Mass measurements of n-rich nuclei with A~70-150

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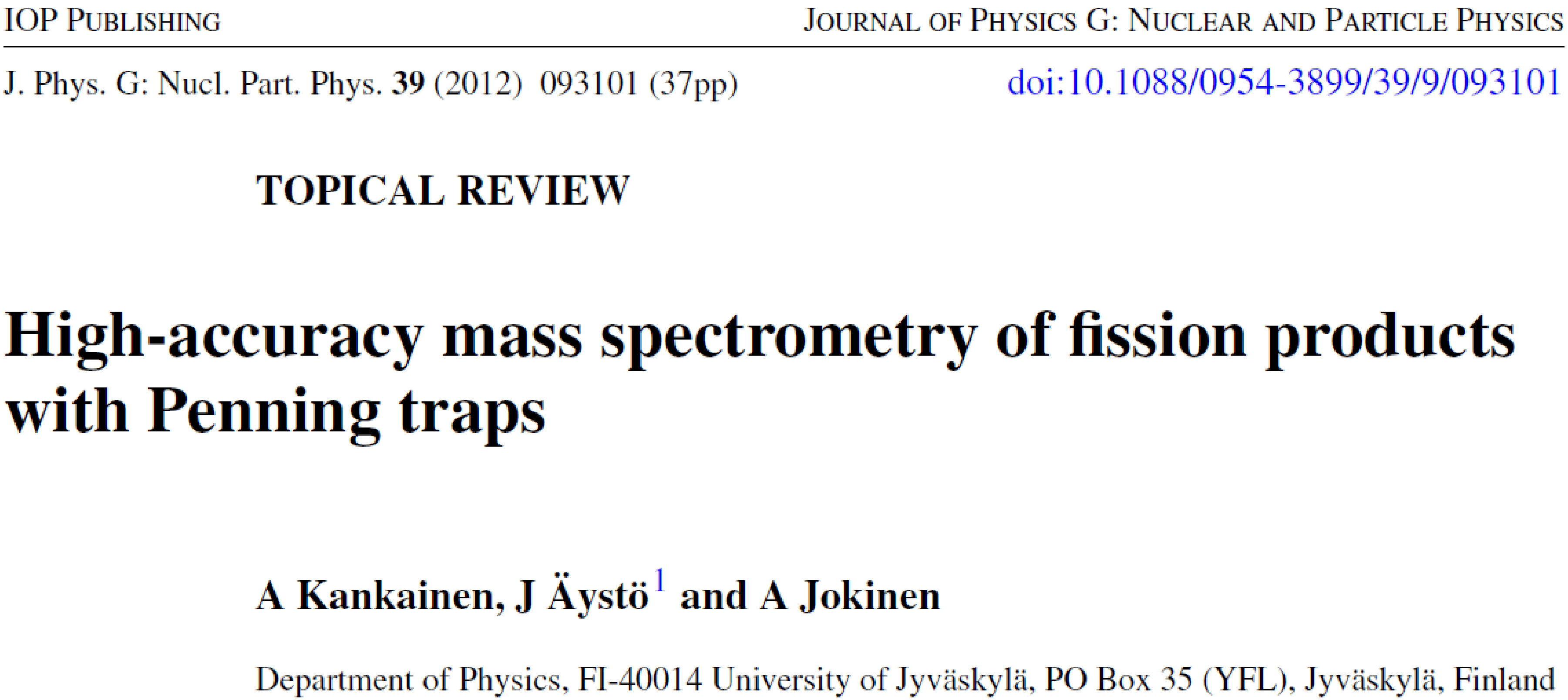
Helsinki Institute of Physics, Helsinki, Finland

in collaboration with: T. Eronen, A. Jokinen, A. Kankainen & IGISOL Coll.
with theory support of J. Dobaczewski, M. Kortelainen

- Experimental approach & status of PT mass measurements
- Comparison to mass predictions
- Two-neutron separation energies and shell gaps
- Odd-even staggering and pairing
- Isomer studies
- Conclusions and outlook



IOP PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **39** (2012) 093101 (37pp) doi:10.1088/0954-3899/39/9/093101

TOPICAL REVIEW

High-accuracy mass spectrometry of fission products with Penning traps

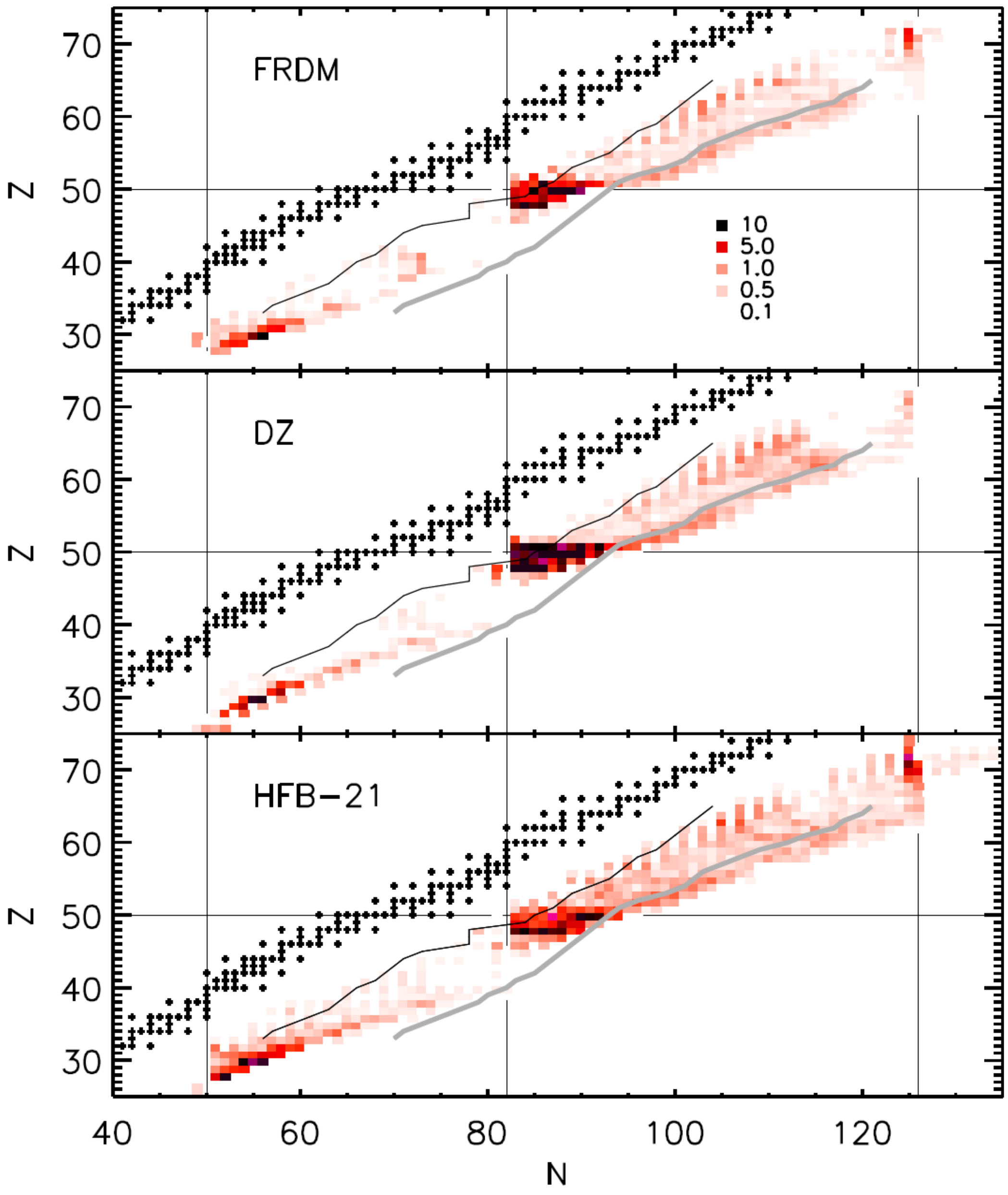
A Kankainen, J Äystö[1] and A Jokinen

Department of Physics, FI-40014 University of Jyväskylä, PO Box 35 (YFL), Jyväskylä, Finland

→ Nuclear data for astrophysical modelling

Eur. Phys. J. A (2012) **48**: 184

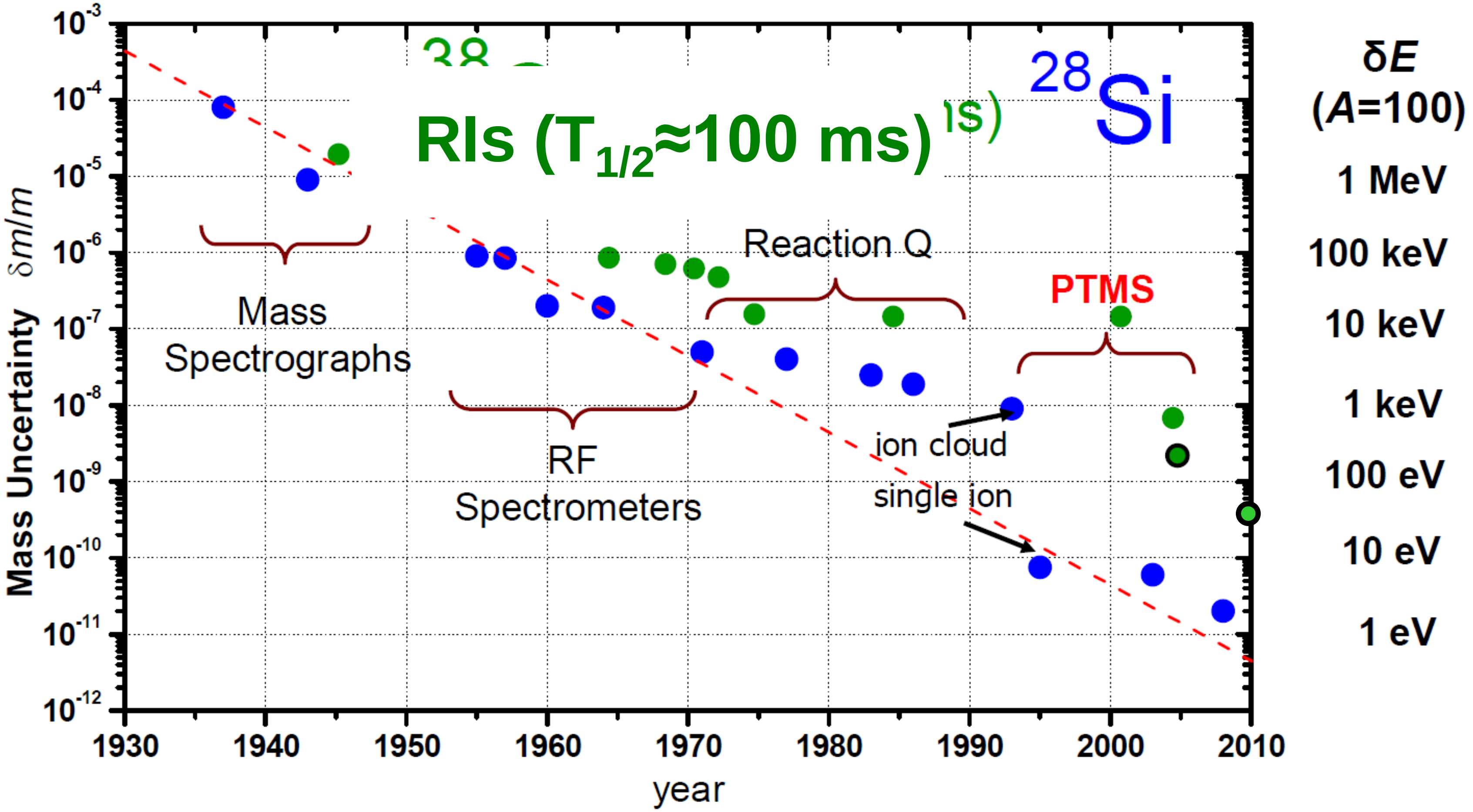
Nuclei whose separation energy variations result in the greatest changes in the resulting r-process abundances.



Rebecca Surman’s talk

Note the Overlap with neutron-rich nuclei from fission !

A brief history of mass spectrometry



SMILETRAP, MIT-TRAP (now at FSU), Seattle-TRAP, HD-TRAP

CPT, ISOLTRAP, JYFLTRAP, LEBIT, SHIPTRAP

Nuclear mass-observables (required accuracy)

Absolute mass --- total binding energy --- Limits of nuclear existence (<0.5 MeV)

Mass differencies

First order differences

Nucleon (s.p) binding energy (1-100 keV)
Nucleon-pair binding energy (1-100 keV)
Decay energy (Q_β, Q_α) (0.1-10 keV)
Coulomb displacement energy (Isospin multiplets) (< 1 keV)

Second order differences

Pairing energy or odd-even staggering (< 10 keV)
Shell-gap energy (< 100 keV)
Valence proton-neutron interaction energy δV_{pn} (< 100 keV)

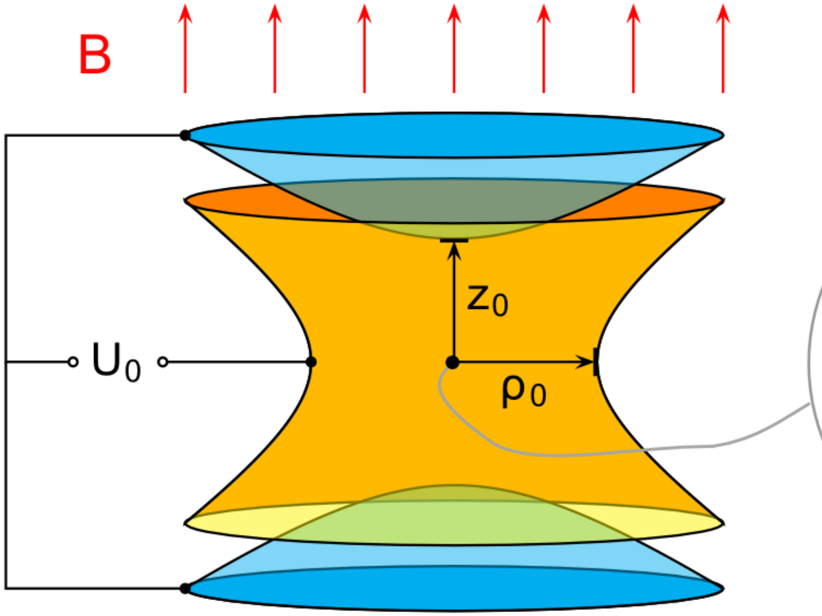
Penning trap

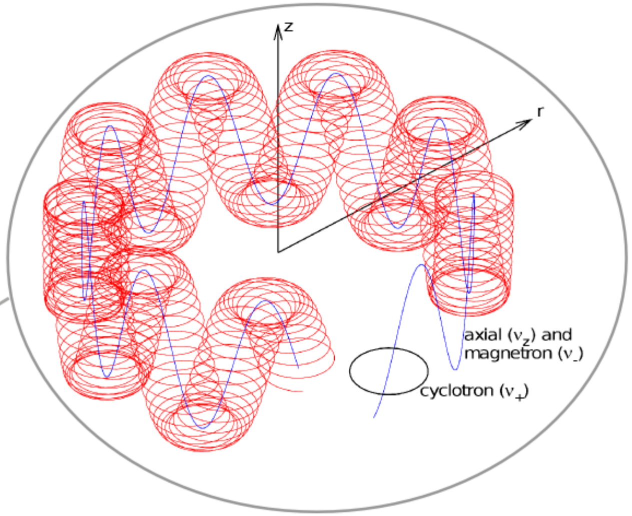
- Homogenous B, quadrupolar V
- Three eigenmotions
  - Axial (ν_z)
  - Magnetron ($\nu_- = 1$ kHz)
  - Modified cyclotron ($\nu_+ =1$ MHz)

- Split ring electrode:
  - Dipolar RF
  - Quadrupolar RF
    - Coupling at ν_c

SIDEBAND MASS SPECTROMETRY:

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

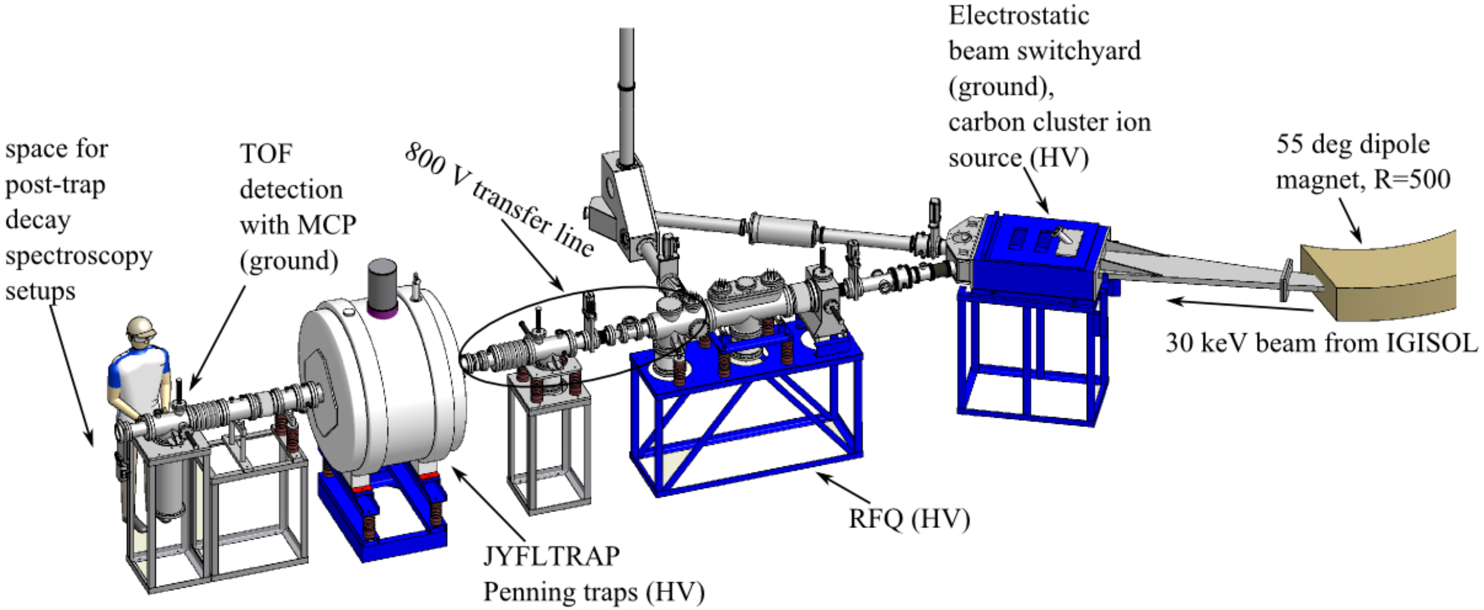


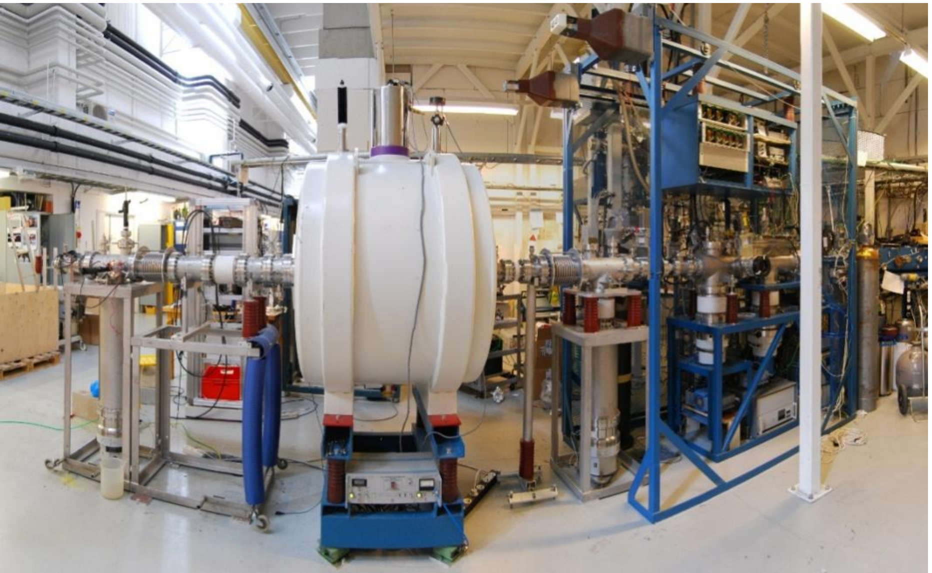


JYFLTRAP @ IGISOL3

fast universal method

Now upgraded to IGISOL4

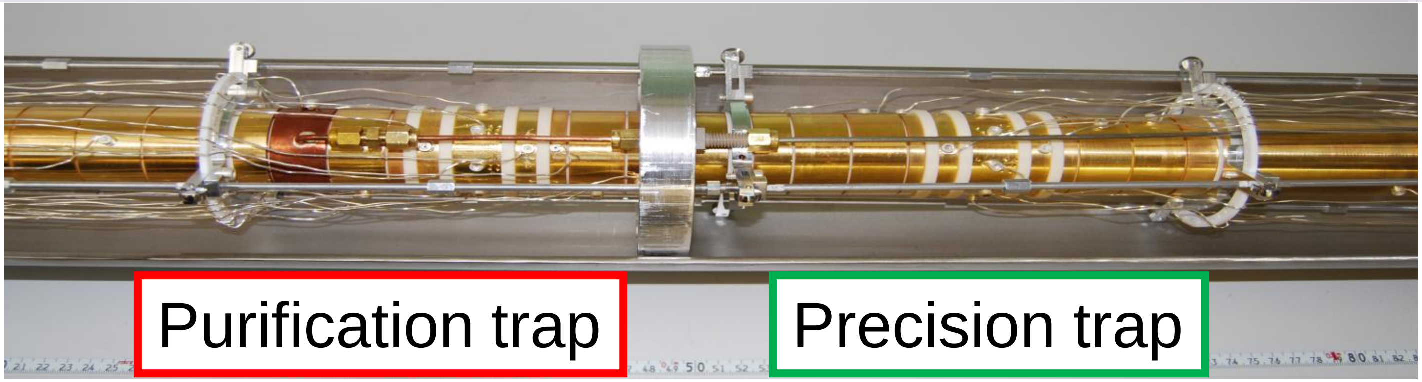




- RFQ + 2 Penning traps
- Isobaric/-meric cleaning
- Mass measurements

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

Mass measurement

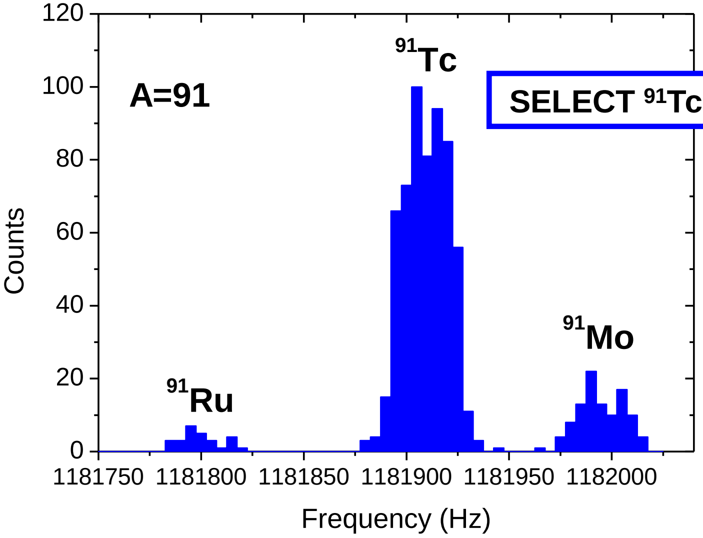


Purification trap

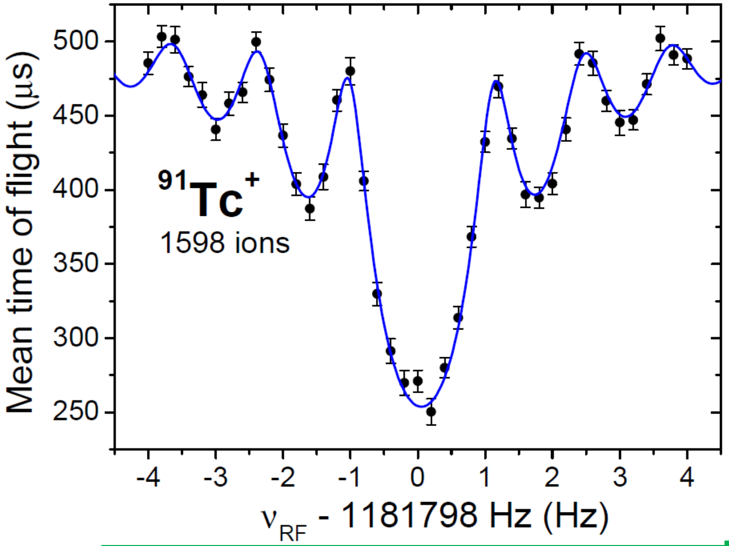
Precision trap

mass-selective
buffer gas cooling

TOF-ICR method



SELECT ^{91}Tc^{+}



Basic equations for mass determination

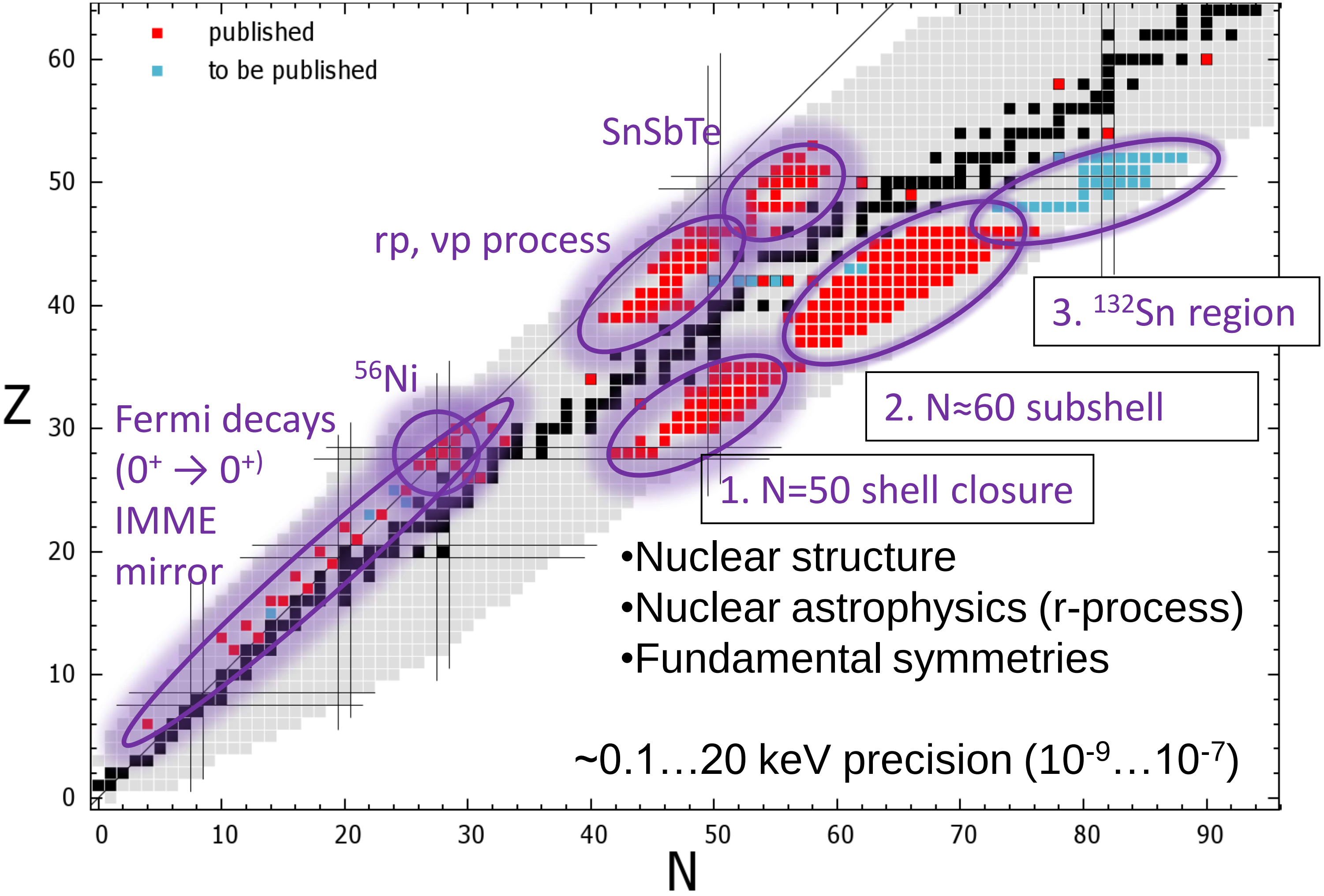
$$f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$

$$\frac{f_{c,\mathrm{ref}}}{f_c} = \frac{m - m_e}{m_{\mathrm{ref}} - m_e}$$

Routinely M/ΔM ~ 10^5

Routinely few keV
If required few tens of eV (**$\delta m/m < 1\cdot10^{-8}$**)

JYFLTRAP mass measurements



Fermi decays
$(0^+ \rightarrow 0^+)$
IMME
mirror

^{56}Ni

rp, νp process

SnSbTe

1. N=50 shell closure

2. N≈60 subshell

3. ^{132}Sn region

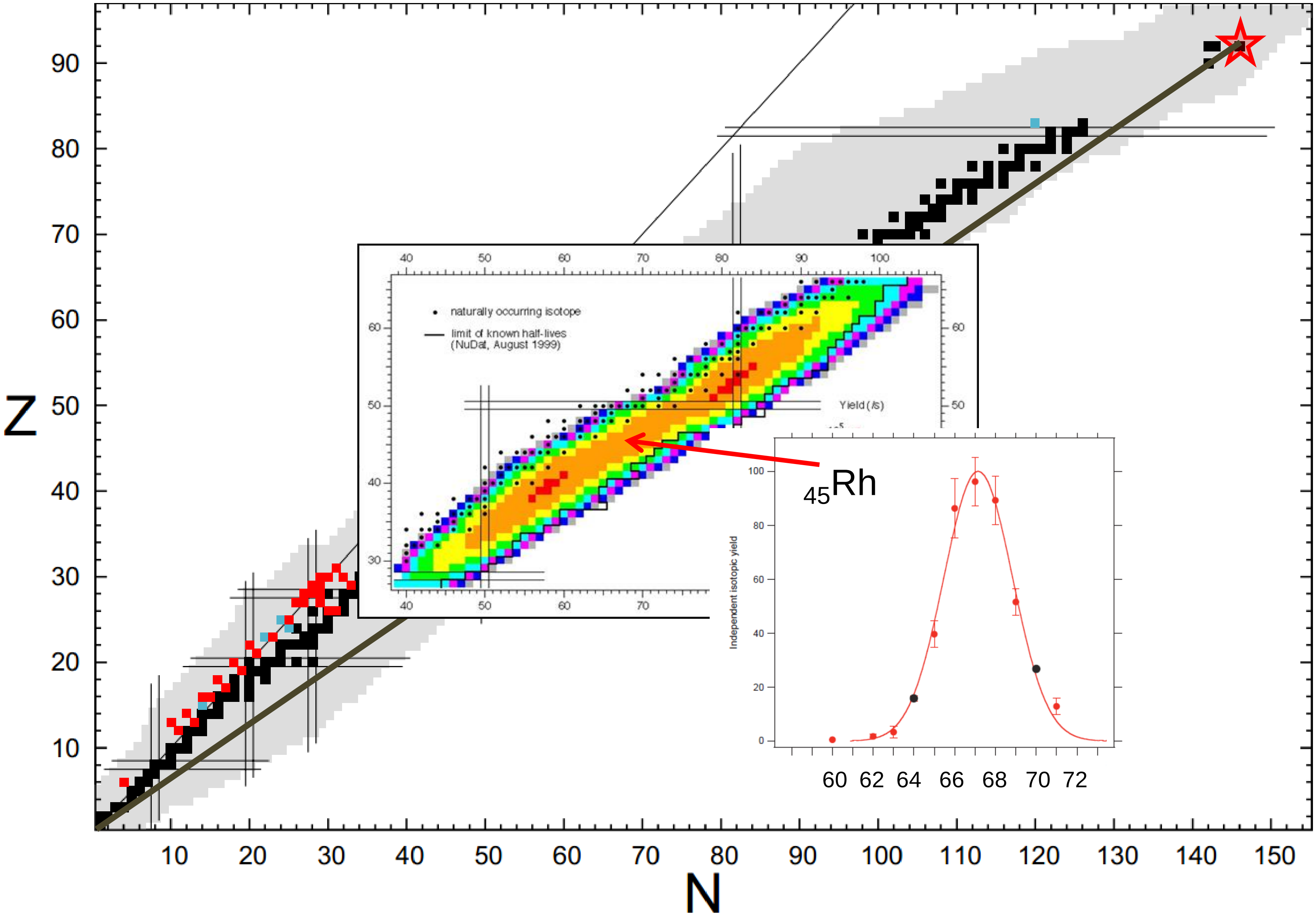
- Nuclear structure
- Nuclear astrophysics (r-process)
- Fundamental symmetries

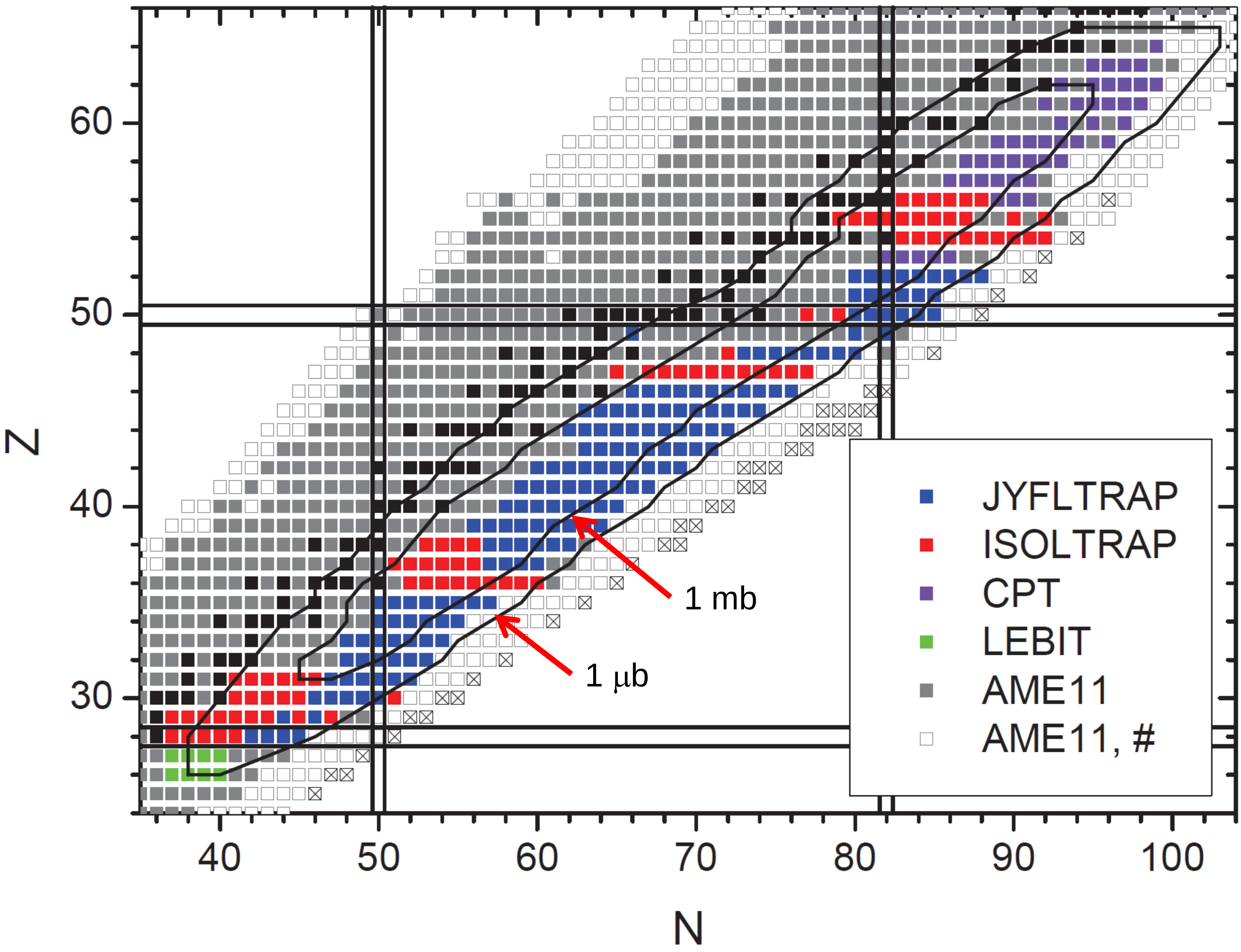
~0.1…20 keV precision ($10^{-9}…10^{-7}$)

Mass spectrometry of fission products

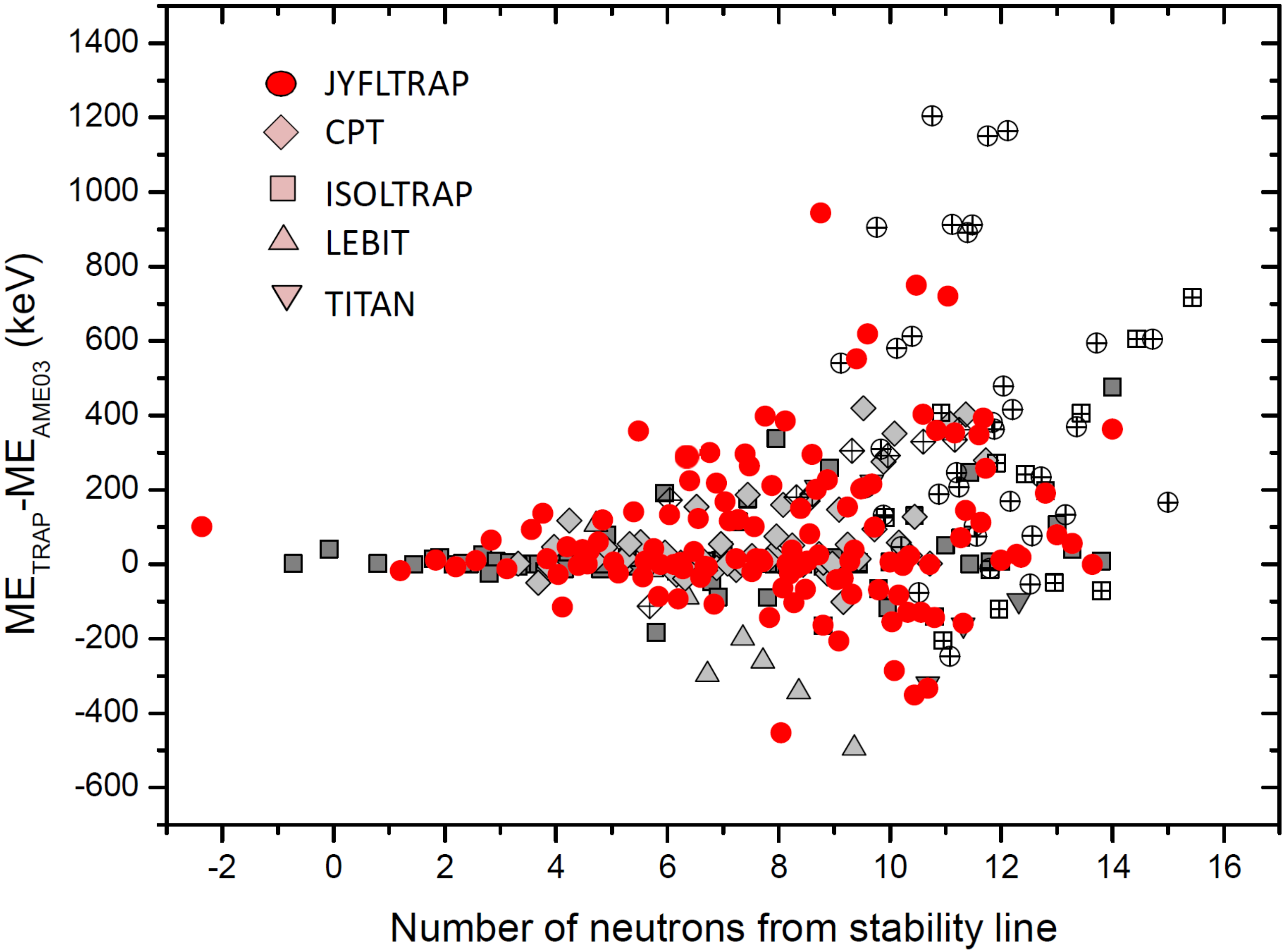
Production in p+U fission

refs.: V. Rubchenya, J. Äystö, Eur. Phys. J. A **48** (2012) 44
H. Penttilä et al., Eur. Phys. J. A **48** (2012) 43



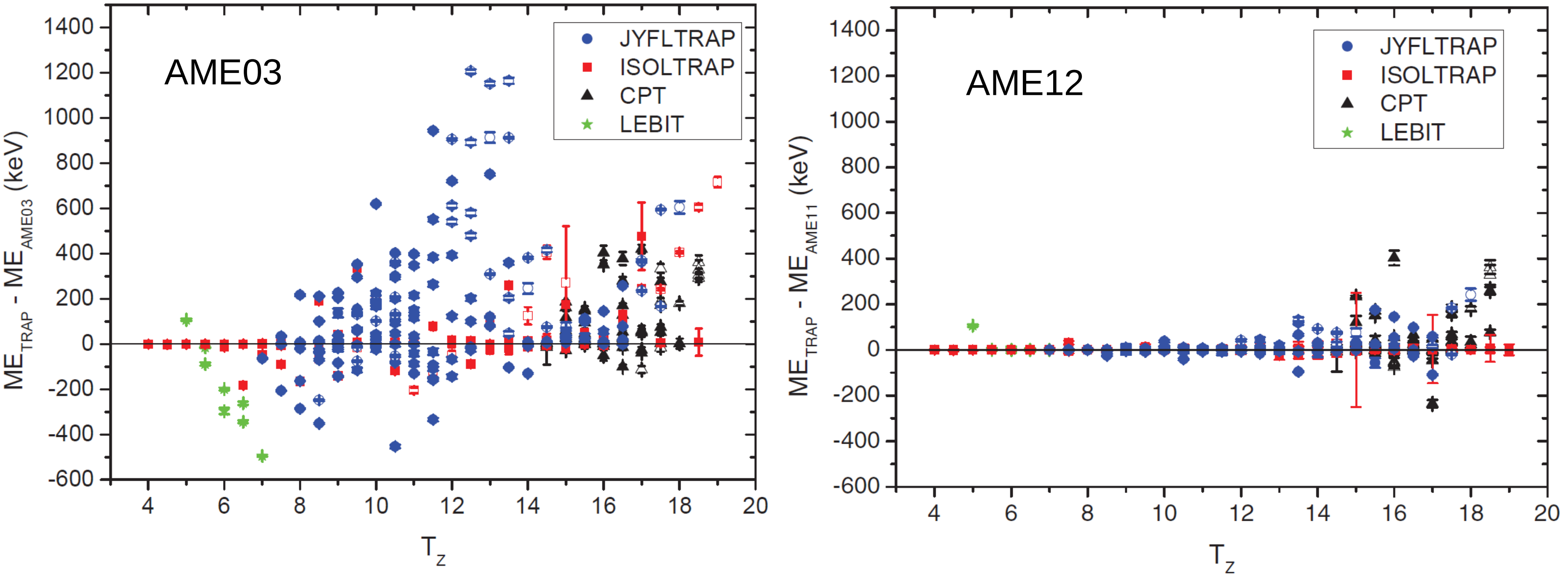


60
50
40
30
Z
40
50
60
70
80
90
100
N
1 mb
1 μb
JYFLTRAP
ISOLTRAP
CPT
LEBIT
AME11
AME11, #


JYFLTRAP
CPT
ISOLTRAP
LEBIT
TITAN
1400
1200
1000
800
600
400
200
0
-200
-400
-600
ME_{TRAP}-ME_{AME03} (keV)
-2
0
2
4
6
8
10
12
14
16
Number of neutrons from stability line

2003/2012 mass evaluation and the PT data

J. Phys. G: Nucl. Part. Phys. **39** (2012) 093101



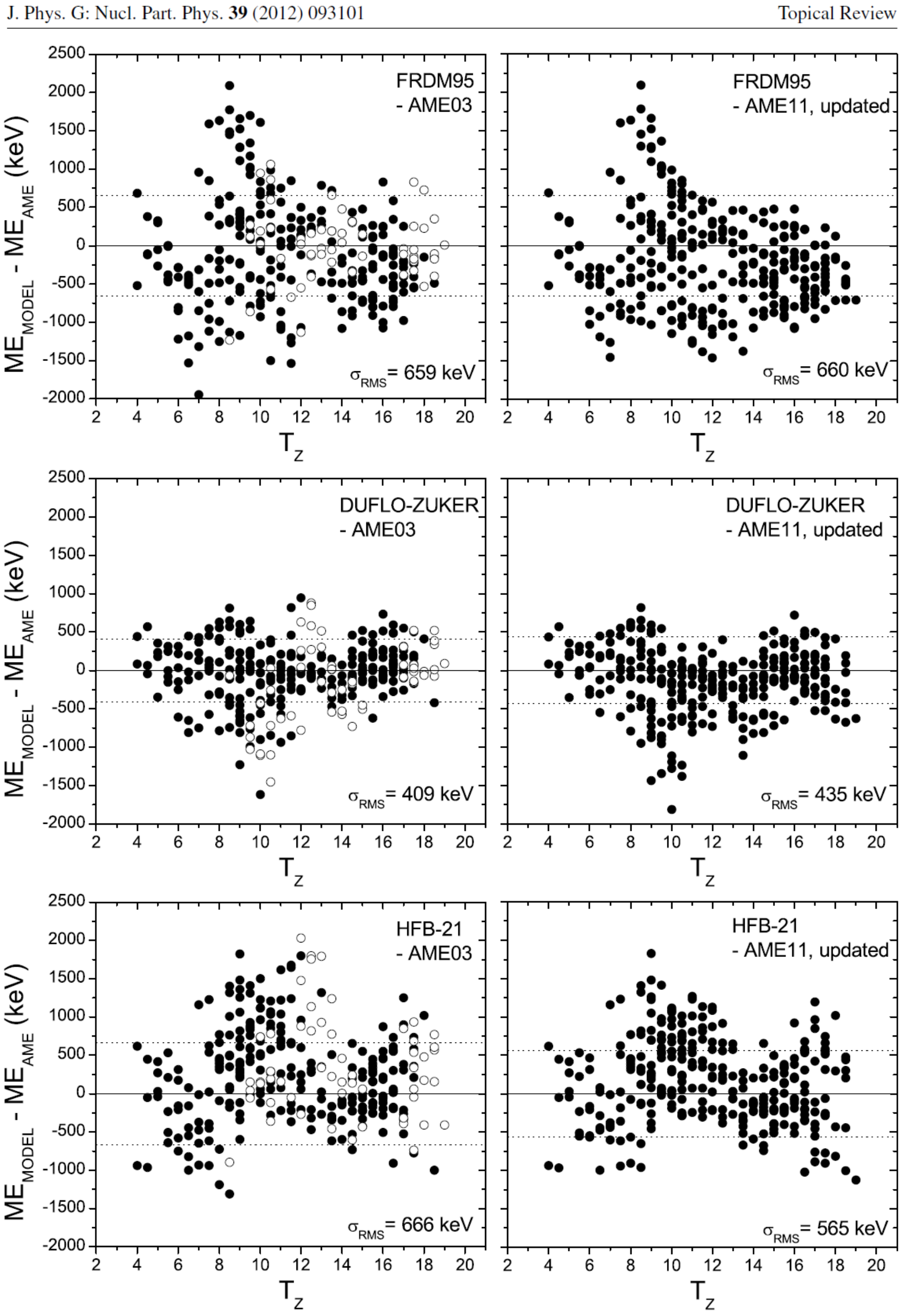
The AME 2012 atomic mass evaluation (II).
M.Wang, G.Audi, A.H.Wapstra, F.G.Kondev, M.MacCormick, X.Xu, B.Pfeiffer
Chinese Physics C36 p. 1603-2014, December 2012.

Mass models vs. AME03, AME11

P. Möller et al.,
ADNDT 59(1995)185

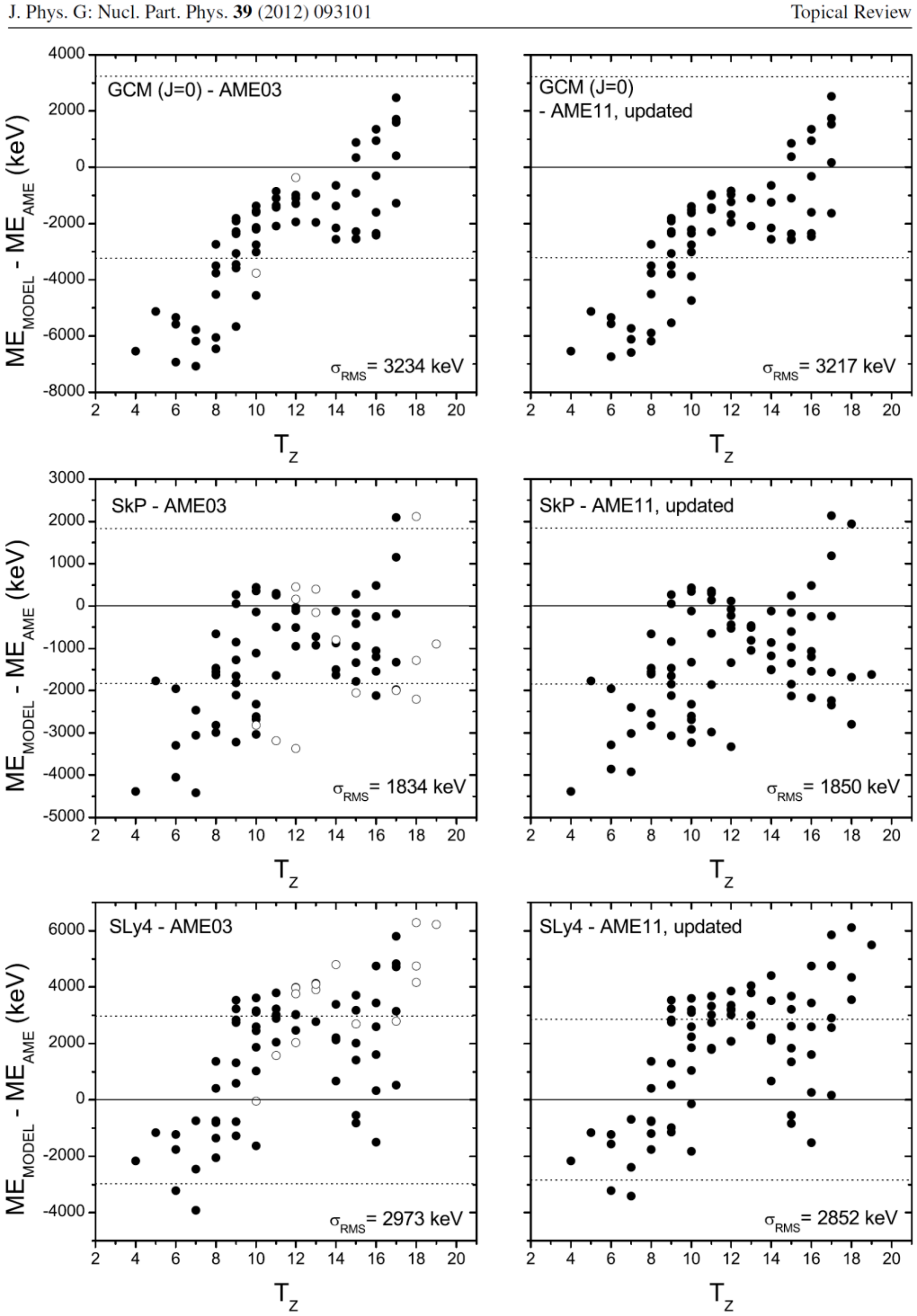
J. Duflo, A. Zuker
PRC 52(1995)R23

S. Goriely et al.,
PRC 82(2010)035804


J. Phys. G: Nucl. Part. Phys. **39** (2012) 093101 Topical Review

Energy density functionals vs AME03/AME11

M. Bender, G. Bertsch, P.G. Heenen
PRC 73(2006)034322
- deformed DFT plus
 quadrupole correlations



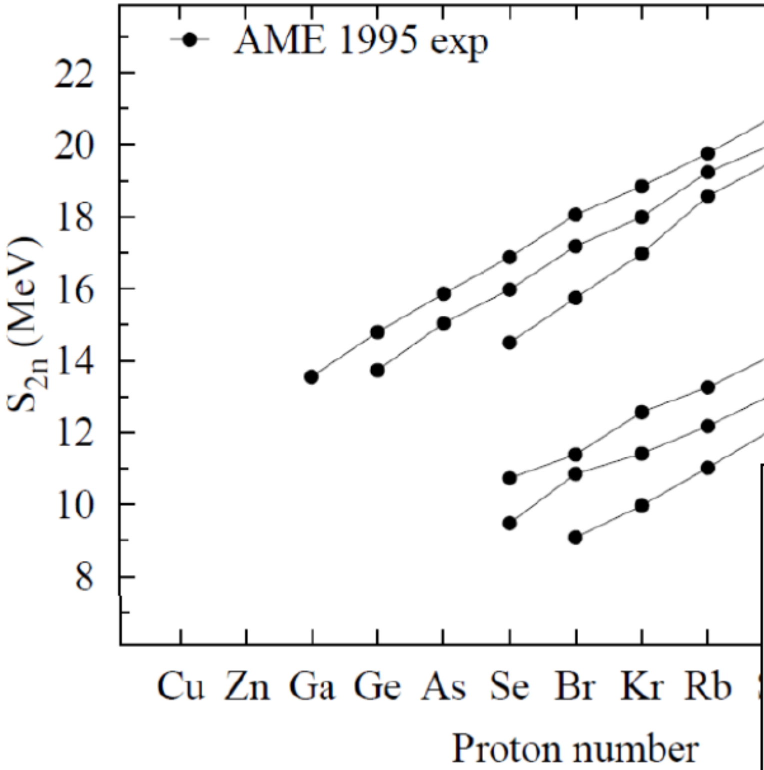
J. Phys. G: Nucl. Part. Phys. **39** (2012) 093101 Topical Review

M. Stoitsov et al.,
PRC 68(2003)054312

M. Stoitsov et al.,
Int. J. Mass Spetctrom 251(2006)243

Two-neutron binding energies
and
shell gaps

N=50 gap data 2009 (Penning traps)

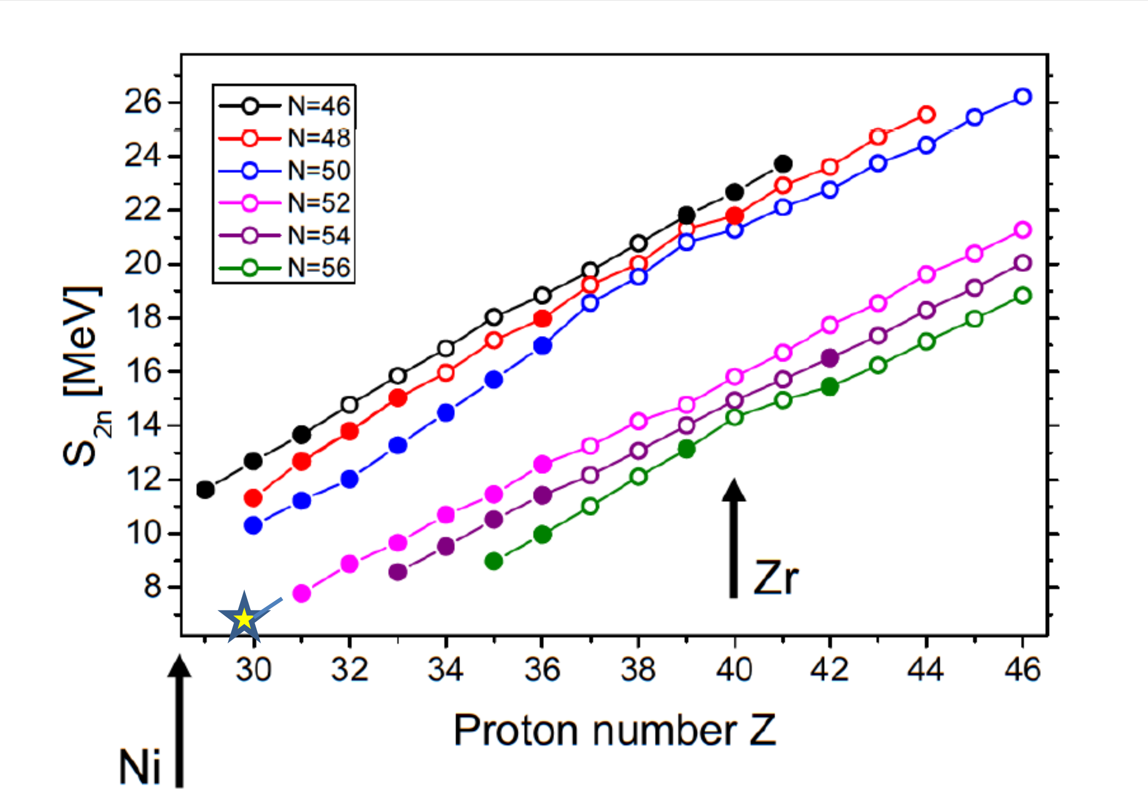


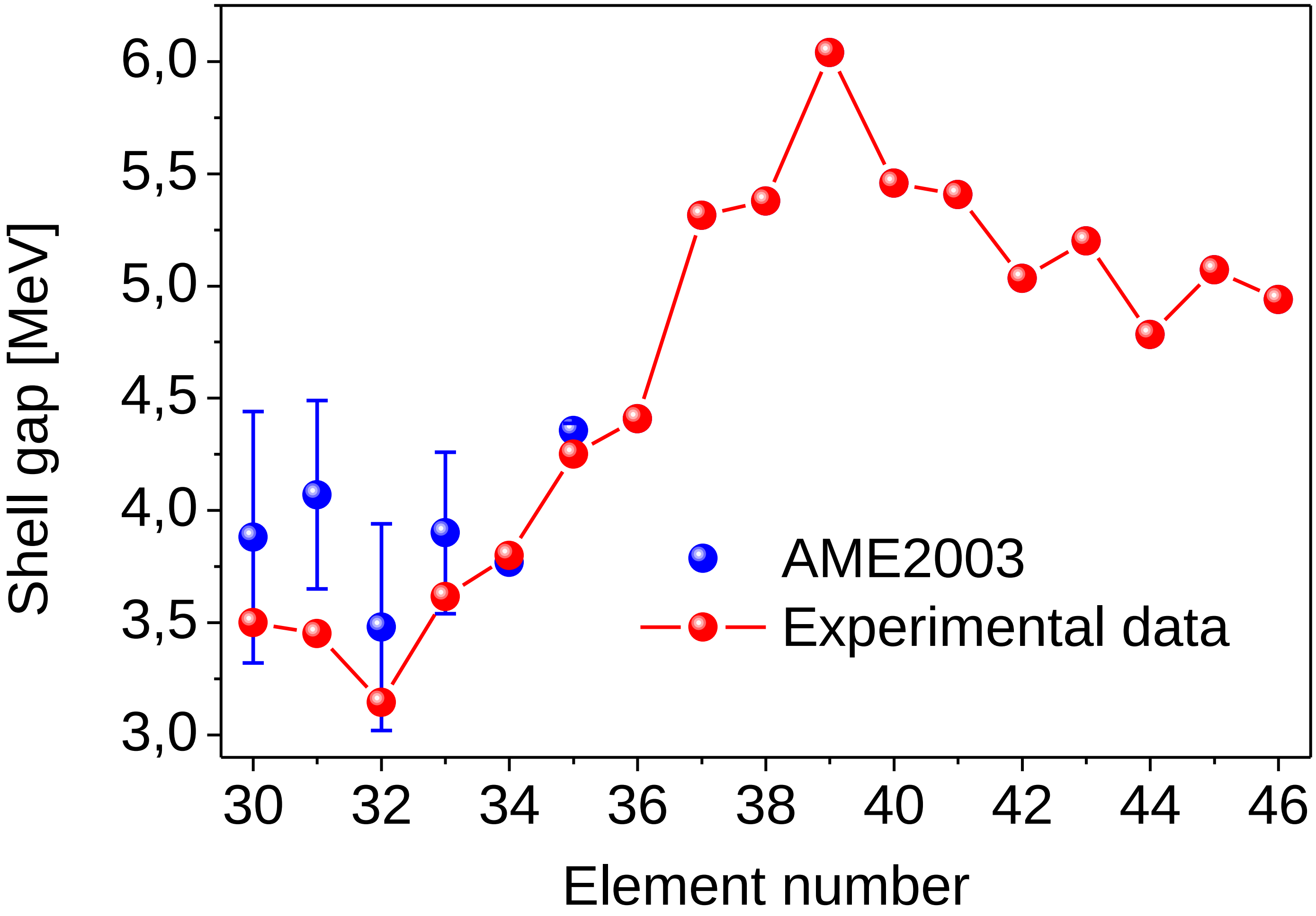
Mass measurements of 30 n-rich Zn, Ga, Ge, As and Se at JYFLTRAP
J. Hakala et al. PRL 101 (2008) 052502

+ ^{81}Zn-isotope at ISOLTRAP
S. Baruah et al., PRL 101 (2008) 262501

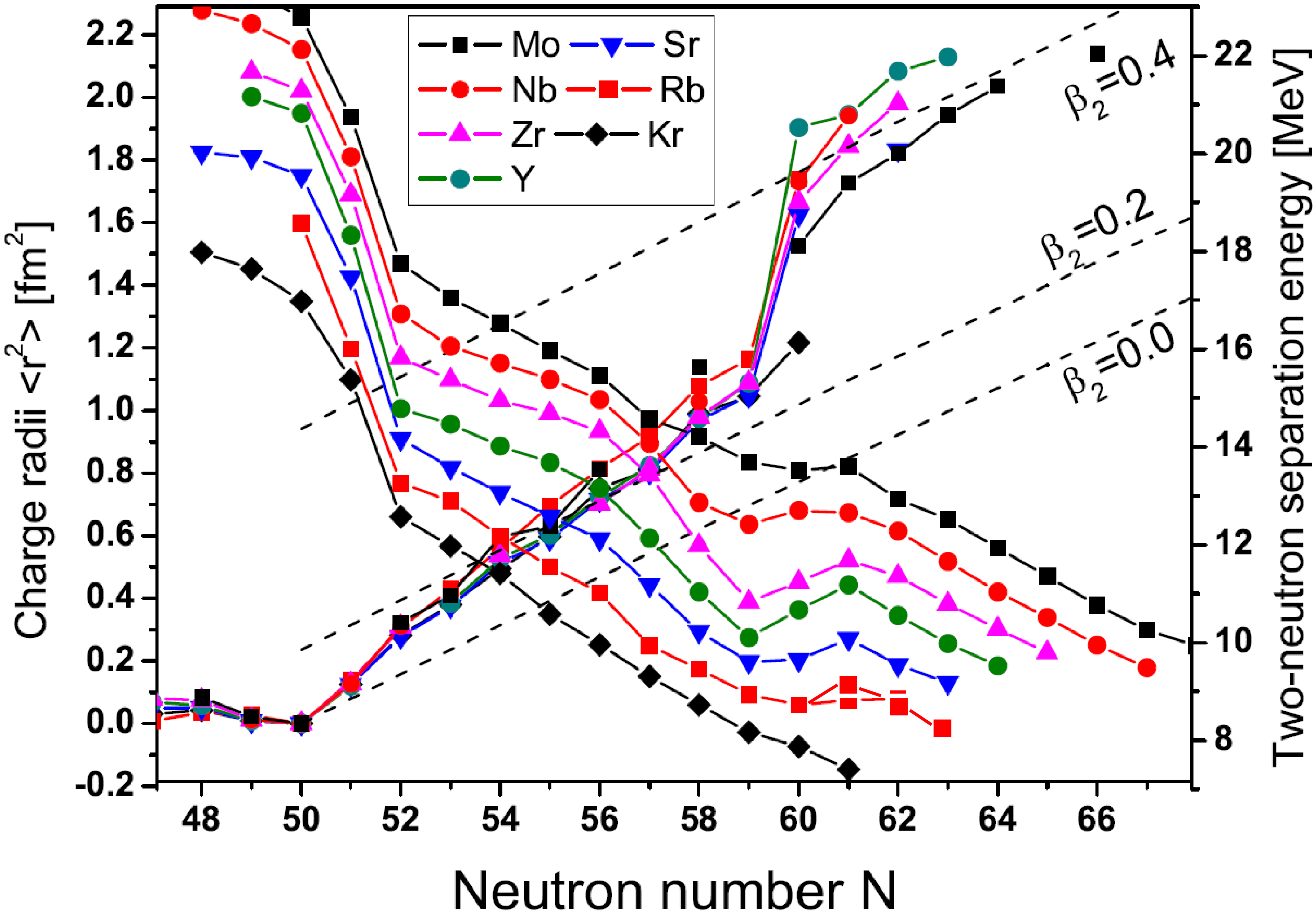
^{82}Zn mass ?

Fresh result from ISOLTRAP
PRL 110 (2013) 041101
See, S. Kreim's talk




Shell gap [MeV]
6,0
5,5
5,0
4,5
4,0
3,5
3,0
30
32
34
36
38
40
42
44
46
Element number
AME2003
Experimental data

Charge radii and two-neutron binding energies

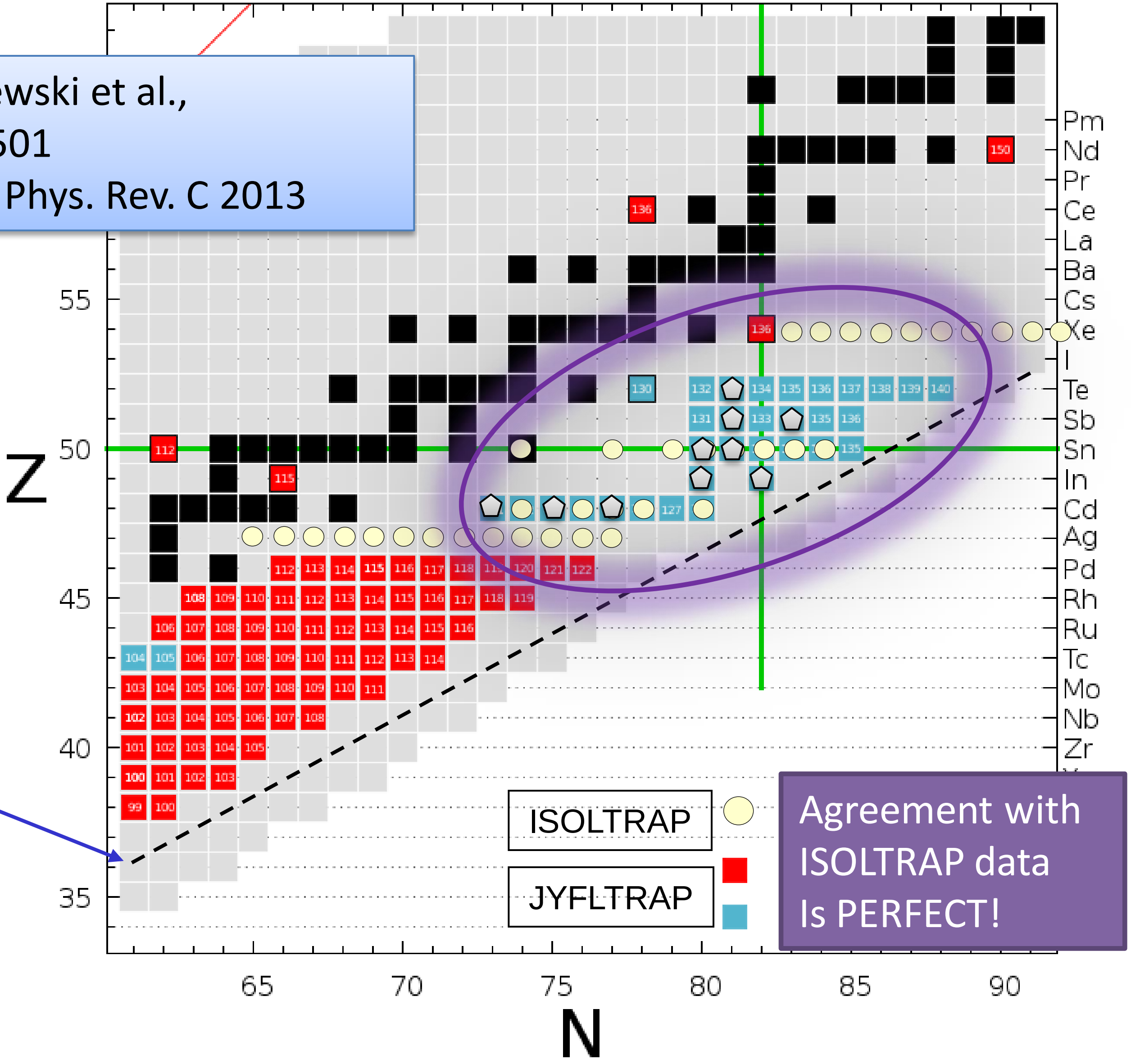


Neutron-rich masses close to ^{132}Sn

J. Hakala, J. Dobaczewski et al.,
PRL 109 (2012) 032501
A. Kankainen, et al., Phys. Rev. C 2013

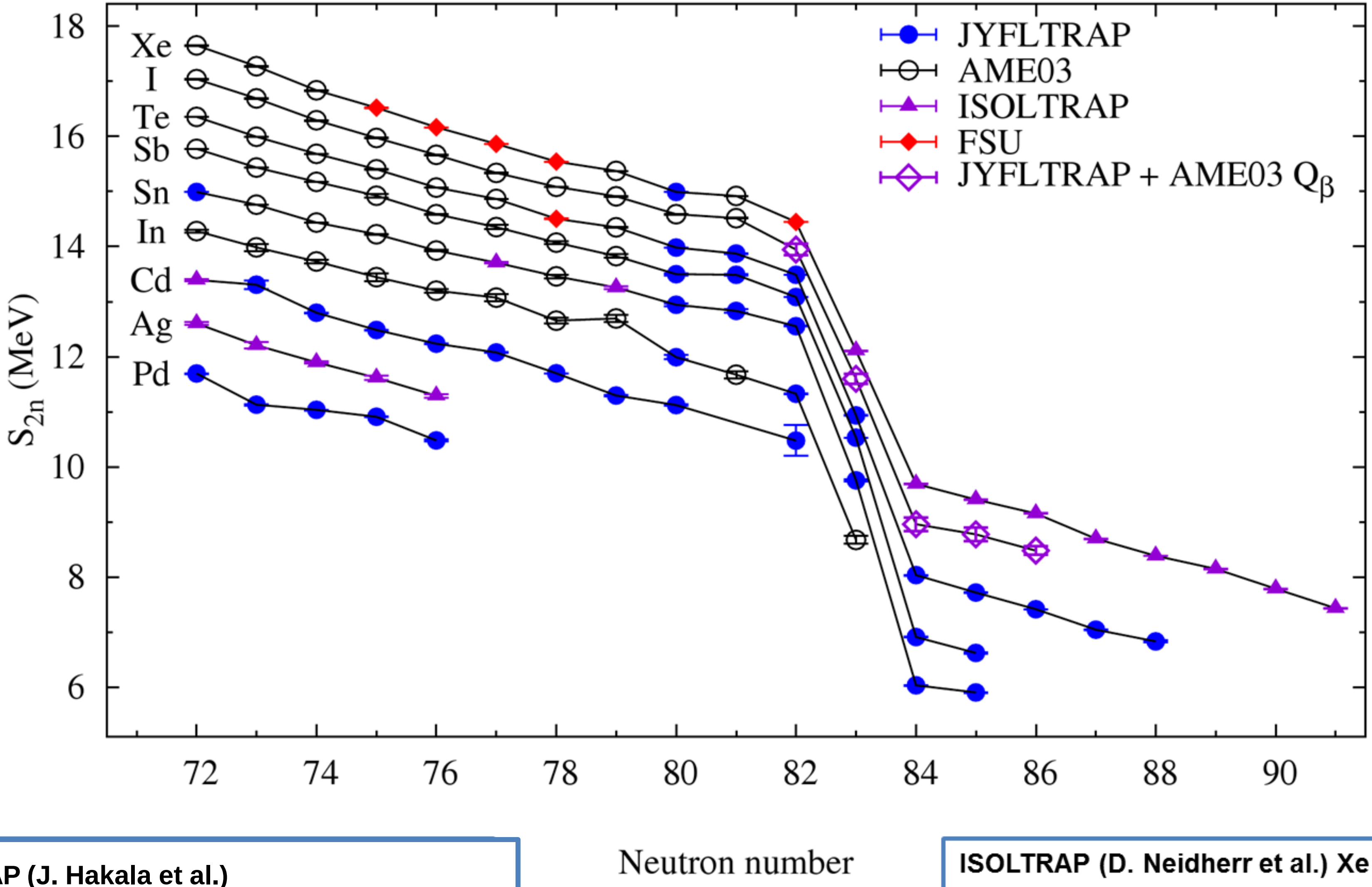
Isomers!
($T_{1/2}$ > 100 ms)

$T_{1/2}$ ≈100 ms



Agreement with
ISOLTRAP data
Is PERFECT!

Two-neutron separation energies (S_{2n})



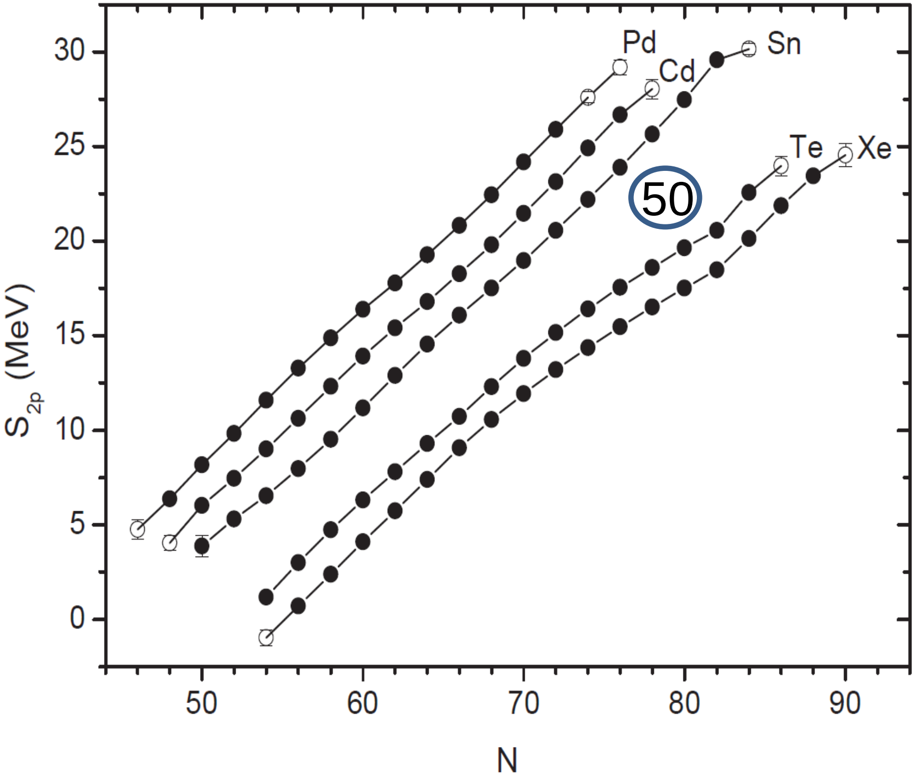
JYFLTRAP (J. Hakala et al.)
PRL 109, 032501 (2012)

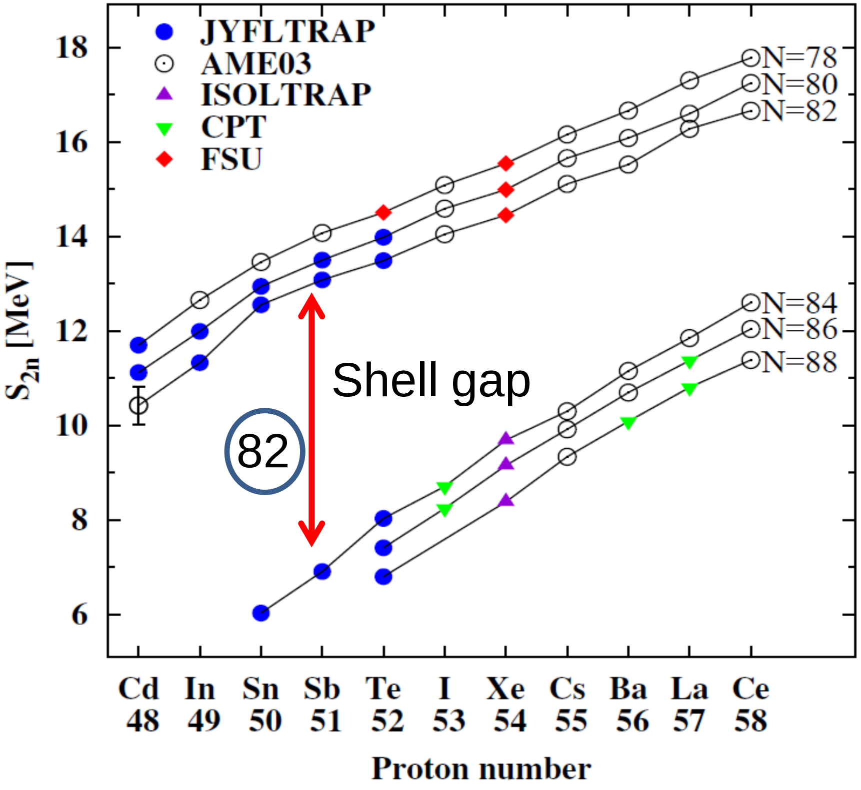
ISOLTRAP (D. Neidherr et al.) Xe
Phys. Rev. C 80, 044323 (2009)

Evolution of shell structure at Z=50 and N=82

Two-proton shell gap for Z=50

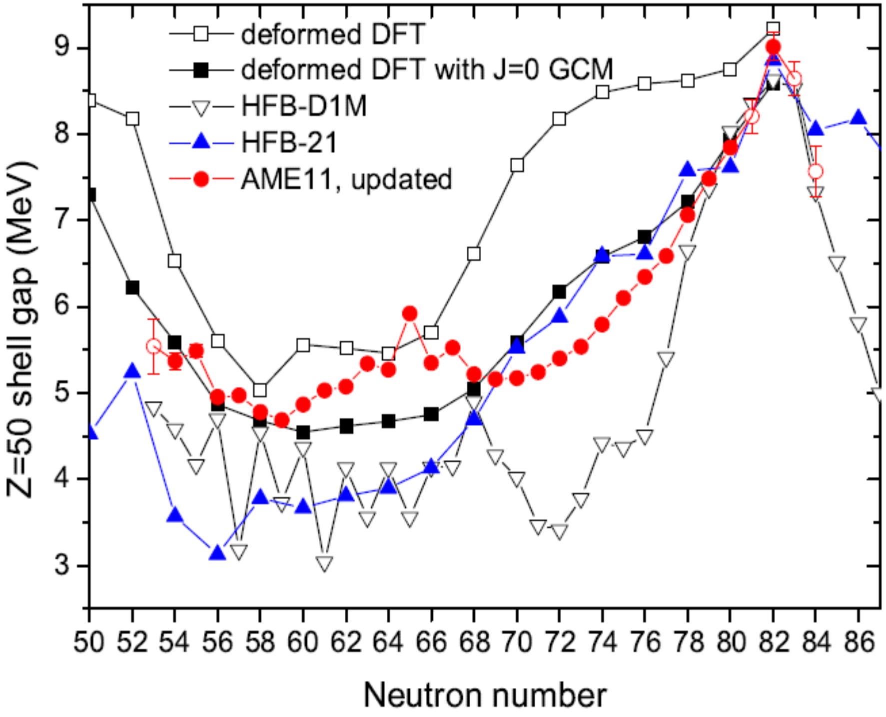
Two-neutron shell gap for N=82

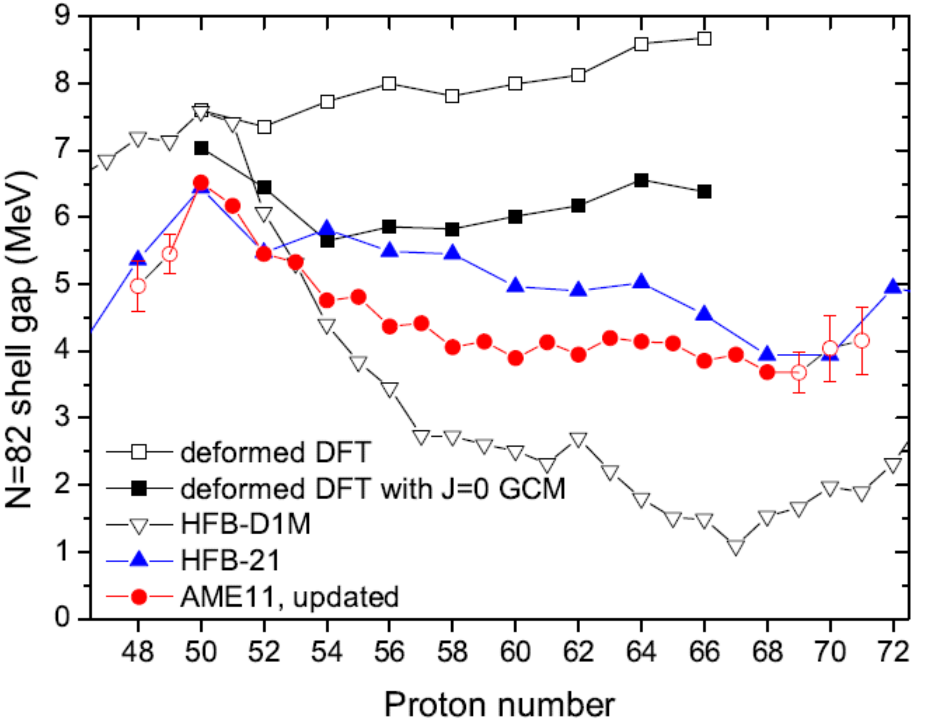




…theory vs. experiment ?

Correlations are very important !!





■ □

▲ ▽

M. Bender, G. F. Bertsch, and P.-H. Heenen.
Phys. Rev. C, ***73*** *(2006) 034322 (DFT, Sly4)*

S. Goriely, et al.
Phys. Rev. Lett., ***102*** *(2009)152503 (HFB-21, Skyrme)*
Phys. Rev. Lett., 102 (2009) 242501 (D1M, Gogny)

Odd-even staggering (OES);

a measure of empirical pairing gap

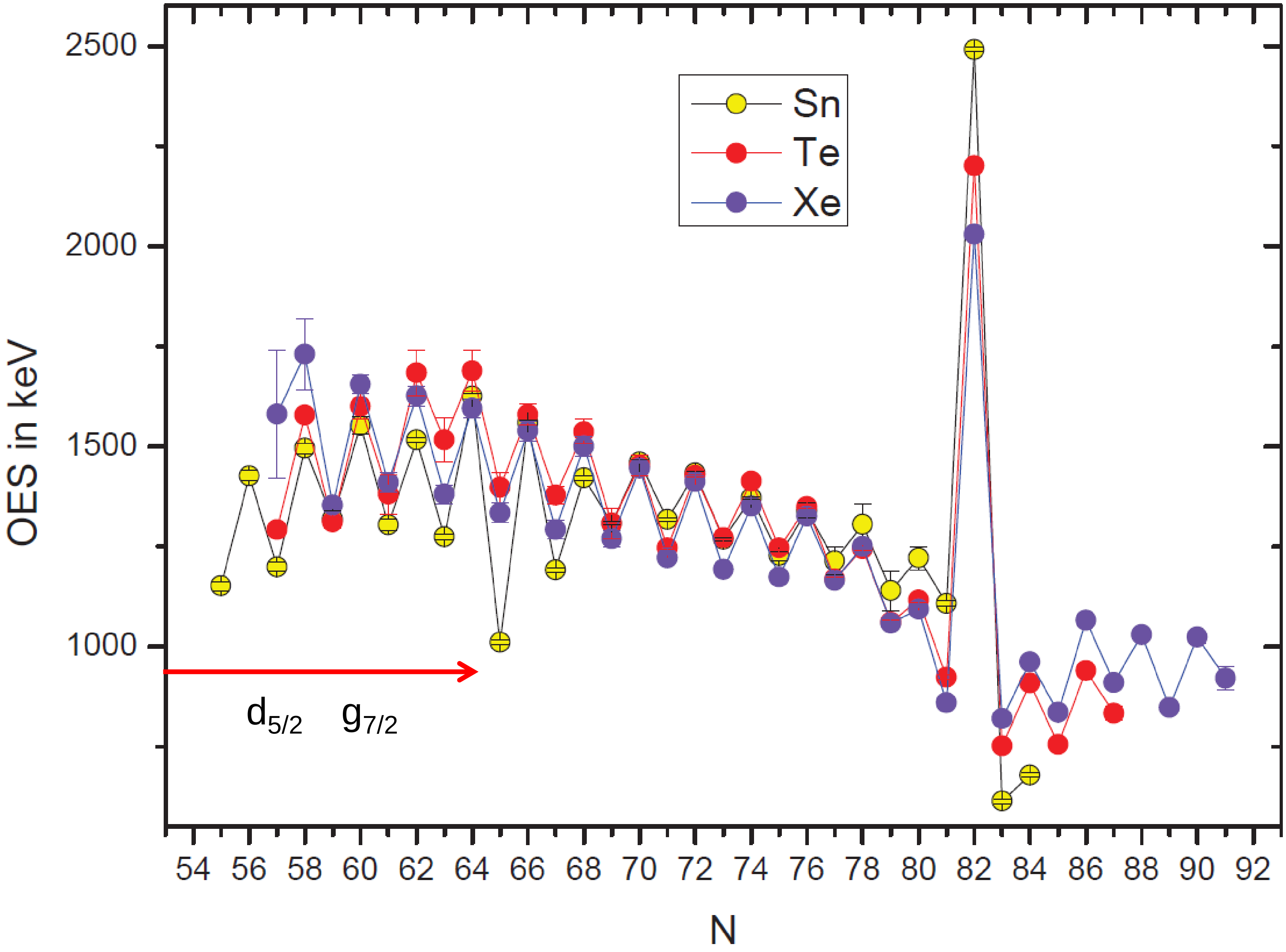
3-point formula

$$\Delta_N^{(3)} = (-1)^N \left[ME(Z,N+1) - 2ME(Z,N) + ME(Z,N-1) \right] /2$$

OES mostly depends on the intensity of nucleonic pairing correlations in nuclei but is also affected by the polarisation effects!

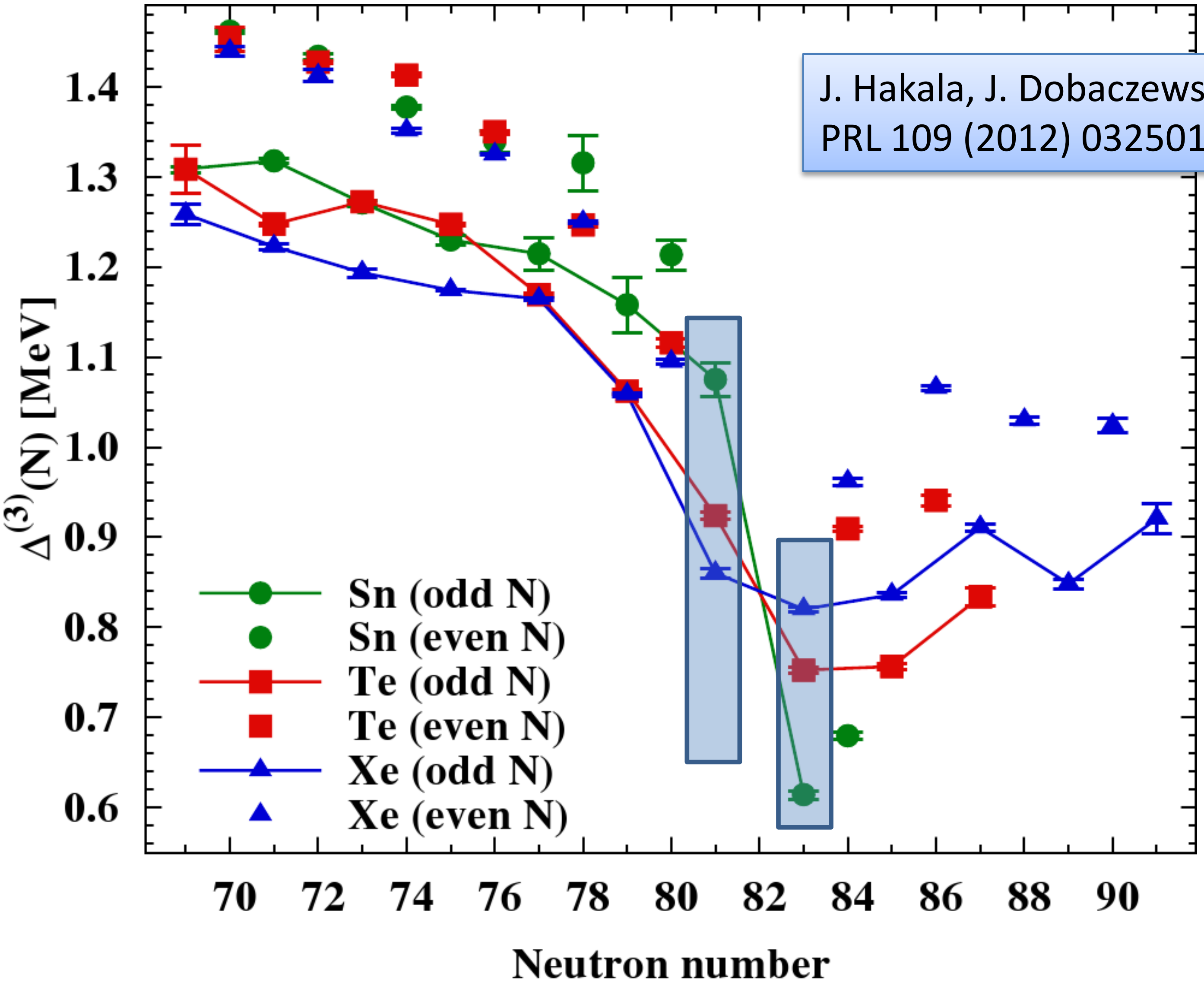
OES(N_{odd}) ~ measure of pairing effects

OES(N_{even}) ~ impacted by single particle states around Fermi level



2500
2000
1500
1000
OES in keV
Sn
Te
Xe
$d_{5/2}$
$g_{7/2}$
54
56
58
60
62
64
66
68
70
72
74
76
78
80
82
84
86
88
90
92
N

Odd-even staggering across the N=82 shell closure

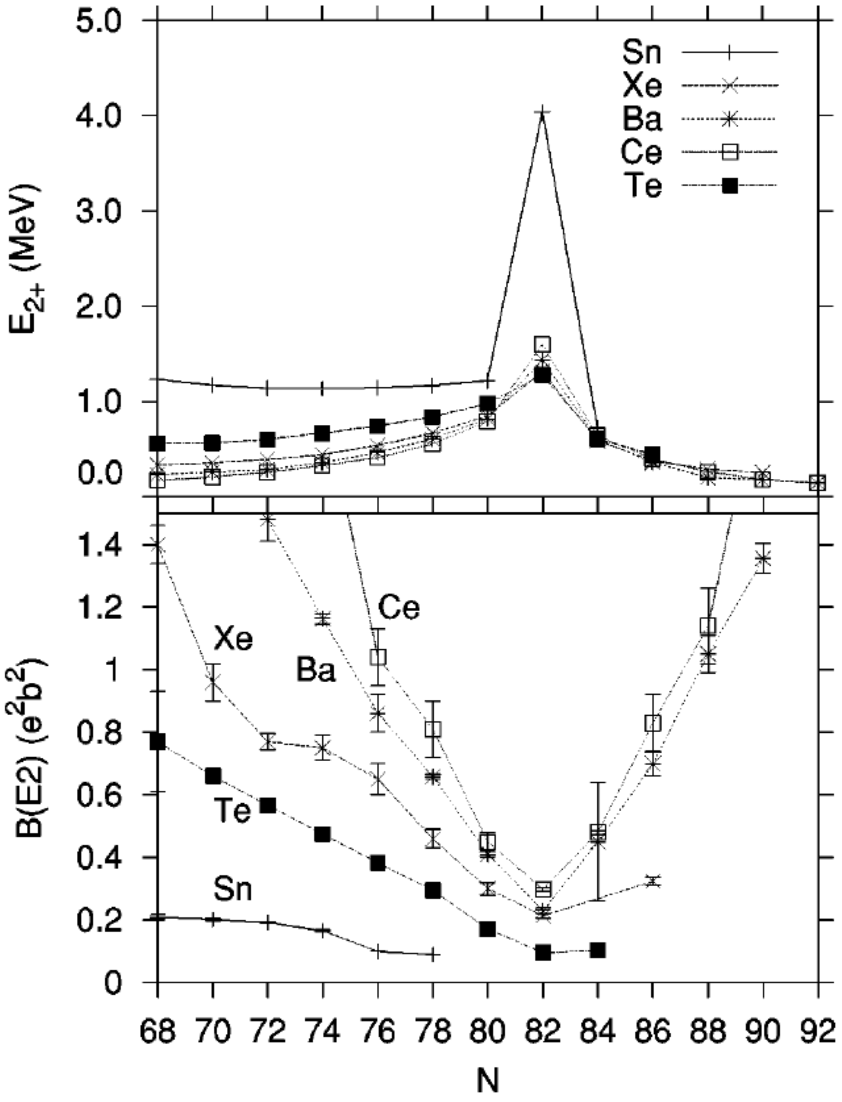


J. Hakala, J. Dobaczewski et al.,
PRL 109 (2012) 032501

PHYSICAL REVIEW C **66**, 054313 (2002)

Anomalous behavior of 2^+ excitations around ^{132}Sn

J. Terasaki,[1,2,3] J. Engel,[4] W. Nazarewicz,[1,2,5] and M. Stoitsov[1,2,3,6]



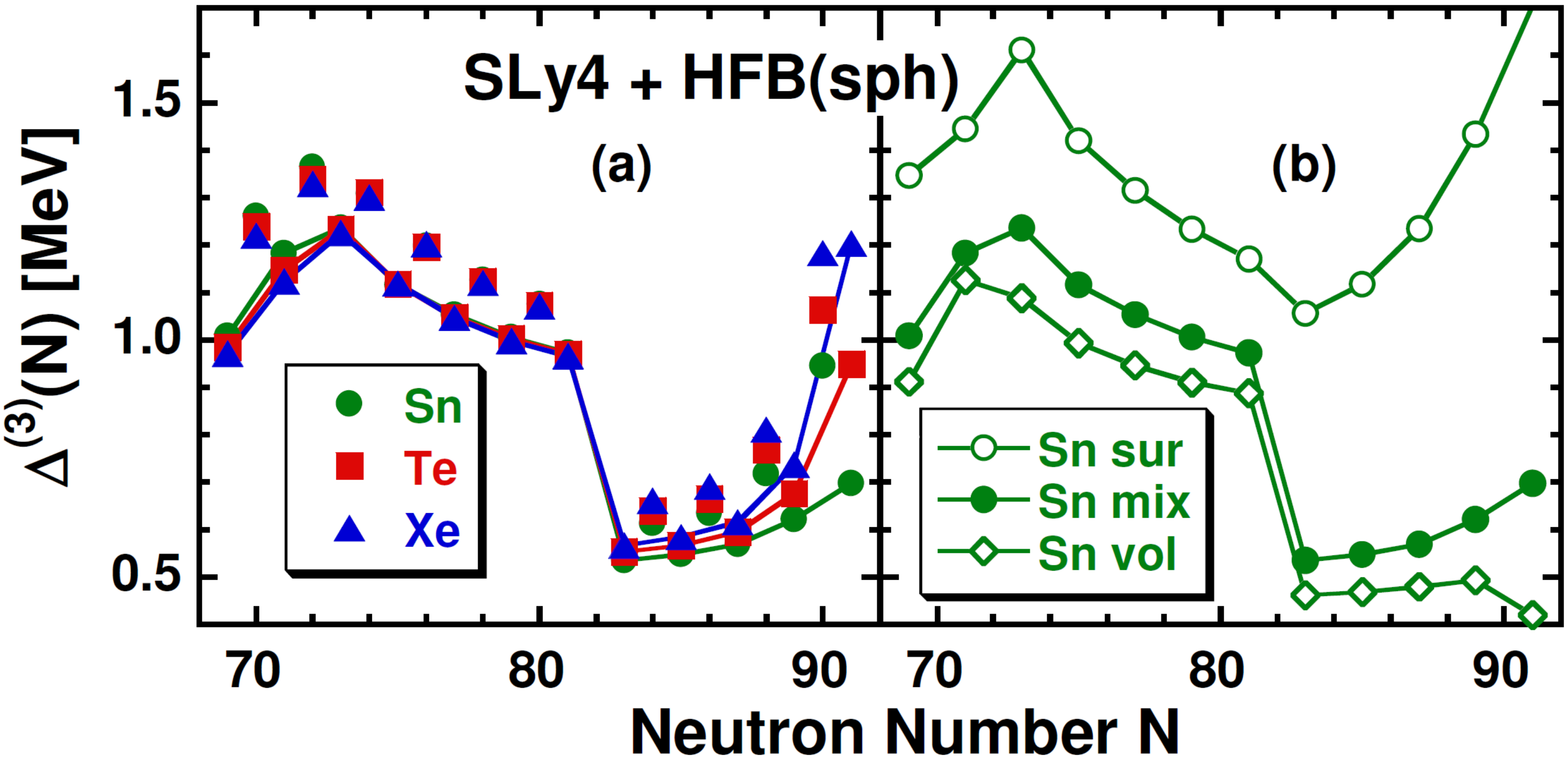
Our QRPA calculations reproduce the behavior seen in experiment.

We trace the cause to the difference in **neutron pairing** below and above *N=82.*

Coulomb Excitation of Radioactive 132,134,136Te Beams and the Low *BE2 of 136Te*
PHYSICAL REVIEW LETTERS 88 (2002) 222501
D. C. Radford,et al.

Spherical self-consistent calculation using Sly4 energy density functional plus contact pairing

Dobaczewski, Flocard, Treiner, Nucl. Phys. A **422**(1984)103



Conclusion: The N=81- 83 asymmetry in staggering indicates

- exclusion of pure surface pairing force
- significant role for polarization effects for Te and Xe!
- same behaviour observed with Gogny interaction!

* Robledo, Bernard, Bertsch, PRC 86(2012)064313

Isomer in trap ?

^{131}In states

g.s: 9/2$^+$, 280 ms

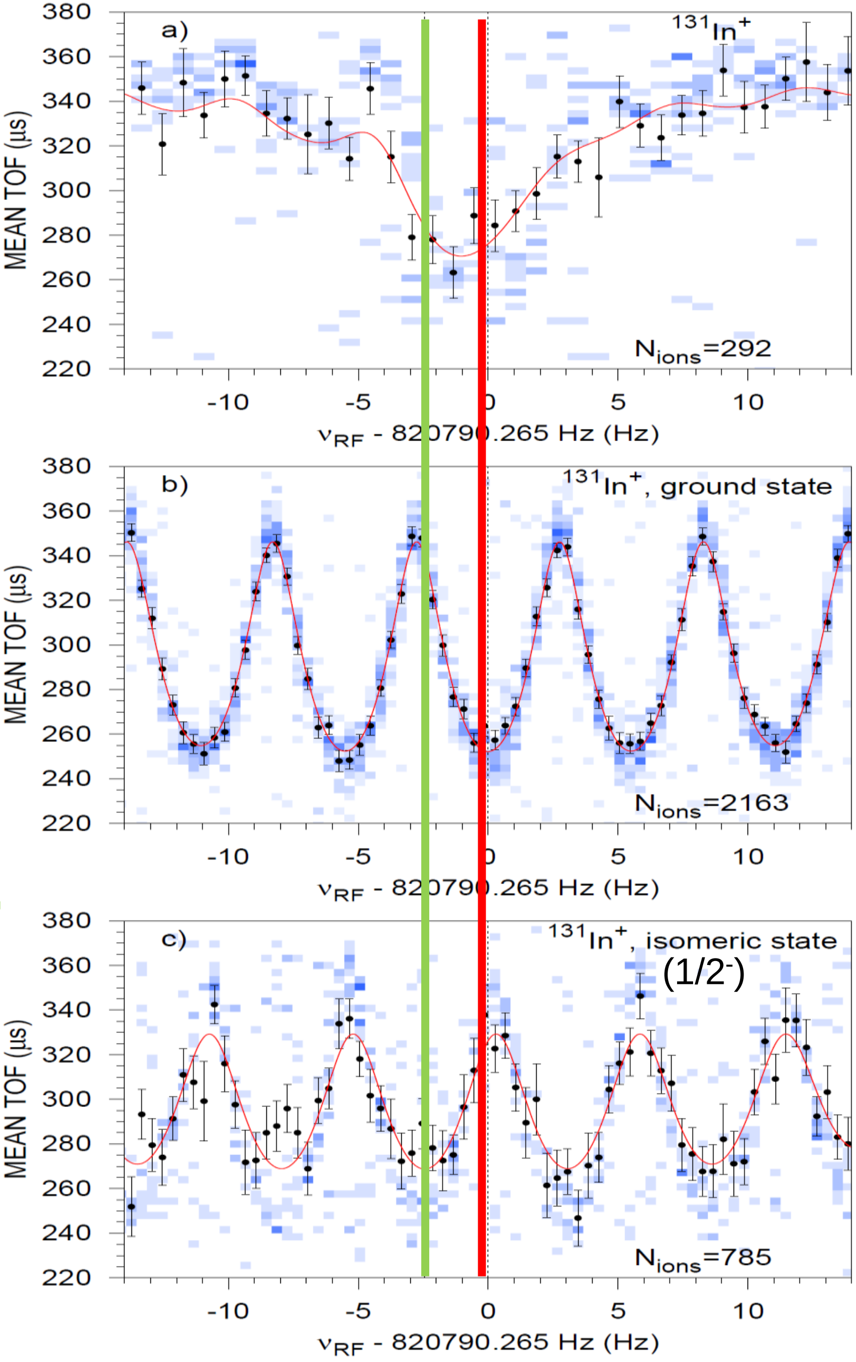
1/2$^-$, 302(32) keV, 350 ms

21/2$^+$, 3764(88) keV, 320 ms

JYFLTRAP result:

E*(1/2$^-$)=365(8) keV

To be published by
A. Kankainen et al.



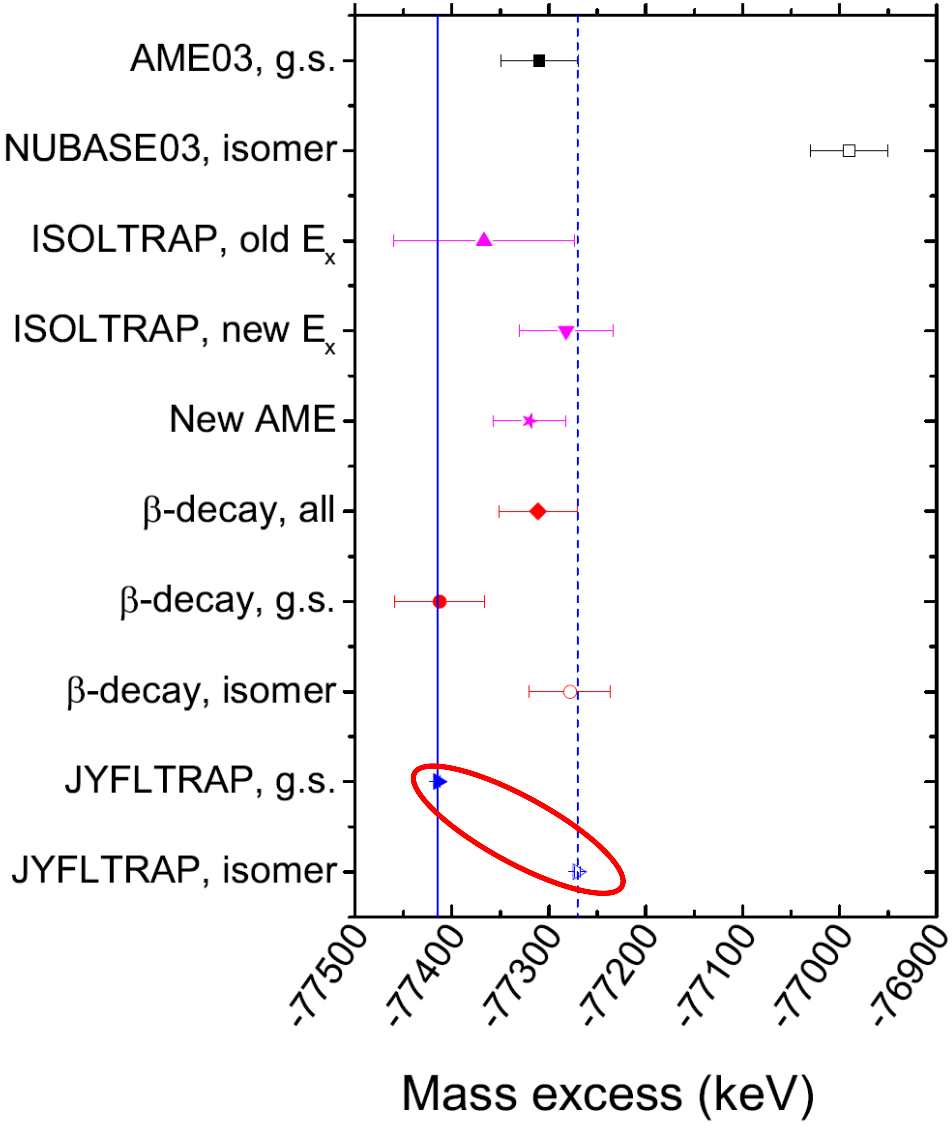
Continuous RF excitation
200 ms

Purification cycles +
pulsed RF excitation
25-150-15 ms

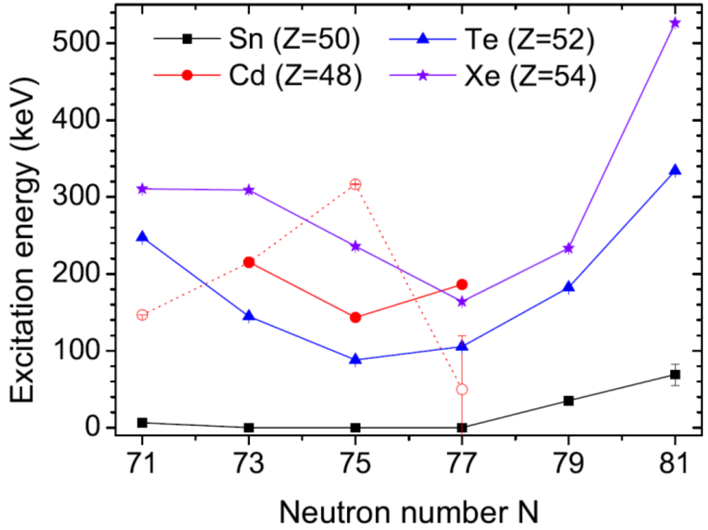
(Ramsey scheme)

Isomers & shell structure close to ^{132}Sn:

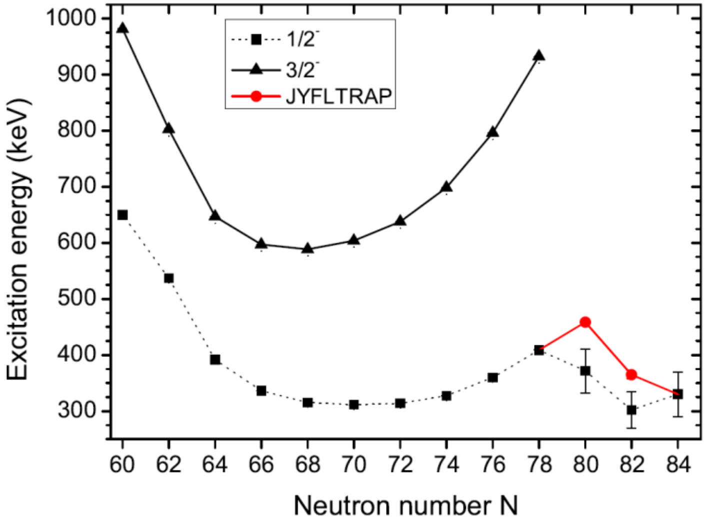
^{123}Cd, 11/2$^-$ isomer at 144(4) keV



Systematics of the 11/2− states in even-Z, odd-N nuclei.



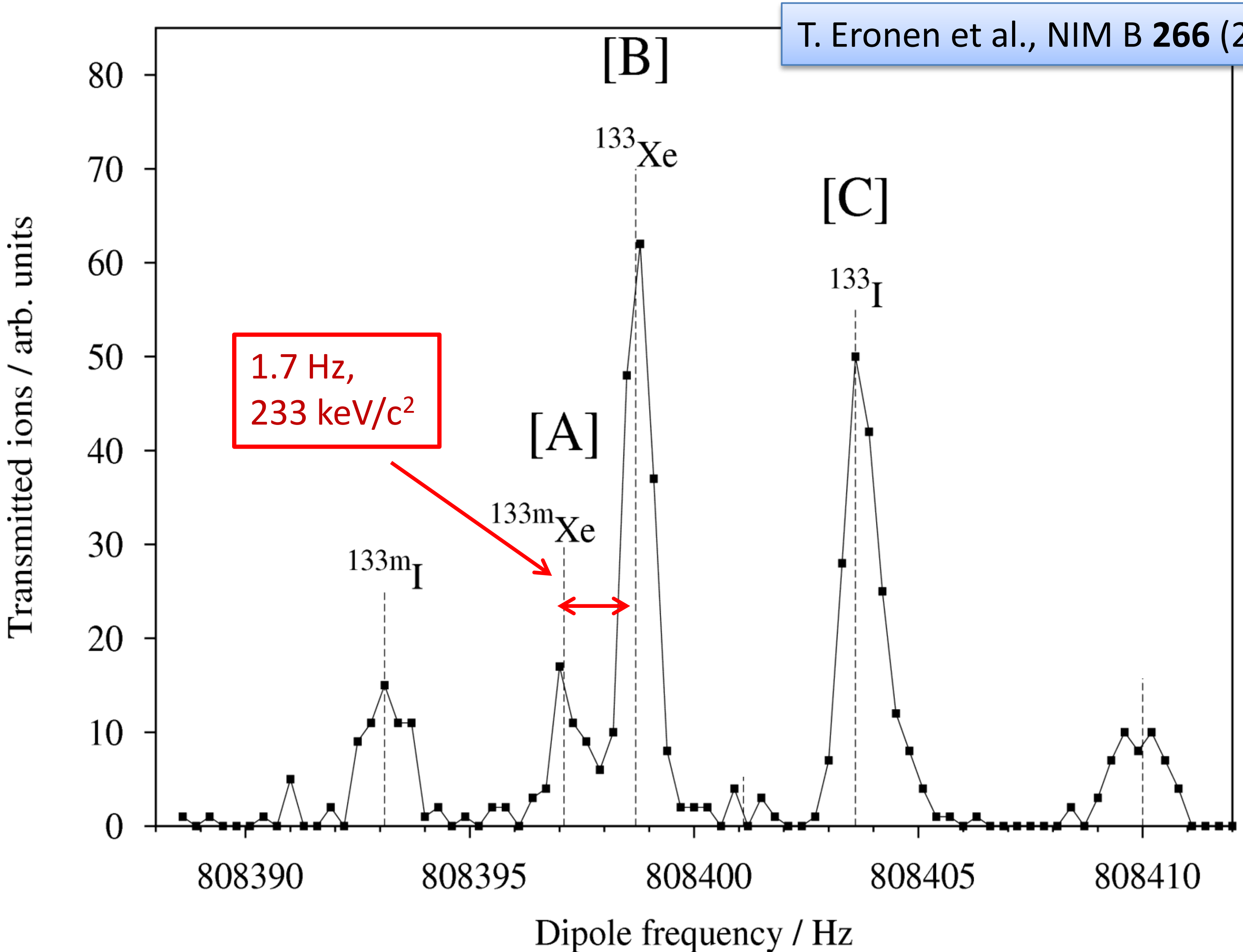
Isomers in even Indium



Isomers can also be separated

→ isomer-to-ground state ratios in fission

T. Eronen et al., NIM B **266** (2008) 4527

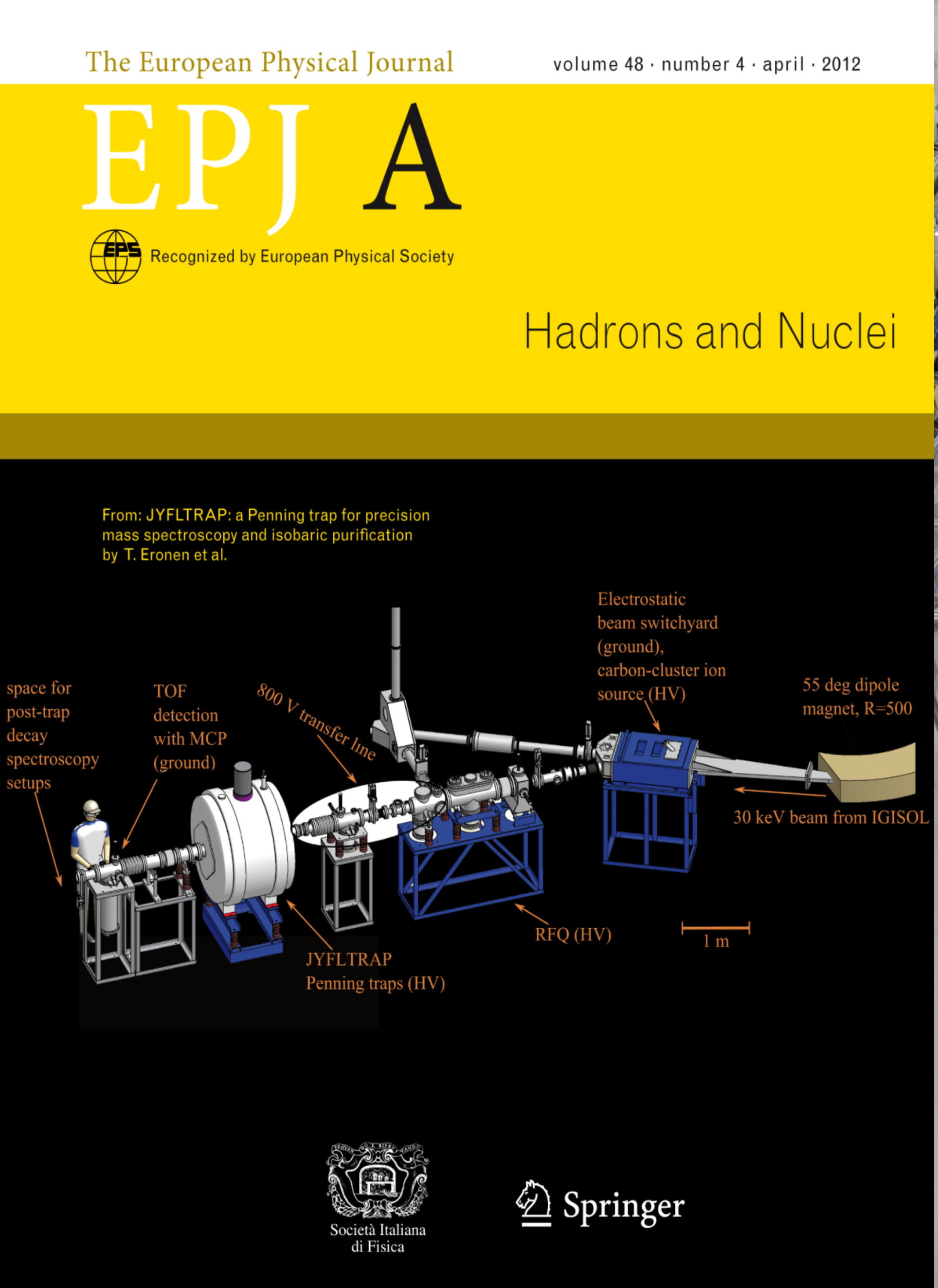


1.7 Hz,
233 keV/c^2

Summary - Outlook

- Knowledge of binding energies of neutron-rich nuclei has experienced a major revision during the last five years due to Penning-trap technique
- Long isotopic chains from Ni to Pr measured at three Penning trap facilities: Jyvaskyla, CERN-ISOLDE and Argonne
- Masses with uncertainties of 10 keV or less have become available
- The present PT experiments provide:
  - A new tool to study fine structure, such as shape changes, shell gaps, odd-even staggering far from stablity
  - A challenge for mass models and theories
  - Improved binding energy and fission data for nuclear astrophysics
  - start (references) for future experiments at new fission and fragmentation facilites (RIKEN, FAIR, FRIB, RAON) plus ISOL laboratories such as SPIRAL2, ISOLDE; IGISOL4

Special issue for IGISOL Science



The European Physical Journal volume 48 · number 4 · april · 2012

EPJ A

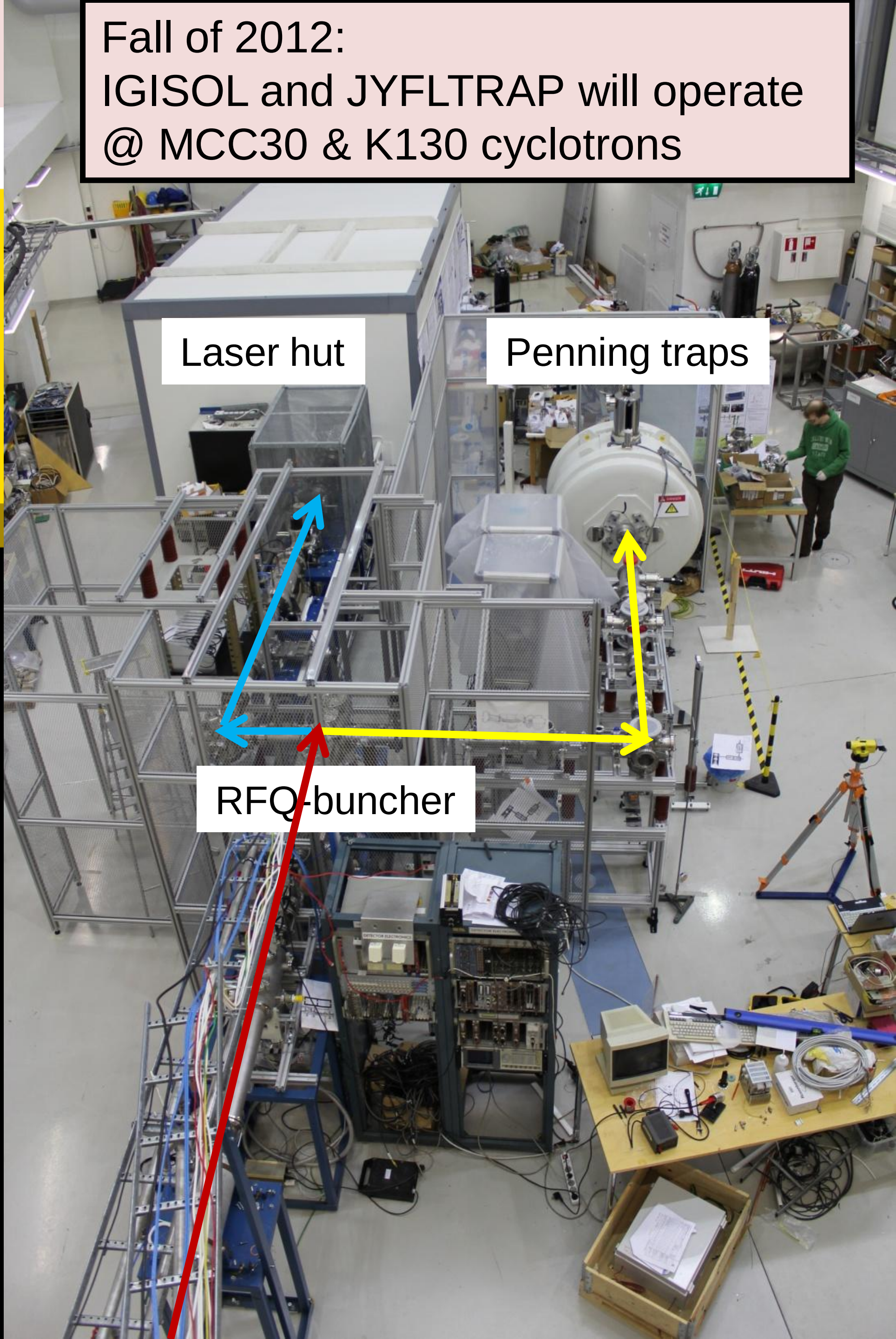
Recognized by European Physical Society

Hadrons and Nuclei

From: JYFLTRAP: a Penning trap for precision
mass spectroscopy and isobaric purification
by T. Eronen et al.

Società Italiana di Fisica

Springer



Fall of 2012:
IGISOL and JYFLTRAP will operate
@ MCC30 & K130 cyclotrons