Precision mass measurements
and
trap-assisted spectroscopy
of
fission products from Ni to Pd

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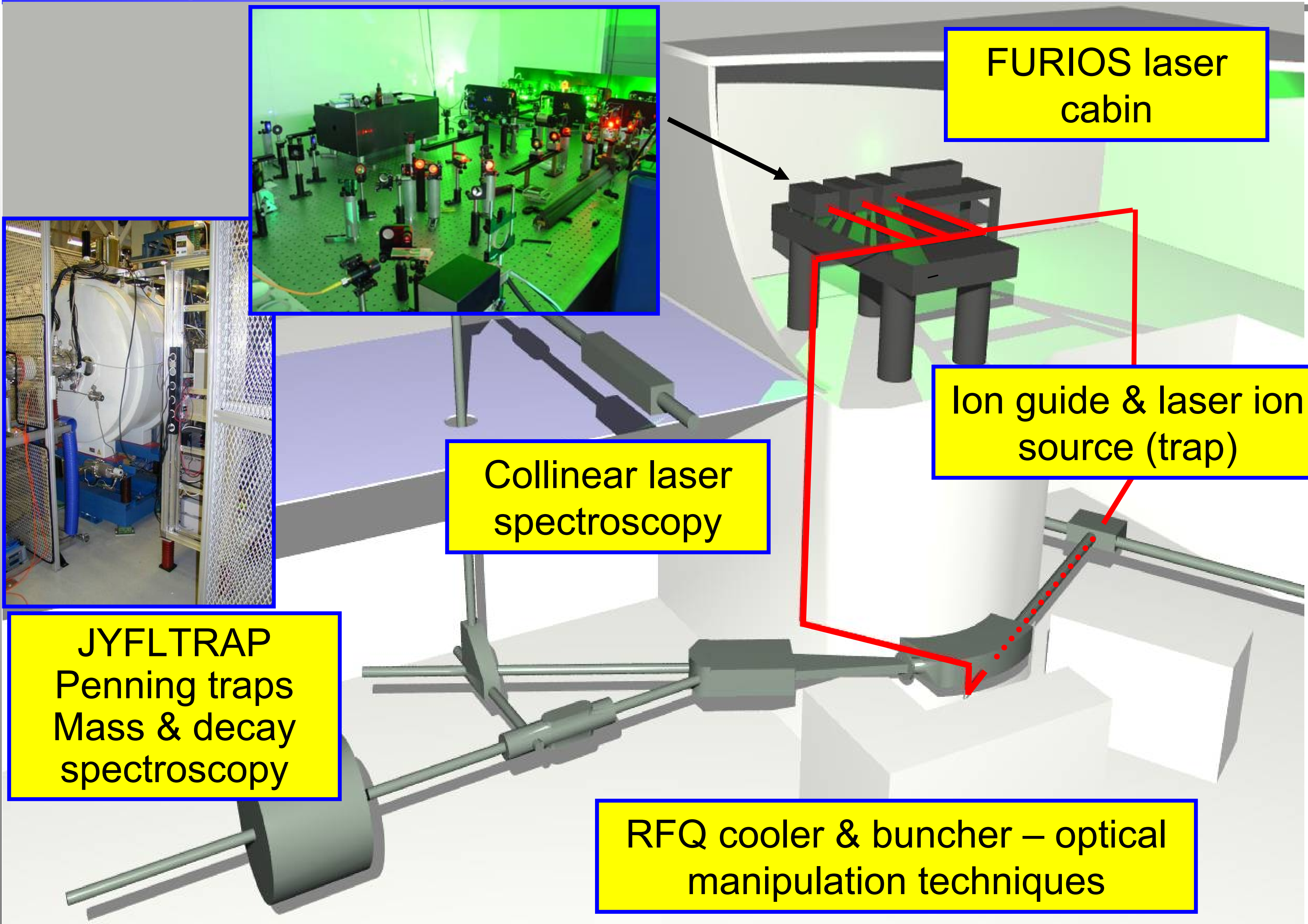
4th Int. Conf. on Fission and Properties of Neutron-Rich Nuclei
Sanibel Island, Florida, November 11-17, 2007

Ion-guide Isotope Separator On-Line (IGISOL)



FURIOS laser cabin

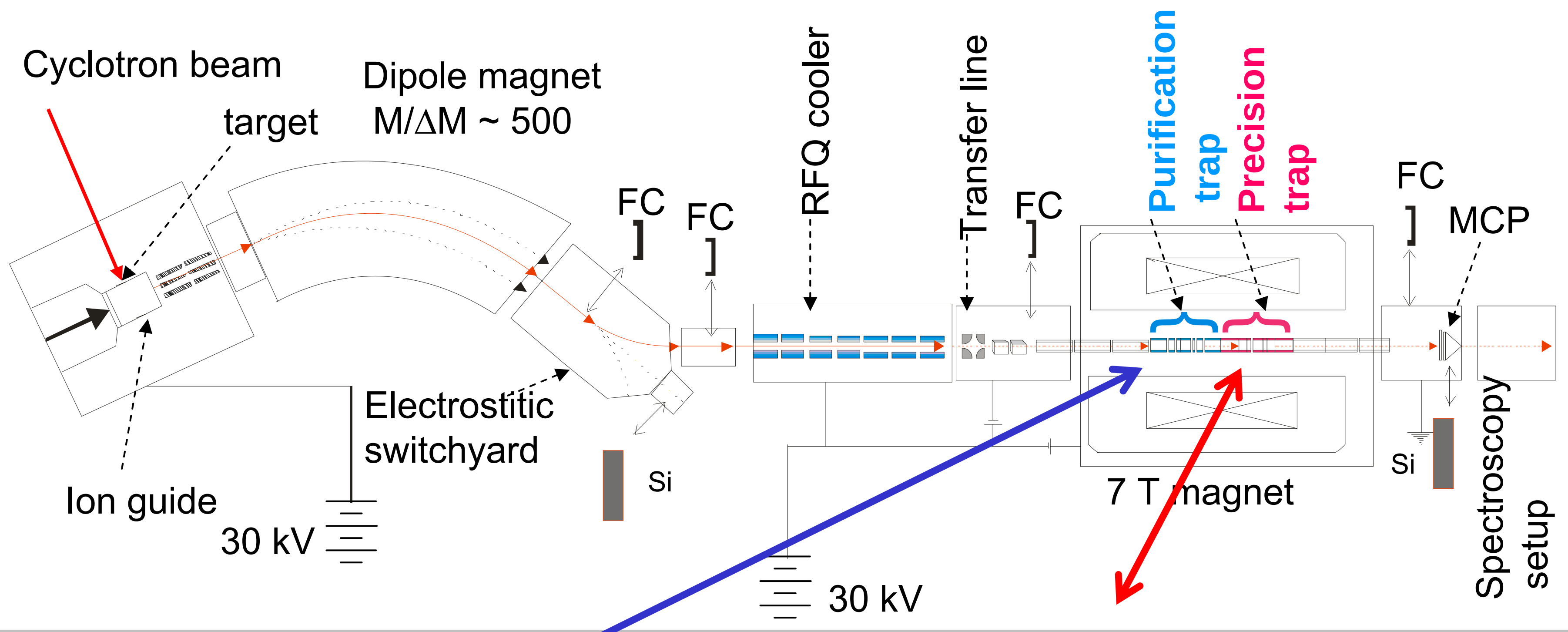
Ion guide & laser ion source (trap)

Collinear laser spectroscopy

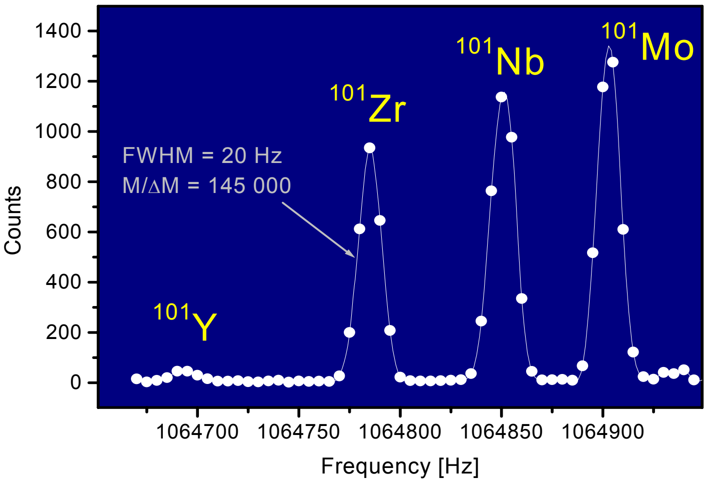
JYFLTRAP
Penning traps
Mass & decay spectroscopy

RFQ cooler & buncher – optical manipulation techniques

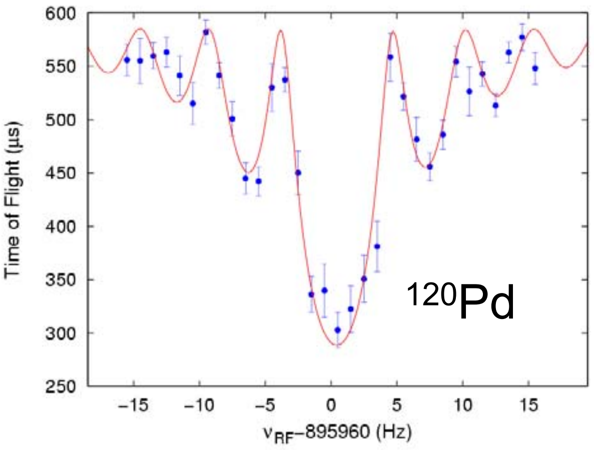
JYFLTRAP setup; closer look



Purification scan



TOF-resonance in Precision trap



Basic equations for mass determination

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

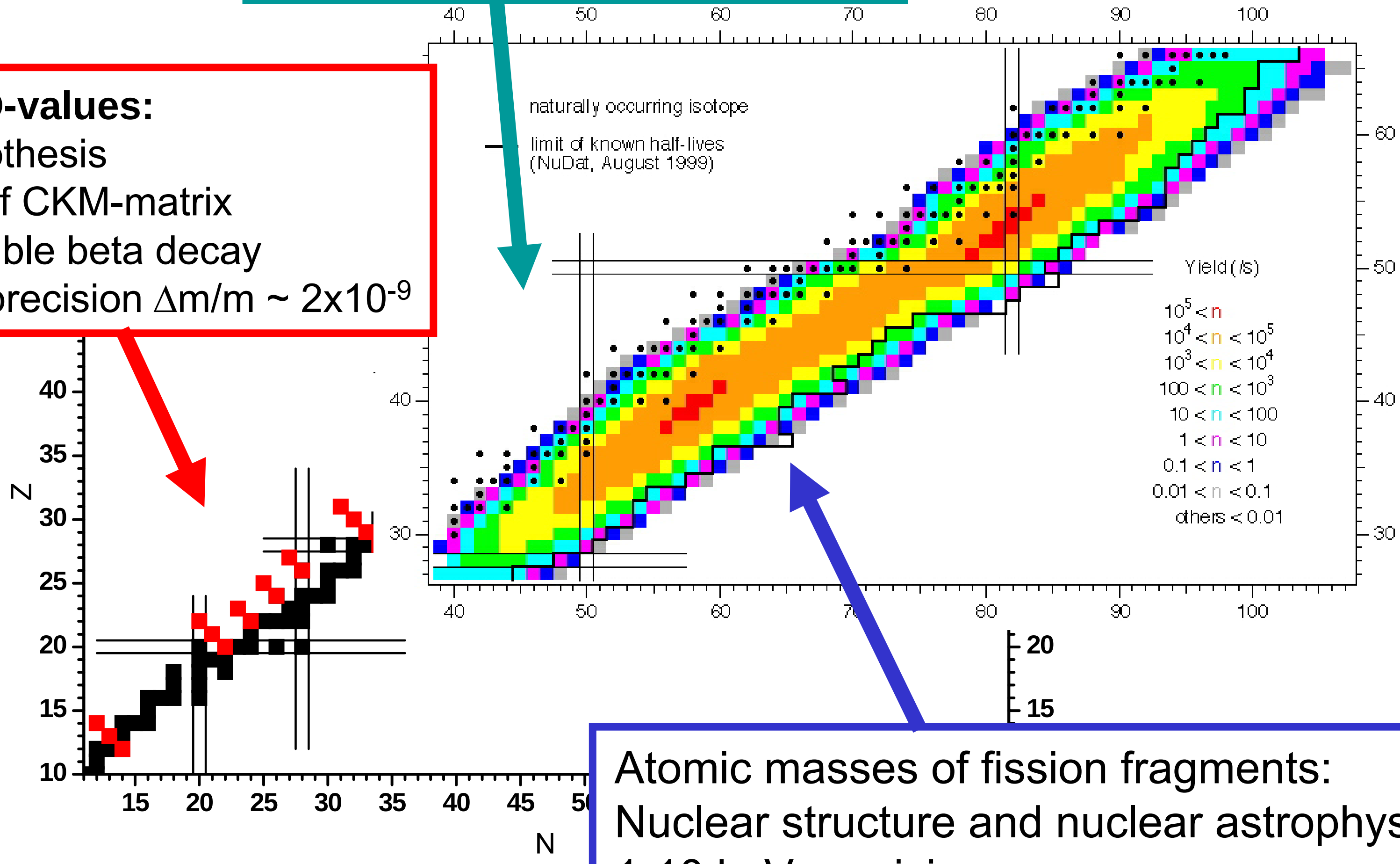
$$\boxed{\frac{f_{c,\mathrm{ref}}}{f_c} = \frac{m - m_e}{m_{\mathrm{ref}} - m_e}}$$

JYFLTRAP program

N-deficient nuclei below ^{100}Sn:
Nuclear structure and astrophysics
1-10 keV precision

P+^{238}U fission yields,
V. Rubchenya

Precise Q-values:
CVC-hypothesis
Unitarity of CKM-matrix
ν-less double beta decay
Sub-keV precision $\Delta m/m \sim 2 \times 10^{-9}$



Atomic masses of fission fragments:
Nuclear structure and nuclear astrophysics
1-10 keV precision

A. Jokinen et al., Int. J. Mass Spectr. 251 (2006) 204

JYFLTRAP program for fission products

N-deficient nuclei below ^{100}Sn:
Nuclear structure and astrophysics
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V. Rubchenya

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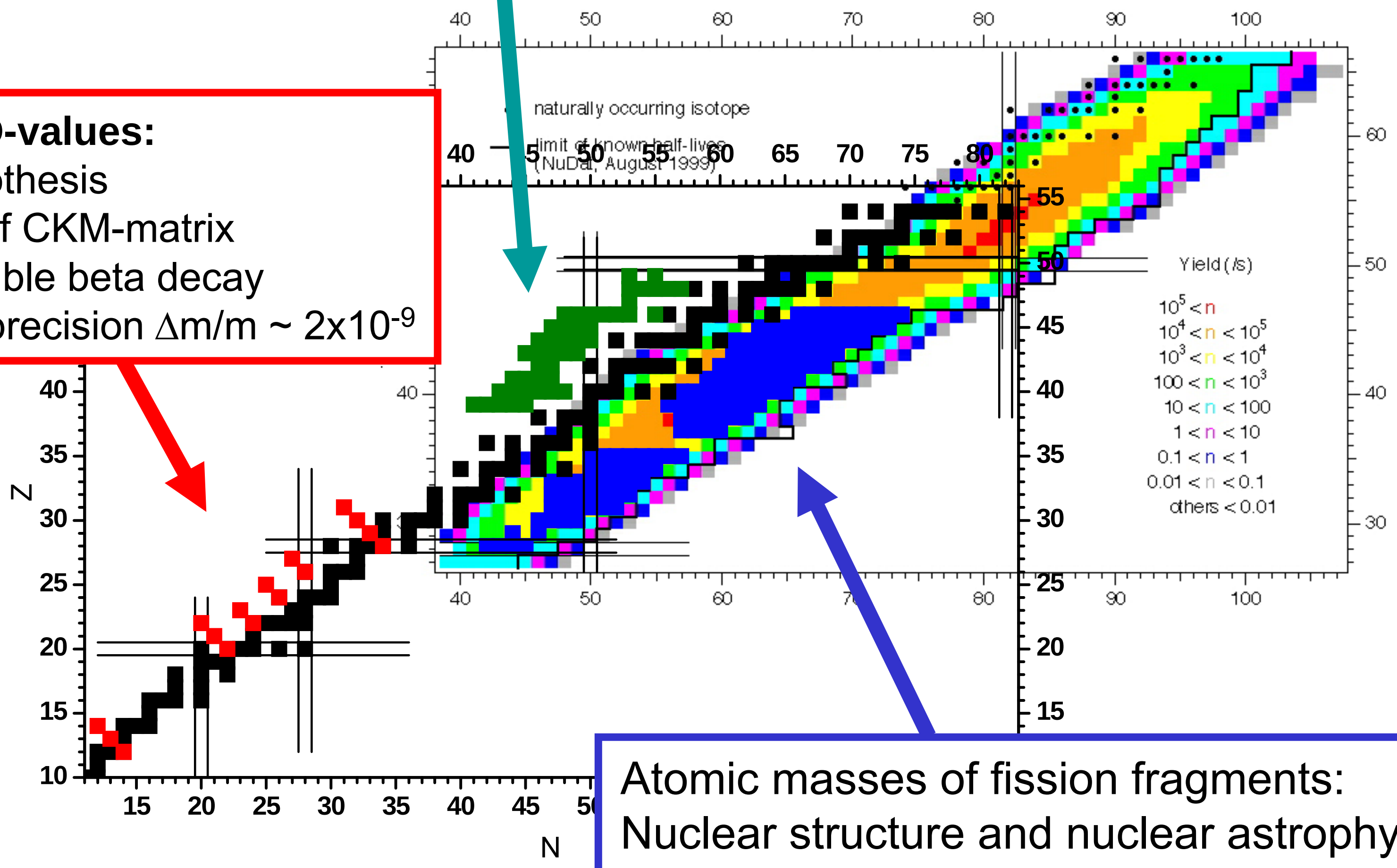
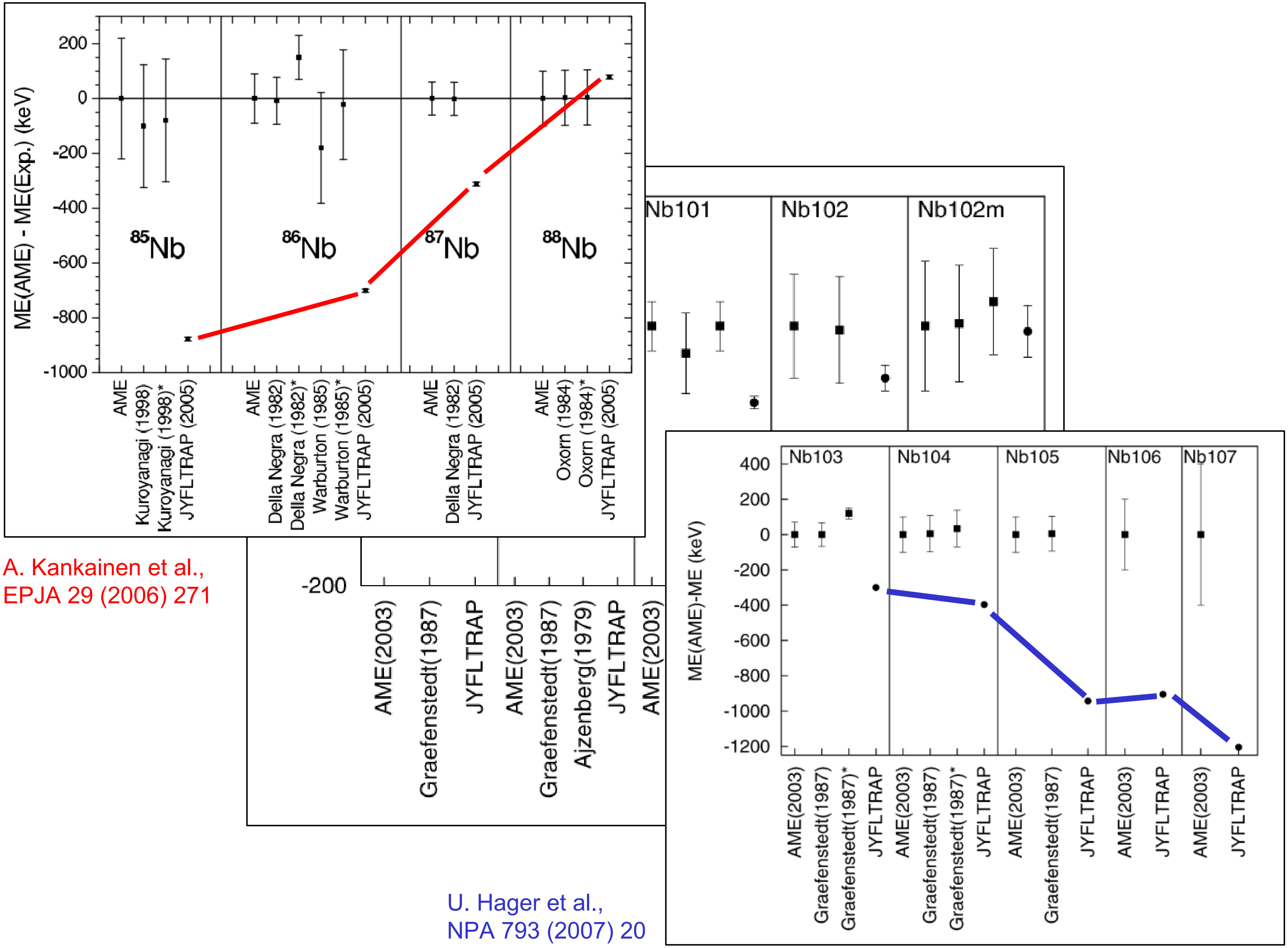
ν-less double beta decay
Sub-keV precision Δm/m ~ 2x10^{-9}



Atomic masses of fission fragments:
Nuclear structure and nuclear astrophysics
1-10 keV precision

A. Jokinen et al., Int. J. Mass Spectr. 251 (2006) 204

Comparison to AME and previous data; Nb

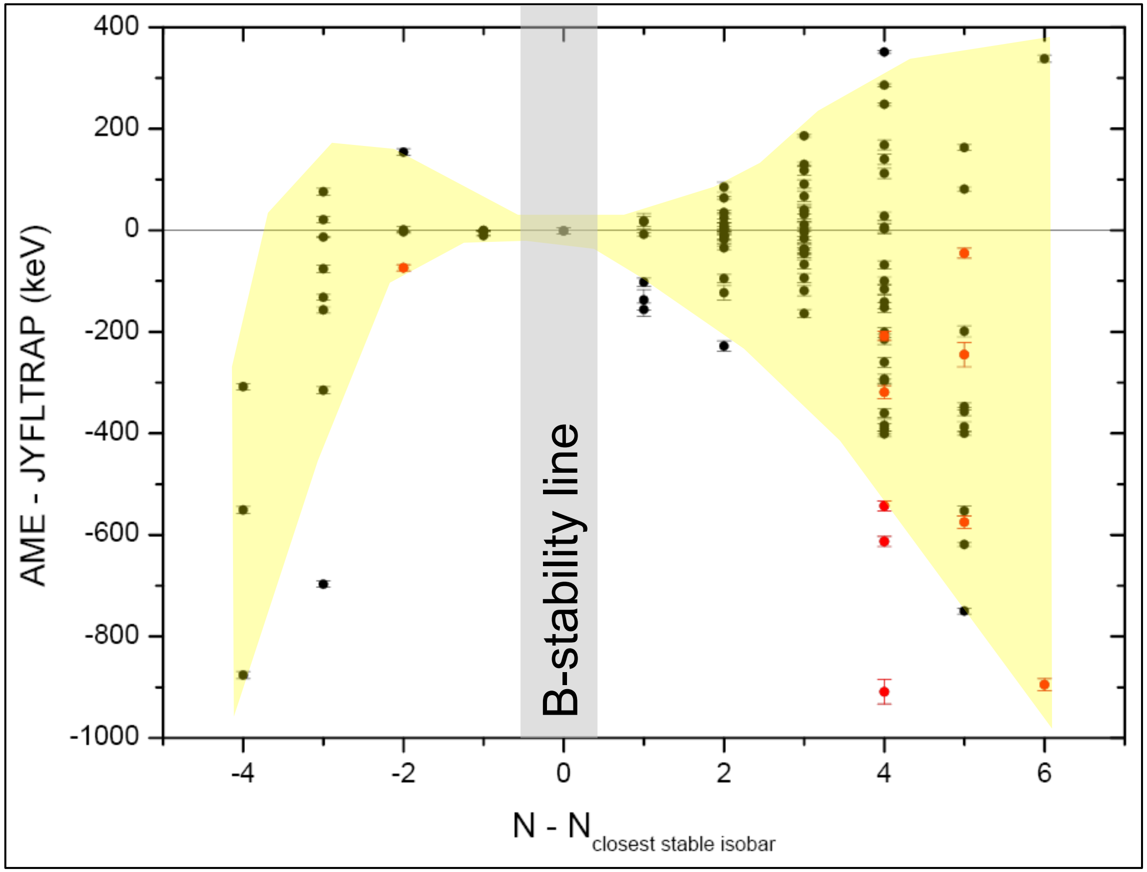


A. Kankainen et al.,
EPJA 29 (2006) 271

U. Hager et al.,
NPA 793 (2007) 20

JYFLTRAP data vs. AME 2003

N-def.

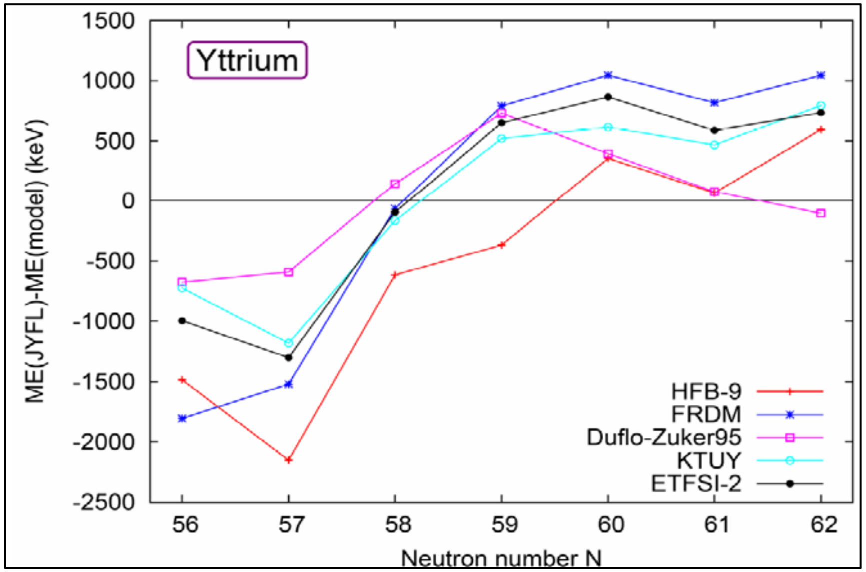


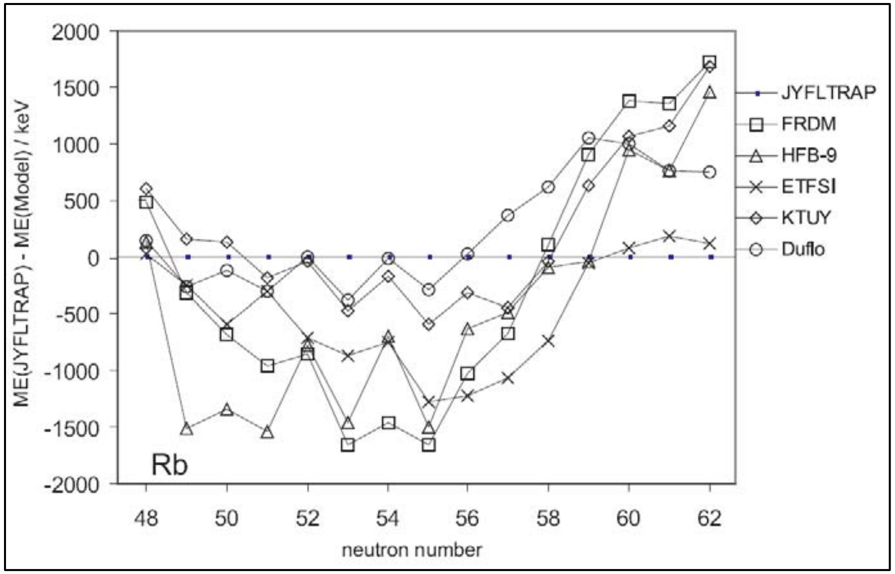
N-rich

Mass predictions vs. JYFLTRAP data

U. Hager et al., NPA 793 (2007) 20

S. Rahaman et al., EPJA 32 (2007) 87



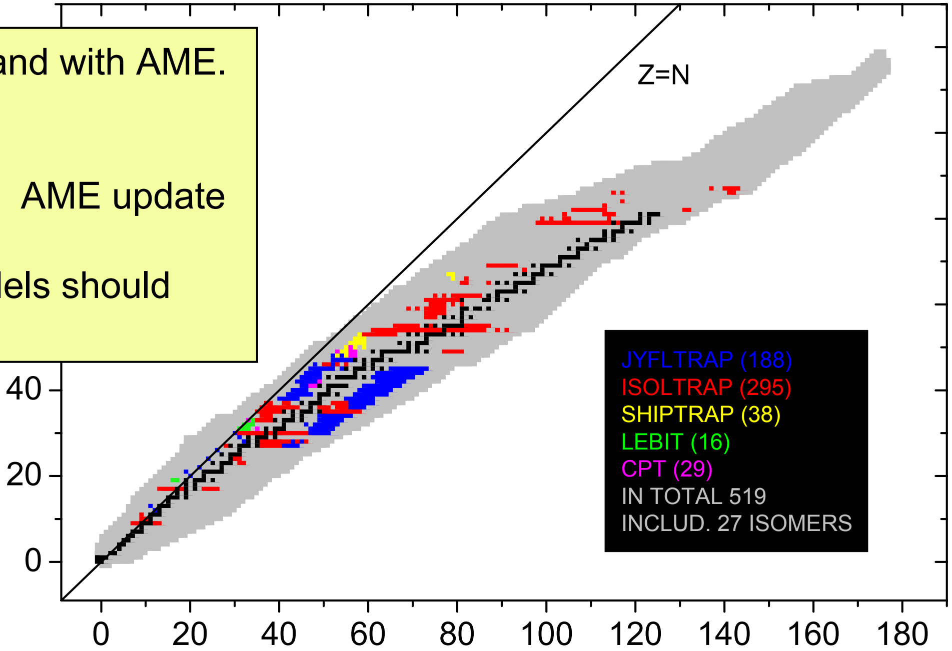


Mass predictions tend to agree with each other and with AME.

→ Are predictions guided by AME ?

Plenty of new exp. data and more is coming, but AME update take years

→ benchmarking and optimization of models should be based on the new data !



Mass measurements for r-process

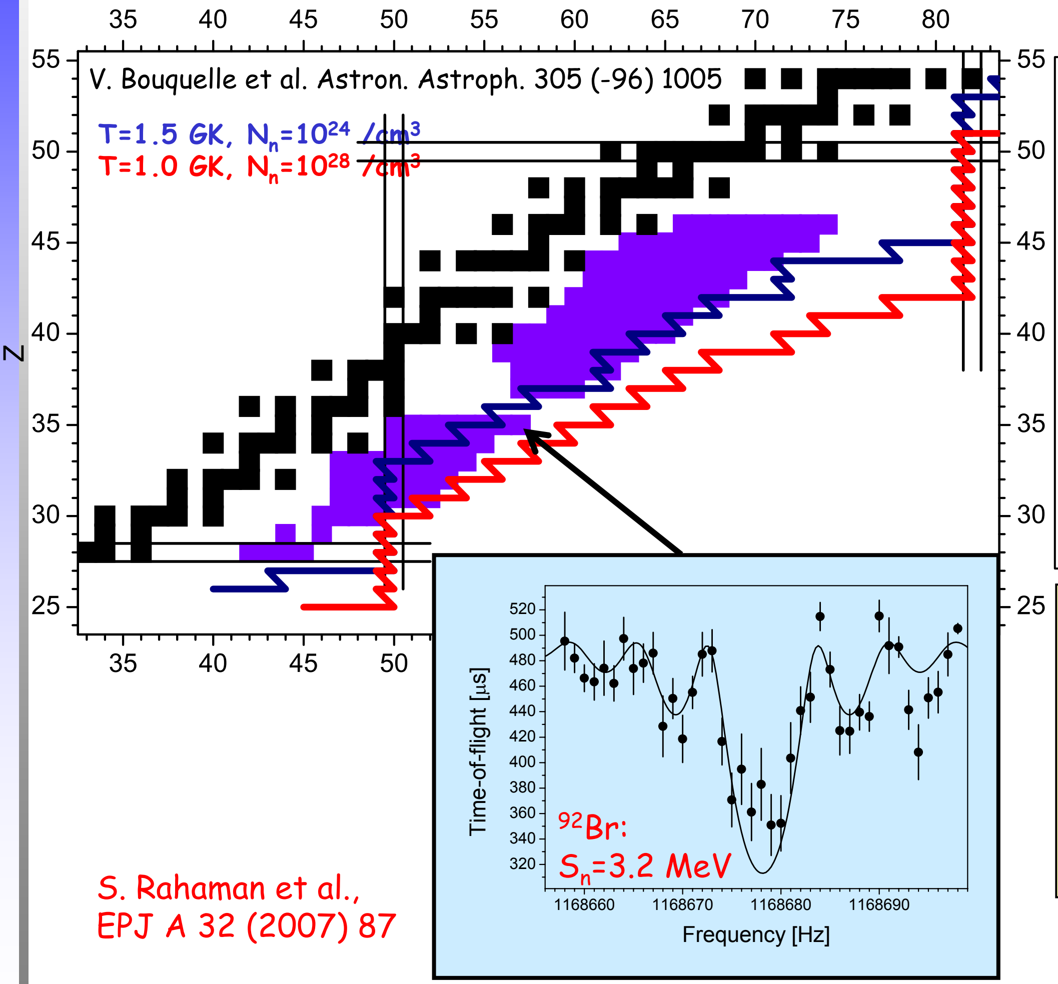
Astrophysics motivation

Synthesis of heavy elements beyond iron (Z>26)

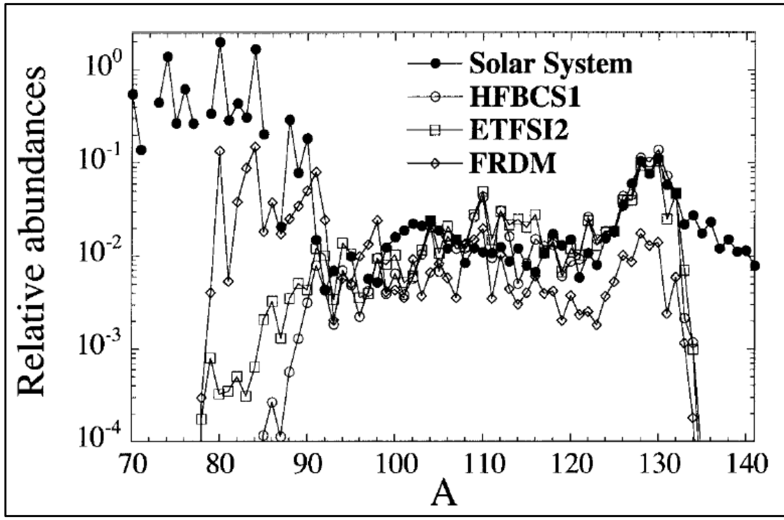
Location of r-process path:

(n,γ) – (γ,n) equilibrium. S_n = 2-4 MeV

$$\lambda_{\gamma n} \propto \frac{T^{3/2}}{N_n} e^{\left(\frac{S_n}{k_B T}\right)} \lambda_{n\gamma}$$



S. Rahaman et al.,
EPJ A 32 (2007) 87



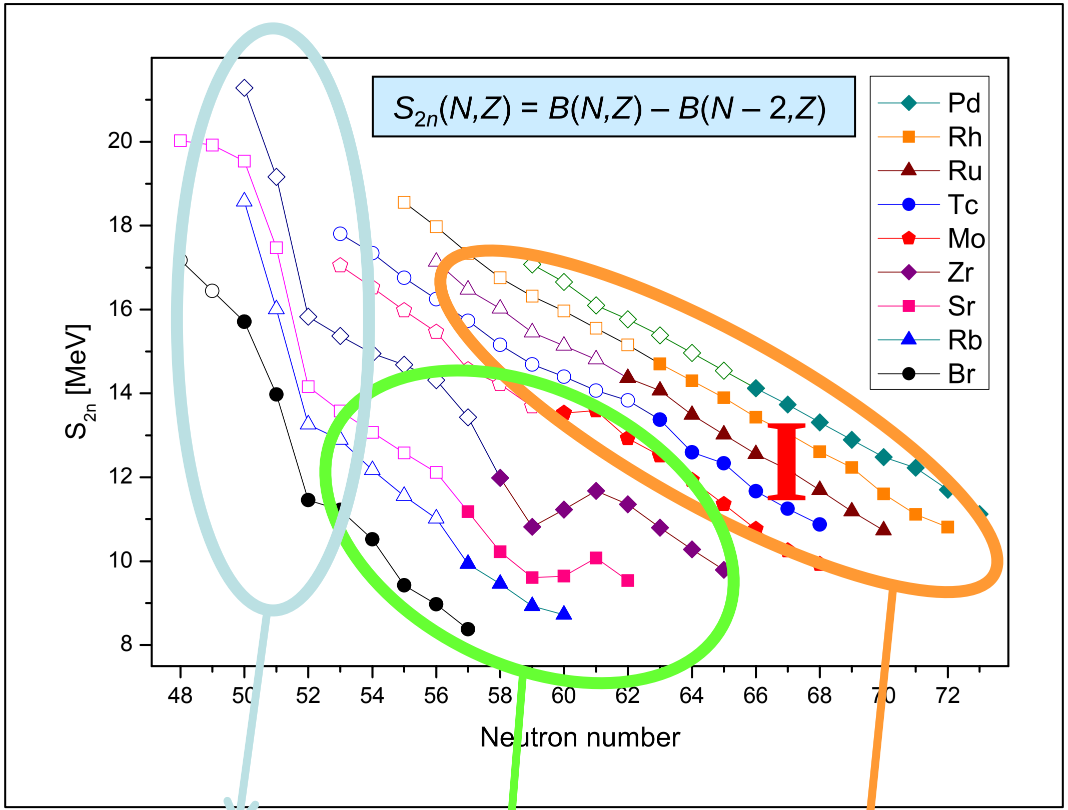
R-process abundances calculated with the HFBCS-1, ETFSI-2 and FRDM mass models in the framework of the canonical model.

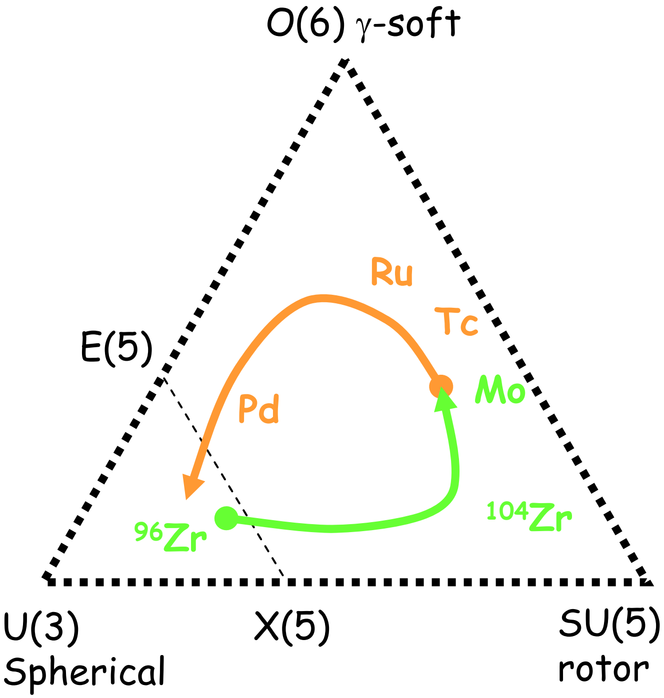
The r-process is characterized by $N_n = 10^{21}$ cm^{-3}, $T = 1.2 \times 10^9$ K and τ = 2.1 s.

S.Goriely, Hyp. Inter. 132 (2001) 105

Nuclear structure aspects and S_{2n}

S_{2n} sensitive for structure effects



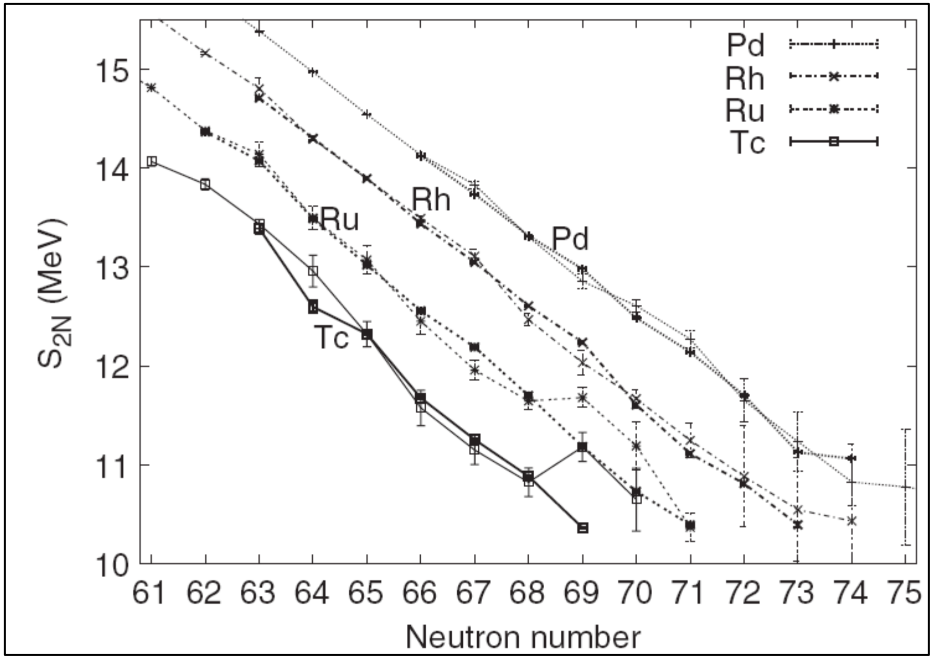


N=50 shell gap

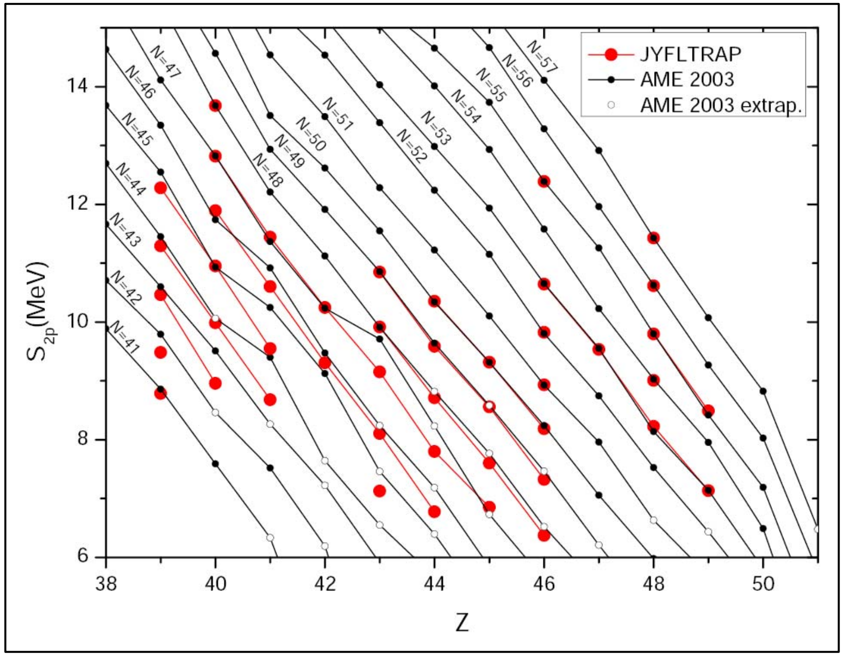
Rapid changes of deformation

Transitional region, γ-soft, triaxiality ?

Two-particle separation energies



U. Hager et al., PRC75 (2007) 064302



V.-V. Elomaa et al., 2007, to be published

New data removes irregularities of the compiled experimental data (AME2003)

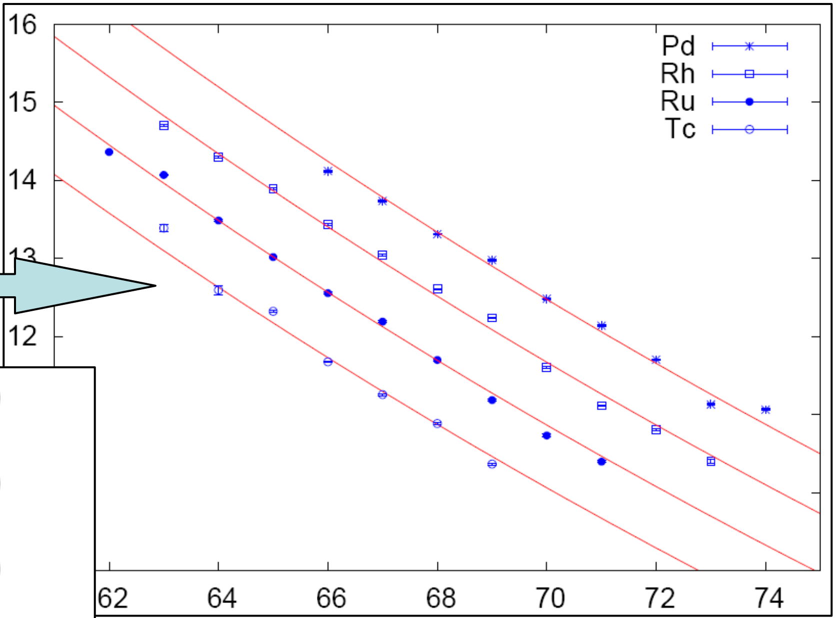
→ Smooth behaviour ← pure liquid-drop behaviour

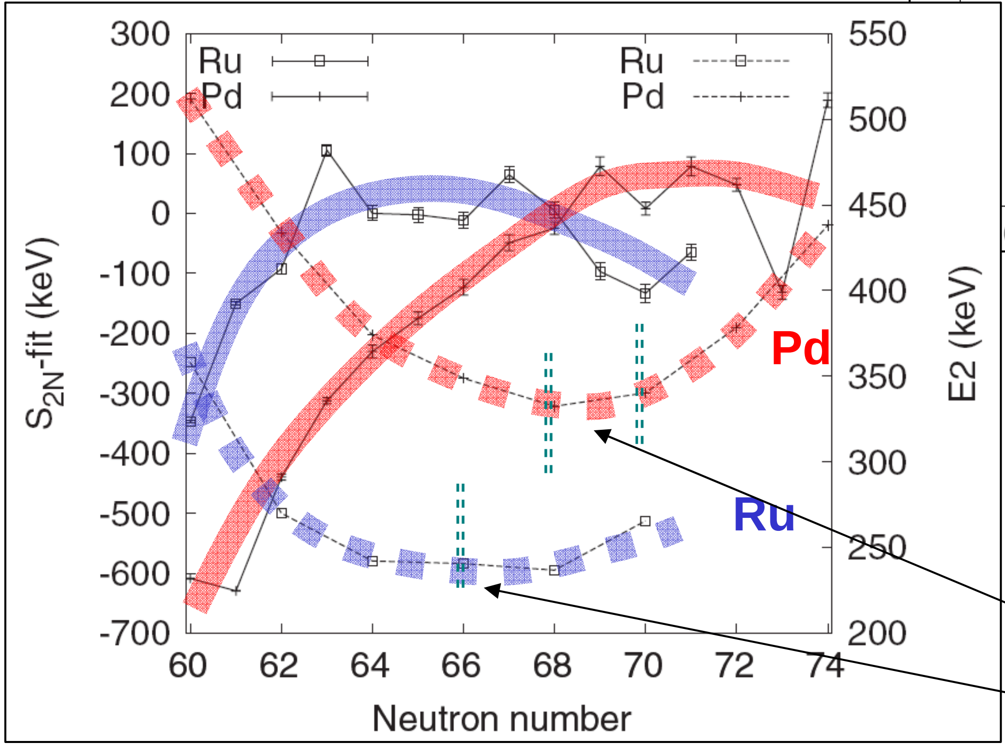
AME2003: G. Audi et al., NPA 729 (2003) 337

Sensitivity of S_{2n} – additional correlations ?

Liquid drop behaviour of S_{2n} :

$$f(Z,A) = \frac{Z^2}{A(A-2)}a + Z(Z-1)A^{-4/3}b + c$$





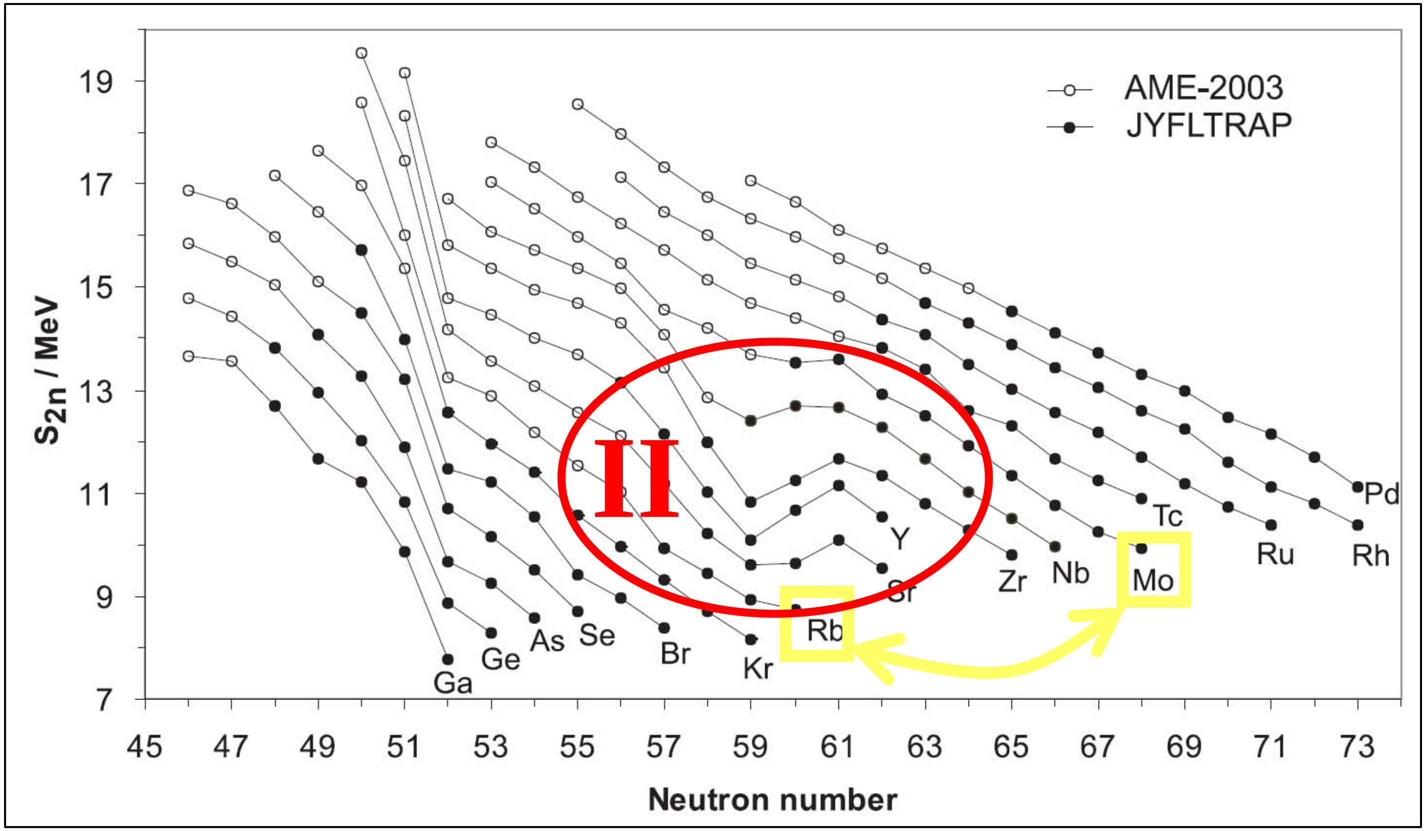
Despite of the apparent smooth behaviour of S_{2n}, systematic structure has been observed which resembels the behaviour of $E(2^+)$ energies.

Shape changes from prolate to oblate:
J. Skalski, S. Mizutori, and W. Nazarewicz, Nucl. Phys. A 617 (1997) 282

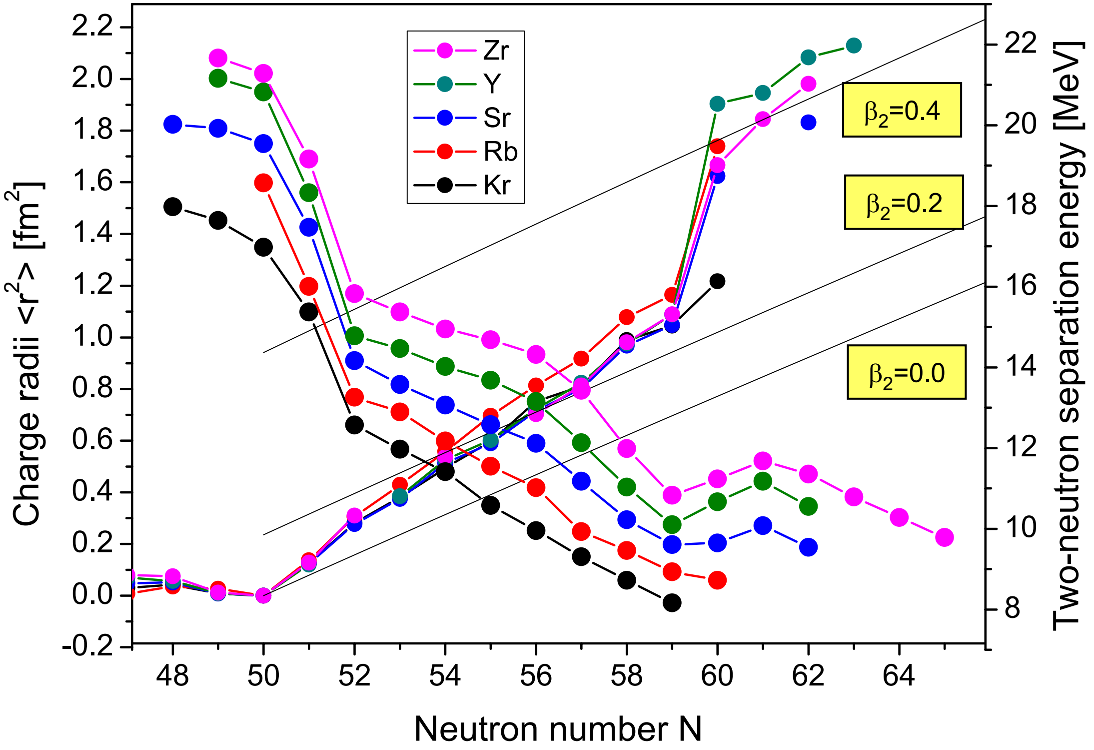
U. Hager et al., Phys. Rev. C75 (2007) 064302

Discontinuity at N~60, Z~40

$$S_{2n}(N,Z) = B(N,Z) - B(N-2,Z)$$



Discontinuity at N~60, Z~40 – shape effect

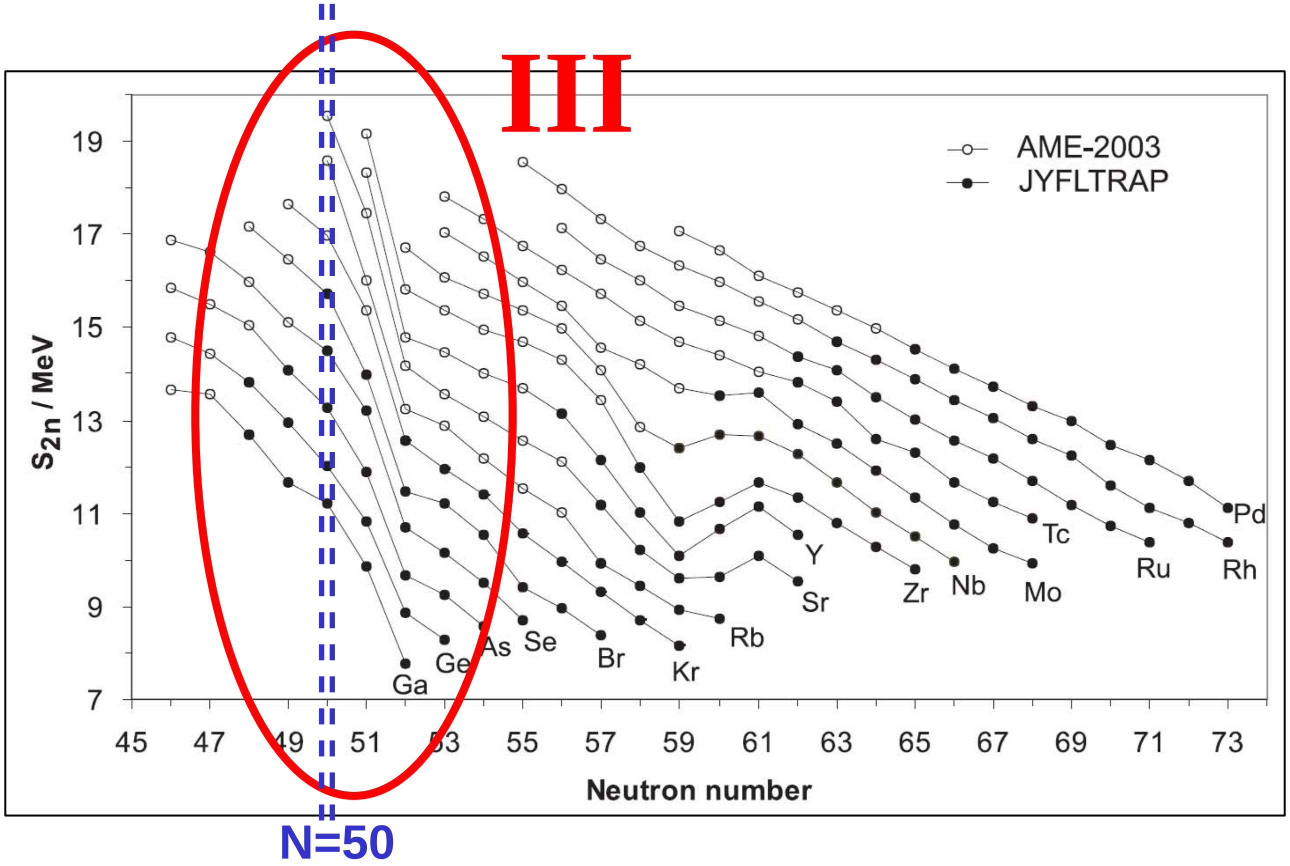


Collinear laser spectroscopy at JYFL:
Zr: P. Campbell et al., PRL 89 (2002) 082501
Y:B. Cheal et al., PLB 645 (2007) 133
(Presentation this afternoon)

JYFLTRAP:
U. Hager et al. PRL 96 (2006) 042504
U. Hager et al., NPA 793 (2007) 20
S. Rahaman et al., EPJA 32 (2007) 87

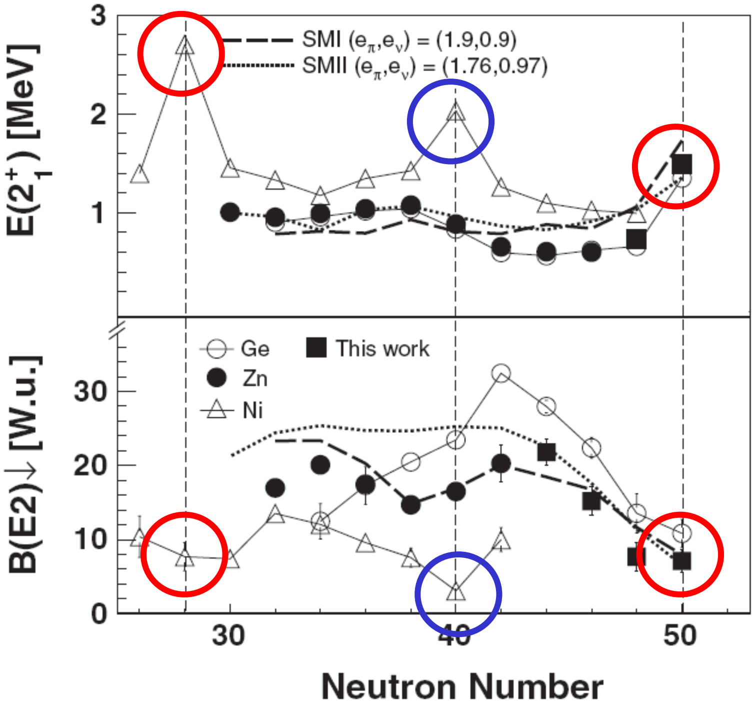
N=50 shell gap

$$S_{2n}(N,Z) = B(N,Z) - B(N-2,Z)$$

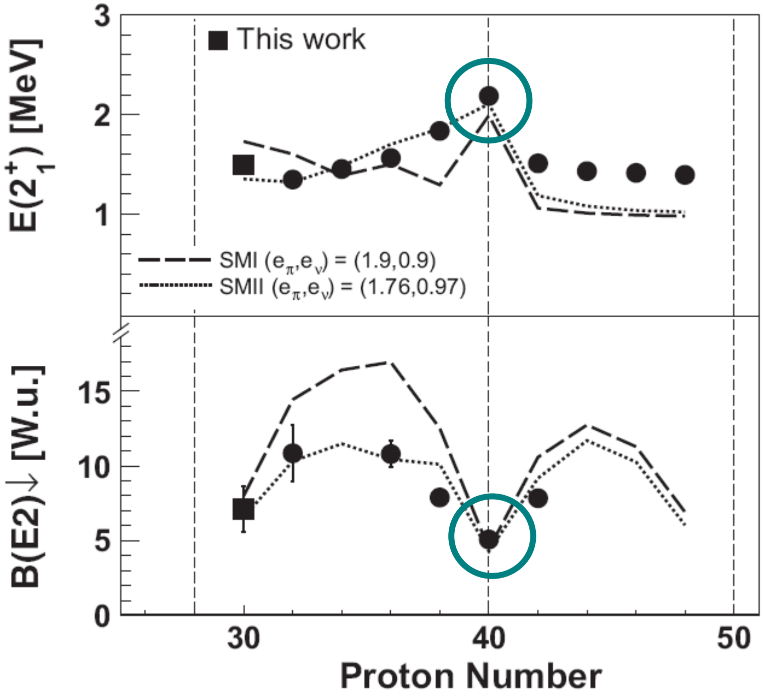


N=40 and 50 shell gaps; spectroscopic data

Z=28,30,32 isotopes



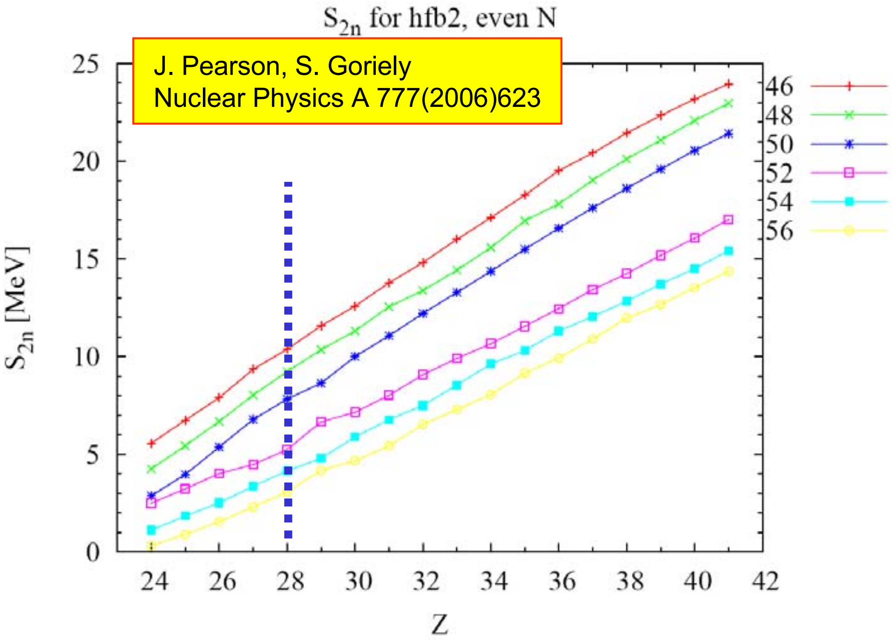
N=50 isotones



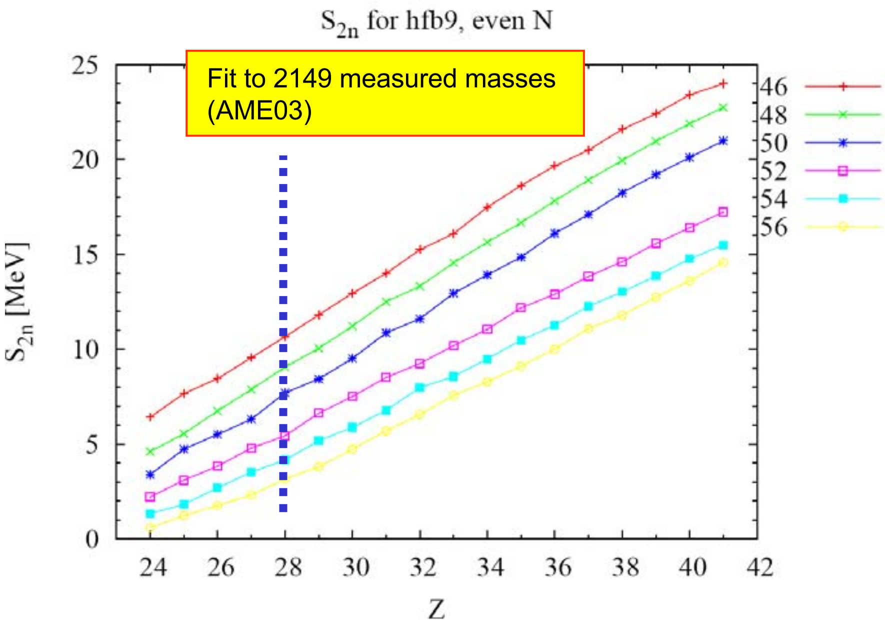
N=28 and N=50 shell gaps
N=40 sub-shell closure
Z=40 sub-shell closure

Figures:
J. Van de Walle, PRL 99 (2007) 142501

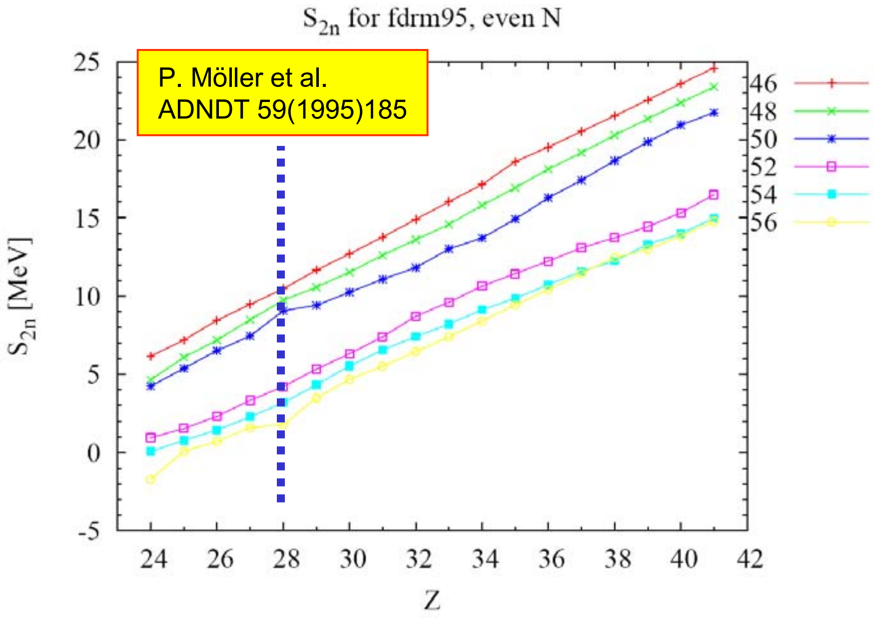
Evolution of N=50 shell gap from theory



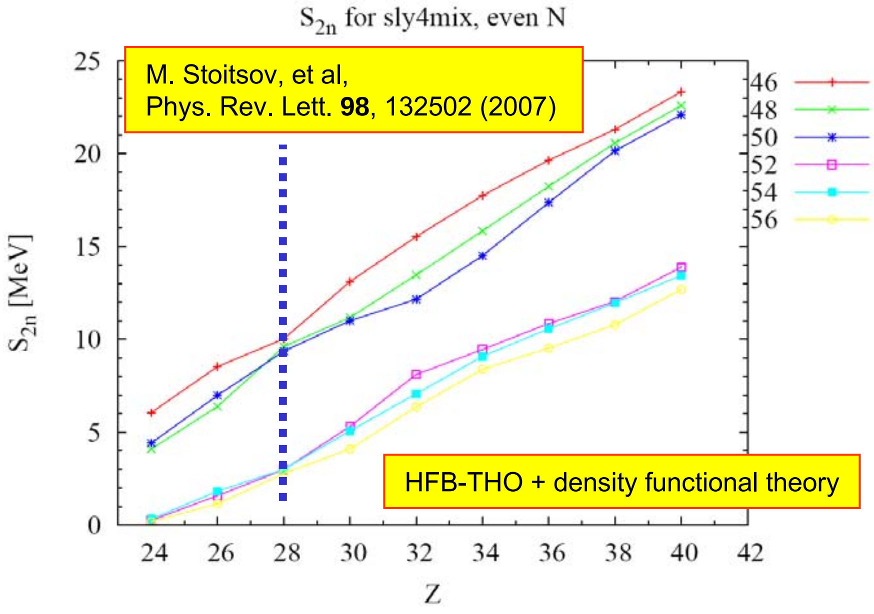
J. Pearson, S. Goriely
Nuclear Physics A 777(2006)623



Fit to 2149 measured masses (AME03)



P. Möller et al.
ADNDT 59(1995)185

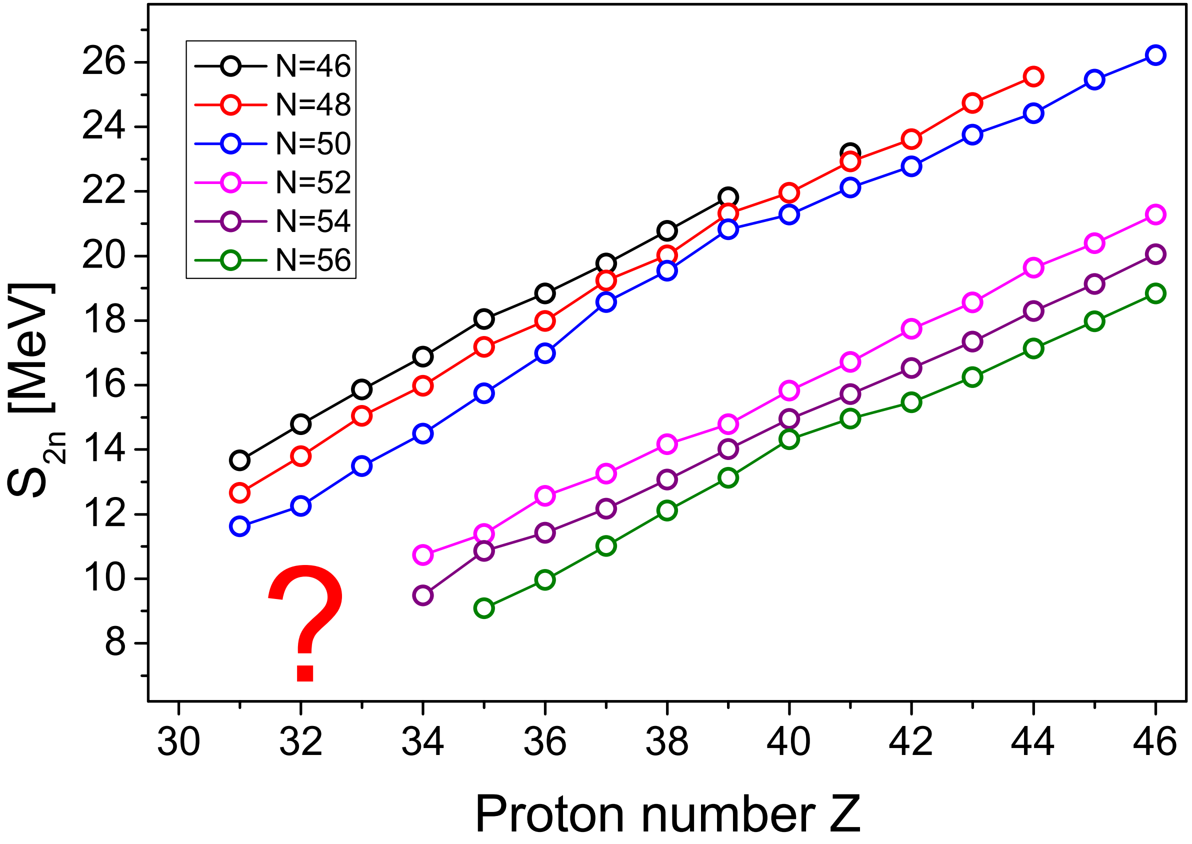


M. Stoitsov, et al,
Phys. Rev. Lett. **98**, 132502 (2007)

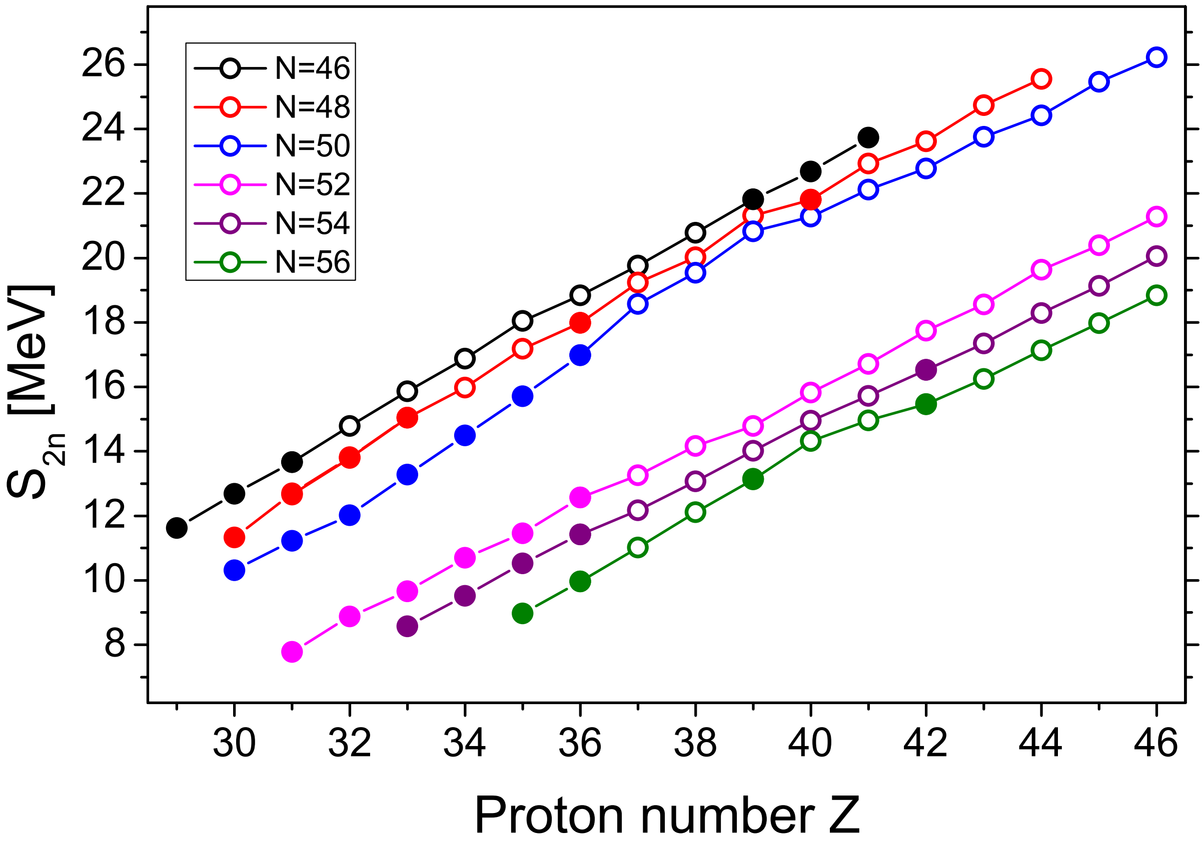
HFB-THO + density functional theory

N=50 shell gap extracted from exp. data

(AME2003 without extrapolations ! G. Audi et al., NPA 729 (2003) 337)



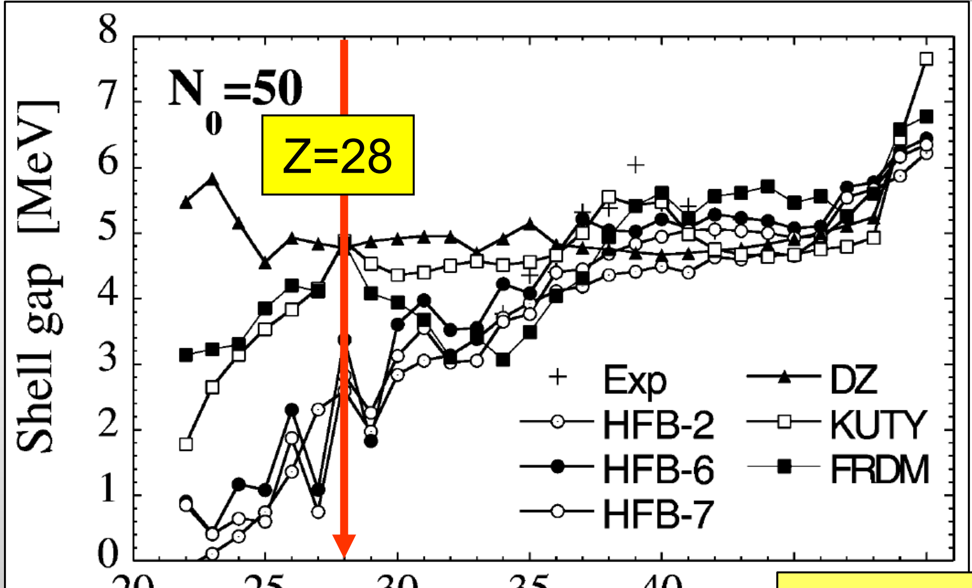
N=50 shell gap from AME2003+Penning trap data



Zn-isotopes from ISOLTRAP; A. Herlert private comm. 2007
+ from JYFLTRAP, Nov. 2007

J. Hakala et al. (2007) to be published

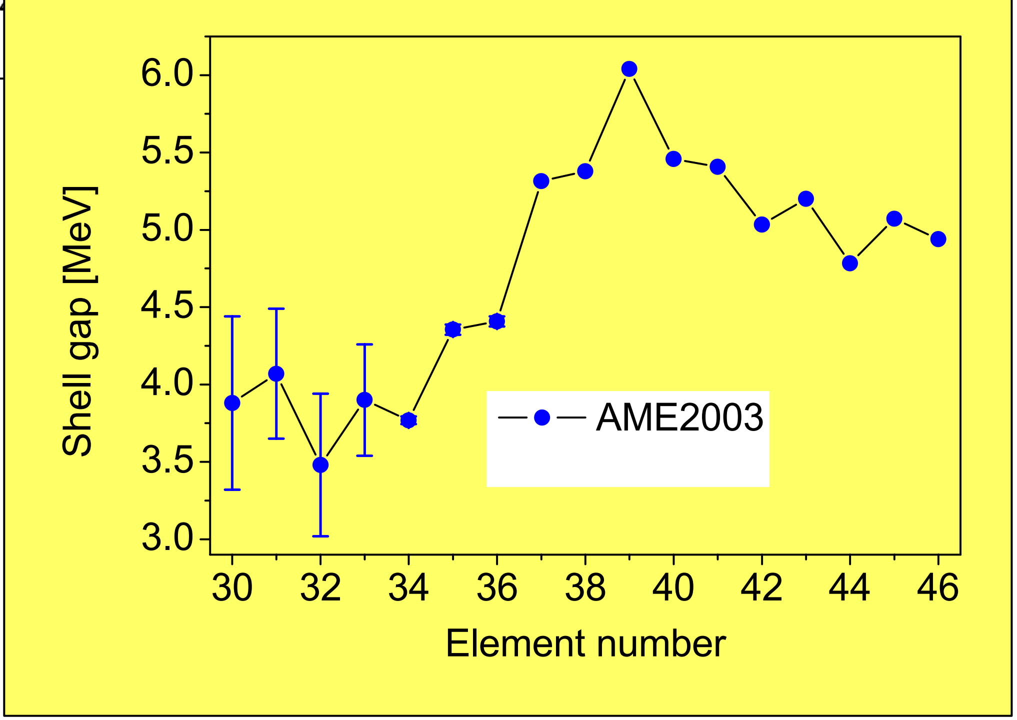
Shell gap energies



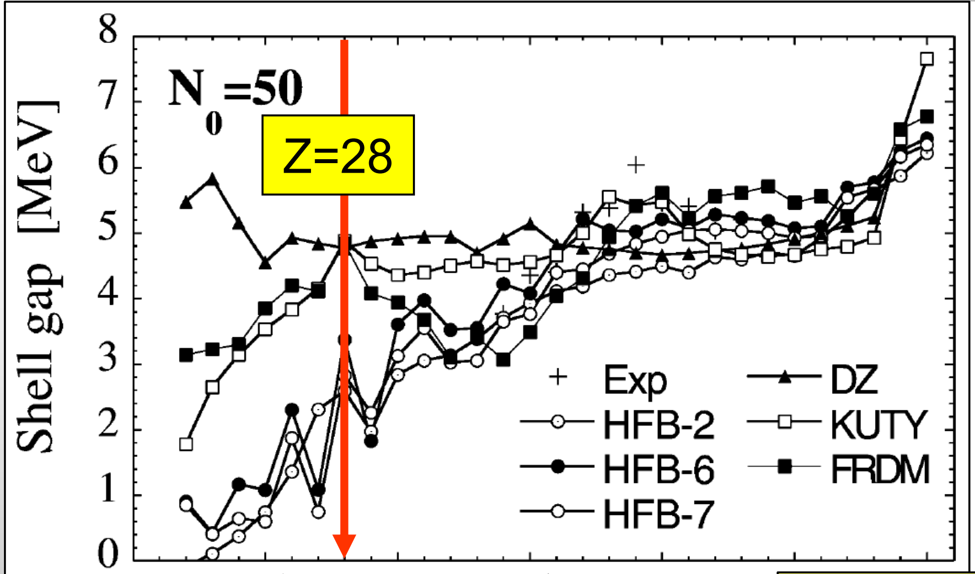
Shell gap equation:

$\Delta_{2n}(N_o) = S_{2n}(N_o)-S_{2n}(N_o+2)$

Comparison of shell gaps deduced from different mass predictions:
J.M. Pearson and S. Goriely,
Nucl. Phys. A 777 (2006) 623



Shell gap energies



Comparison of shell gaps deduced from different mass predictions:
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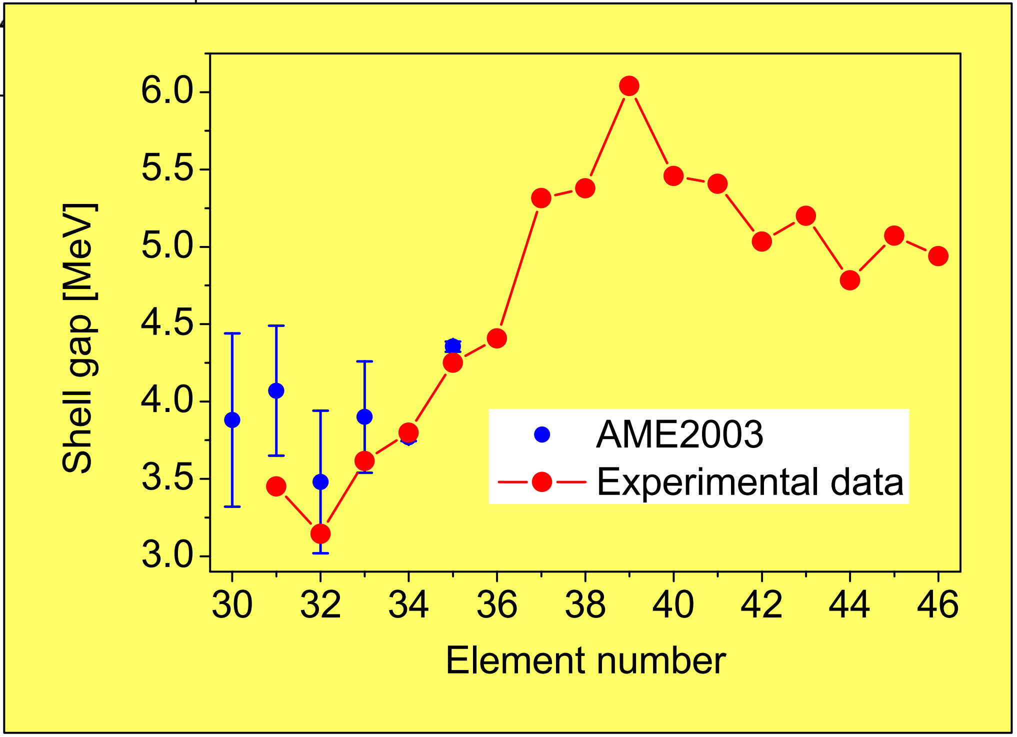

New data:
Smaller gap ?
Z<31 needed !

J. Hakala et al. to be published, 2007

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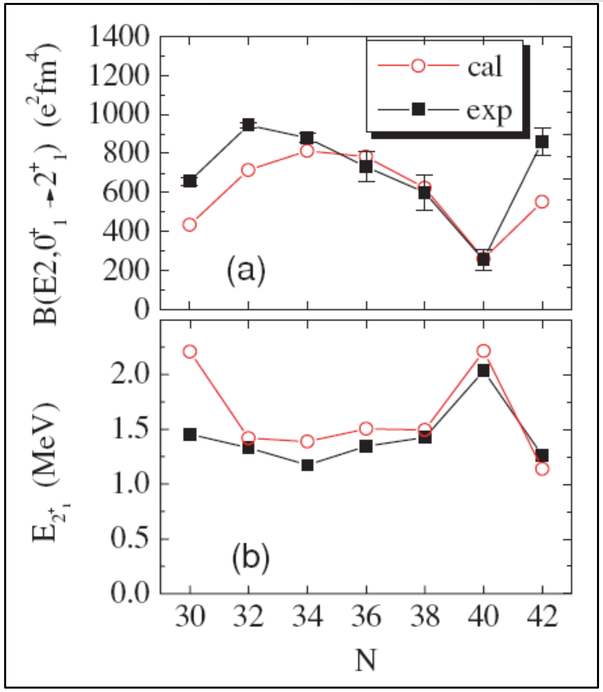
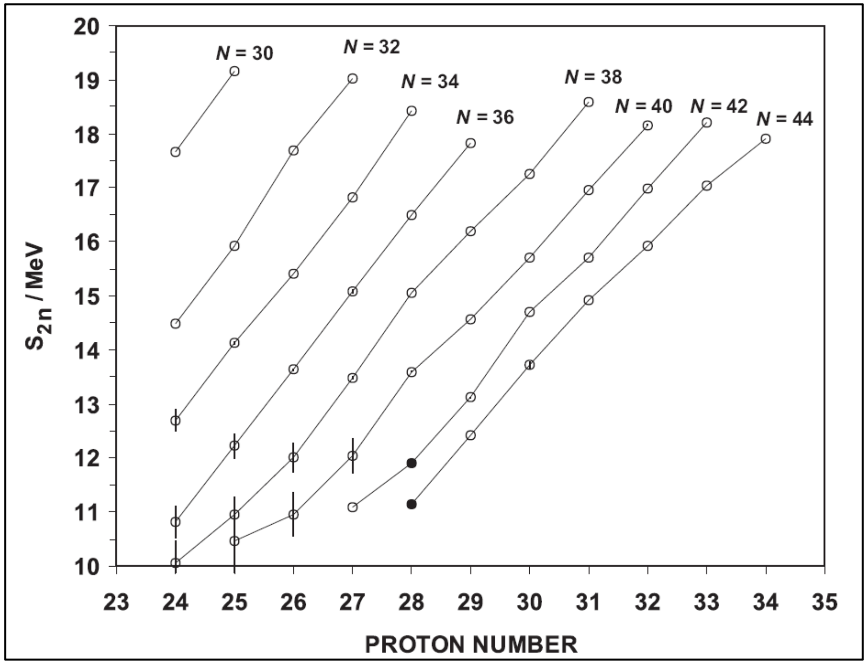
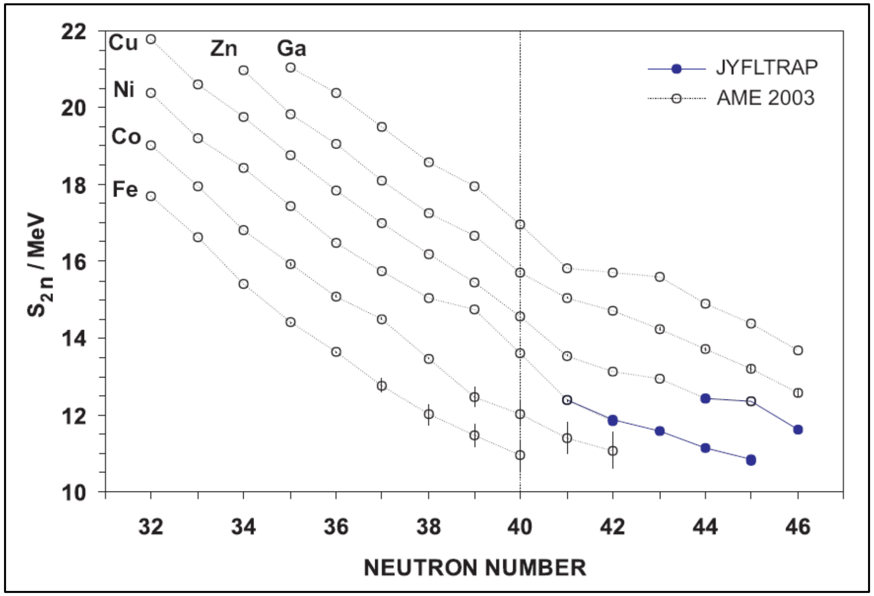
Sub-shell closure at N=40



Spectroscopic data for Ni:
Reduction of B(E2) and increase of E(2^+) implies the sub-shell closure at N=40
Shell-model calculations:
K. Kaneko et al., PRC 74 (2006) 024321





No signature of the gap in S_{2n}(N) data
No visible N=40 gap in S_{2n}(Z) graph
Change of the slope at N=40 ← tensor-force and the role of the filling of $g_{9/2}$ neutron-orbit ?
S. Rahaman et al., PRC (2007) in press

Pairing, global view on JYFLTRAP data

OES of nuclear binding energies ←→ pairing-gap energy in the standard BCS theory

Differences of measured masses

→ Δ_n or Δ_p

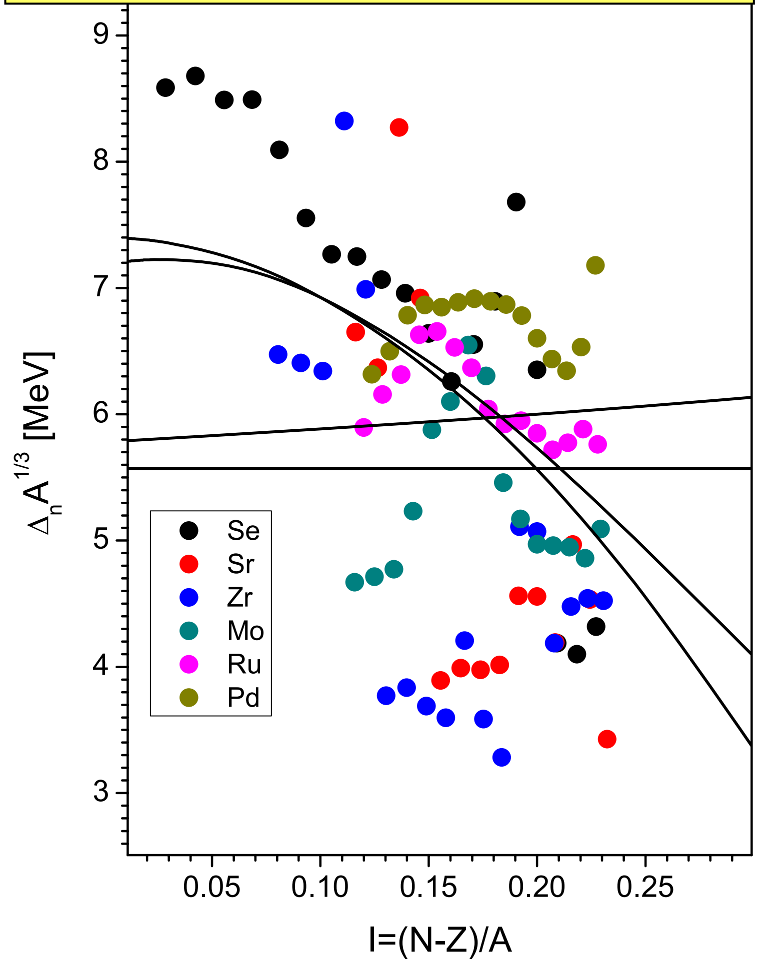
$$\Delta_n = \tfrac{1}{4}(-1)^{A-Z+1}[S_n(A+1,Z)-2S_n(A,Z)+S_n(A-1,Z)]c^2$$
$$= \tfrac{1}{4}(-1)^{A-Z+1}[-M(A+1,Z)+3M(A,Z)-3M(A-1,Z)+M(A-2,Z)]c^2$$

$$\frac{2}{G} = \sum_{\nu} \frac{1}{\sqrt{(\varepsilon_\nu - \lambda)^2 + \Delta^2}}$$

G = strength of the pairing interaction

ε_ν = single-particle energy

λ = chemical potential



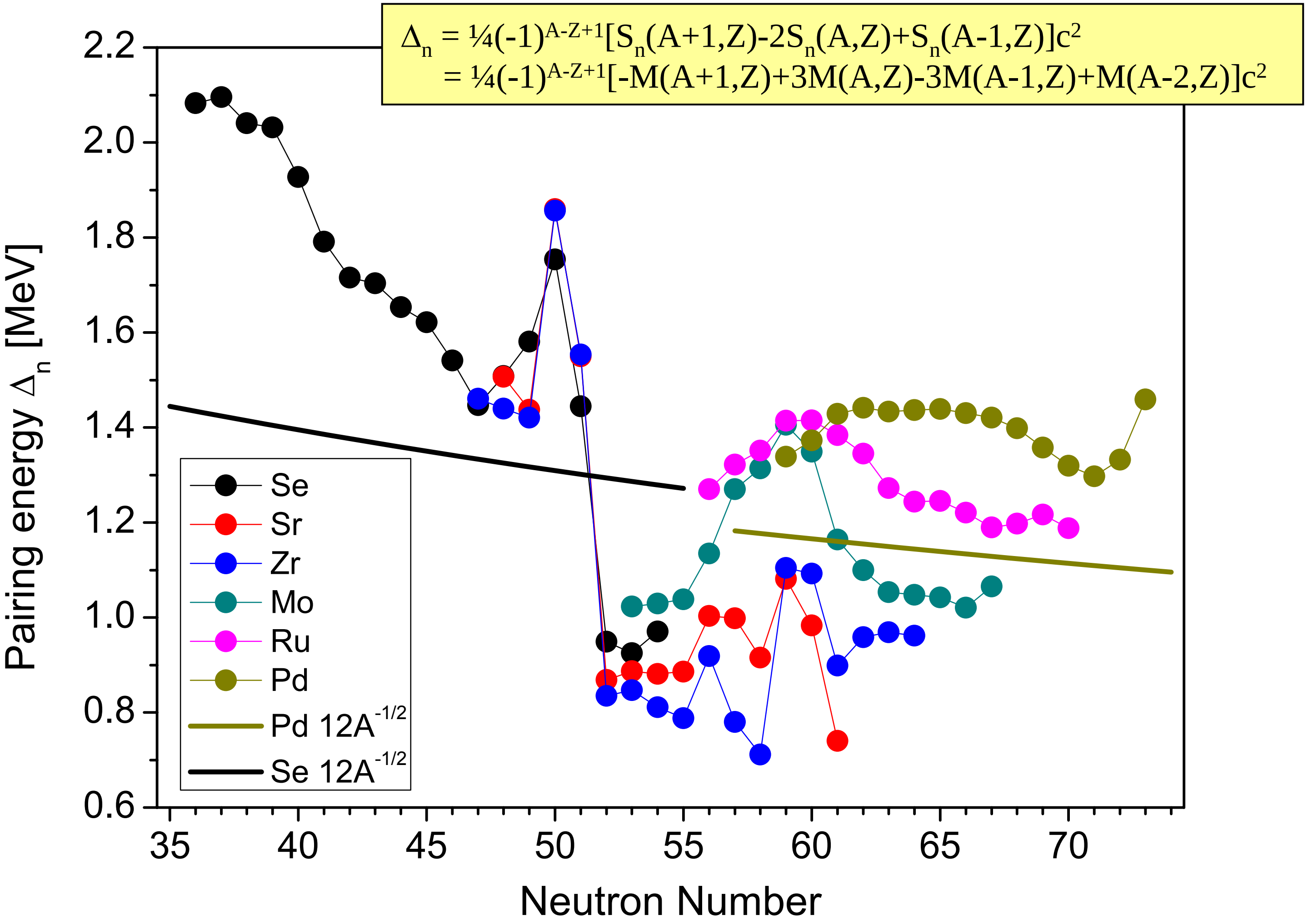
Bohr-Mottelson
$\Delta_n = 12/A^{1/2}$ [MeV], fixed Z

Bohr-Mottelson
$\Delta_n = 12/A^{1/2}$ [MeV], fixed A

D.G. Madland and J.R. Nix, NPA476 (1988) 1
$\Delta_n = 5.7\exp(0.12I-8I^2)/N^{1/3}$ [MeV]

P. Vogel, B. Jonson and P.G. Hansen, PL 139B (1984) 227
$\Delta_n = (7.4-45I^2)/A^{1/3}$ [MeV]

Pairing energies; close look as f(N)



$$\Delta_n = \tfrac{1}{4}(-1)^{A-Z+1}[S_n(A+1,Z)-2S_n(A,Z)+S_n(A-1,Z)]c^2$$
$$= \tfrac{1}{4}(-1)^{A-Z+1}[-M(A+1,Z)+3M(A,Z)-3M(A-1,Z)+M(A-2,Z)]c^2$$

Is there need for more microscopic treatment of pairing ?
Δ_n from atomic masses vs. Δ in BCS-theory

Trap-assisted spectroscopy

is a broad concept !!! (Post-trap and in-trap modes)

RFQ or Paul traps:

Cooled and bunched sources → <mm^2 & <eV

Collinear laser spectroscopy with few ions/s !

Implantations for high-precision experiments

Penning traps:

Confined , massless (no implantation matrix) sources coupled with very high mass resolution and strong focusing for charged particles

Ultra-high mass resolving power

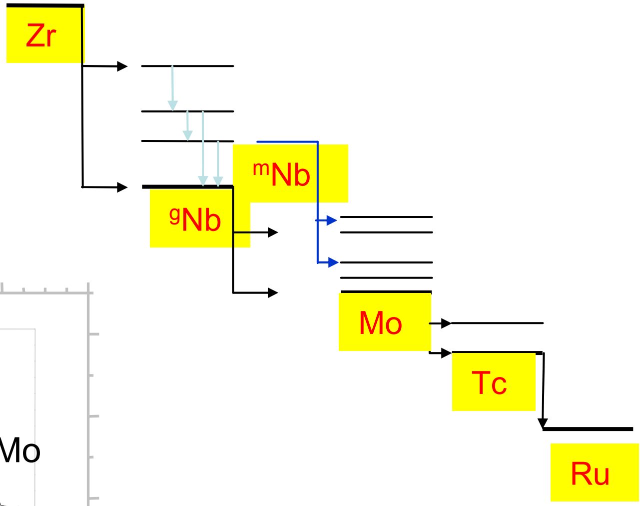
→ isobar and isomer separation

Optical traps:

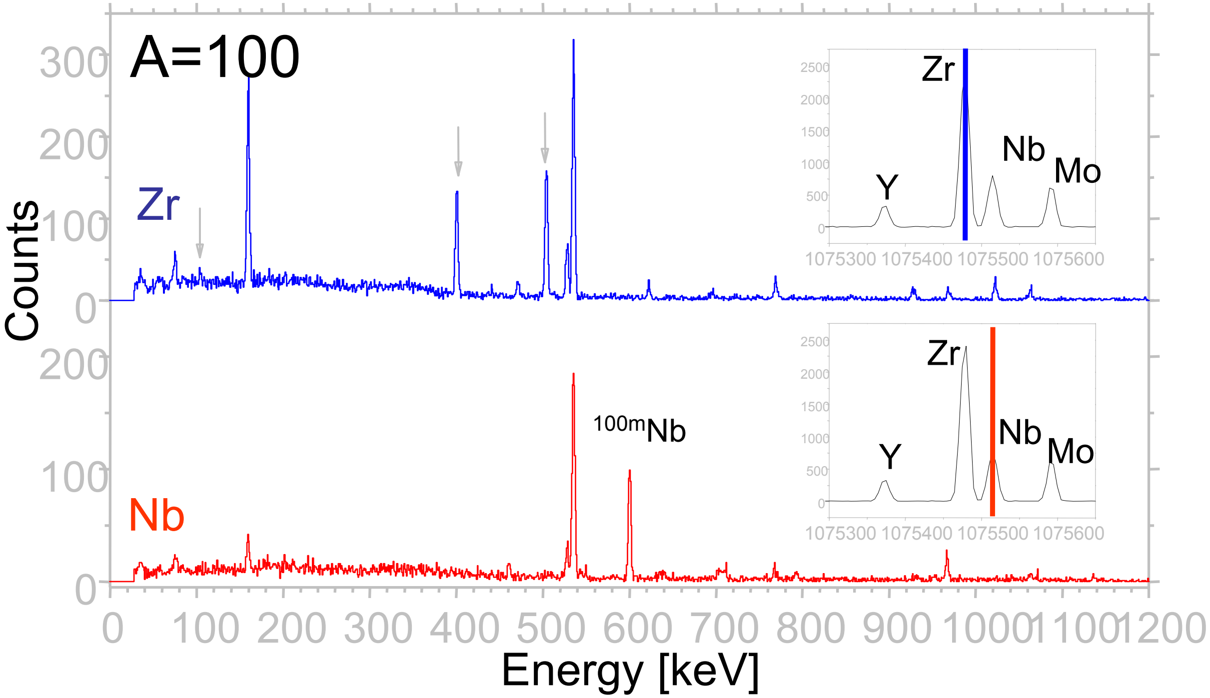
Confined & pure sources for fundamental studies

Decay studies of ^{100,102,104}Zr

S. Rinta-Antila et al., Eur. Phys. J. A31 (2007) 1



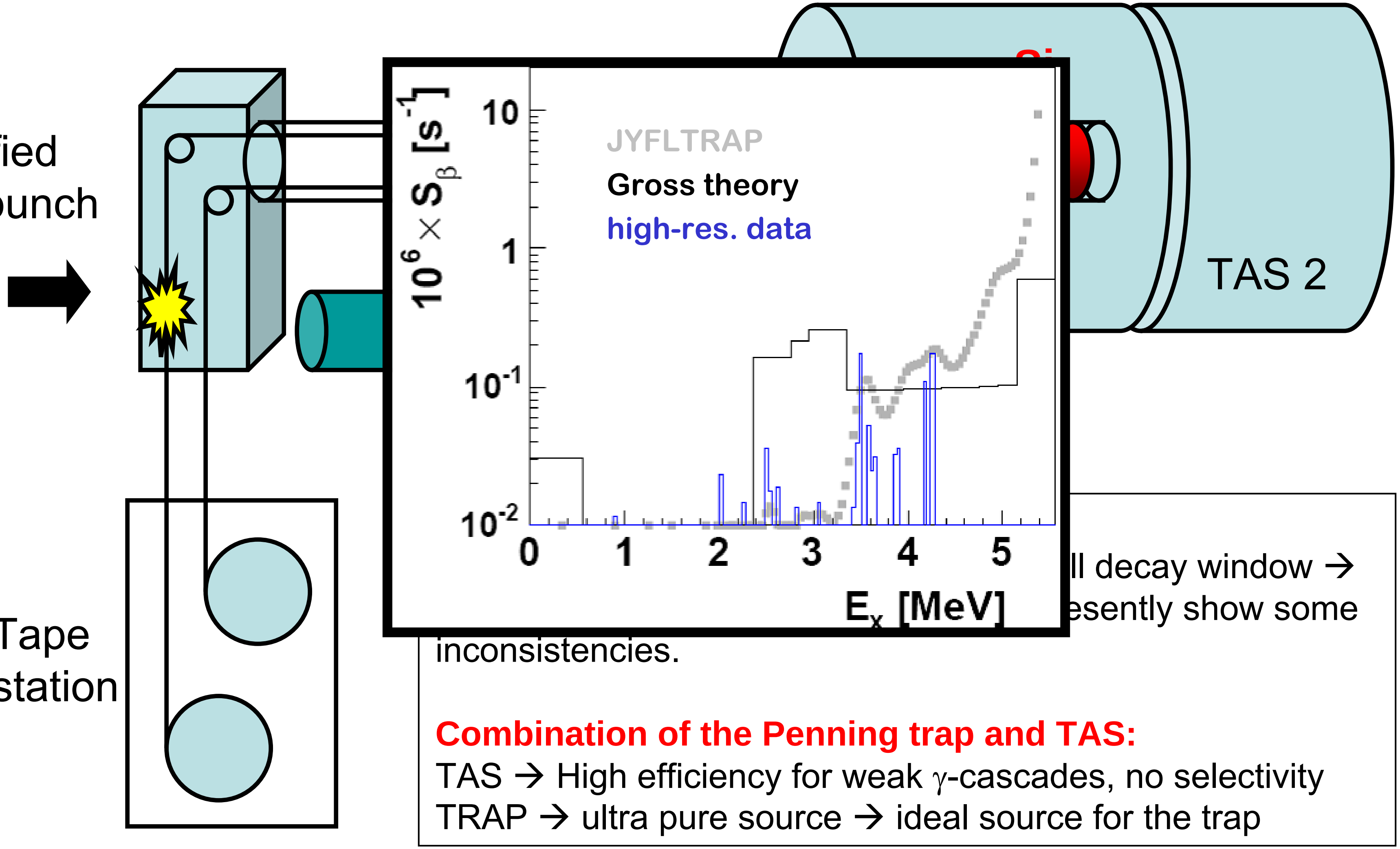
Purification in the first trap for Zr of Nb
Transmission 40 %
β–γ-coincidence setup after the trap



Proof-of-principle experiment, physics goal in GT-strength studies

S. Rinta-Antila et al., Eur. Phys. J. A31 (2007) 1

TAS-run in 2006, prel. data for ^{104}Tc



Purified ion bunch

Tape station

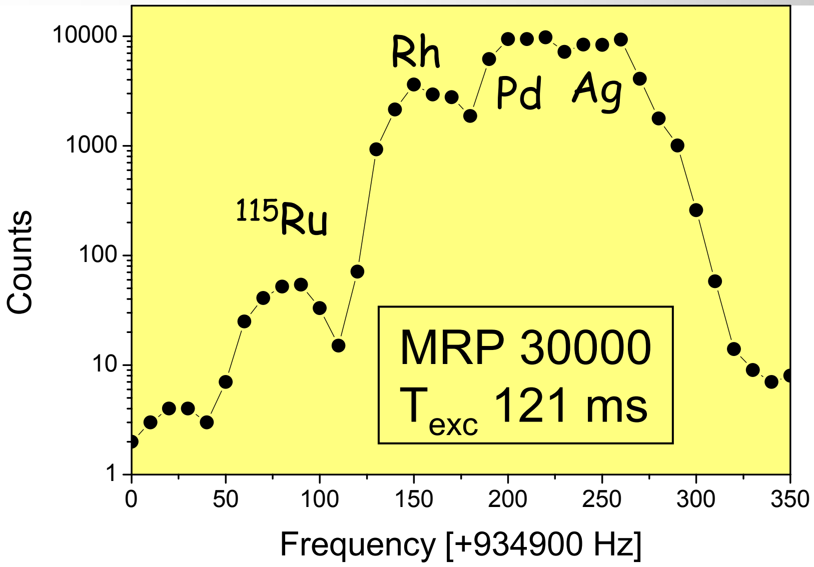
TAS 2

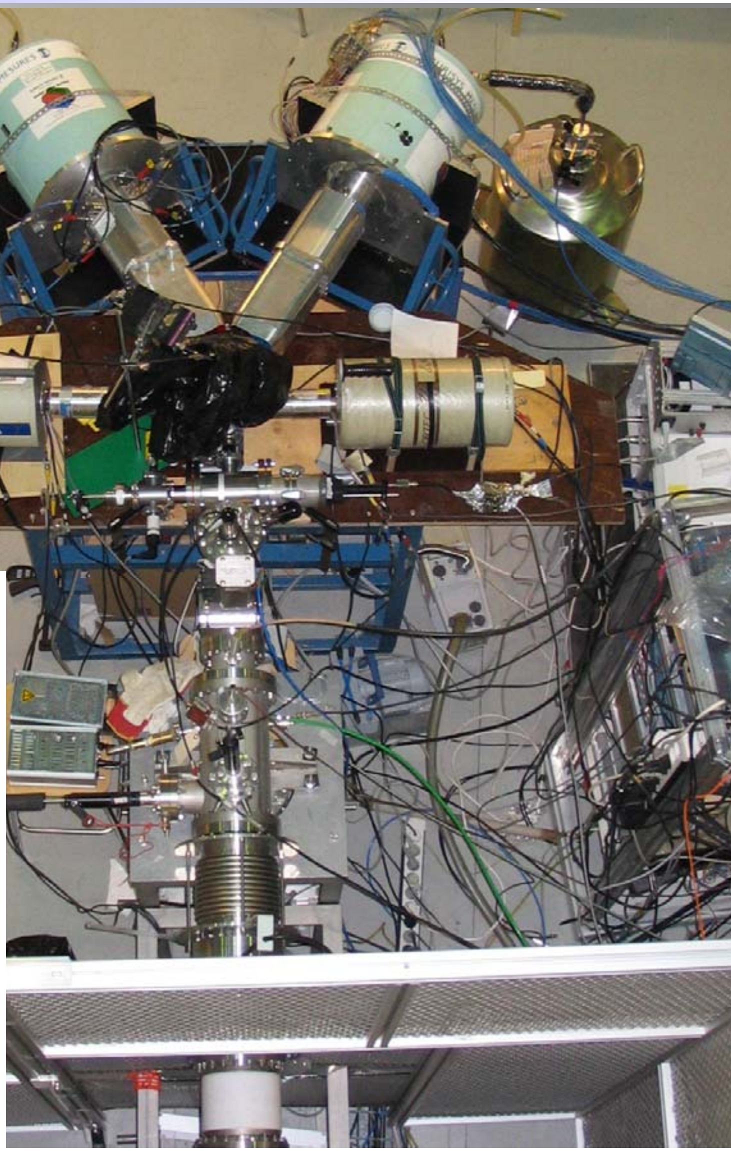
ll decay window →
esently show some
inconsistencies.

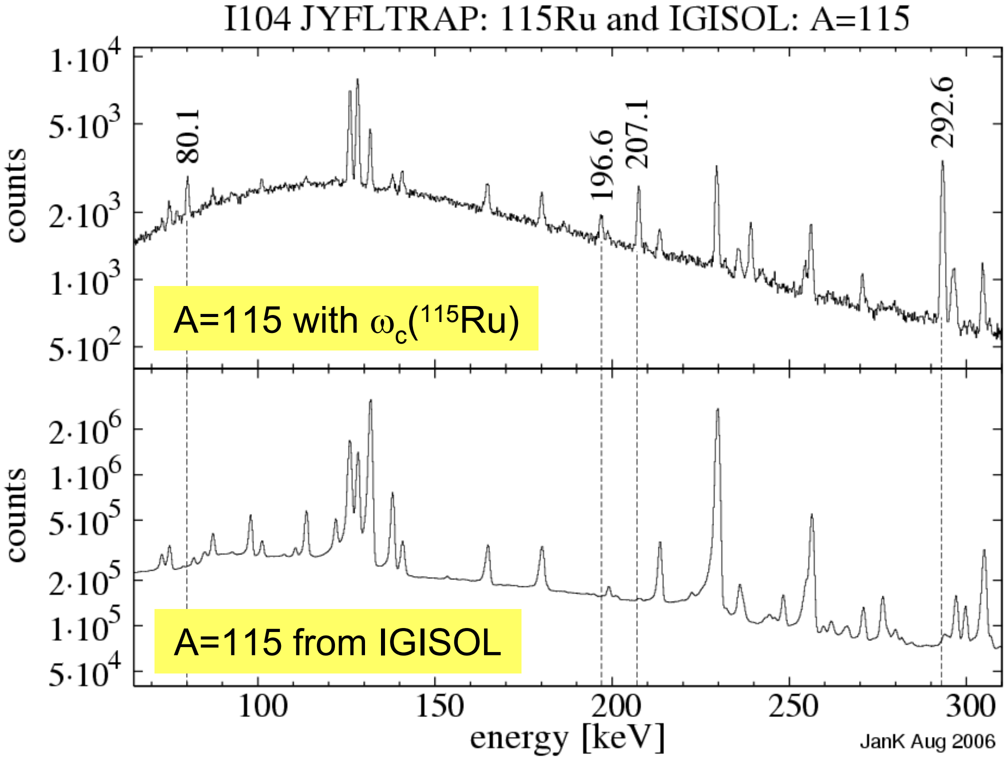
Combination of the Penning trap and TAS:
TAS → High efficiency for weak γ-cascades, no selectivity
TRAP → ultra pure source → ideal source for the trap

(A. Algora et al.)

The first new decay scheme observed: ^{115}Ru

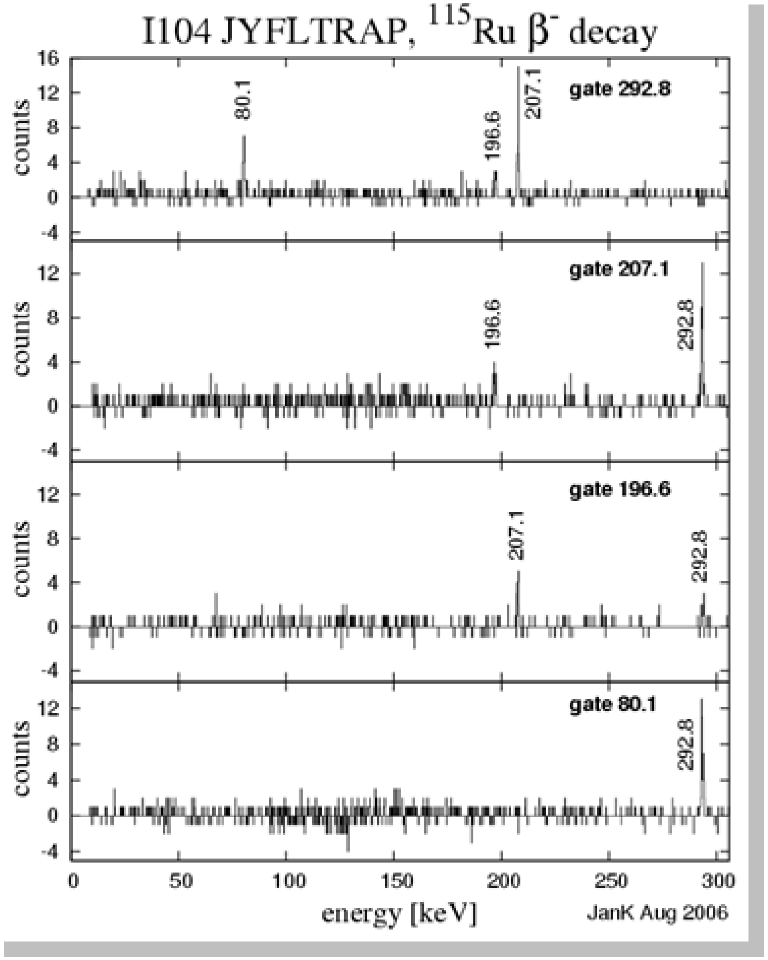


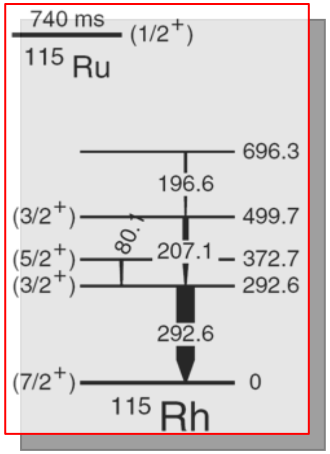


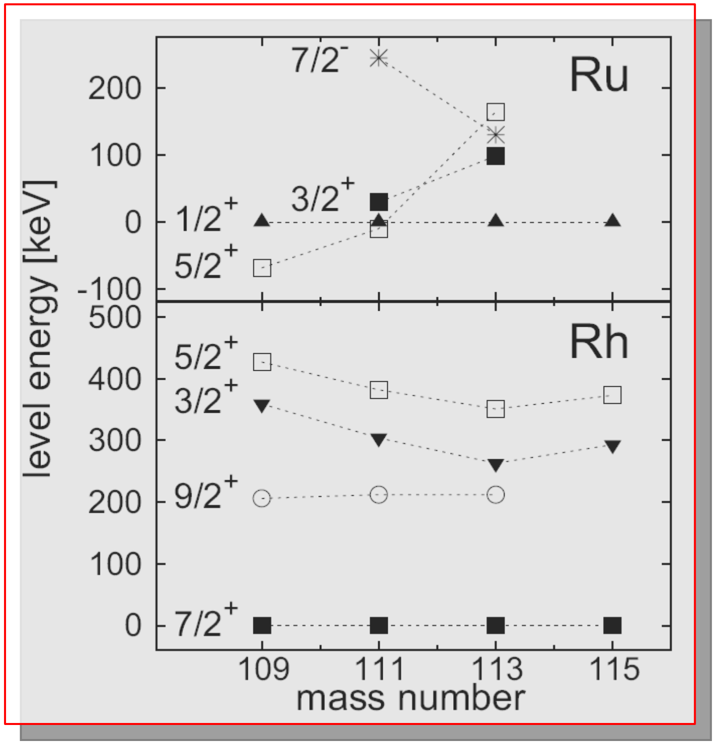


J. Kurpeta et al. EPJ A 31 (2007) 263

Systematics of low-energy levels in odd Ru and Rh-isotopes



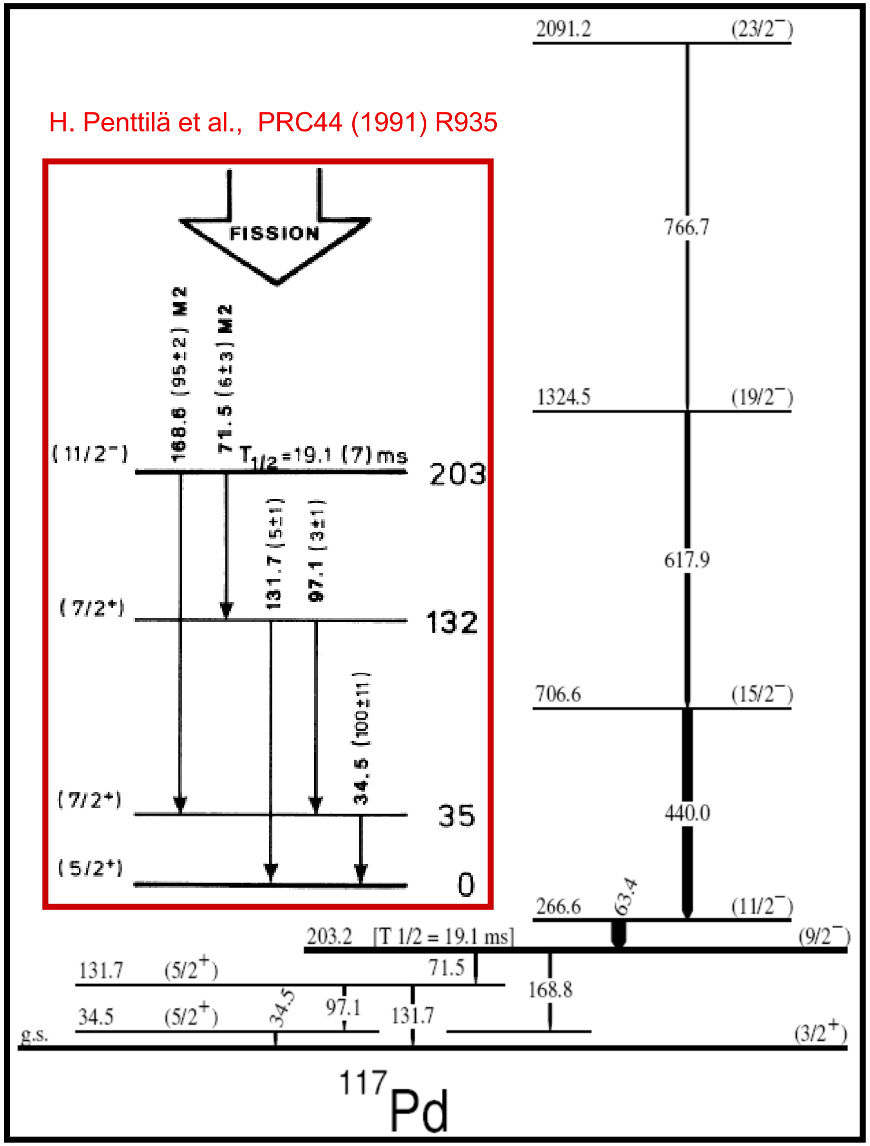




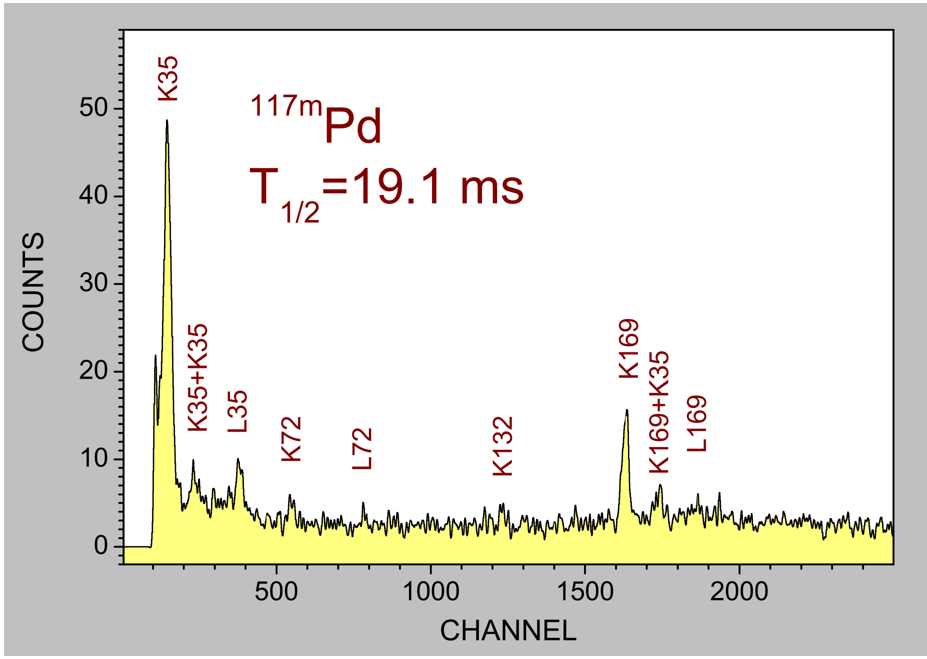
A=115 J. Kurpeta et al., EPJ A31 (2007) 263
A=113 J. Kurpeta et al. EPJ A 33 (2007) 307
A=111 W. Urban et al., EPJ A 22 (2004) 231

J. Kurpeta et al., EPJ A31 (2007) 263

In-trap spectroscopy; commissioning run for ^{117m}Pd



W. Urban et al., EPJA 22 (2004) 157



- ✓ ^{238}U(p,f) @ 25 MeV
- ✓ 10 mm² Si-detector @ B=0.7 T
- ✓ Excellent lineshape
- ✓ Efficient collection of electrons
- ✓ Background-free spectra
- ✓ Extends to very low energies (K35=9.9keV)
- ✓ No X-rays !
- ✓ Applicable to rather short-lived states

J. Rissanen et al. EPJA (2007) in press

Summary

- Plenty of new data with 1-10 keV precision
    - AME and old exp. found to deviate from the new precision data
    - Single and two-nucleon separation energies
    - Evolution of shell gaps and sub-shell closures
    - Pairing gaps
    - Proton-neutron correlations (V_{pn})
    - Nuclear astrophysics applications
    - …
- Complete spectroscopy of ground-state properties at JYFL
    - precision atomic masses
    - charge radii, moments (B. Cheal, this afternoon)
- Trap-assisted spectroscopy after the trap
    - Decay studies of n-rich Zr and Nb isotopes at A=100,102,104
    - New decay scheme of ^{115}Ru and s.p. energies of odd Rh-isotopes
    - TAS-spectroscopy (reactor decay heat calculations)
    - Fission yields (H. Penttilä, next session)
    - Beta-delayed neutron spectroscopy
- In-trap spectroscopy
    - Proof-of-principle case ^{117m}Pd ($T_{1/2}$=19.1 ms)
    - Physics case and further development of the technique required
    - Isomerism, e-cascades, very low electron energies, …
- Highest precision ($\delta m/m=2\times10^{-9}$) for Q-value measurements for superallowed beta decay and double beta decay

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4th Int. Conf. on Fission and Properties of Neutron-Rich Nuclei
Sanibel Island, Florida, November 11-17, 2007