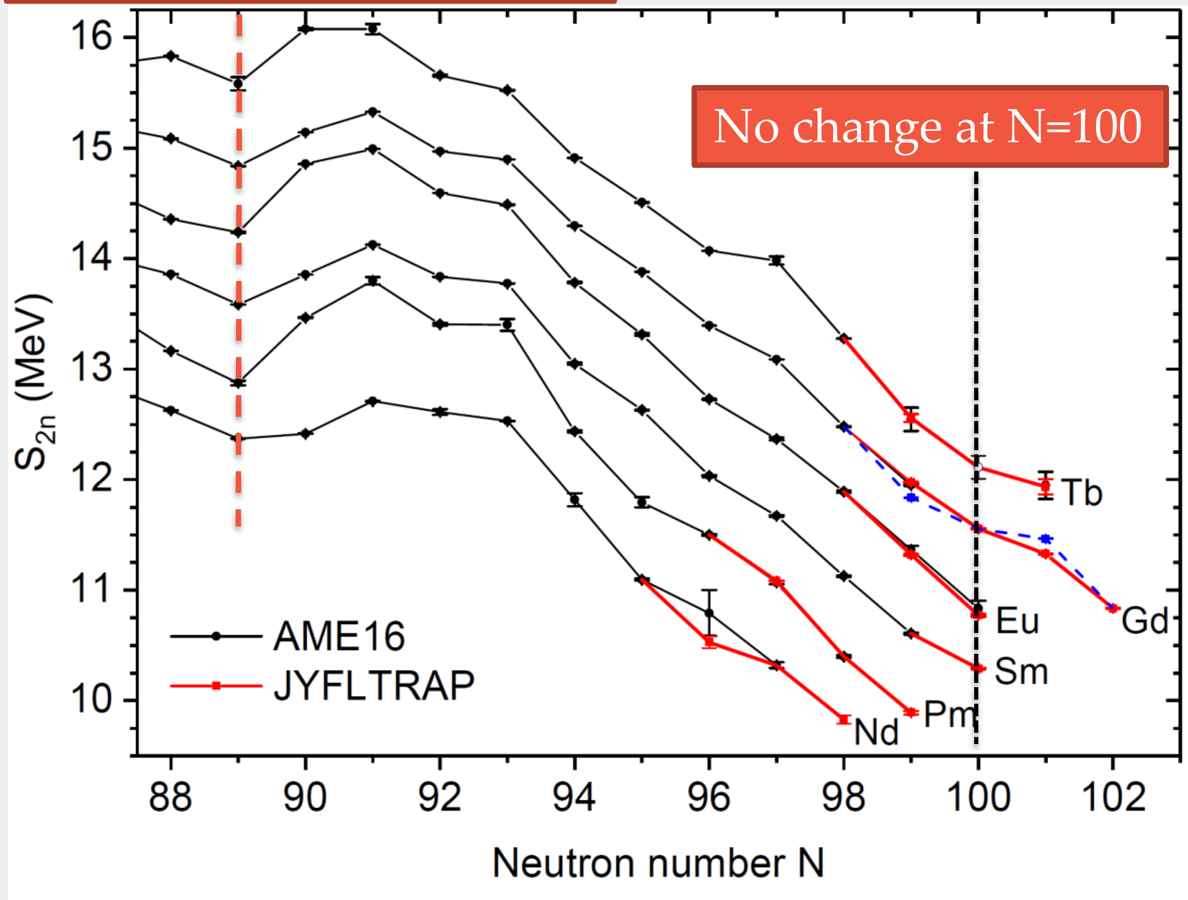
E.F. Jones et al, Eur. Phys. J. A 25 (2005) 467



^{164}Gd (N=100) more rigid than ^{160,162}Gd
Change in structure at N=98?

Two-neutron separation energies S_{2n}

Onset of deformation

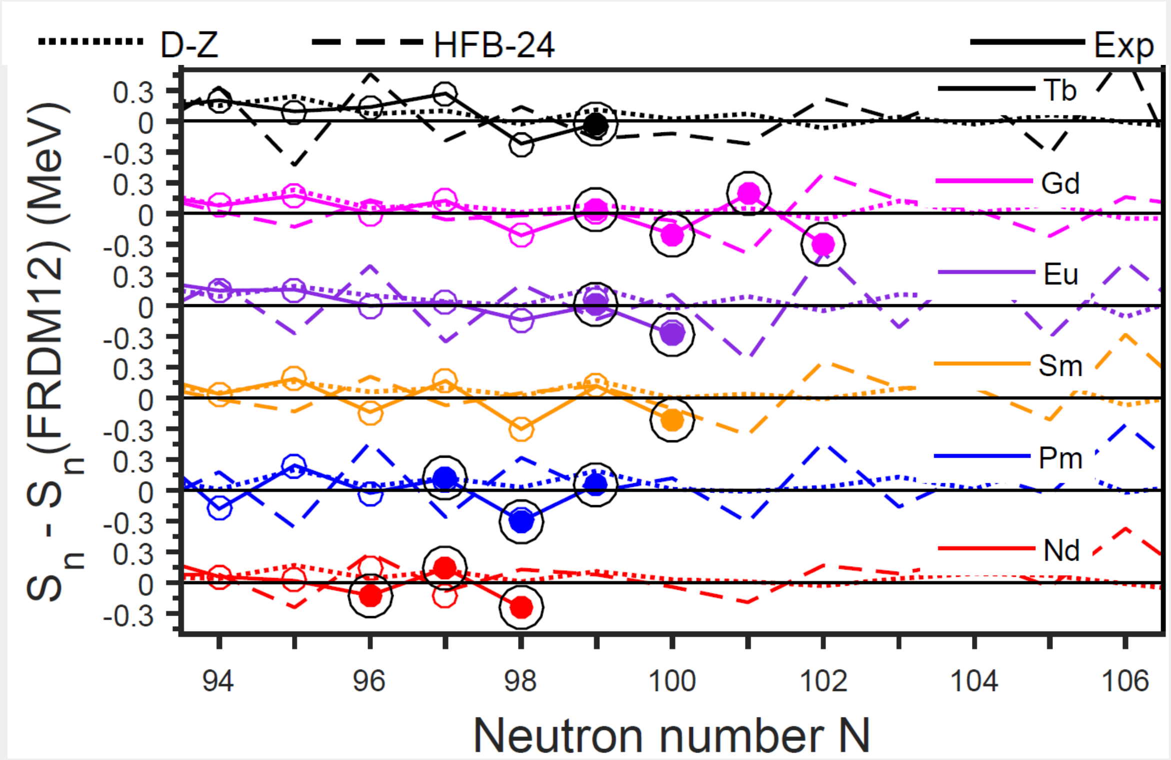


M. Vilén et al., PRL 120, 262701 (2018)

^{163}Gd g.s. measured

No clear indication of a subshell closure at N=100 based on two-neutron separation energies

Neutron separation energies S_n



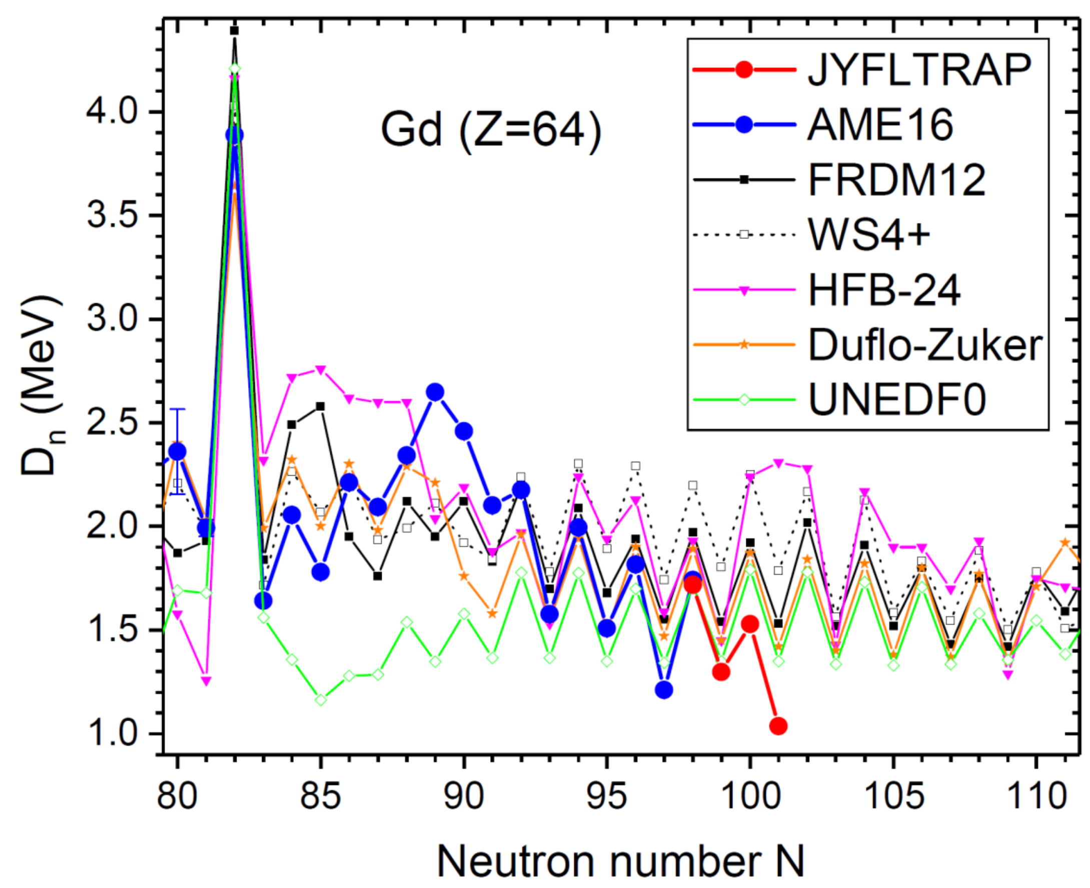
Lower for N = 96, 98, 100, 102
Higher for N = 97, 99, 101

Less odd-even staggering (weaker pairing) than predicted by the models

Neutron pairing

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

Empirical neutron pairing gap or odd-even staggering parameter



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

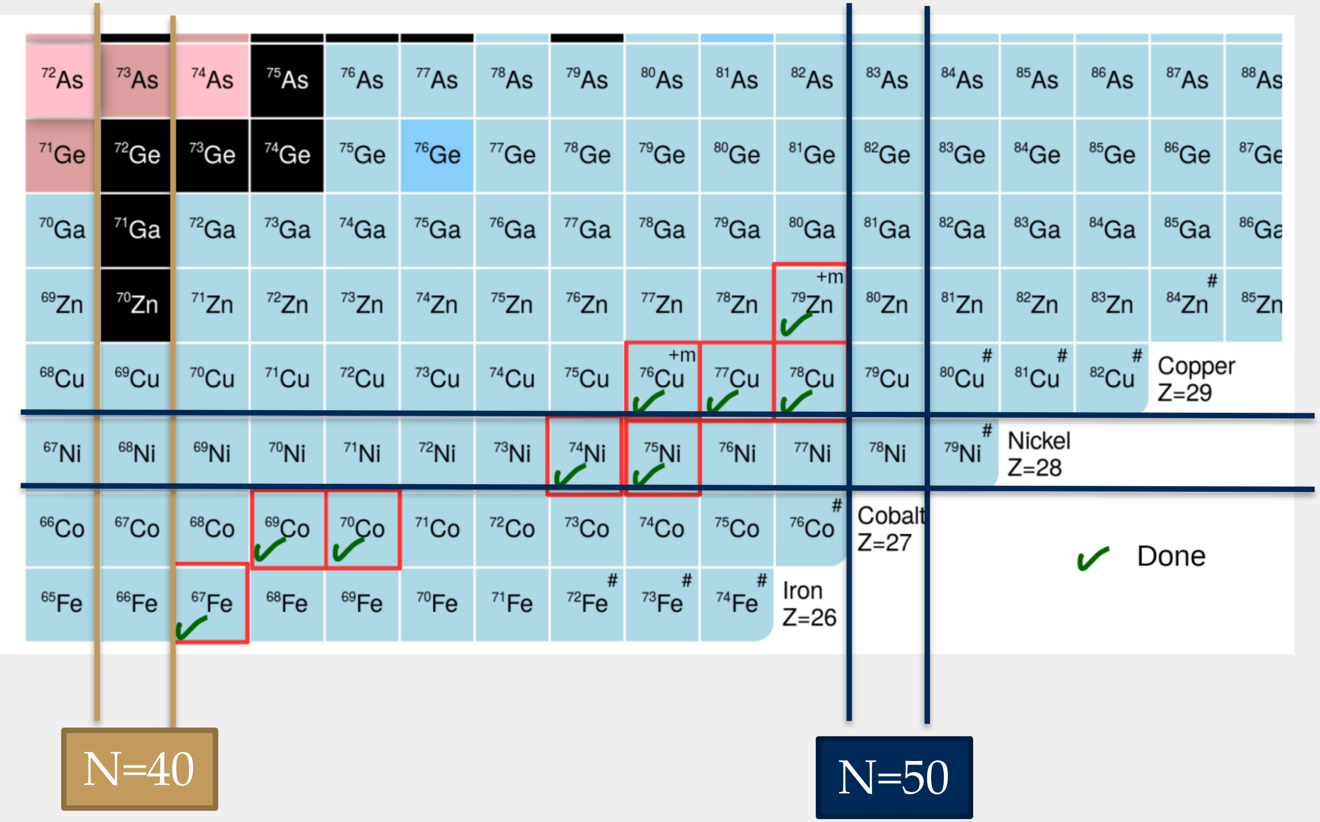
Experimental **neutron pairing weaker** than predicted by theoretical models when approaching the midshell!

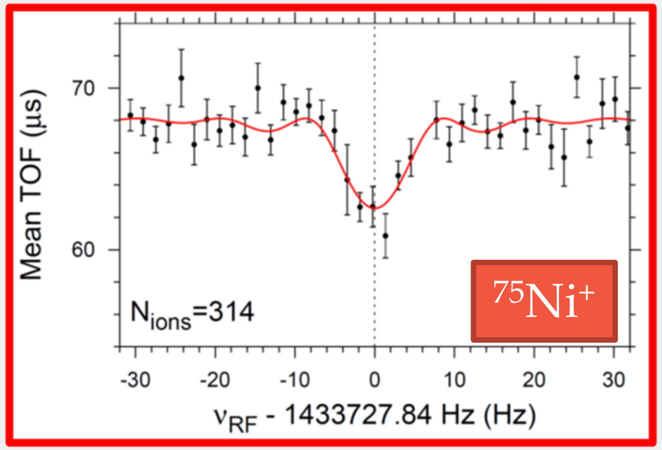
Nuclei close to ^{78}Ni

Mass measurements close to N=40 and N=50

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

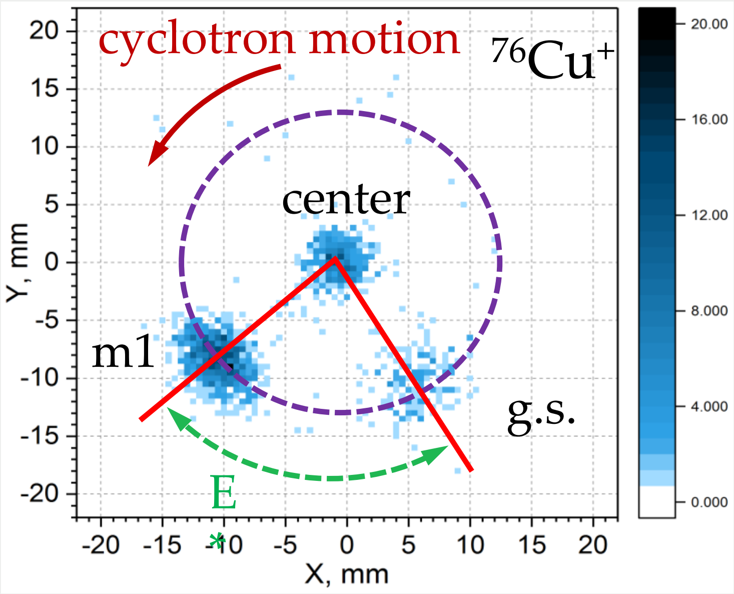
L.C. Canete, S. Giraud, A. Kankainen, B. Bastin et al., in preparation



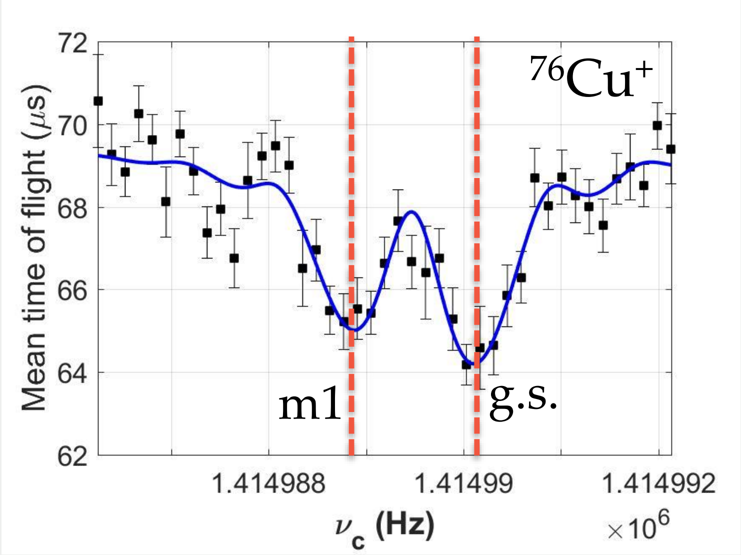


Phase-Imaging Ion Cyclotron Resonance technique (PI-ICR): resolving low-lying isomers

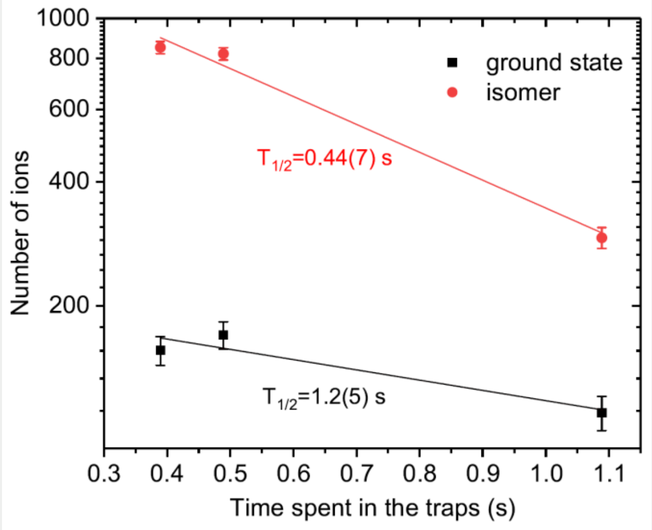
JYFLTRAP: PI-ICR, t_{acc} = 200 ms



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



JYFLTRAP: estimate for $T_{1/2}$



^{76}Cu

NUBASE 2016

J^{π} = (1,3) $T_{1/2}$ = 1.27(30) s

E* = 0#(200#) keV

?

J^{π} = (3,4) $T_{1/2}$ = 637.7(55) ms

ME = -50976(7) keV

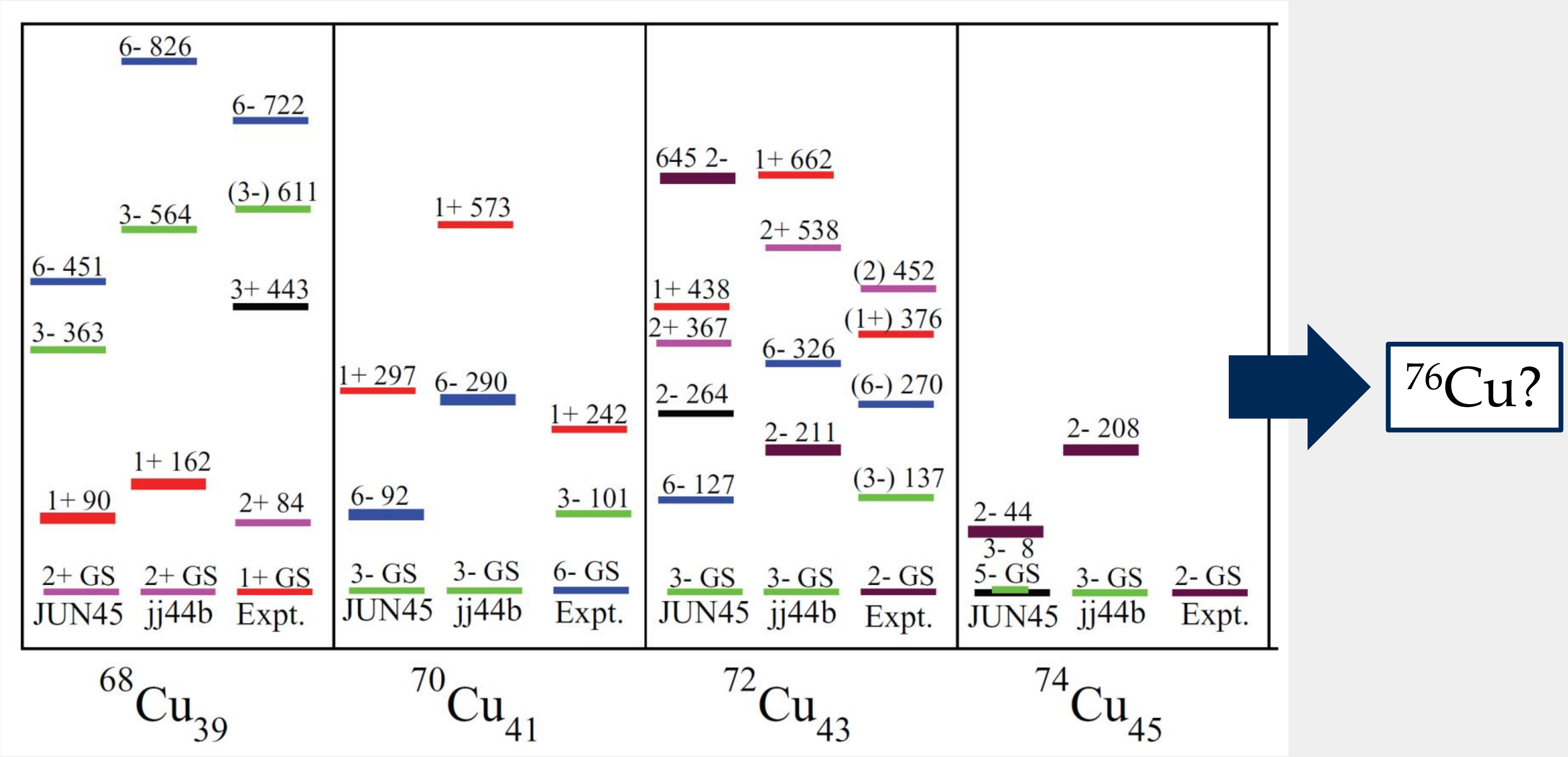
Two half-lives (TRISTAN):
J. A. Winger et al, PRC 42, 954 (1990).

Mass of ^{76}Cu (638 ms state; ISOLTRAP):
C. Guenaut et al., PRC 75, 044303 (2007);
A. Welker et al., PRL 119, 192502 (2017).

✓ There are two states!

Systematics of Cu isotopes

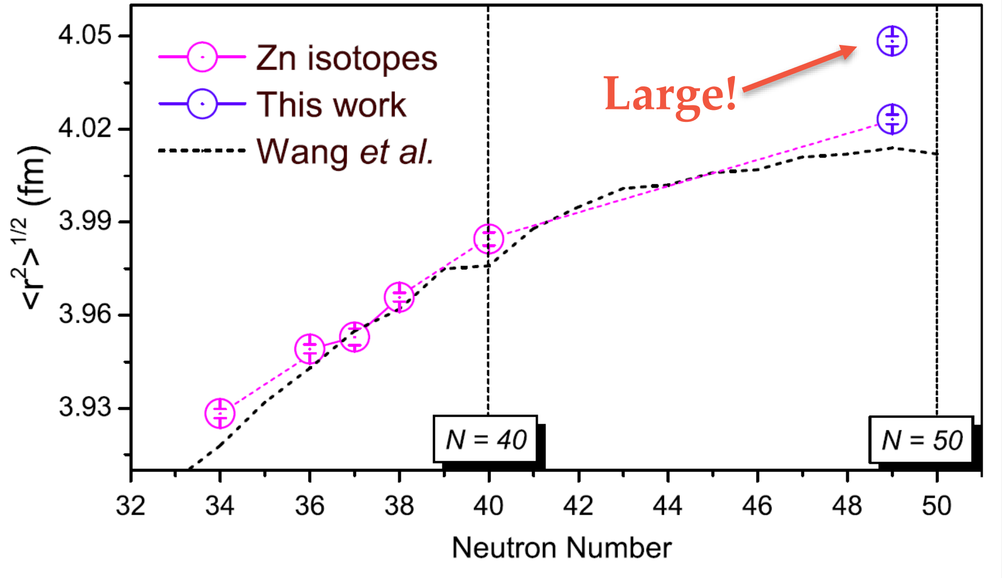
Vingerhoets et al., PRC 82 (2010) 064311



Shape coexistence in the ^{78}Ni region: ^{79}Zn^{m}

Isomeric state with an exceptionally large root-mean-square radius and spin $1/2^+$

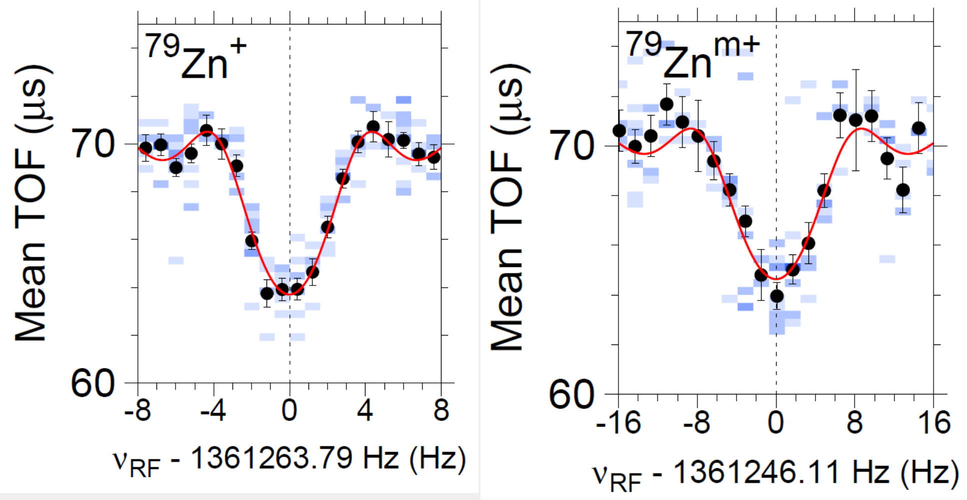
Collinear laser spectroscopy at ISOLDE



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

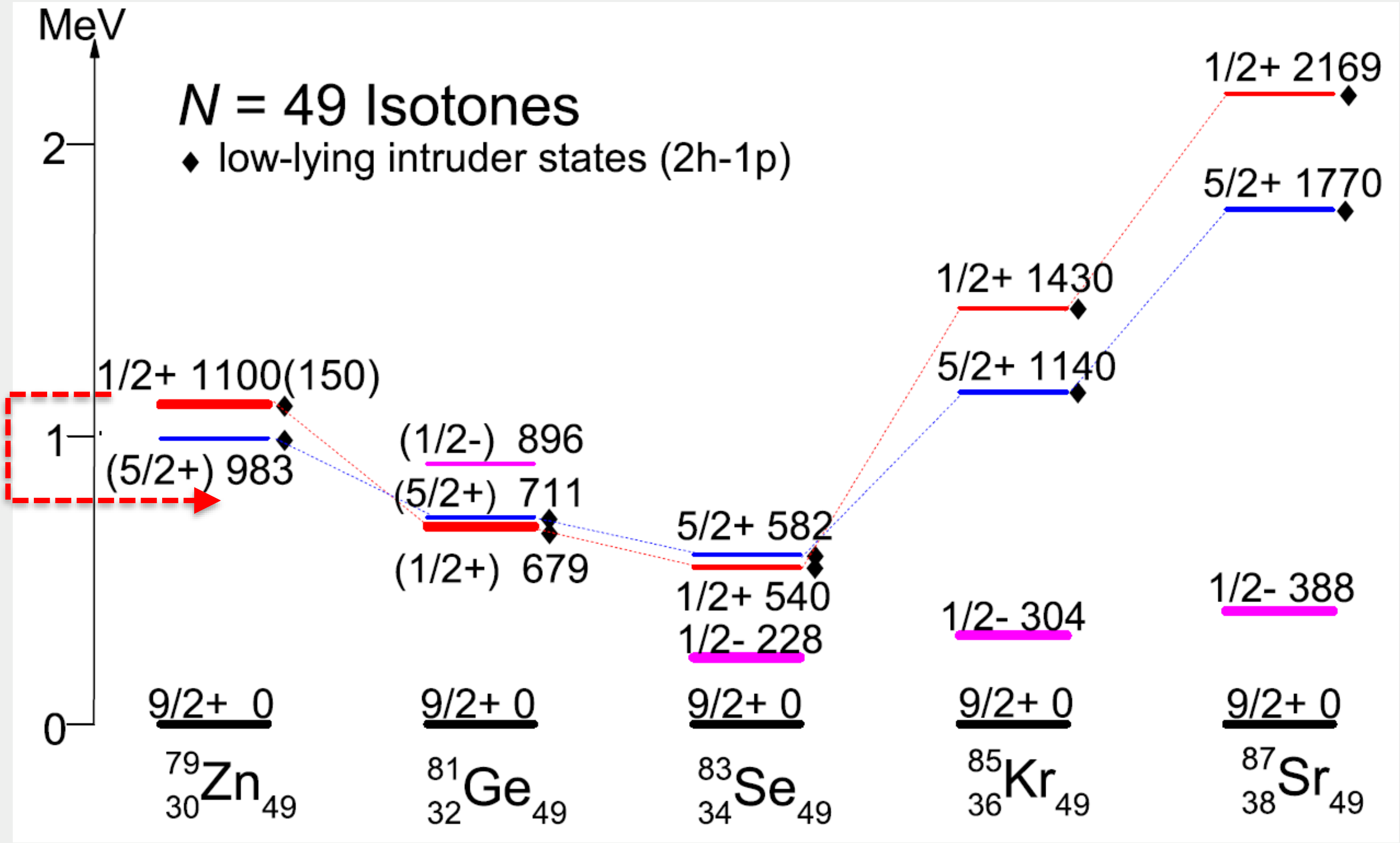
Excitation energy from masses:
$E_x = [m(isomer)-m(g.s.)]c^2$

JYFLTRAP TOF-ICR measurements



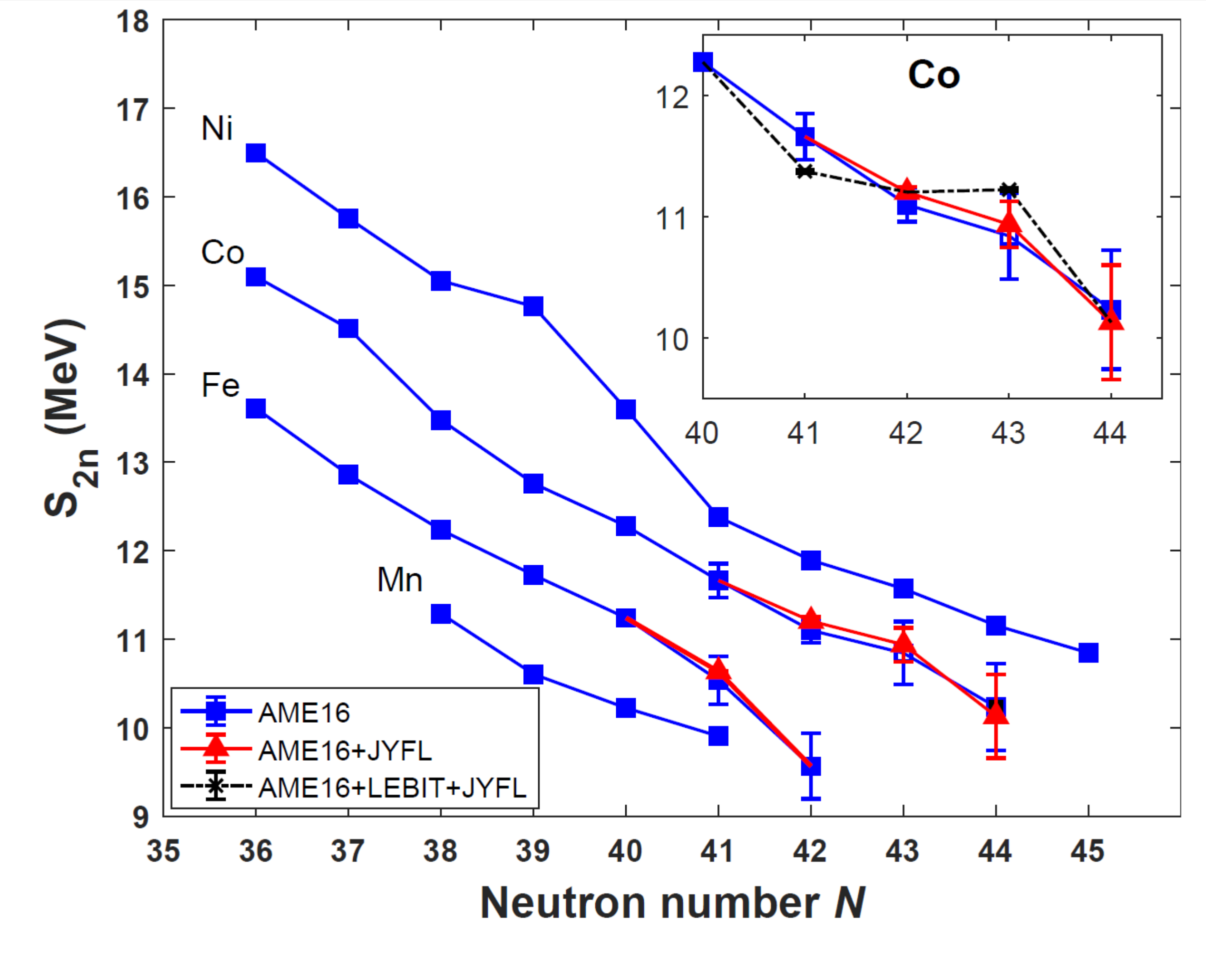
Systematics of N=49 isotones

Shell evolution when moving further away from stability



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

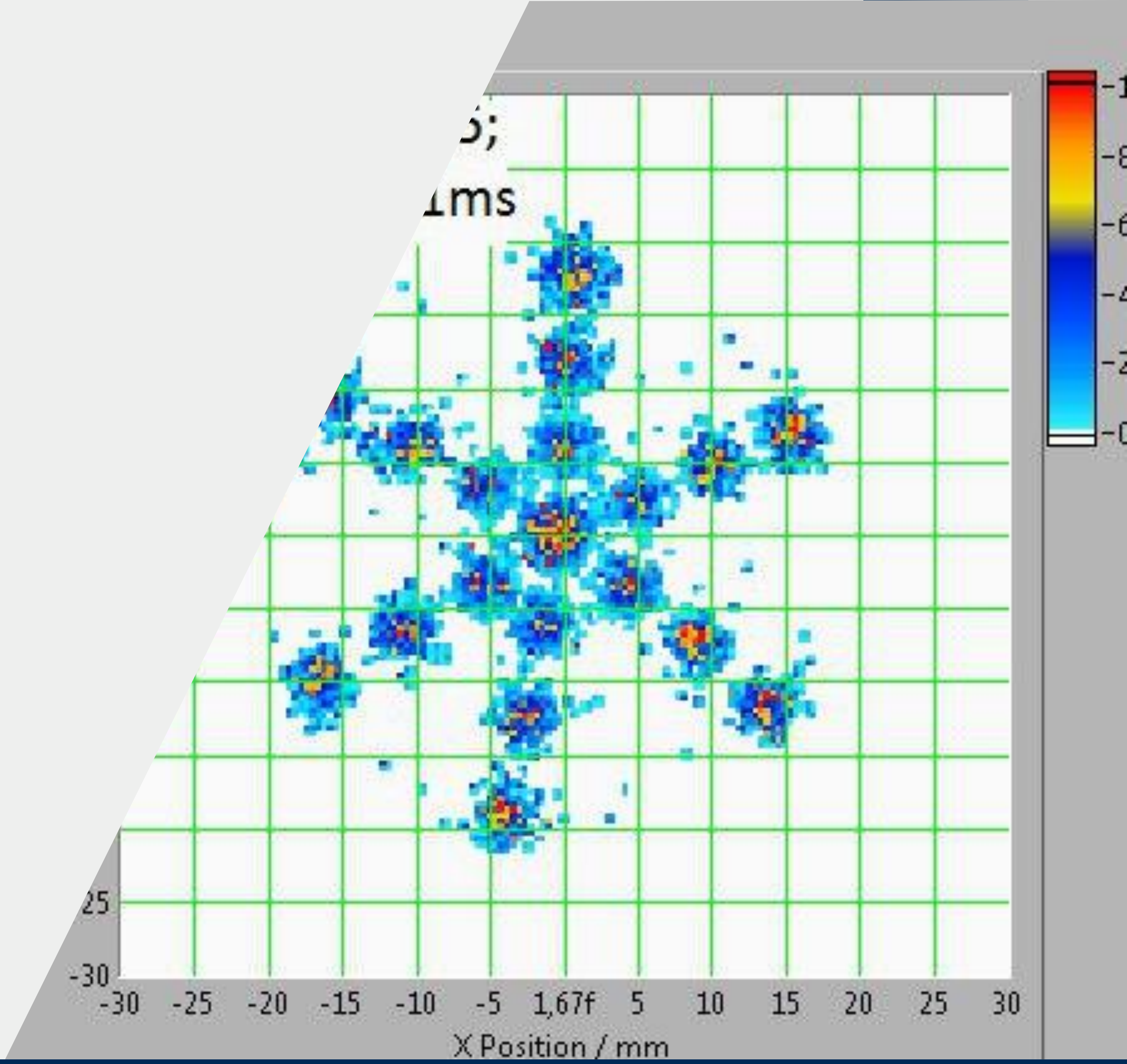
N=40 subshell closure



L. Canete, S. Giraud, A. Kankainen, B. Bastin et al., submitted

- Measurements of ^{67}Fe and ^{69,70}Co at JYFLTRAP
- N=40 subshell closure below ^{68}Ni weak
- Previous measurements of ^{68}Co and ^{69}Co [*Izzo et al., PRC 97, 014309 (2018)*] most likely measured the isomer, not the ground state
  → anomaly in the S_{2n} plot
- Ground and isomeric states determined for ^{69}Co at JYFLTRAP
  → location of the 1/2- intruder state at N=42

Nuclei close to ^{132}Sn

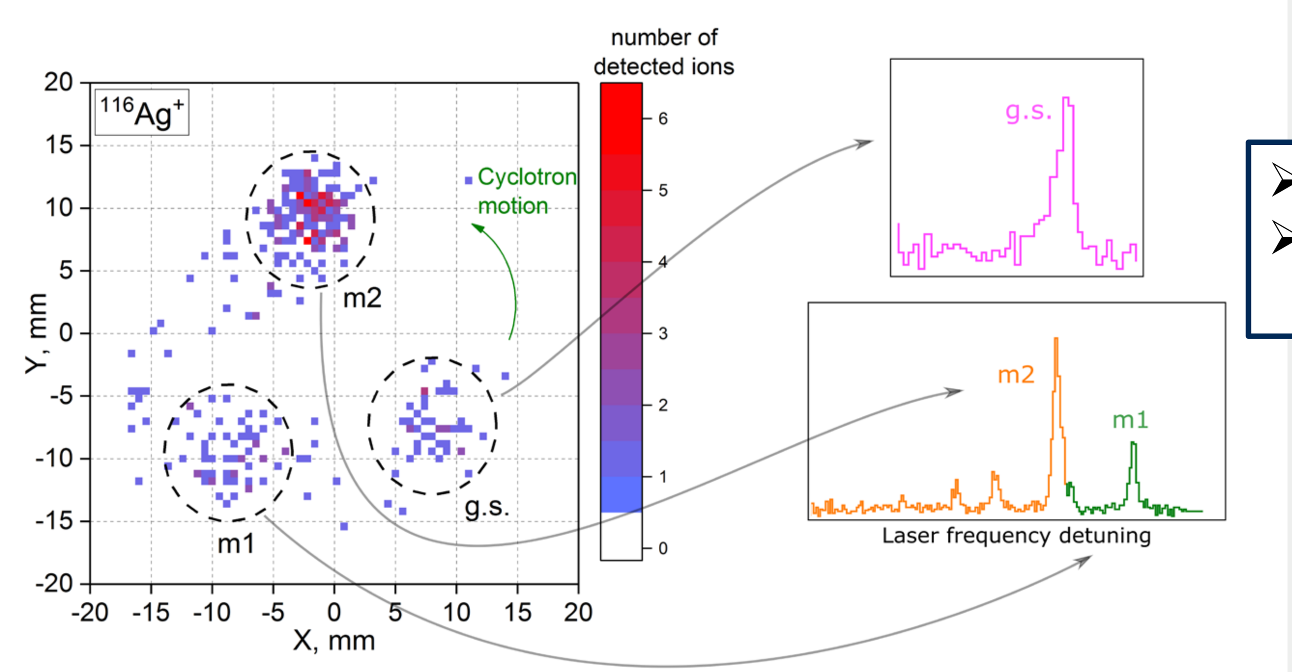


Neutron-rich silver isotopes

ENSDF

(6^-)	129.8	9.3 s
(3^+)	47.9	20 s
(0^-)	0	230 s

^{116}Ag



- Z=40 subshell closure
- Comparison to shell model predictions

Measurement campaign at the IGISOL facility 2018 - 2019
→ Excitation energies and more <u>accurate</u> ground-state mass values (PI-ICR)
→ Spins of the states (laser spectroscopy)

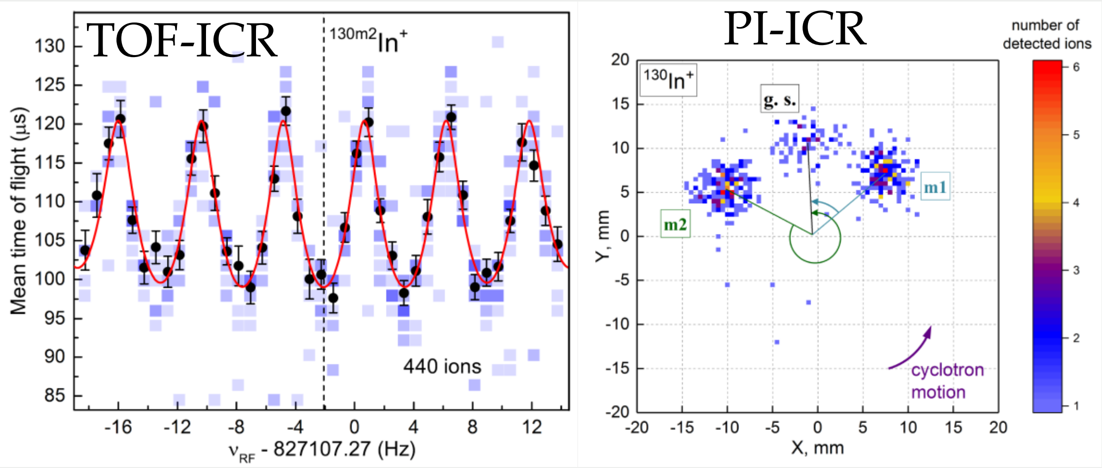
^{128}In and ^{130}In studied with TOF-ICR and PI-ICR

Close to ^{132}Sn

$$^{130}\mathrm{In}: (\pi 0g_{9/2})^{-1} (\nu 0h_{11/2})^{-1}$$

$$^{128}\mathrm{In}: (\pi 0g_{9/2})^{-1} (\nu 0h_{11/2})^{-3}$$

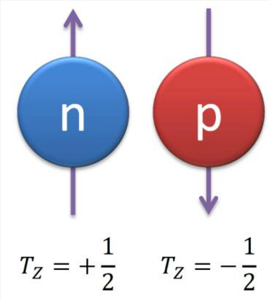
All three states in ^{130}In resolved and measured with PI-ICR

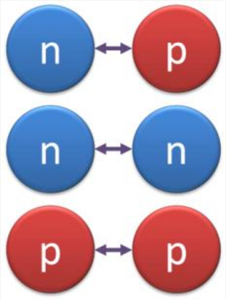


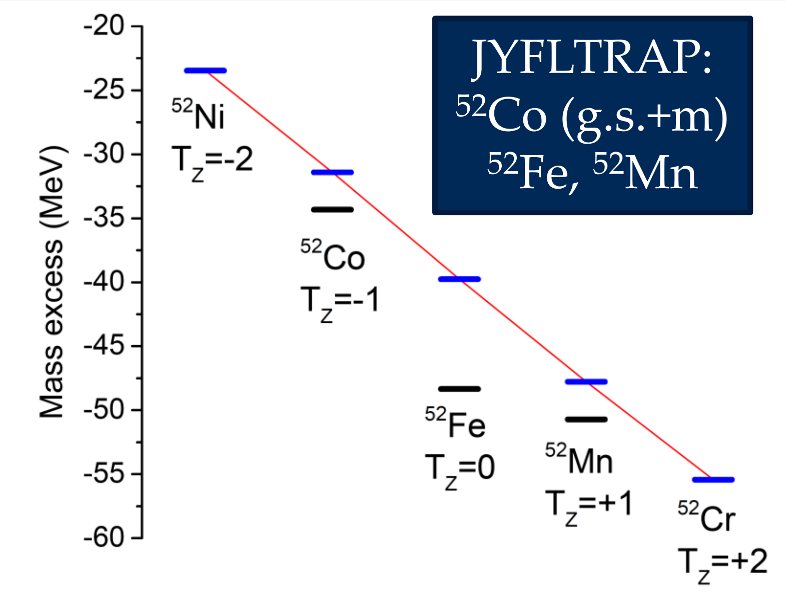
Isospin symmetry

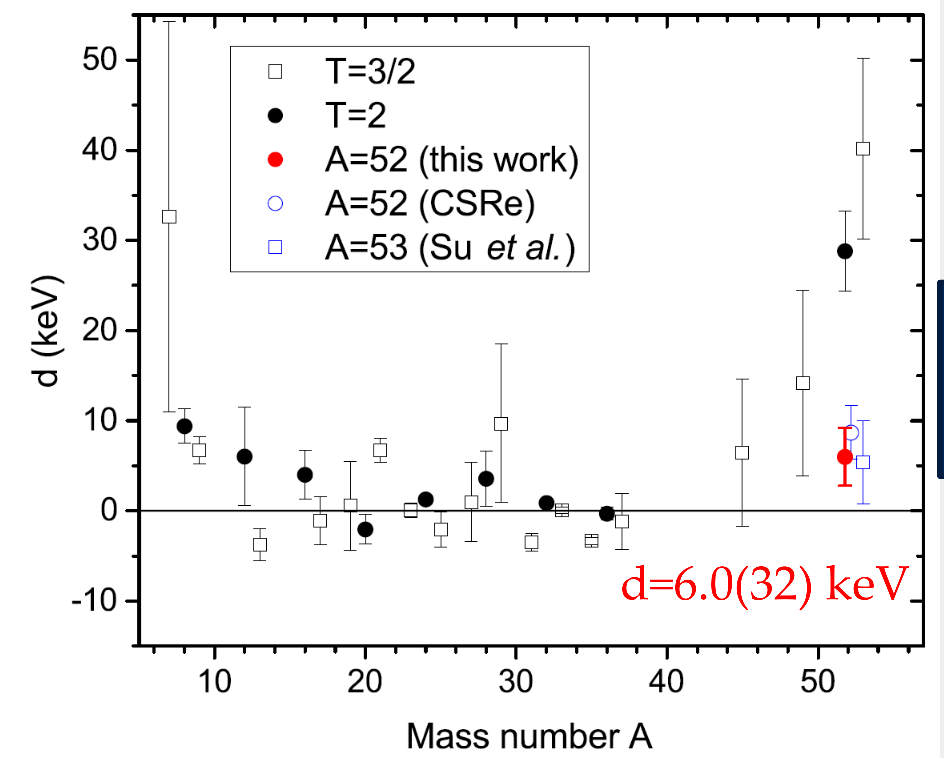
Isobaric Multiplet Mass Equation at A=52

Charge-independence







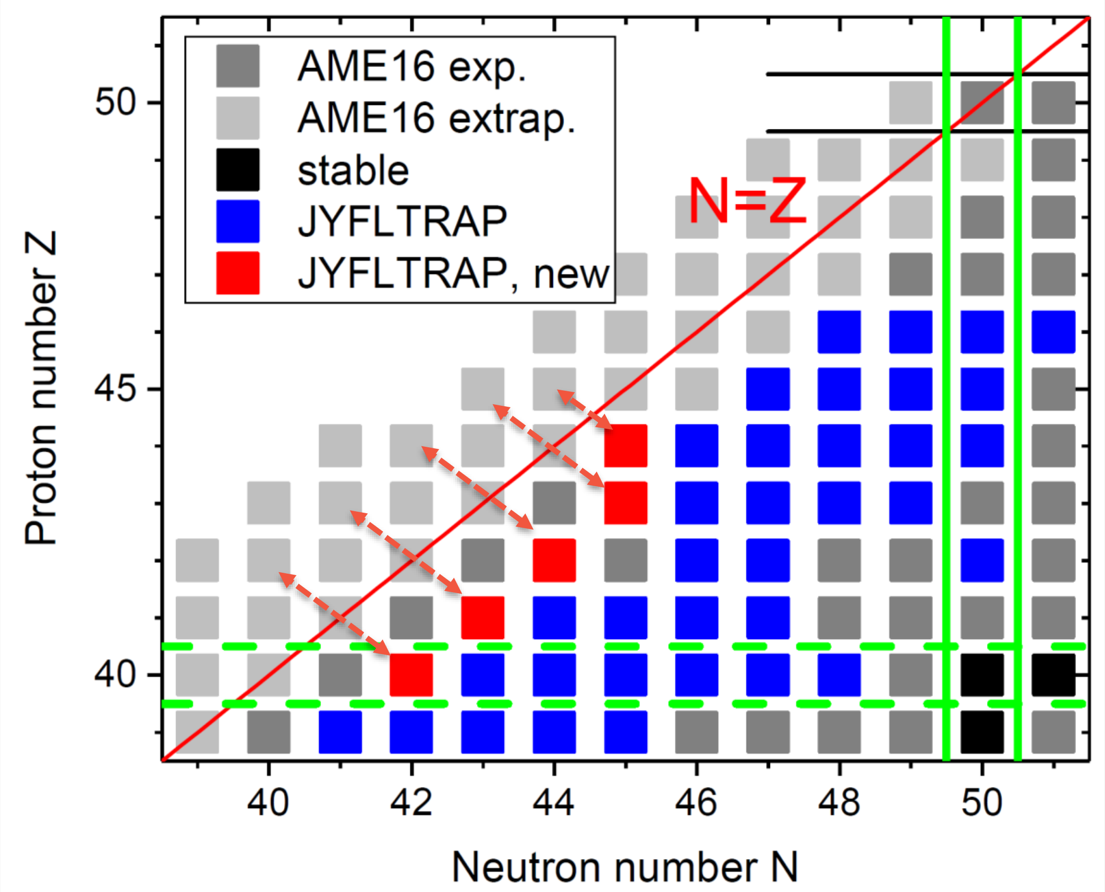


D. A. Nesterenko, AK et al., J. Phys. G: Nucl. Part. Phys. 44 (2017) 065103

Conclusions:
Compatible with d=0
No big changes above A=40

Isospin symmetry in the heavier mass region

- Precision measurements of T_Z=+1 nuclei: **^{82}Zr, ^{84}Nb, ^{86}Mo, and ^{88}Tc**
- ^{88}Tc^{m} and ^{89}Ru (T_Z=+1/2) measured for the first time
- ^{89}Ru more bound than predicted in AME16
- MDE predictions for ^{82}Mo and ^{86}Ru also more bound and more precise than AME16 extrapolations

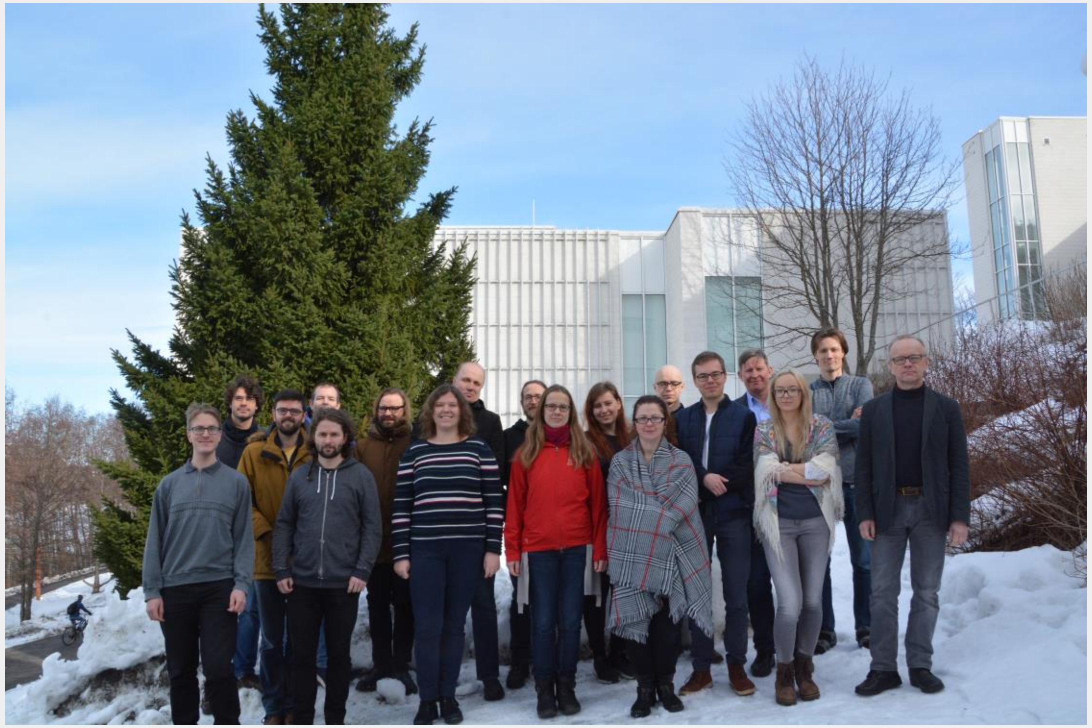


M. Vilen et al., to be submitted

Summary and outlook

- Penning traps are versatile tools to study nuclear structure via nuclear binding energies
- PI-ICR method opens new possibilities to study low-lying isomeric states unreachable with other techniques
- MR-TOF to be installed before JYFLTRAP later this year
  → decay spectroscopy with purified beams (MONSTER)
  → mass measurements

Acknowledgements



IGISOL group in Jyväskylä
and all experimental and theoretical
collaborations related to the presented work!

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SUOMEN TIEDESEURA — THE FINNISH SOCIETY OF SCIENCES AND LETTERS

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