"Highlights from radioactive beam experiments using MINIBALL and REX-ISOLDE ."

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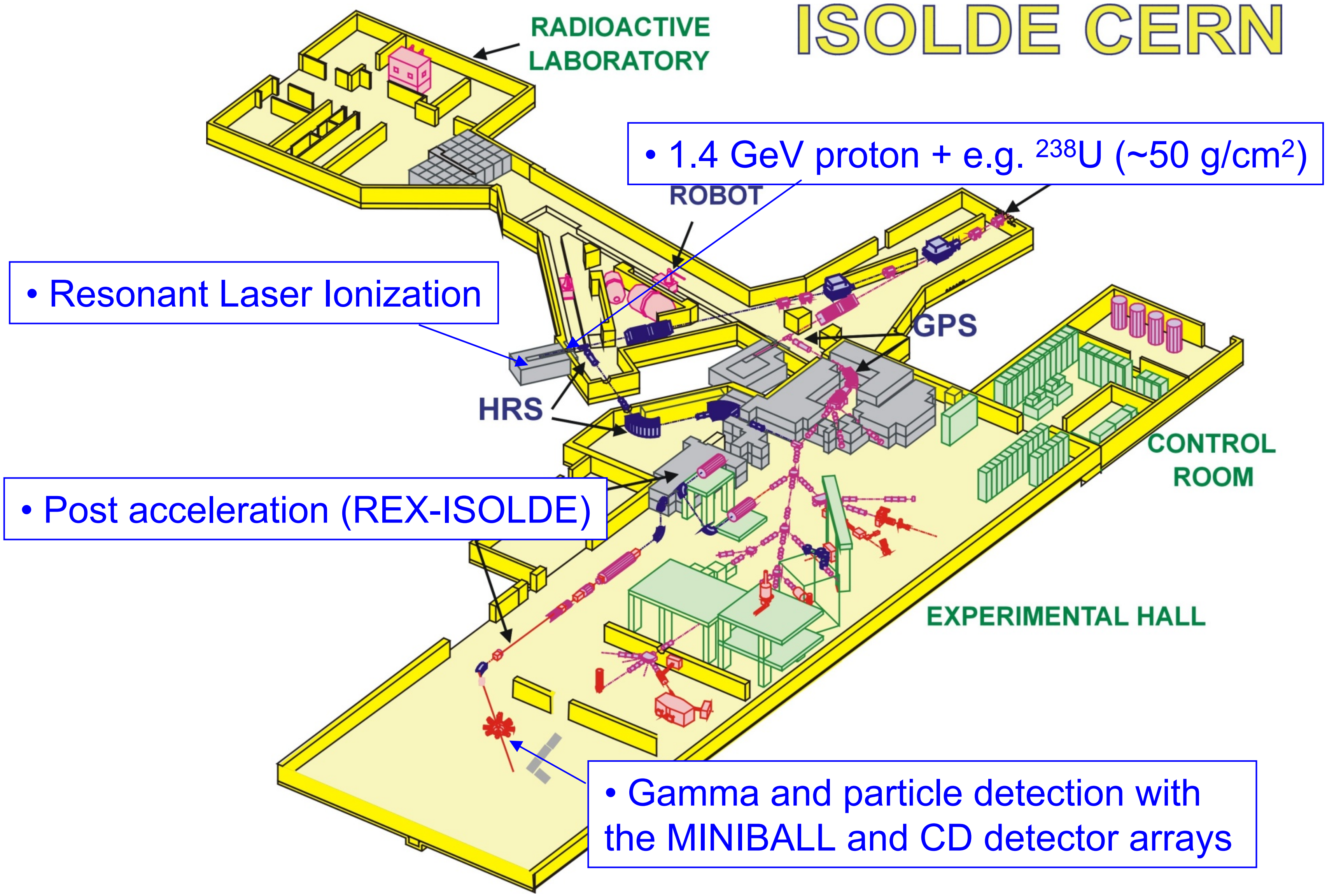
for the MINIBALL, REX- and HIE-ISOLDE collaboration

Outline

- **MINIBALL at REX-ISOLDE, CERN:**
  - Radioactive beams at ISOLDE
  - Coulomb excitation and transfer reactions using MINIBALL
- **Physics case and results:**
  - General overview of MINIBALL campaigns (two examples: close to ^{100}Sn and to ^{132}Sn)
  - Nuclear structure along Z=28 from N=40 towards N=50 (Coulomb excitation: $^{67-73}$Cu isotopes, β-decay of ^{67}Fe-^{67}Co-^{67}Ni)
  - Evidence for intruder states and shape coexistence
- **Conclusion and outlook**
  - HIE-ISOLDE

see also talks by
V. Bildenstein, N. Bree, J. Van de Walle, D. Mücher

ISOLDE @ CERN



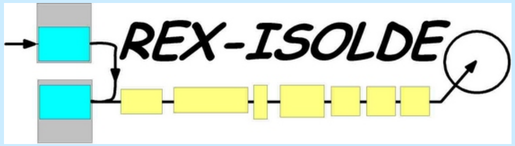
"Isotope Separation On Line and Post Acceleration"
Lecture Notes on Physics 700 (2006) 37-77, Springer Verlag Berlin

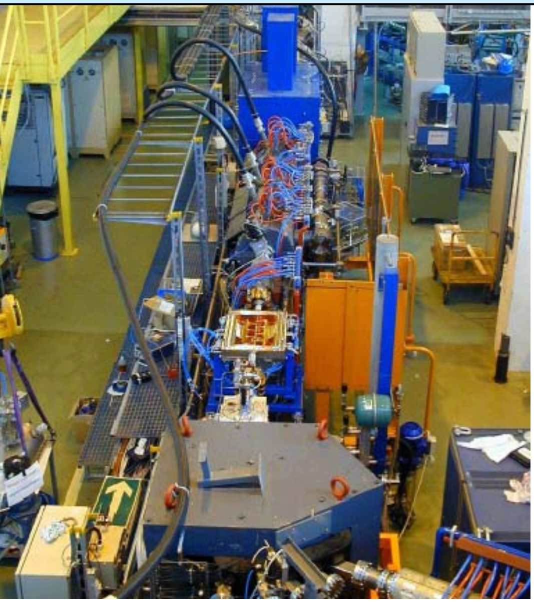
BriX

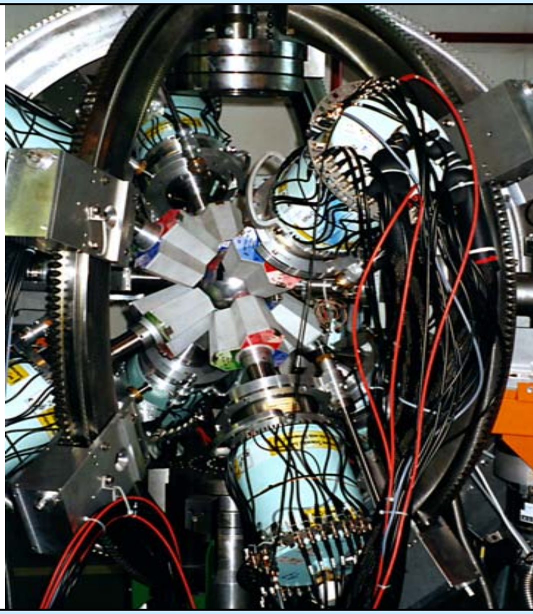
Radioactive Beam Experiments at ISOLDE

- **ISOLDE-CERN**:
  - beams of over 700 radioactive isotopes available at 60 keV
  - physical and chemical properties to purify (e.g. laser ion source, molecular beams)

- **R**adioactive ion beam **EX**periment at **ISOLDE (REX ISOLDE)**:
  - an efficient concept for post-accelerating radioactive isotopes up to 3 MeV/u, essentially all existing ISOLDE beams
  - proposed in 1995, first experiments 2002
  - production of energetic isomeric beams (laser ionization)

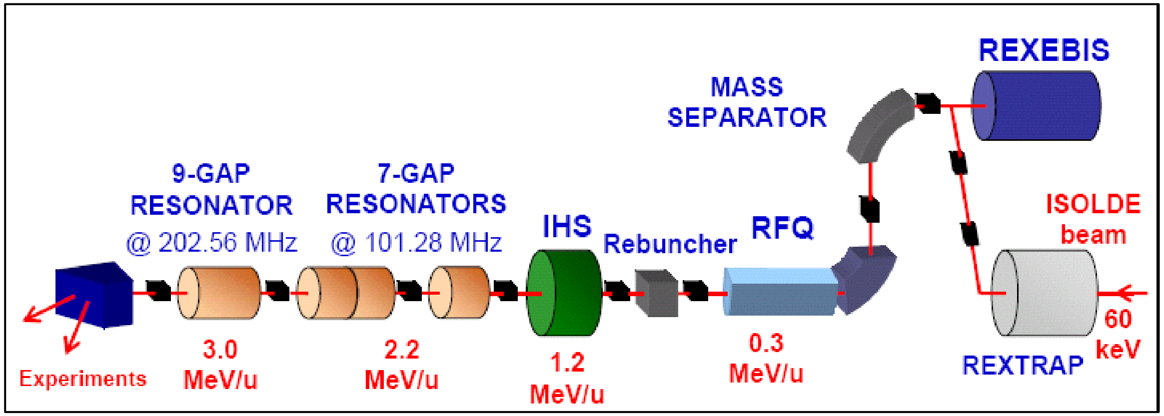


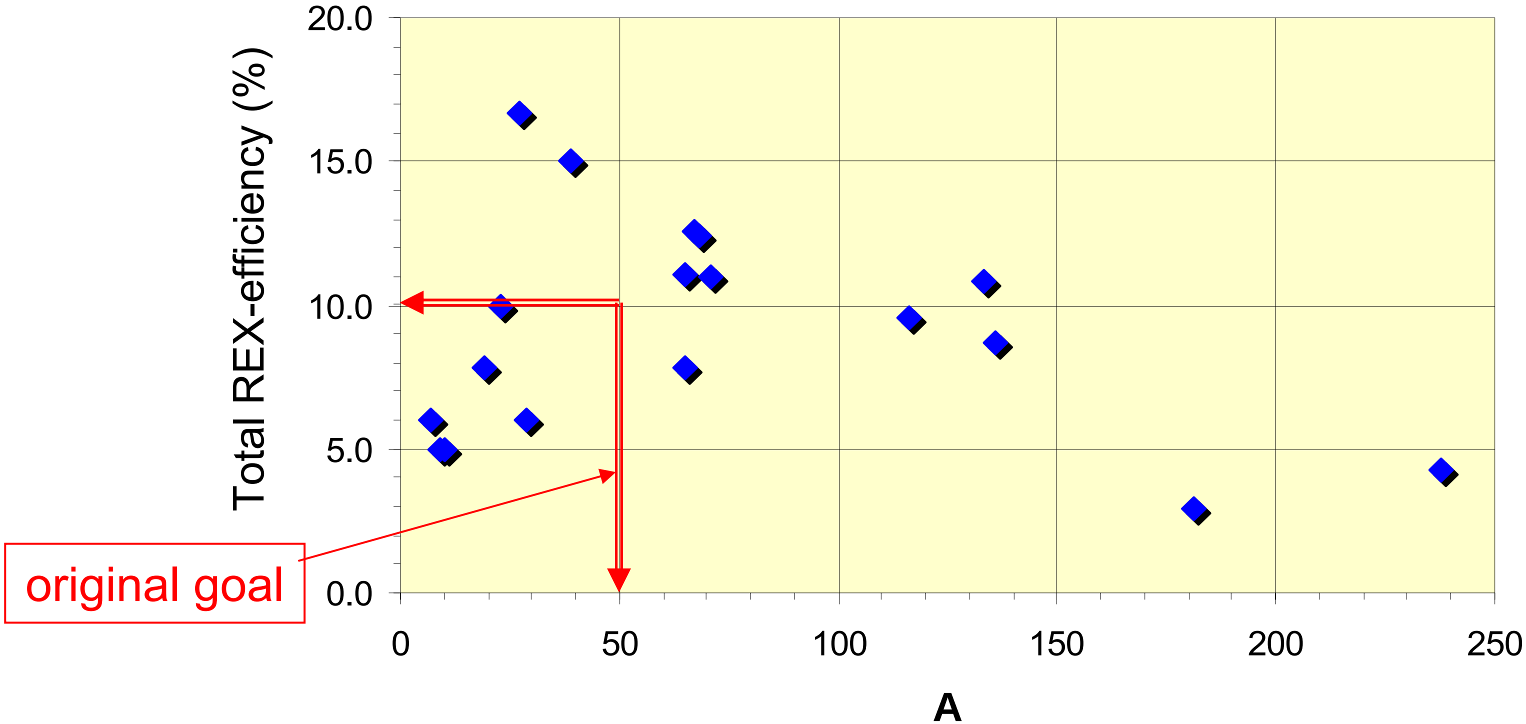




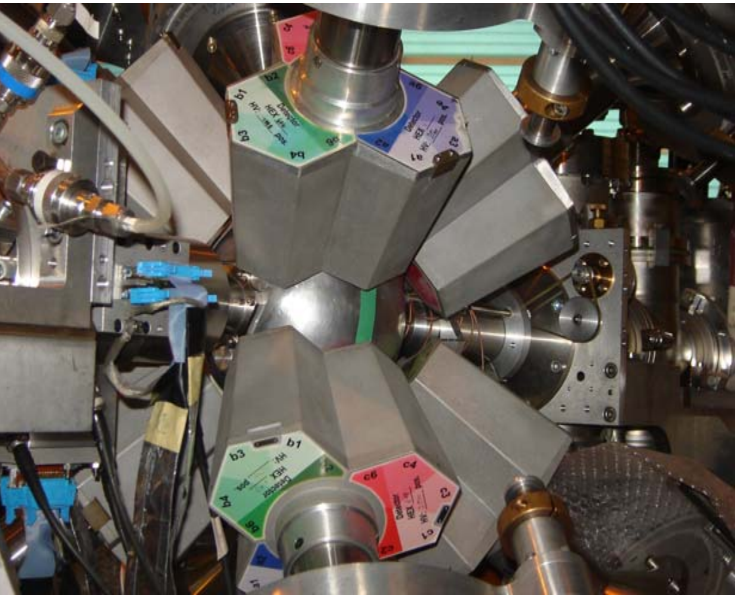
- **The MINIBALL Germanium array:**
  - efficient, flexible Ge array for low-multiplicity experiments with weak RIB
  - segmented Ge detectors in combination with segmented Si detector

REX ISOLDE performance



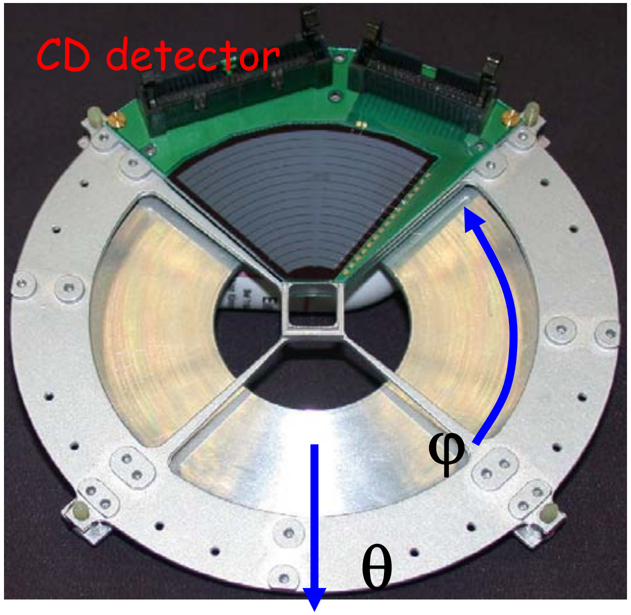


MINIBALL detector array



Miniball: 8 clusters, 3 X 6 fold segmented

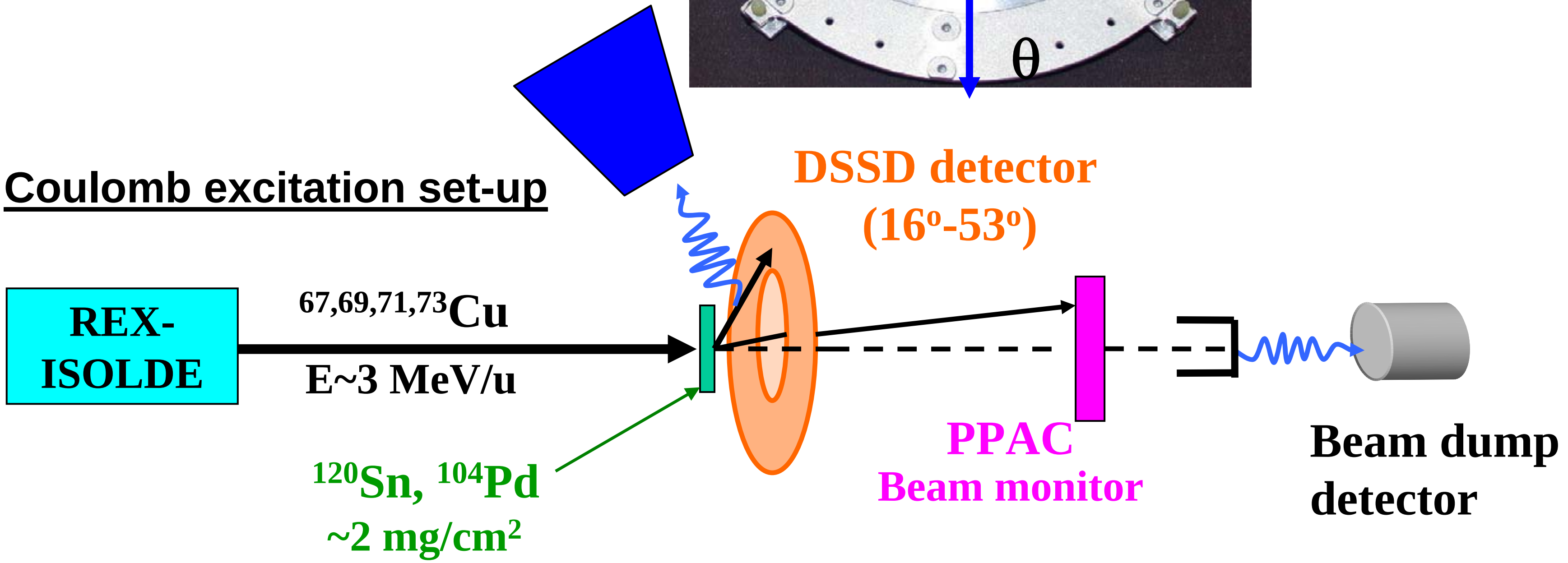
ε_{MB}~8.5% @ 1 MeV (12 cm from the target)



DSSSD:

- 4 quadrants
- 16 annular strips (θ)
- 24 sector strips (ϕ)

Coulomb excitation set-up



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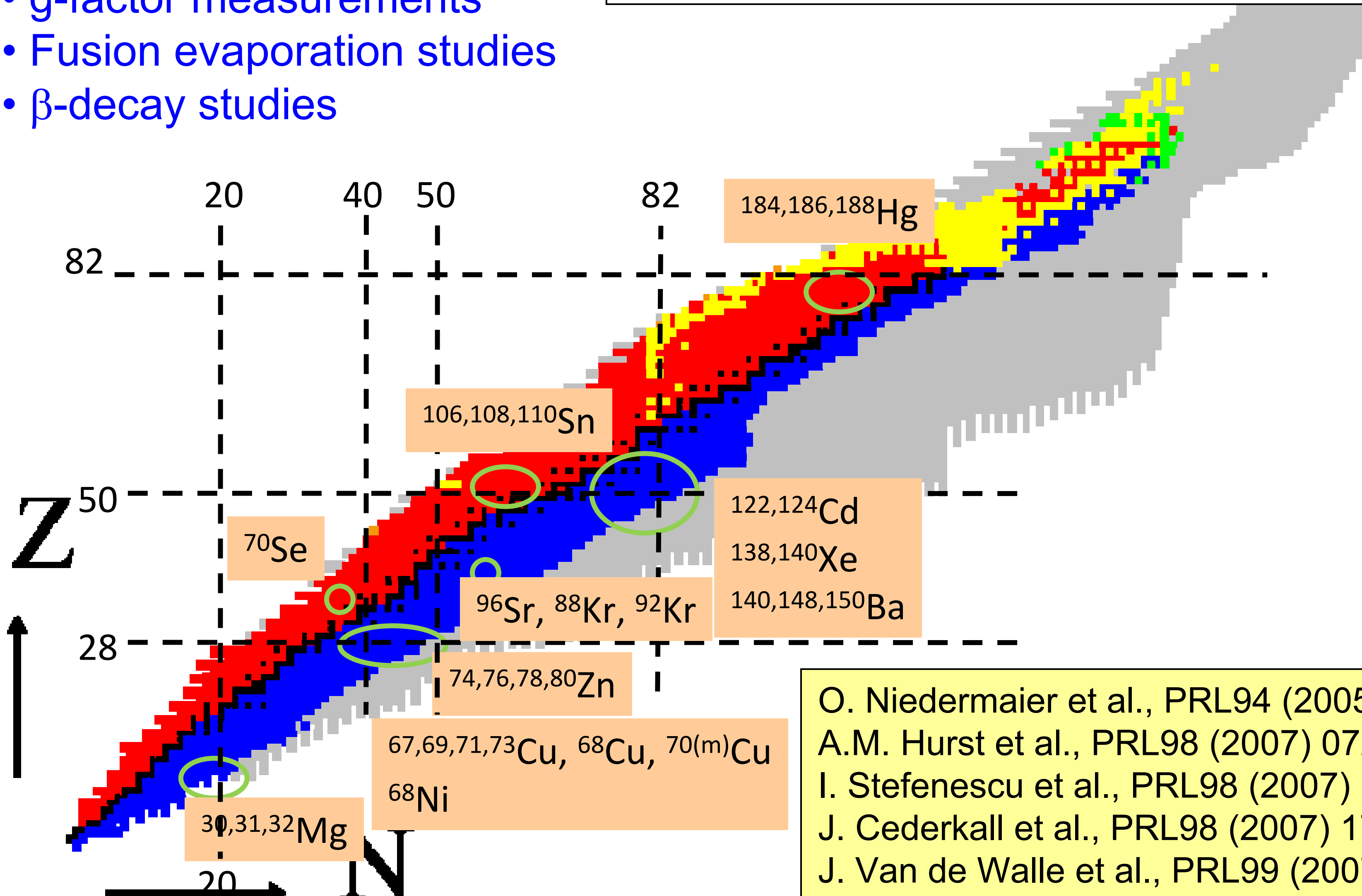
MINIBALL experiments at ISOLDE

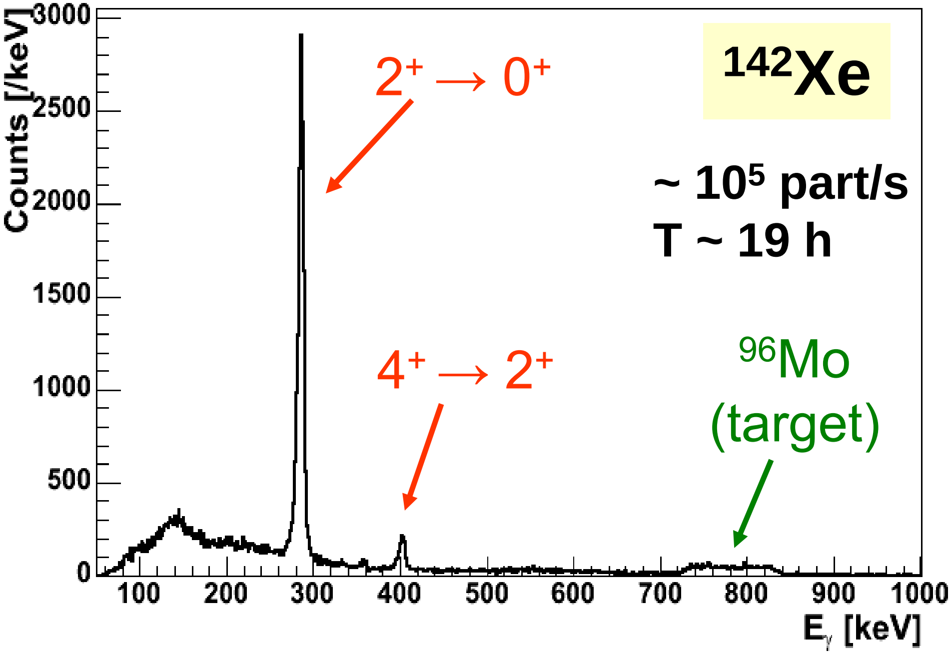
- Coulomb excitation
- Neutron transfer reactions
- g-factor measurements
- Fusion evaporation studies
- β-decay studies

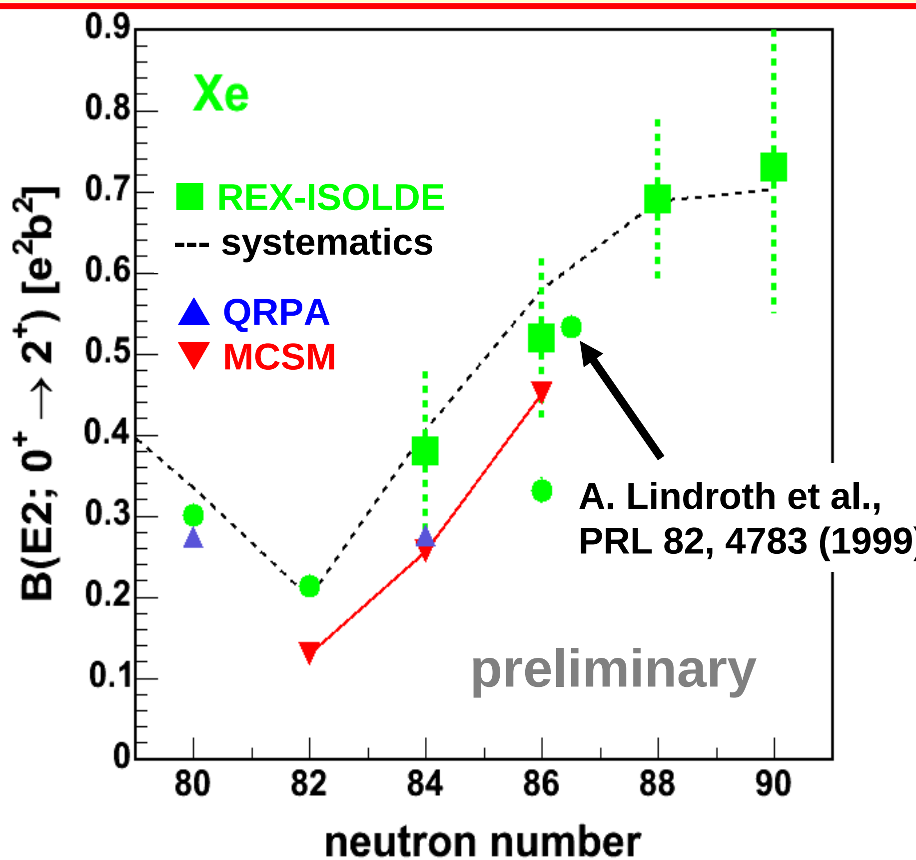
see also talks by
V. Bildenstein, N. Bree, J. Van de Walle, D. Mücher



O. Niedermaier et al., PRL94 (2005) 172501
A.M. Hurst et al., PRL98 (2007) 072501
I. Stefenescu et al., PRL98 (2007) 122701
J. Cederkall et al., PRL98 (2007) 172501
J. Van de Walle et al., PRL99 (2007) 142501
I. Stefanescu et al., PRL100 (2008)112502

B(E2) systematics for Xe isotopes (T.U.München, Th. Kröll)





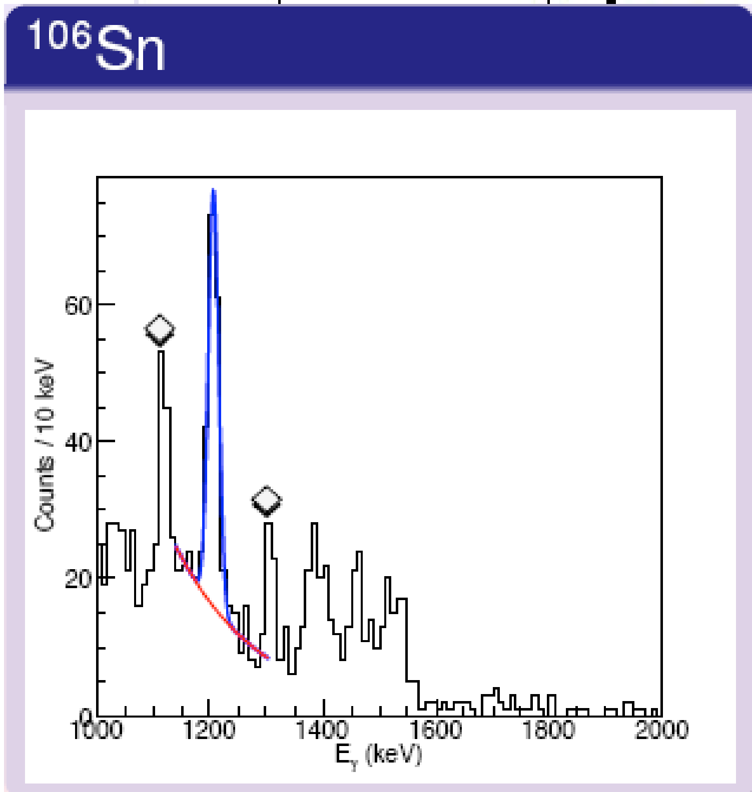
Conclusion:

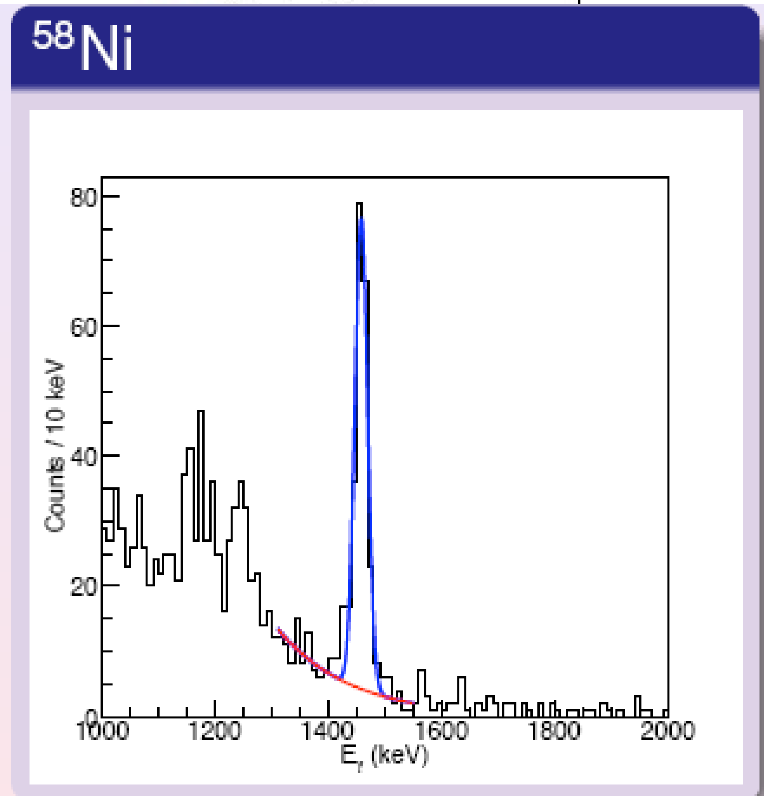
B(E2) values of Cd, Xe (and Ba) around N=82 don´t show particular anomalies

Systematics: modified Grodzins´ rule
D. Habs, R. Krücken
QRPA:
J. Terasaki,- PRC 66, 054313 (2002)
Monte Carlo Shell Model:
N. Shimizu,- J. Phys.Conf. Ser. 49, 178 (2006)

Sn isotopes (CERN/Lund, J. Cederkäll, A. Ekström)

- ^{106}Sn(2.83 MeV/u, 29%) + ^{58}Ni(2 mg/cm^2)





- Shell-model calculations including proton-neutron excitation across Z=N=50 needed

J. Cederkäll et al., PRL98 (2007) 172501
A. Ekström et al., to be published

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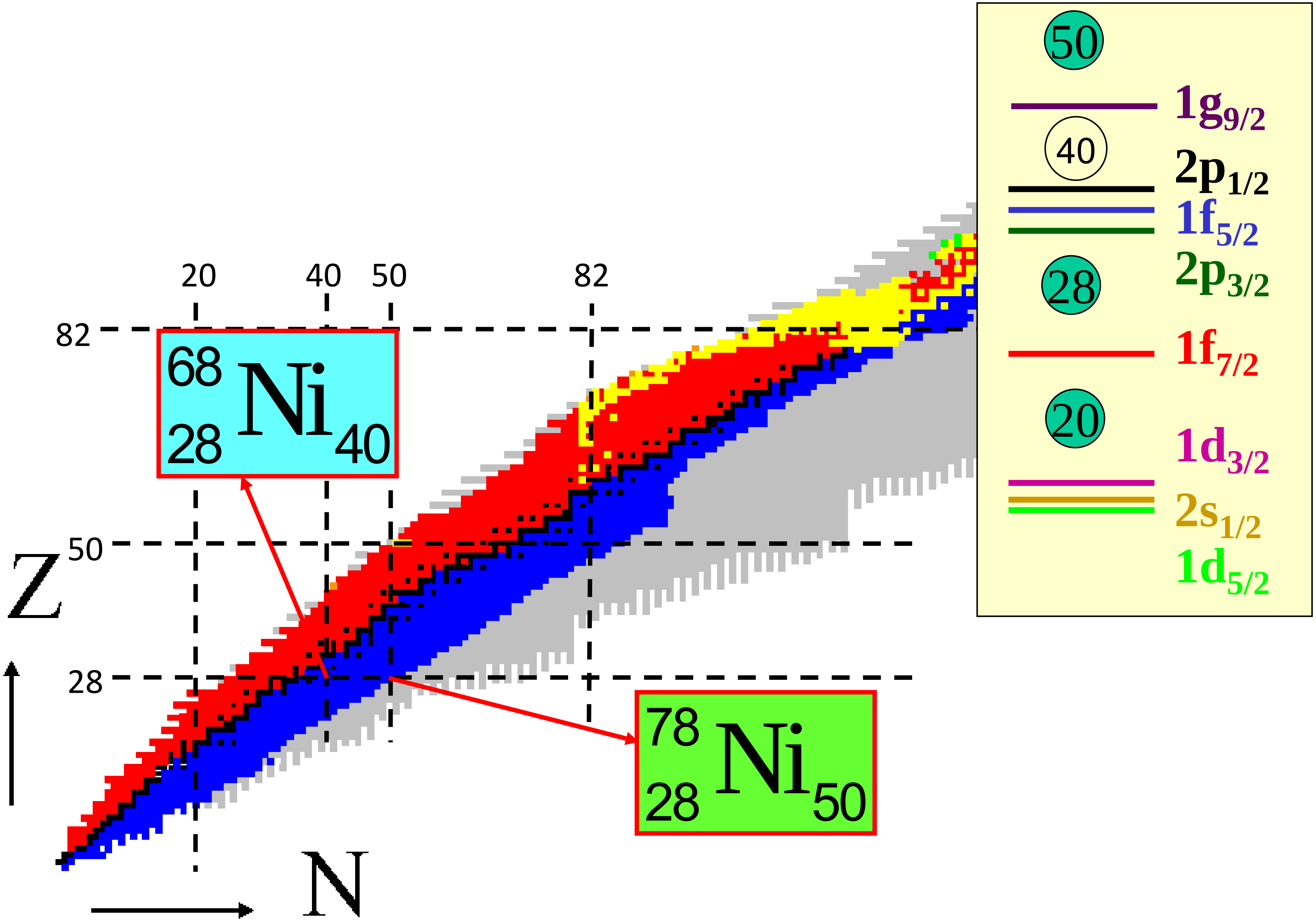
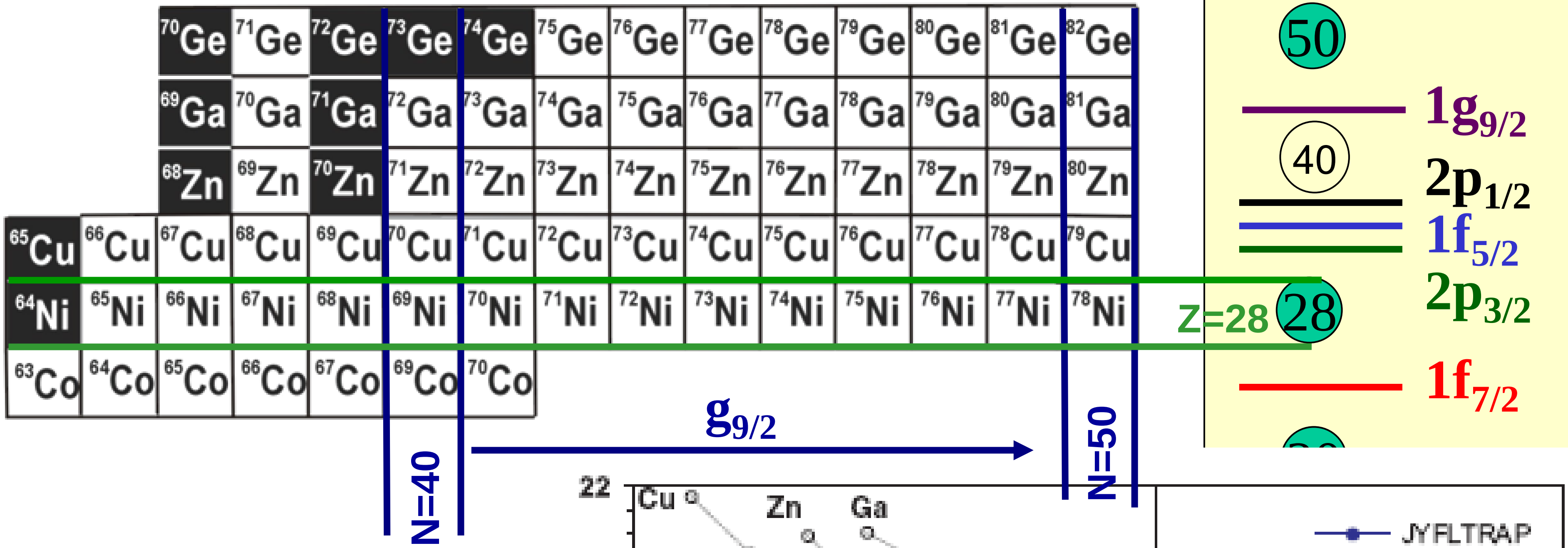
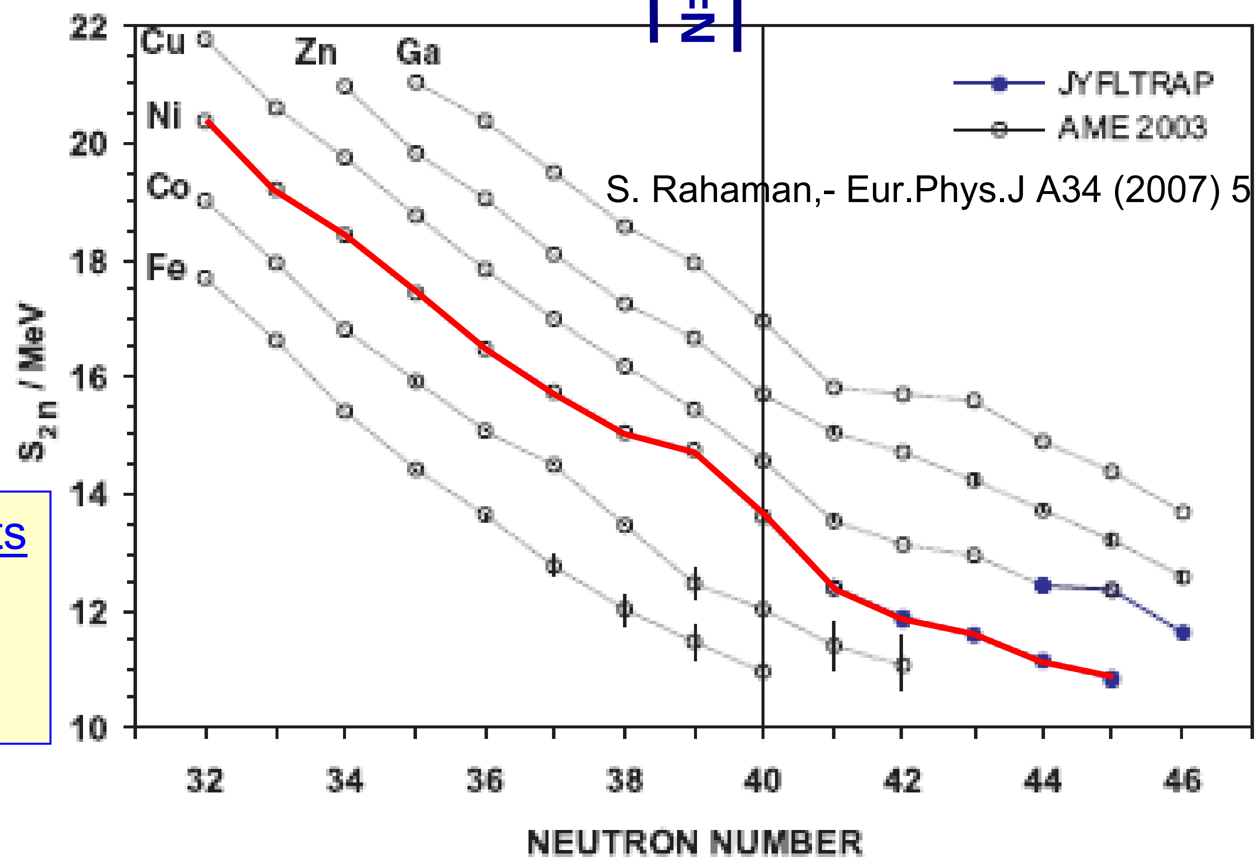
The Z=28 and N=40,50 shell closures





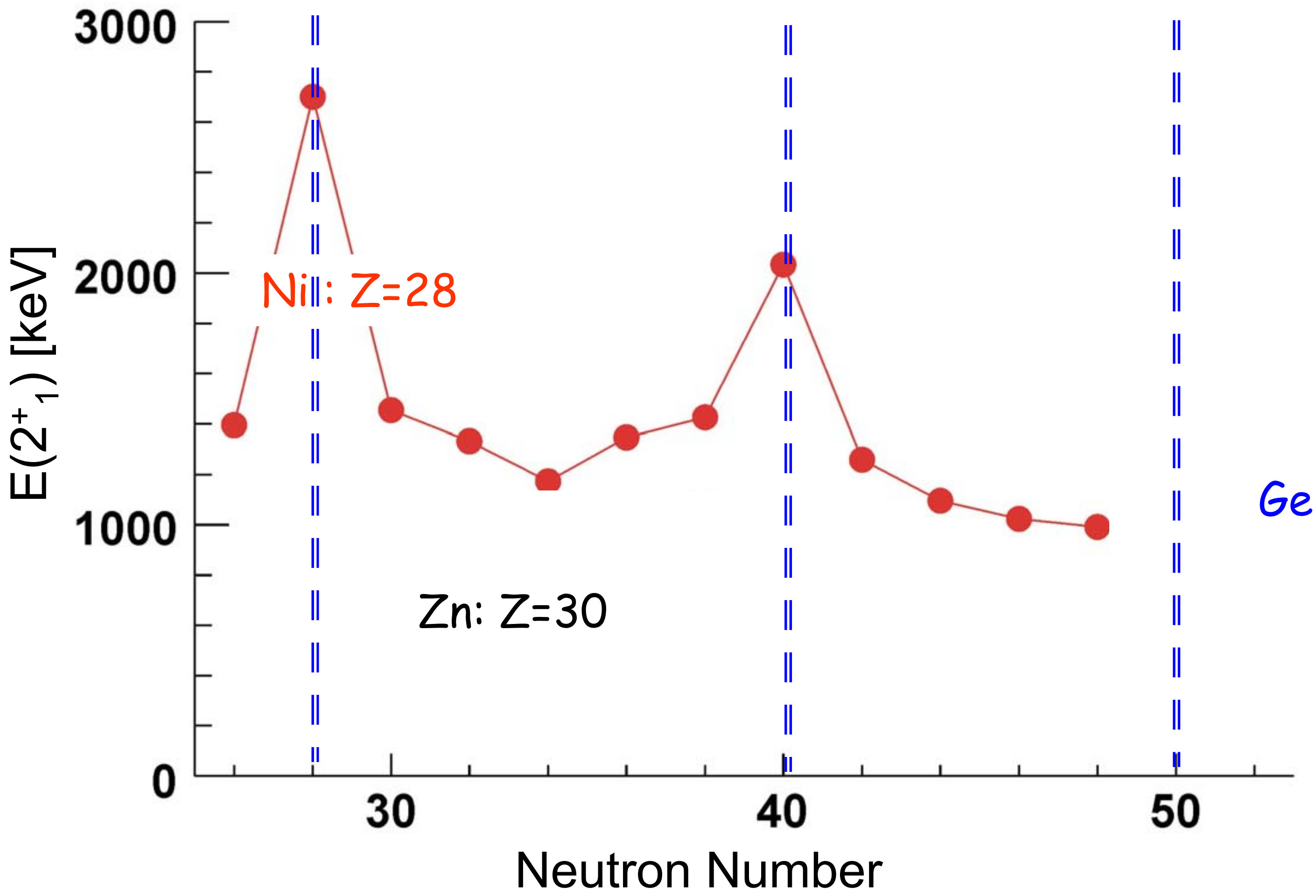


<u>Recent mass measurements</u>

- S_{2n}: weak gap at N=40
- S_{2p}: strong gap at Z=28

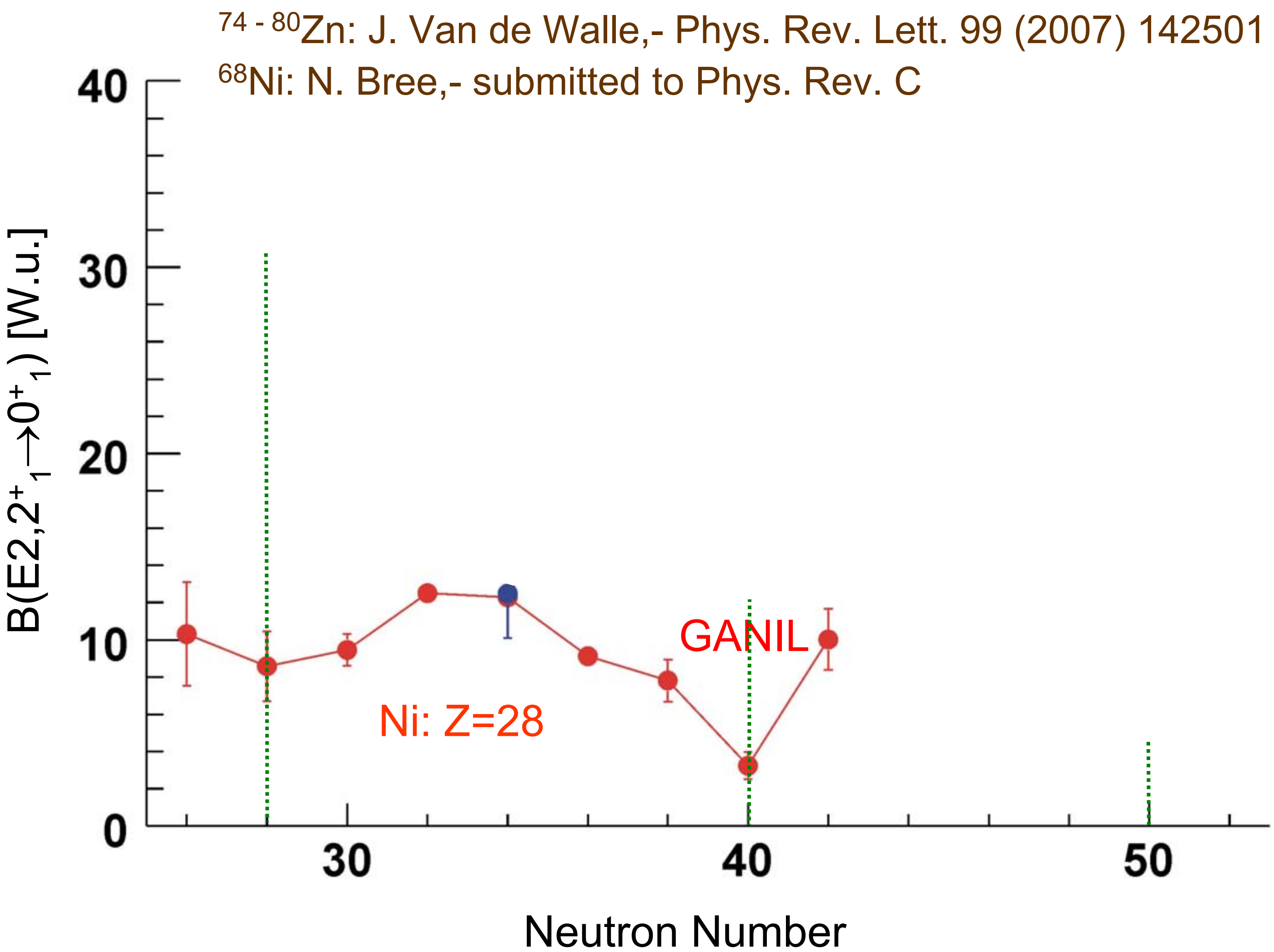
Energy systematics of the 2^+_1 state

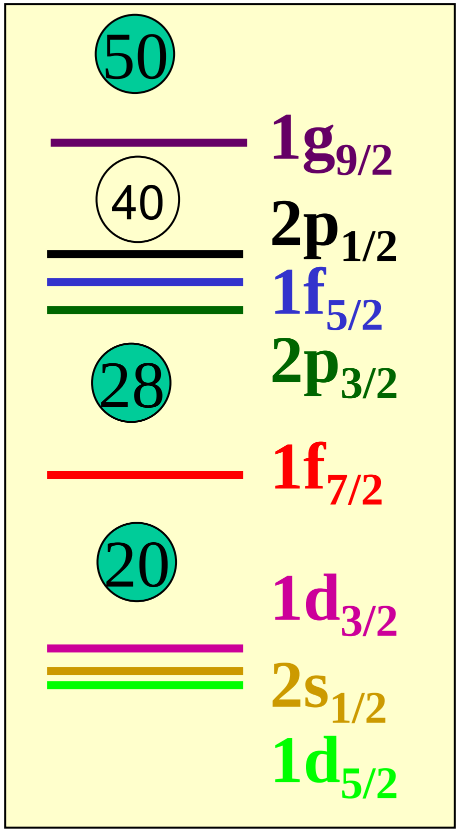
J. Van de Walle,- Phys. Rev. Lett. 99 (2007) 142501



C. Mazzocchi *et al*, PLB**622** 45 (2005) - NSCL,MSU
J. Van Roosbroeck *et al*, PRC**67** 054307 (2005) - ISOLDE

B(E2: 2^+_1-0^+_1) systematics





C. Mazzocchi *et al*, PLB **622** 45 (2005) - NSCL,MSU

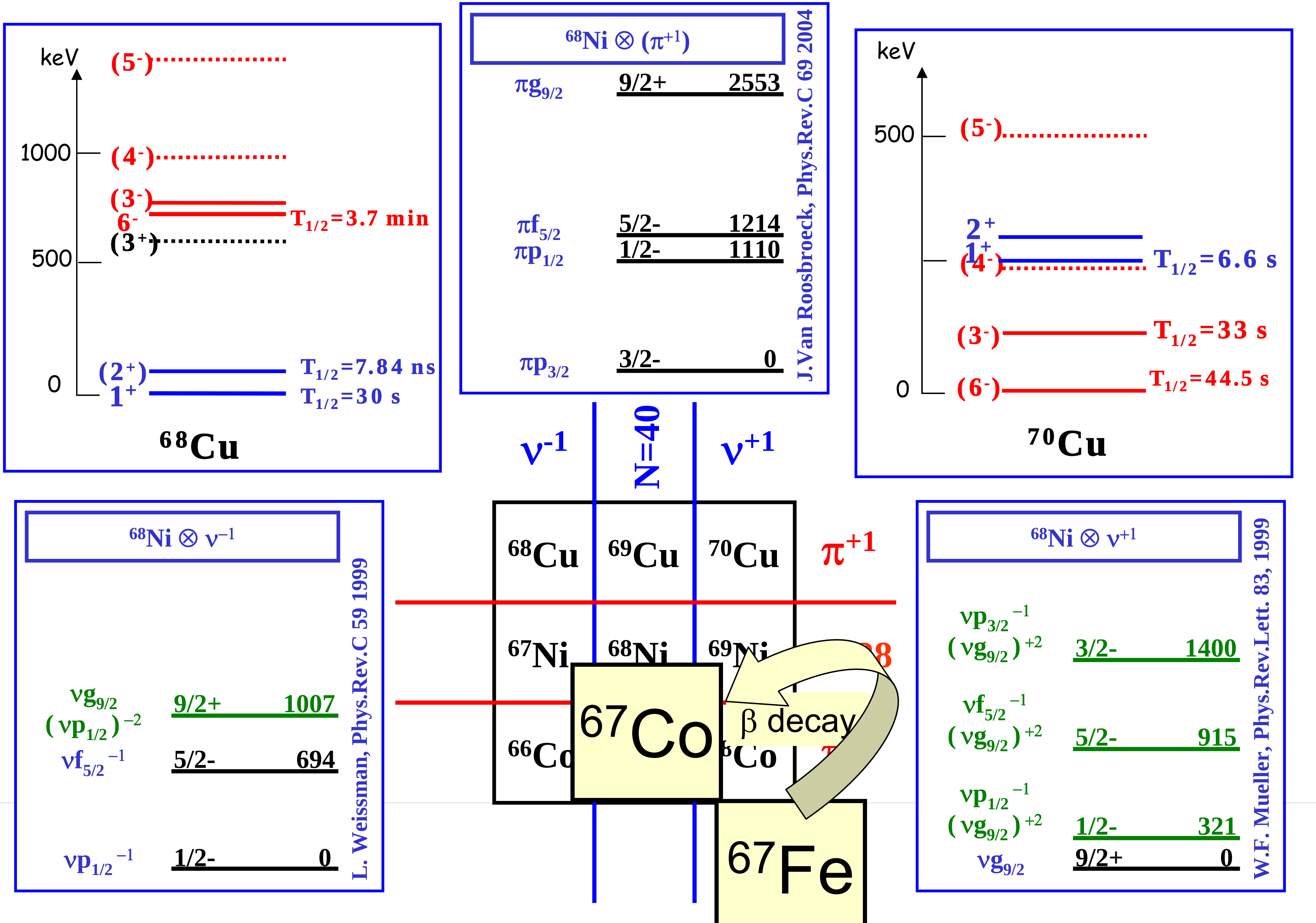
O. Perru *et al*, PRL **96** 232501 (2006) – GANIL

E. Padilla-Rodal *et al*, PRL**70** 024301 (2004) - ORNL

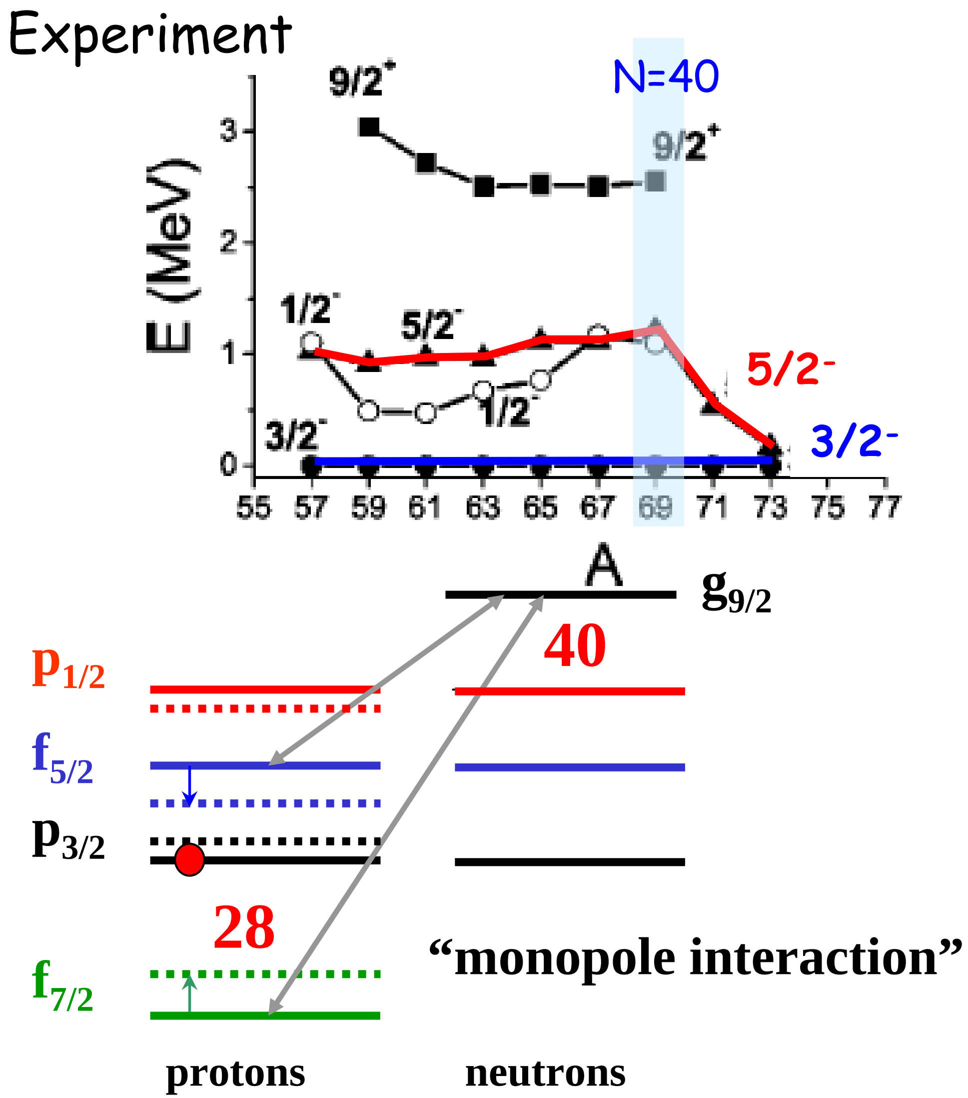
O. Sorlin *et al*, PRL **88**, 2002

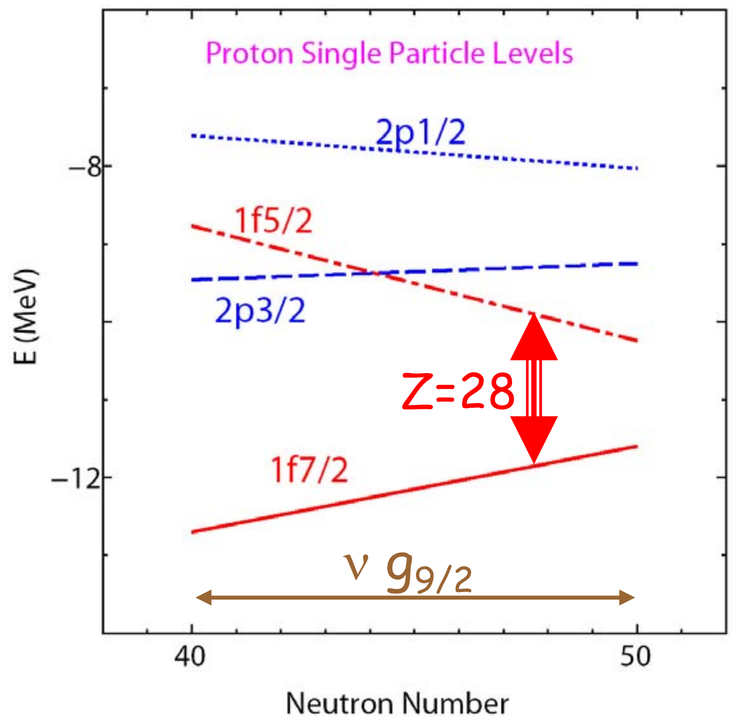
K.-H. Langanke *et al*, PRC 67, 2003

Structure of $^{68}Ni \otimes \nu^{+/-1}$ or $\pi^{+/-1}$



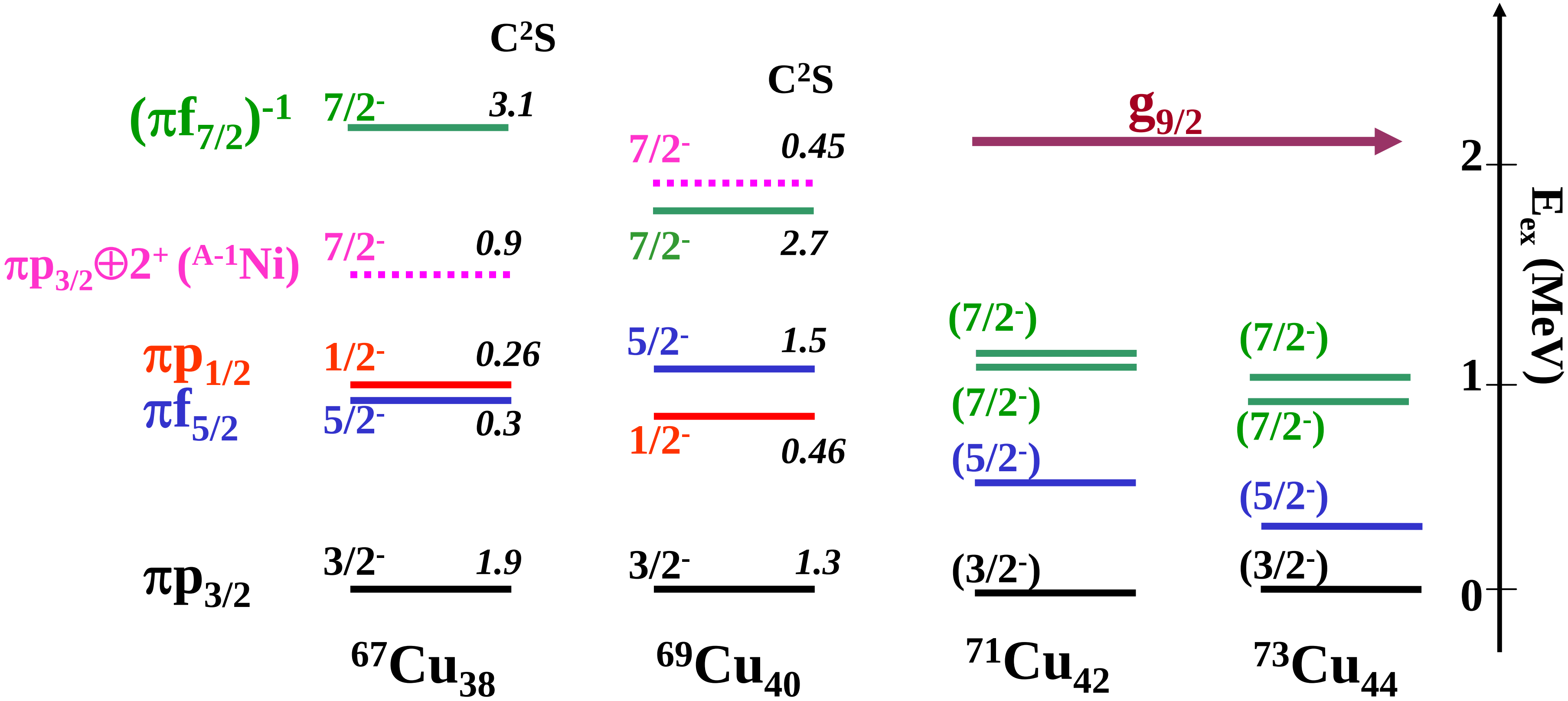
Monopole interaction: Cu (Z=29)





S. Franchoo et al., PRL81 (1998) 3100, PRC64 (2001) 054308
N. Smirnova et al., PRC69 (2004) 044306
A. Lisetskiy *et al*, PRC**70** 044314 (2004)
T. Otsuka et al., PRL 85 (2005) 232502

^{67,69,71,73}Cu systematics



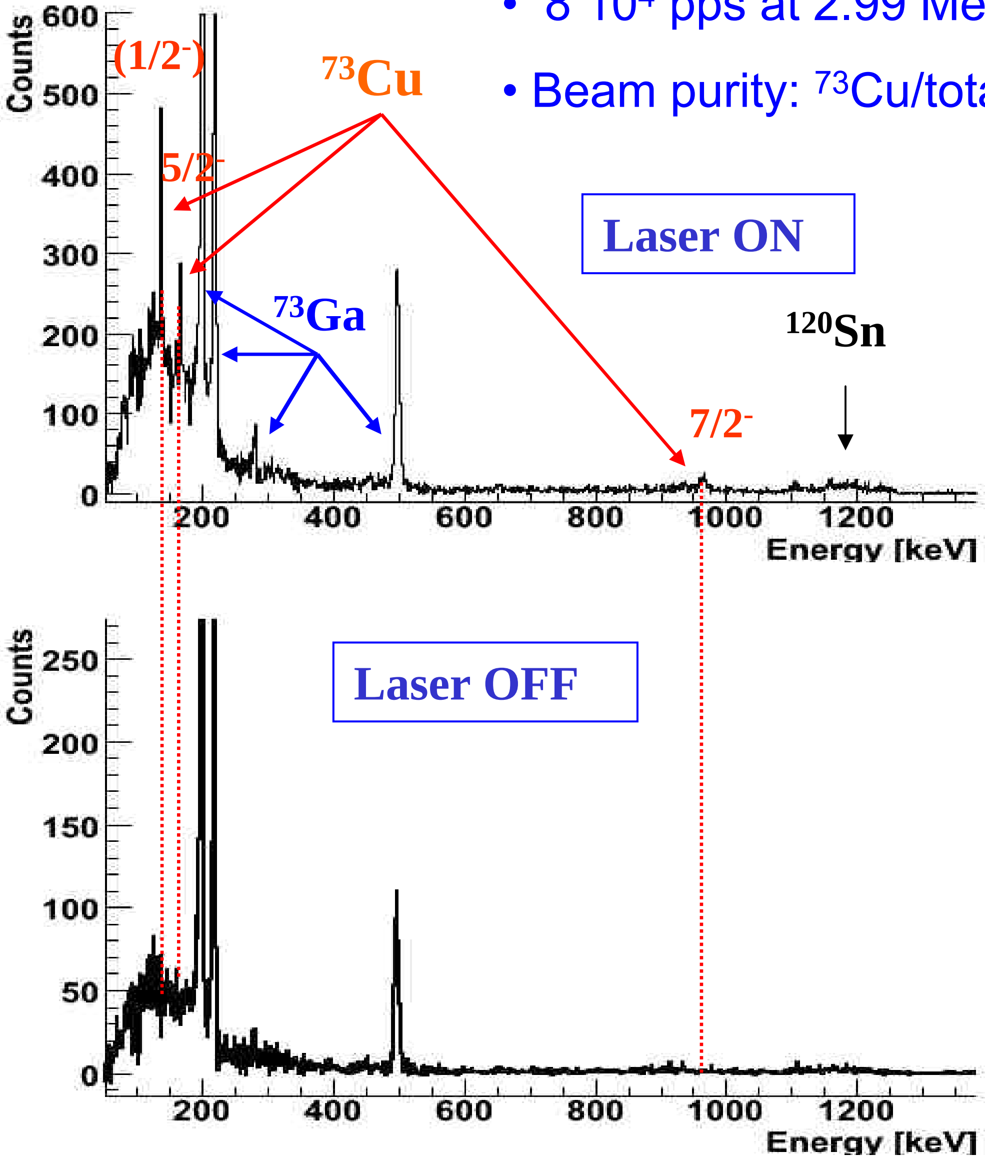
^{67,69}Cu: B. Zeidman et al., PRC 18, 2122(1978): $^{A+1}$Zn(d,^{3}He)^{A}Cu

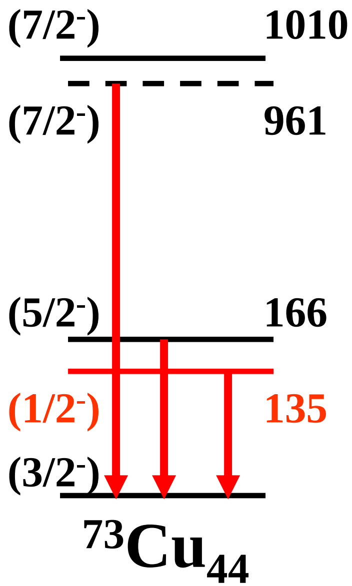
^{71}Cu: R. Grzywacz et al., PRL 81, 766 (1998).

^{69,71,73}Cu: S. Franchoo et al., PRL 81, 3100(1998).

Coulomb excitation of ^{73}Cu

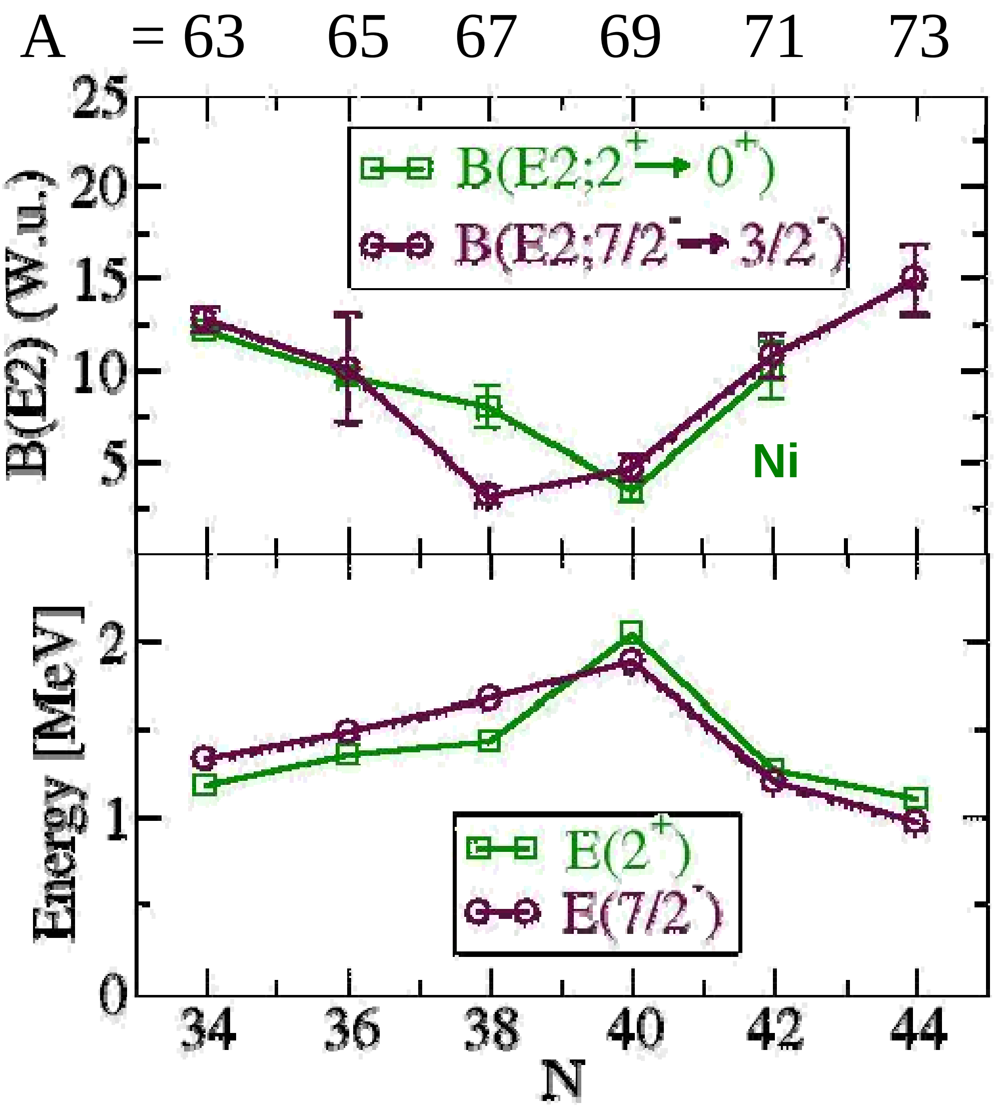
- 8 10^4 pps at 2.99 MeV/u on a 2 mg/cm^2 ^{120}Sn target
- Beam purity: ^{73}Cu/total = 17 %





- Unknown B(E2) values determined relative to the known B(E2;2$^+$→ 0$^+$) in ^{120}Sn or ^{104}Pd.

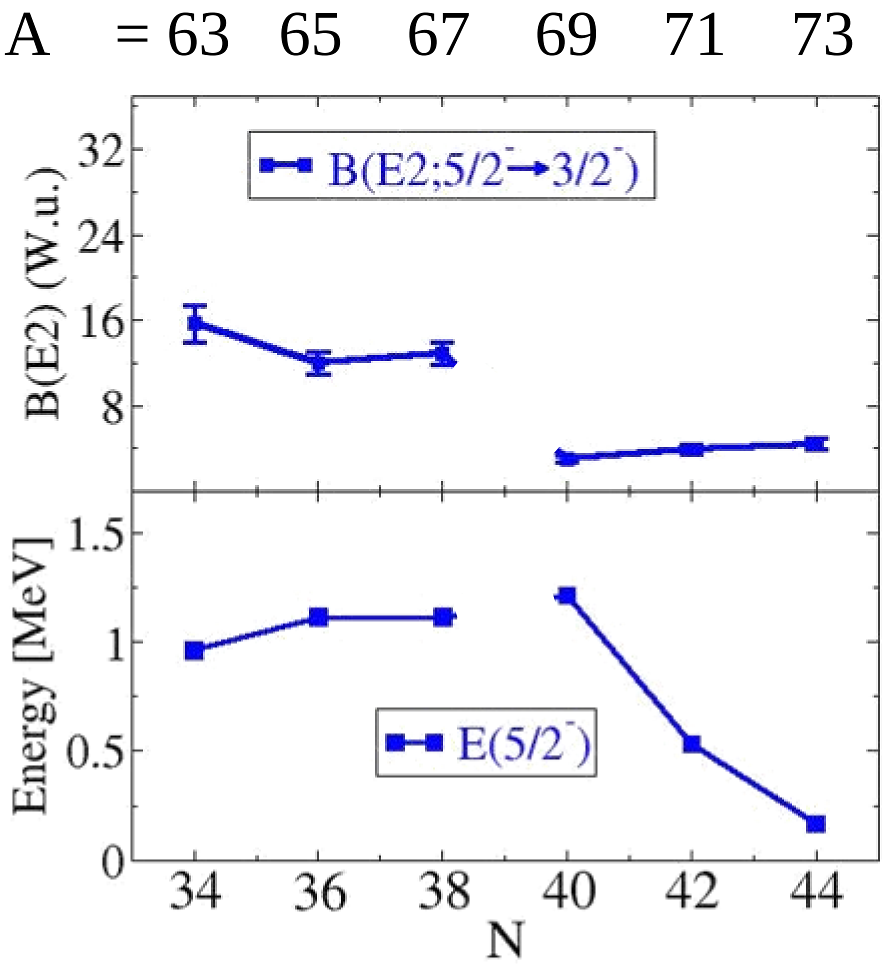
Results: the 7/2⁻ states



- B(E2; 7/2$^-$ → 3/2$^-$) ≅ B(E2; 2$^+$ → 0$^+$) in agreement with the proposed $\pi p_{3/2} \oplus 2^+$ nature for the 7/2$^-$ states
- Only one of the two 7/2- states populated in Coulomb excitation (identification of the πf7/2 intruder state in ^{71,73}Cu)

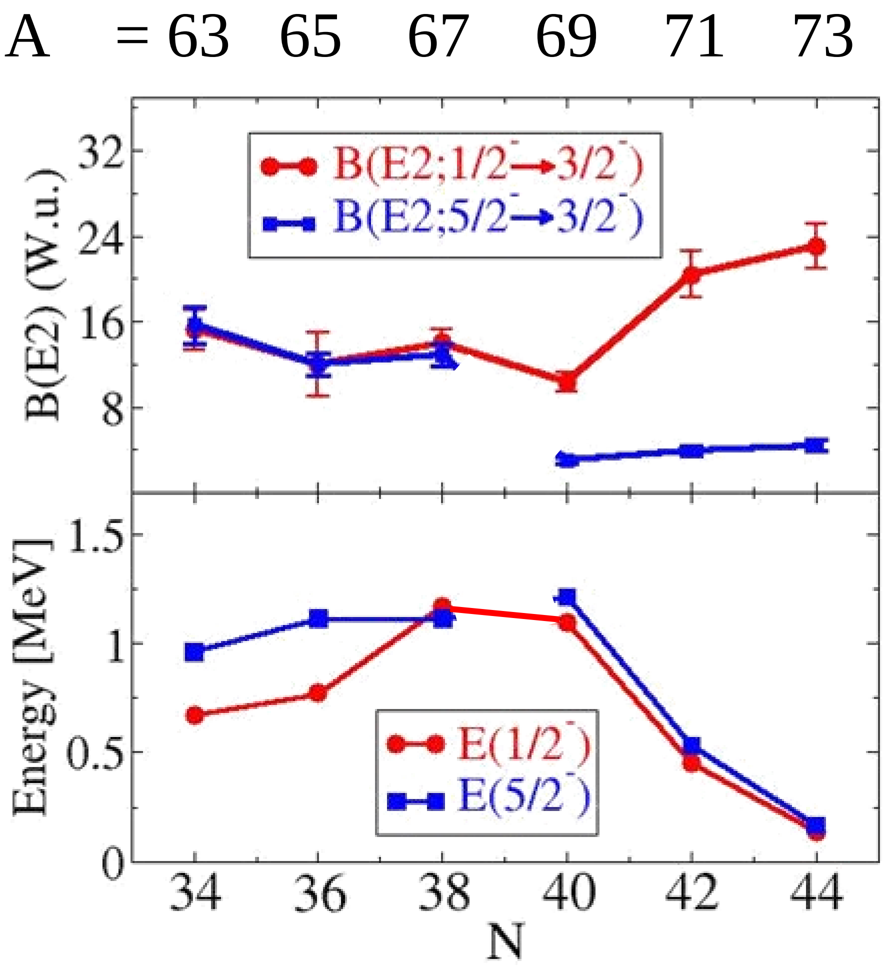
B(E2) values in ^{63,65}Cu: R.L. Robinson et al., Phys. Rev. 134, B567, 1964.

Results: the 5/2$^-$ states



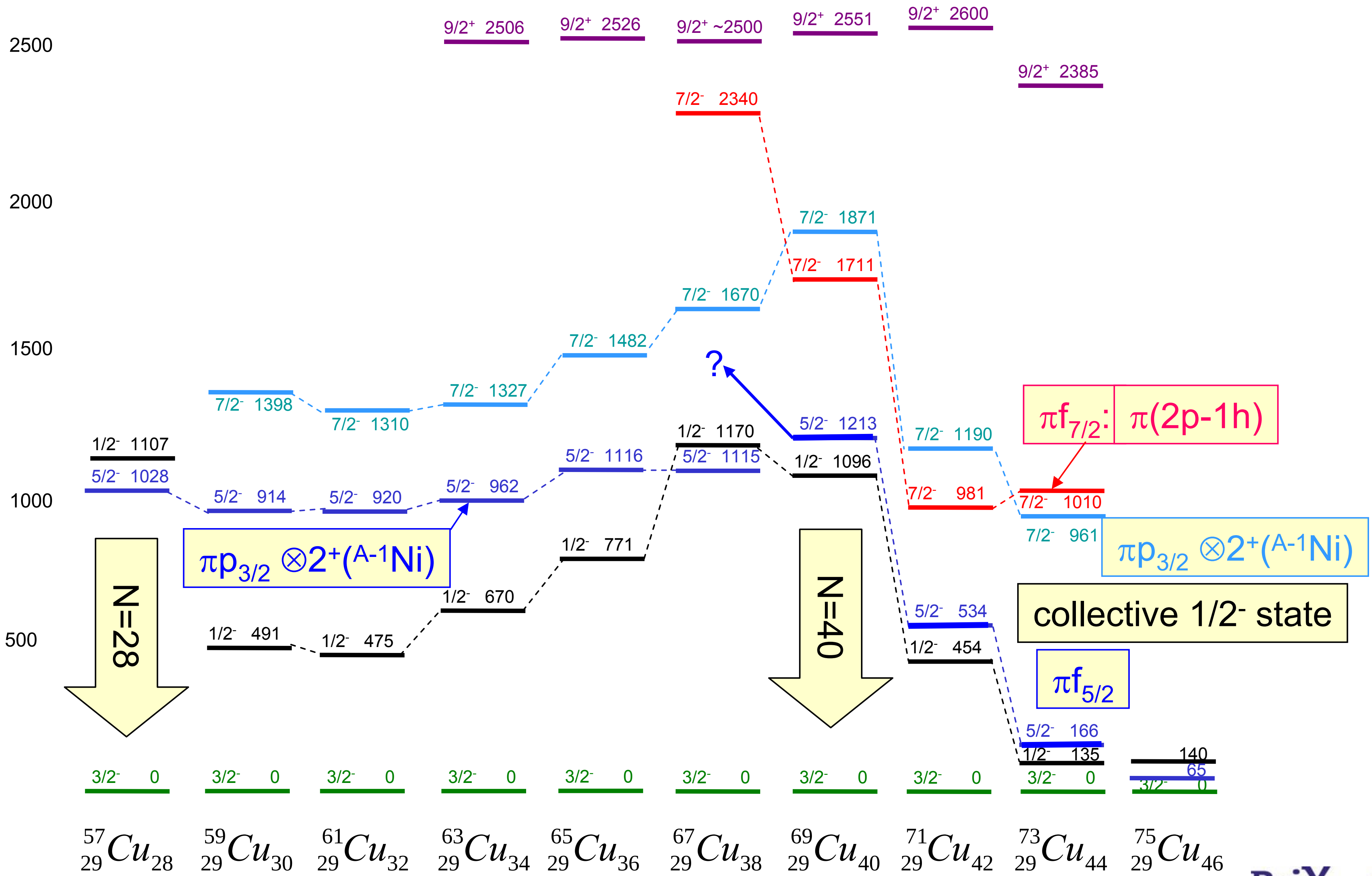
- at N=40 (^{69}Cu), the $5/2^-_1$ states undergo a significant loss in collectivity, are of different character
- the low B(E2; 5/2$^-$ → 3/2$^-$) value from N=40 onwards indicates that the 5/2$^-$ state is essentially of single-particle character

Results: the 1/2$^-$ states



- at N=40 (^{69}Cu), 5/2$^-$ states undergoes a significant loss in collectivity, are of different character
- the low B(E2; 5/2$^-$ → 3/2$^-$) value from N=40 onwards indicates that the 5/2$^-$ state is essentially of single-particle character
- the proposed 1/2$^-$ shows an important increase in collectivity beyond N=40;
- onset of collectivity related to the filling of the g9/2 neutron state.

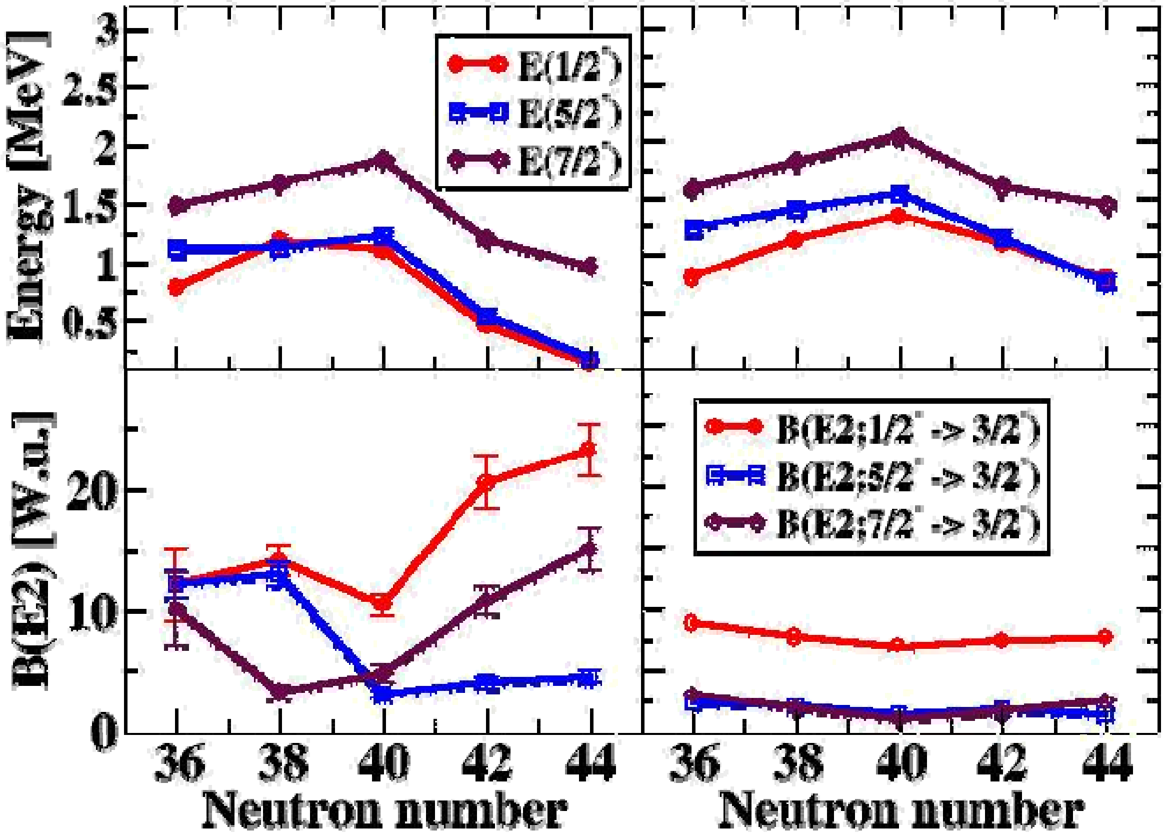
Energy systematics in the odd-mass Cu isotopes



Energy systematics in the odd-mass Cu isotopes

EXP. **Shell-model**

N. Smirnova et al., PRC 69(2004) 044306.

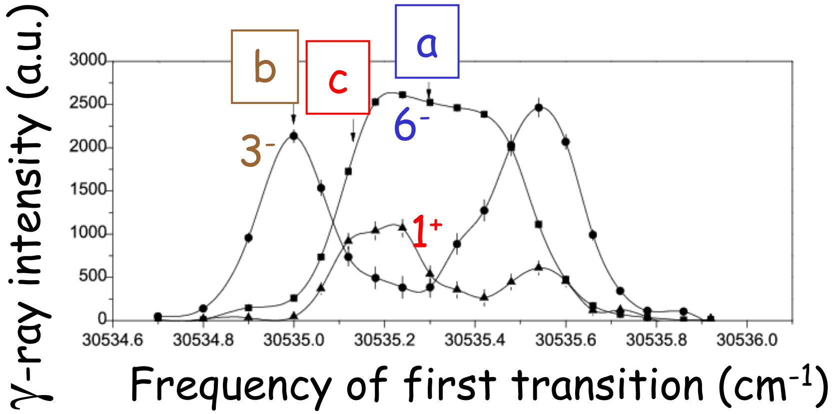


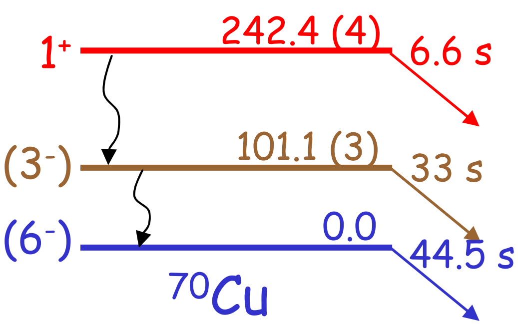
shell-model calculations with a realistic interaction based on G-matrix with the monopole part modified by F. Nowacki.

Valence space consisted of pfg orbitals outside the ^{56}Ni core.

e_p=1.5e, e_n=0.5e.

Production of isomeric beams: resonant laser ionization



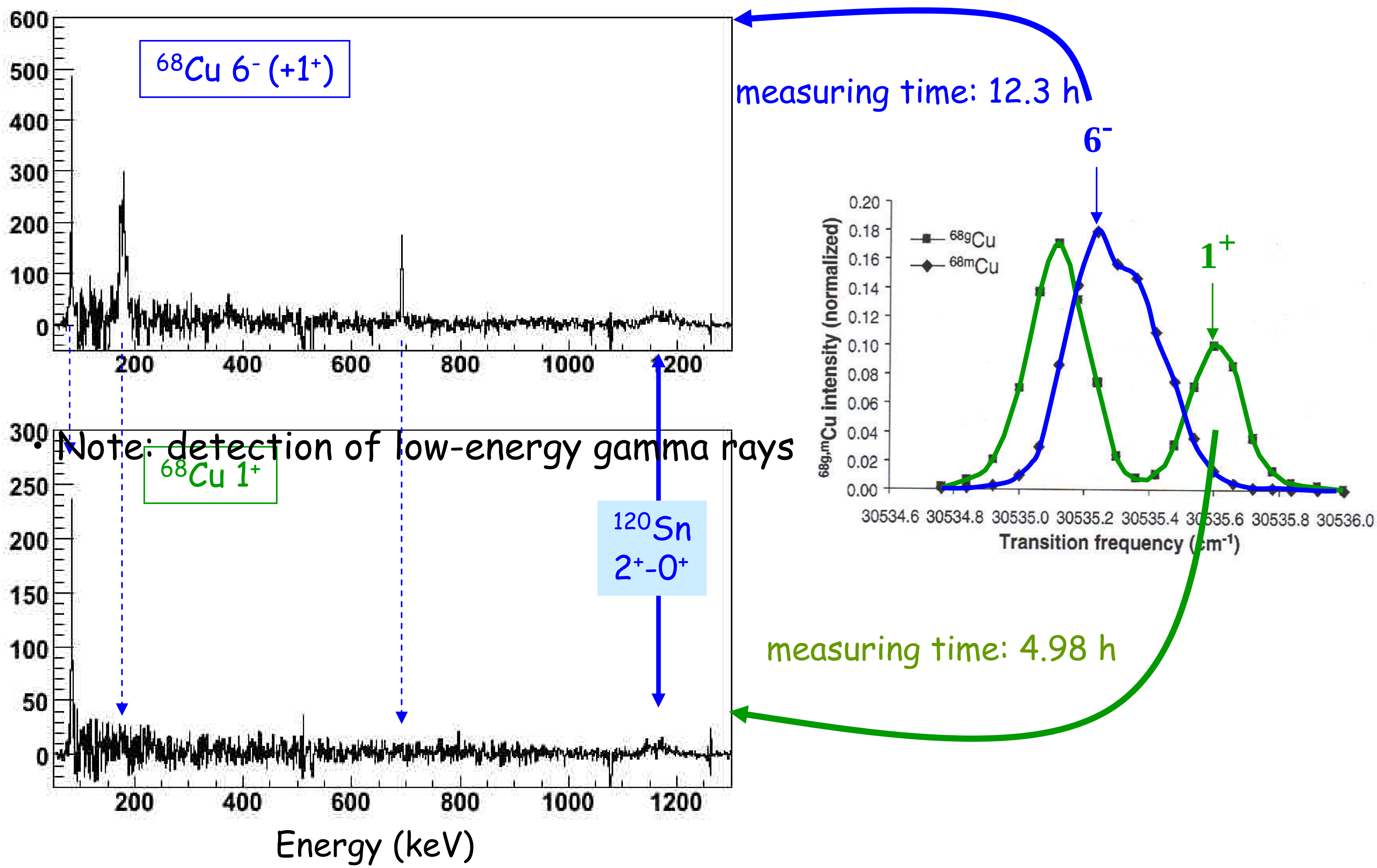


J. Van Roosbroeck,- Phys. Rev. Lett. 92 (2004) 112501

- Purified isomeric beams:
  - Determine properties
  - Study decay characteristics
  - Coulomb excitation and transfer reactions (after post-acceleration)

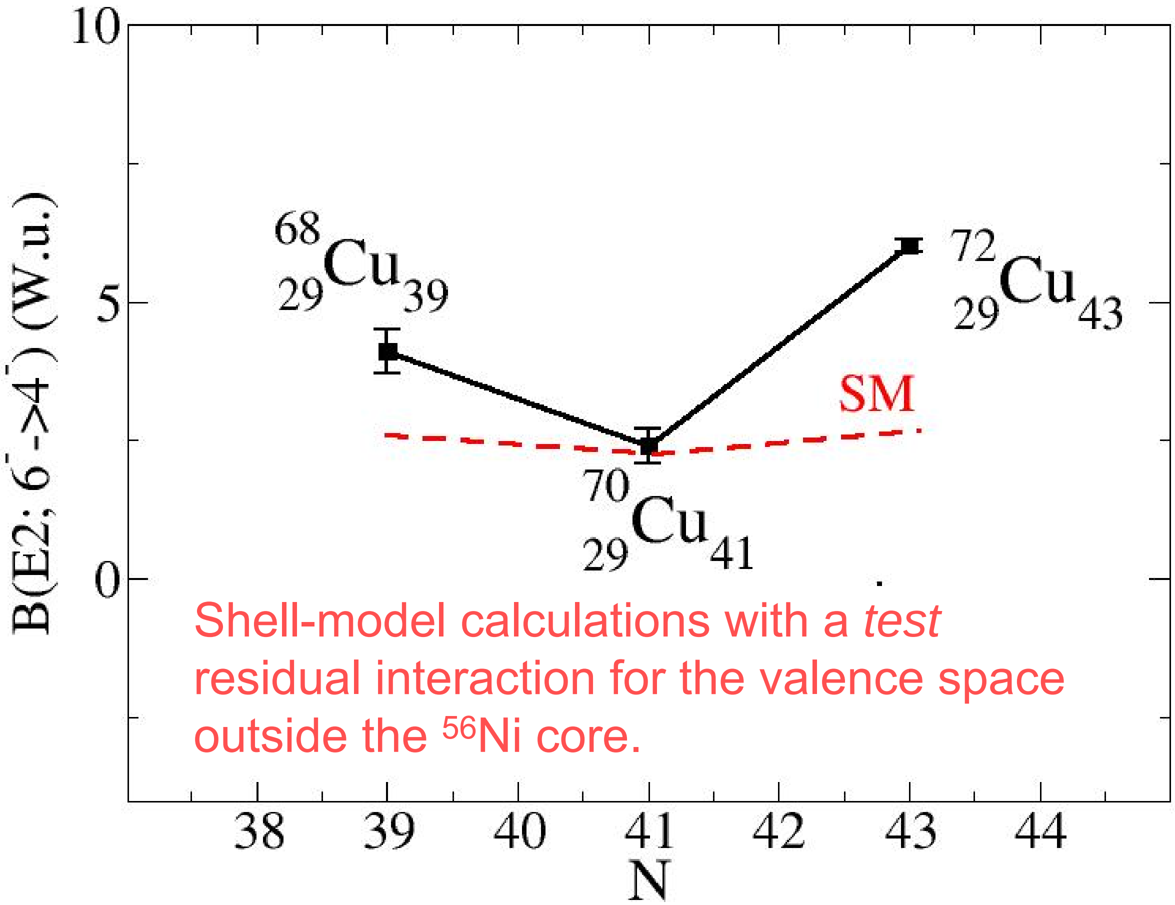
➢ ^{68m,g}Cu (2.86 MeV/u, 3 10^5 pps, 74% pure) @ ^{120}Sn (2.3 mg/cm^2)

➢ Post-accelerated isomeric beams!



- Note: detection of low-energy gamma rays

B(E2;6⁻ → 4⁻) values in ^{68,70}Cu

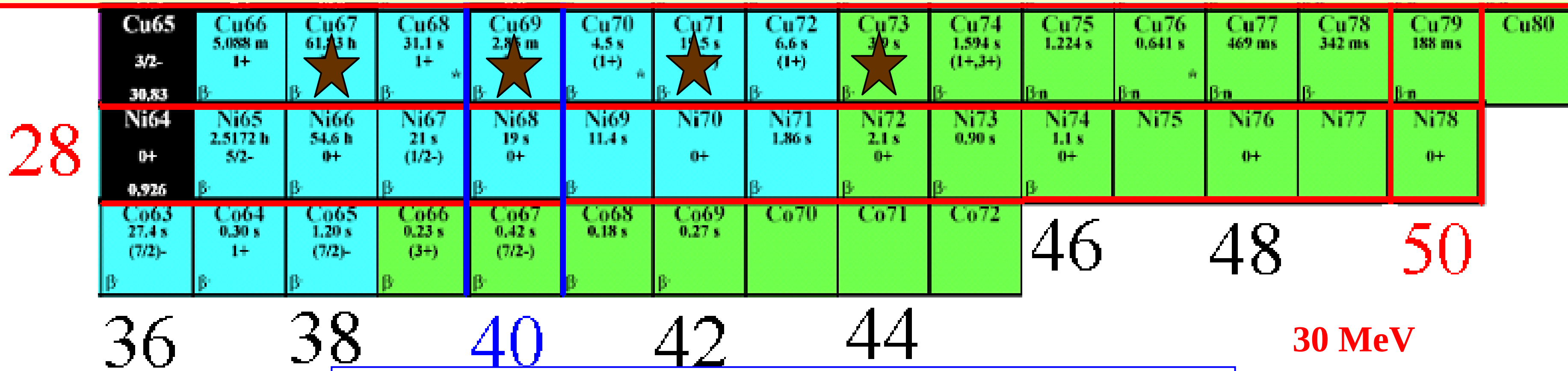


*B(E2;6⁻ → 4⁻) in ^{72}Cu from $T_{1/2,\ exp}$(6-) R. Grywacz,- PRL81 (1998) 766

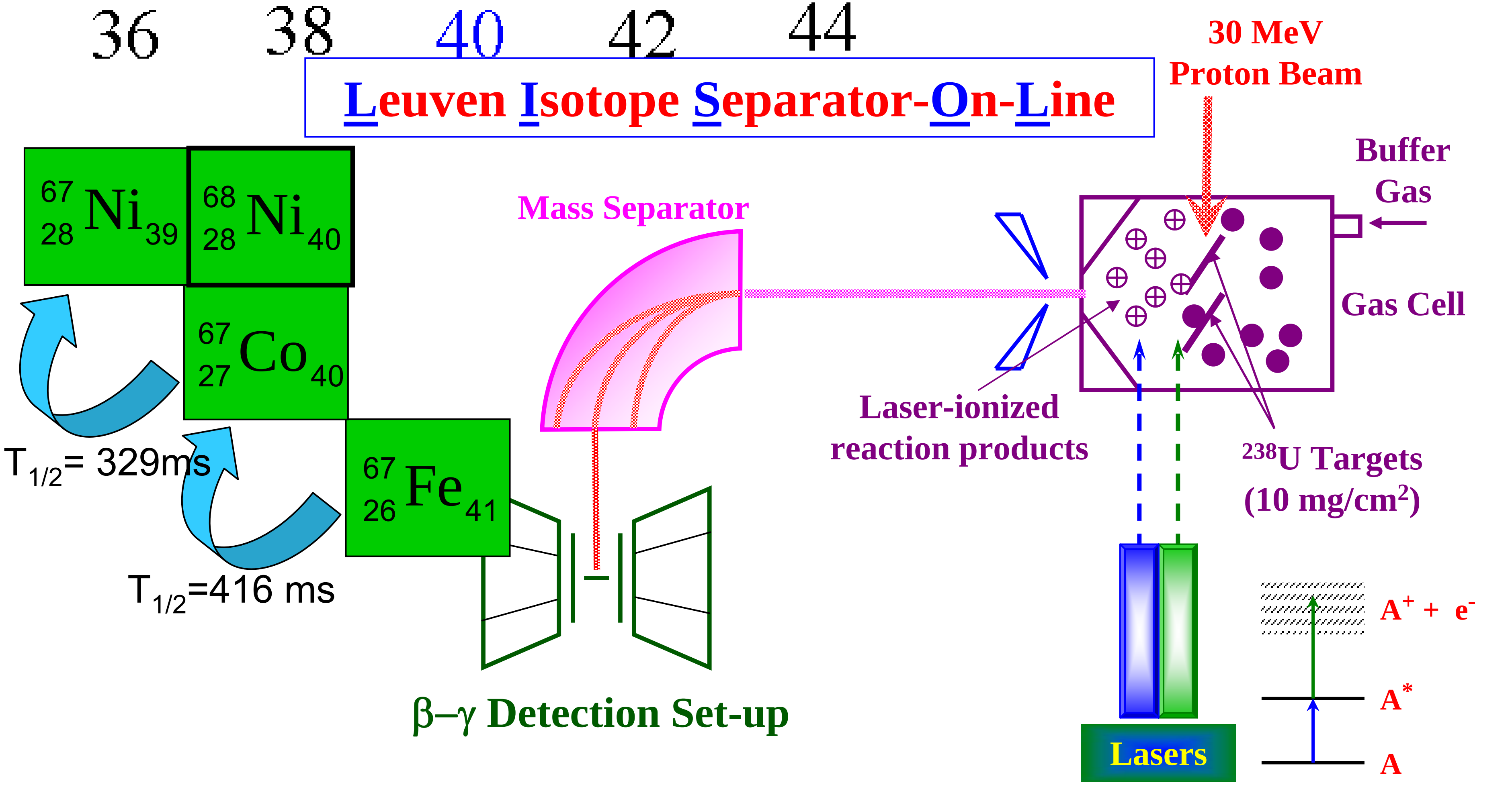
→ the poor agreement between the experiment and theory for ^{68,72}Cu pointing to the importance of proton excitations across the Z=28 shell gap;

I. Stefenescu et al., PRL98 (2007) 122701

Decay study of ^{67}Fe - ^{67}Co – ^{67}Ni



Leuven Isotope Separator-On-Line



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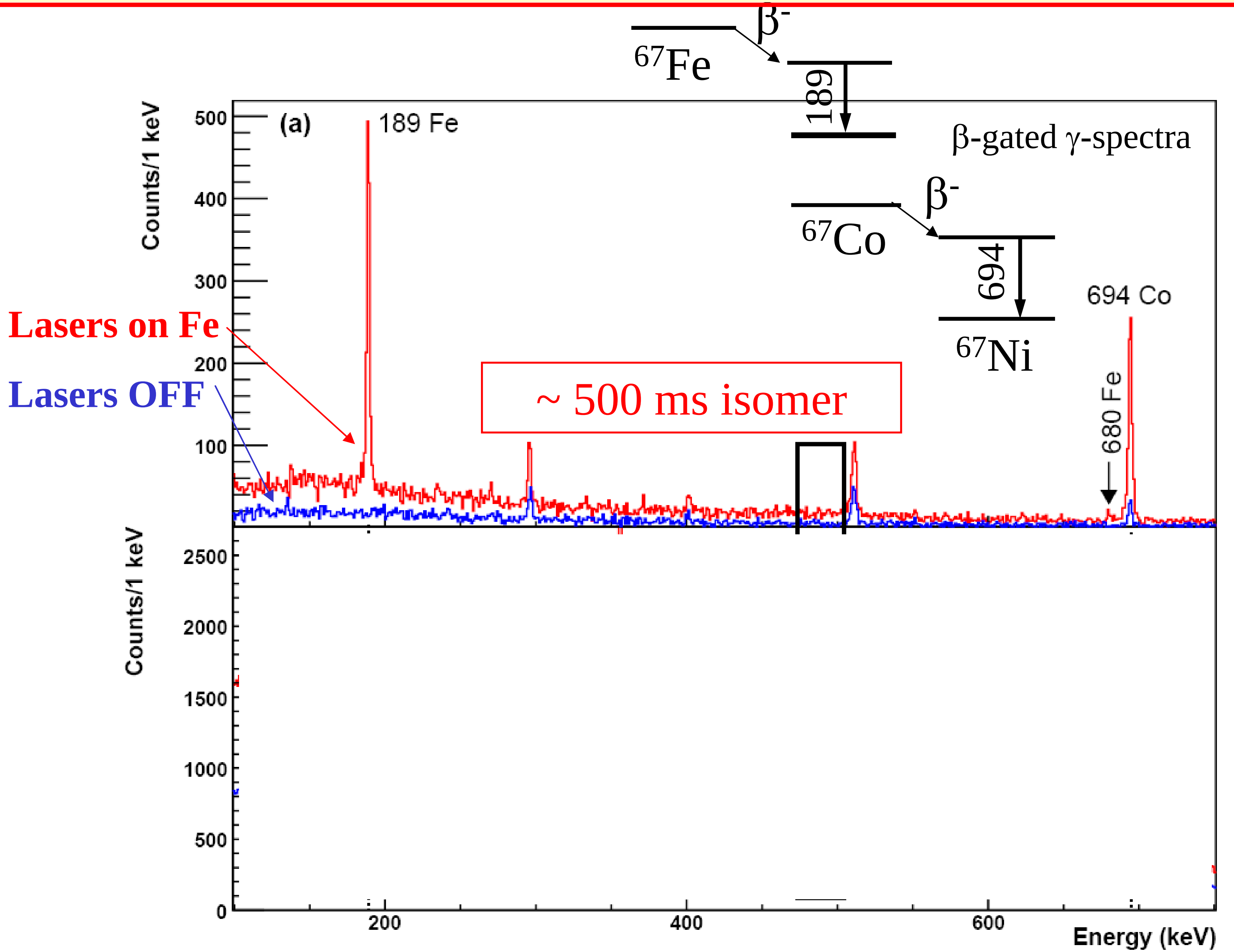
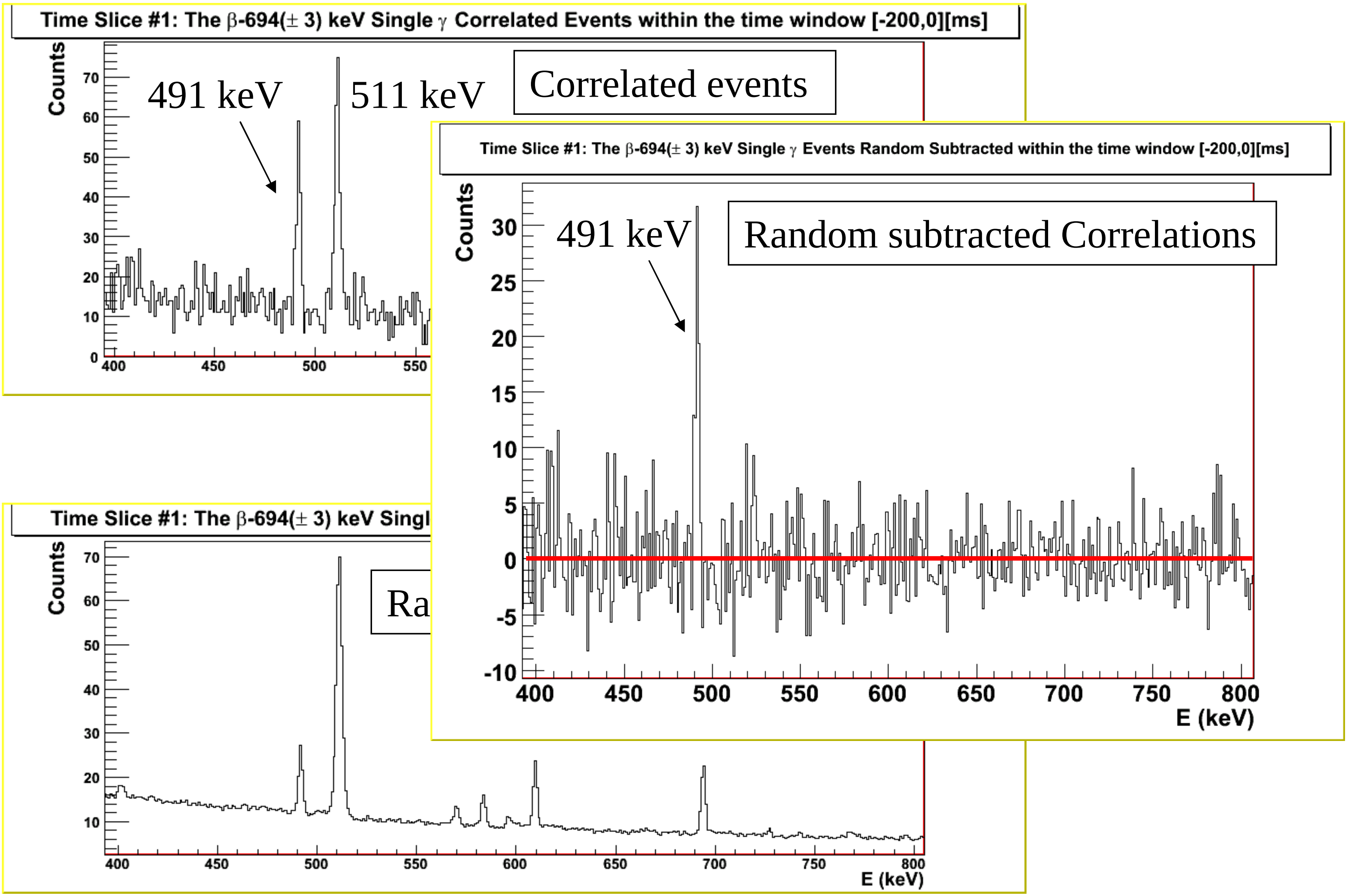
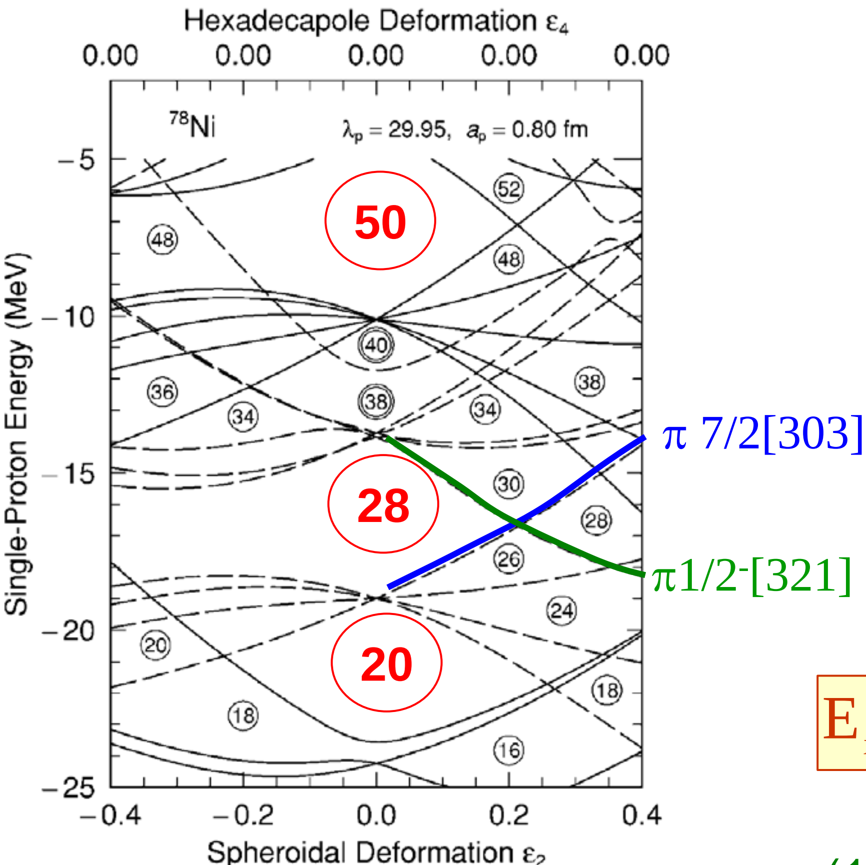


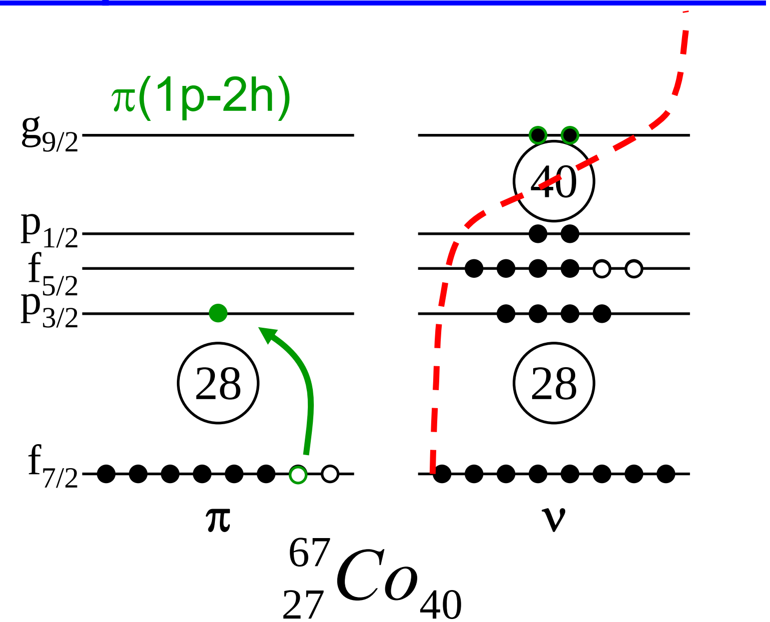
β–γ–γ correlations:
single γ's before (-200 – 0 ms) a β-694 keV (in ^{67}Co) trigger



Proton intruder state in ^{67}Co

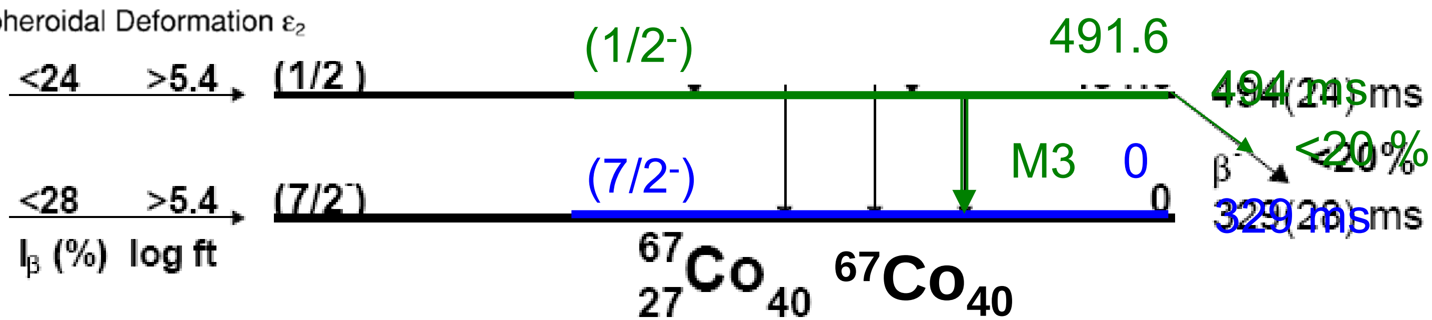


1p-2h proton intruder states in ^{67}Co



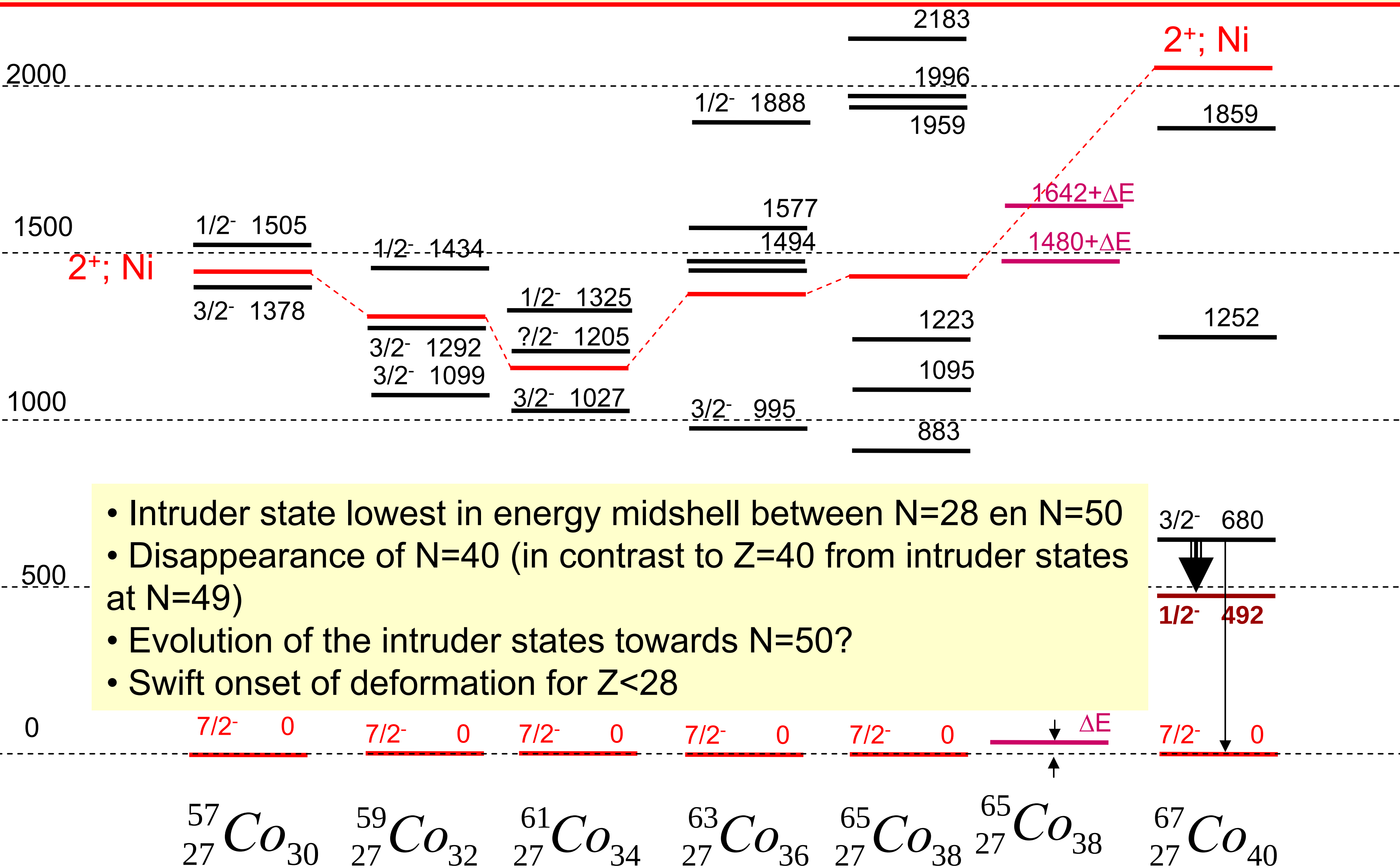
$$E_x(\pi:1p-2h) = \left(\varepsilon_{j\pi} - \varepsilon'_{j'\pi}\right) - \Delta_{pairing} + \langle V_{\pi\nu} \rangle$$

K.Heyde et al., Phys. Rep. (1983)



K.U. Leuven

Energy systematics of the neutron rich Co isotopes



- Intruder state lowest in energy midshell between N=28 en N=50
- Disappearance of N=40 (in contrast to Z=40 from intruder states at N=49)
- Evolution of the intruder states towards N=50?
- Swift onset of deformation for Z<28

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HIE-ISOLDE: three objectives

- REX energy upgrade and increase of current capacity

  Energy upgrade in three stages: 5.5 MeV/u and 10 MeV/u and lower energy capacity

  REX trap and breeder upgrade

- ISOLDE proton driver beam intensity upgrade 2 to 6 μA (linac 4)

  Faster cycling of the booster

  New target stations for ISOLDE

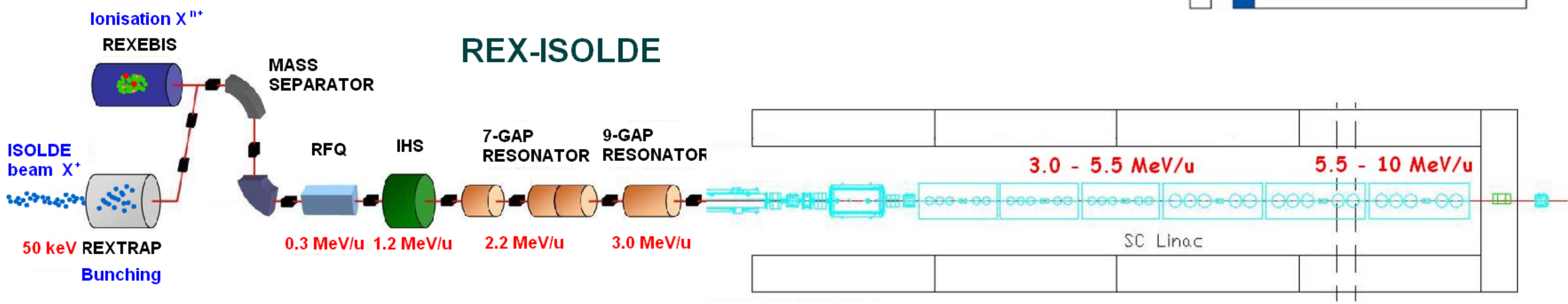
- ISOLDE radioactive ion beam quality improvement

  Smaller longitudinal and transverse emittance

  Higher charge state for selected users

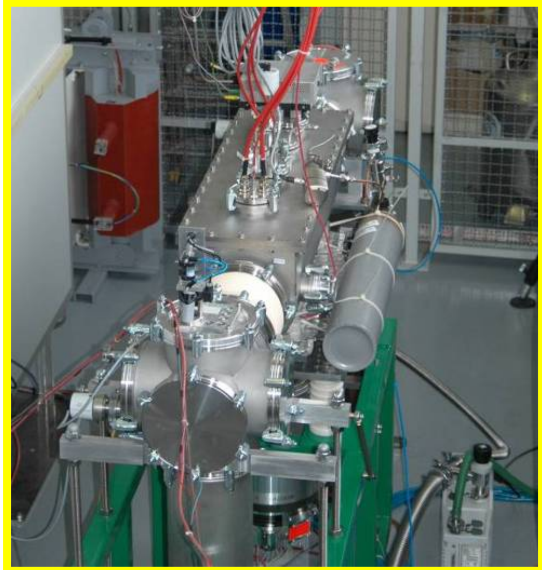
  Better mass resolution

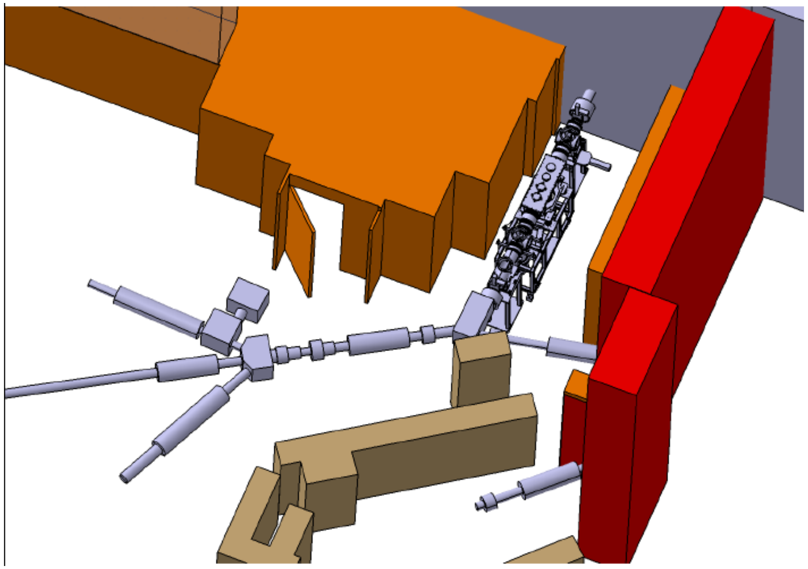
  Target and ion source development e.g. RILIS



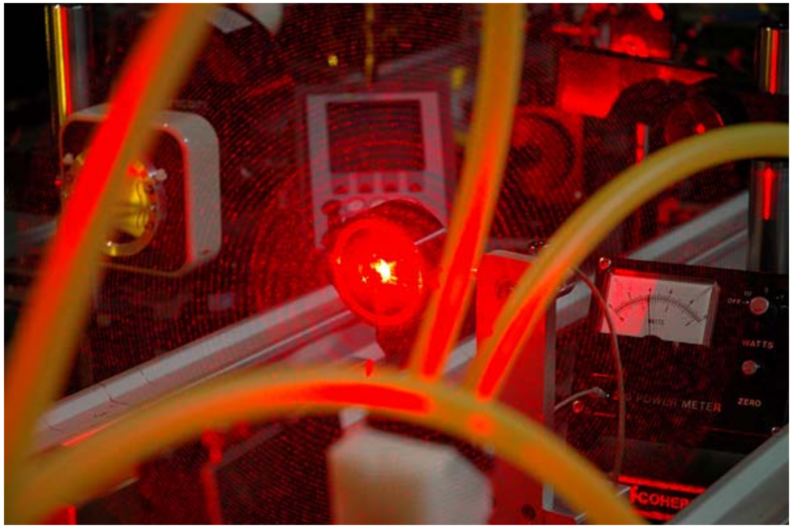
Already ongoing work

RFQ cooler
UK, JYFL, Mainz..
(see talk K. Flanagan)





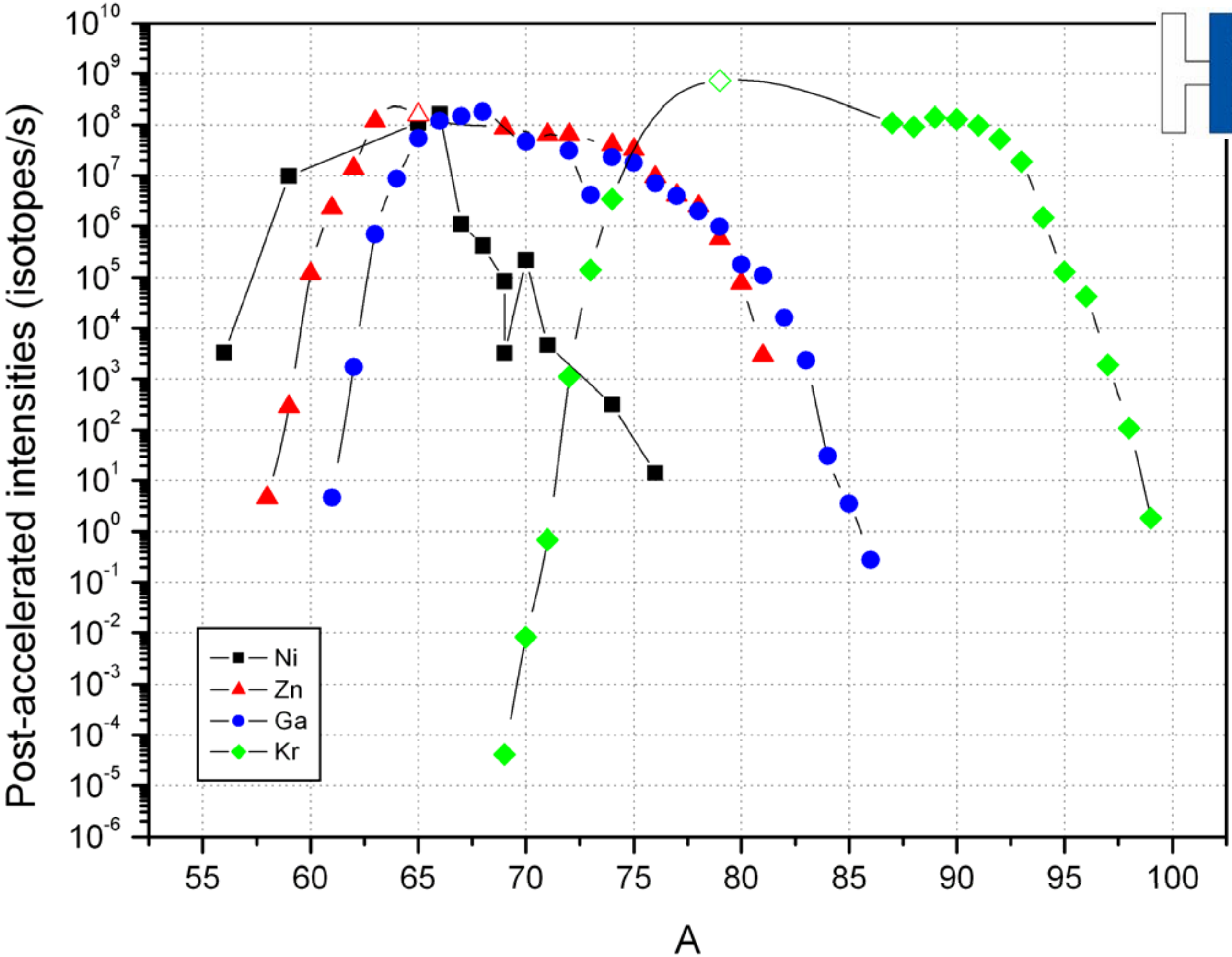
RILIS upgrade
Sweden (Wallenberg)



REX extension
Leuven, UK (Cockcroft Institute..),...

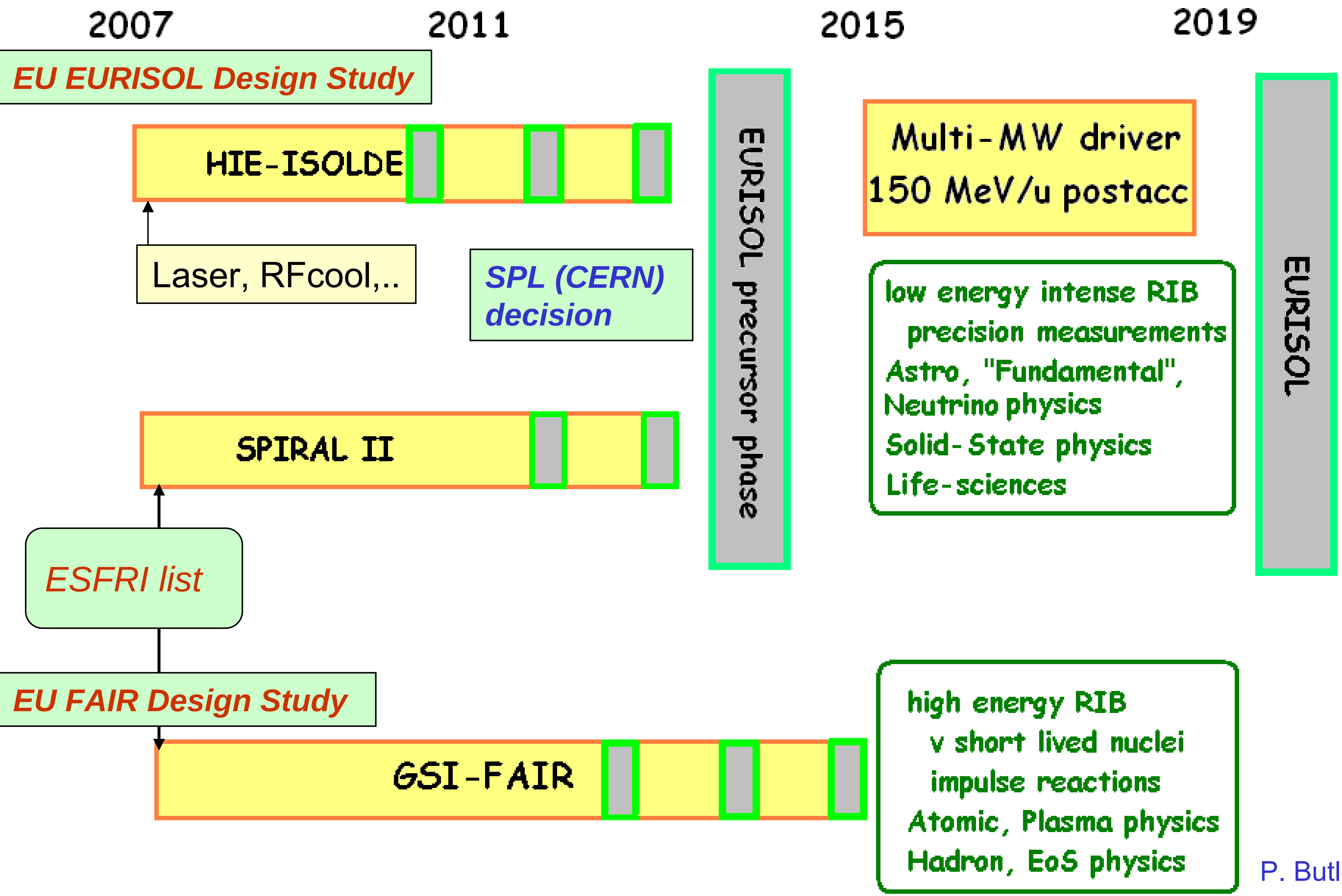
ISOLDE

Expected yields from HIE-ISOLDE (CERN report 2007 – 008)



- Multi-step Coulex, transfer reactions, deep-inelastic reactions
- Construction of a dedicated recoil separator at ISOLDE

European Roadmap for Radioactive Ion Beam Facilities



P. Butler

Conclusion and outlook

- Good quality post accelerated beams from REX-ISOLDE combined with the MINIBALL segmented germanium array form a powerful tool for experiments on far unstable nuclei: Coulomb excitation, transfer reactions, isomeric beams

- Coulomb excitation on the neutron-rich Cu isotopes:
  - single particle character of the $5/2^-_1$ states
  - onset of collectivity for the $1/2^-$ states
  - observation of presumably $\pi f_{7/2}$ (2p-1h) intruder states in ^{71,73}Cu

- Beta-decay studies of ^{67}Fe to ^{67}Co:
  - low-lying (E=492 keV) isomeric $1/2^-$ proton intruder state (1p-2h) in ^{67}Co

- Challenge for theory to reproduce these findings: proton excitation through Z=28

The collaboration

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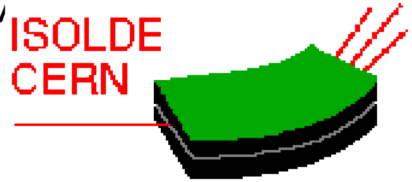
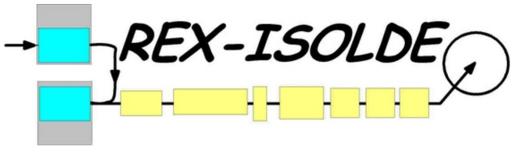




Experimental method & setup: $^{2}H(^{66}Ni,p)^{67}Ni$

- γ-ray detection:

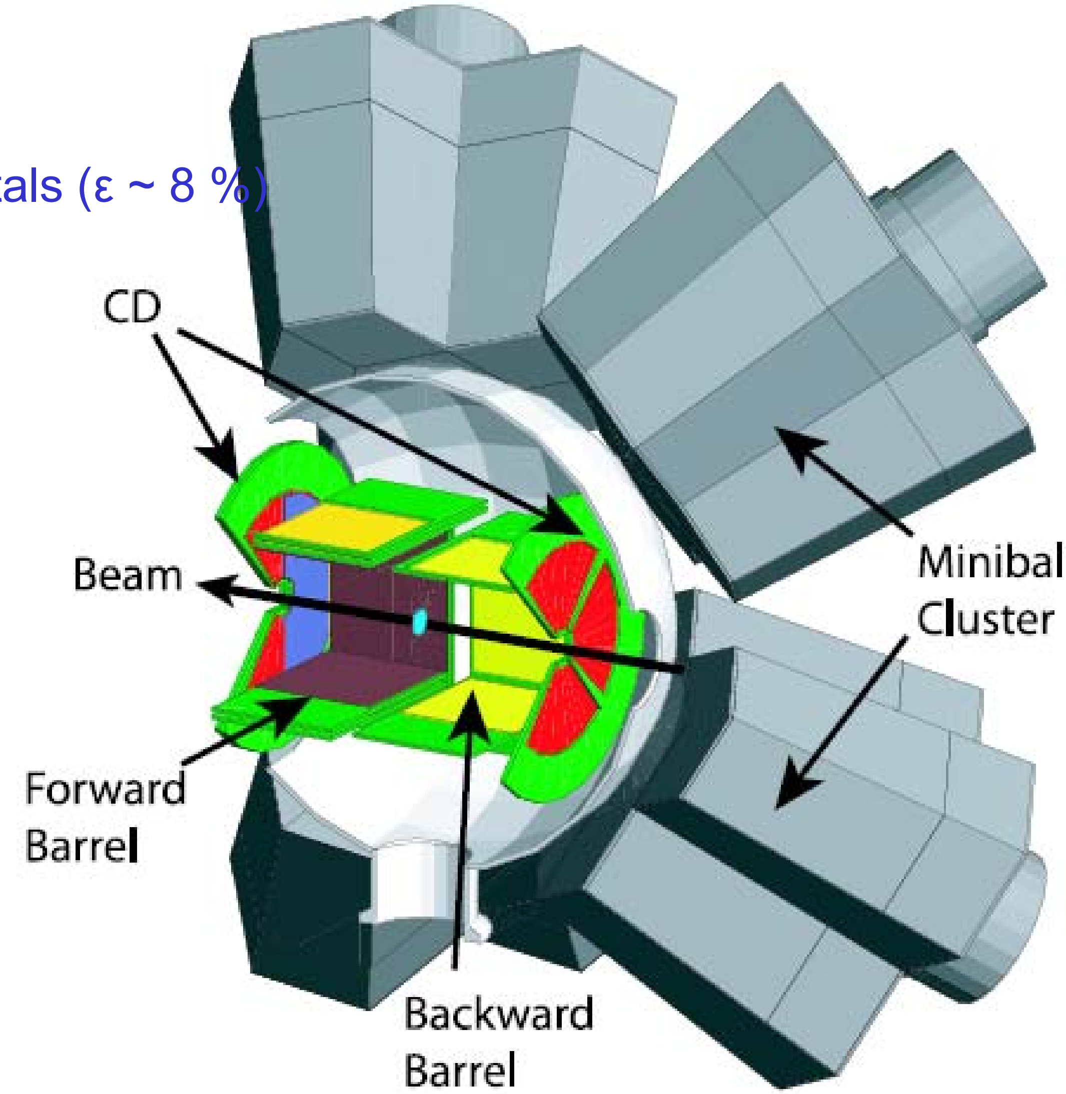
8 MINIBALL triple clusters
24 6-fold segmented germanium crystals (ε ~ 8 %)

- Particle detection (Si)

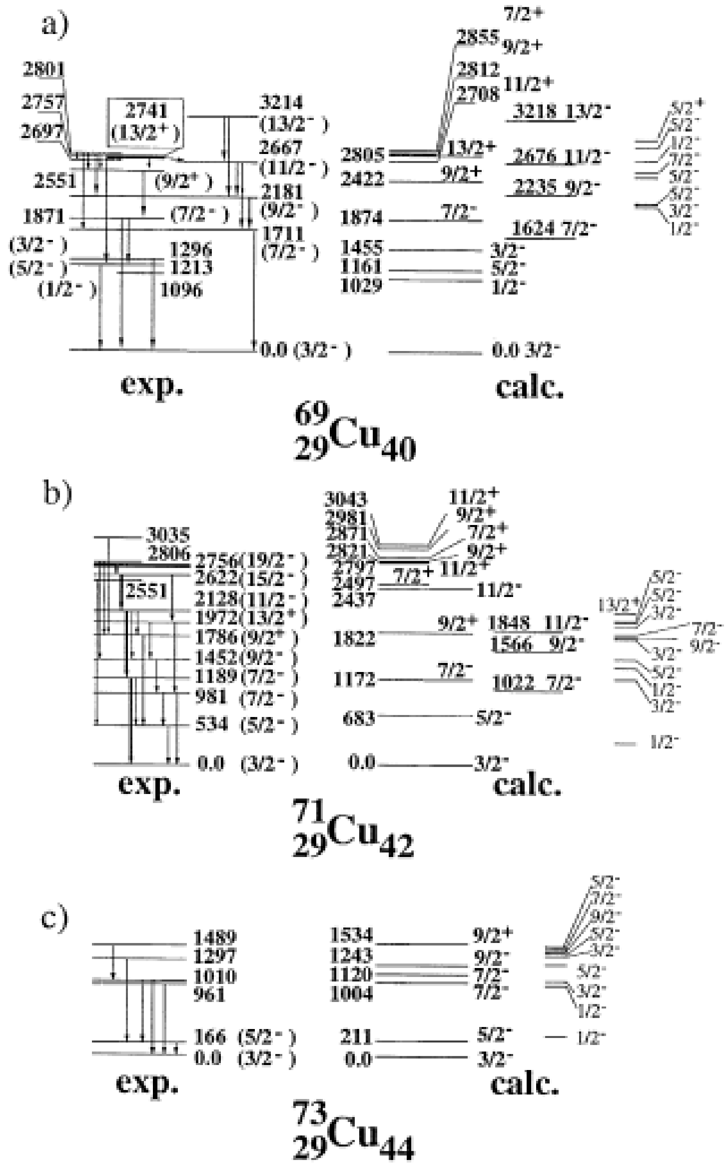
forward barrel: ΔE 140 – E 1000 μm
forward CD: DE 300 – E 1500 μm
backward barrel: E 500 μm silicon
backward CD: E 500 μm

- Beam composition:

Bragg detector, Laser on/off



Experiment vs. particle-core coupling model

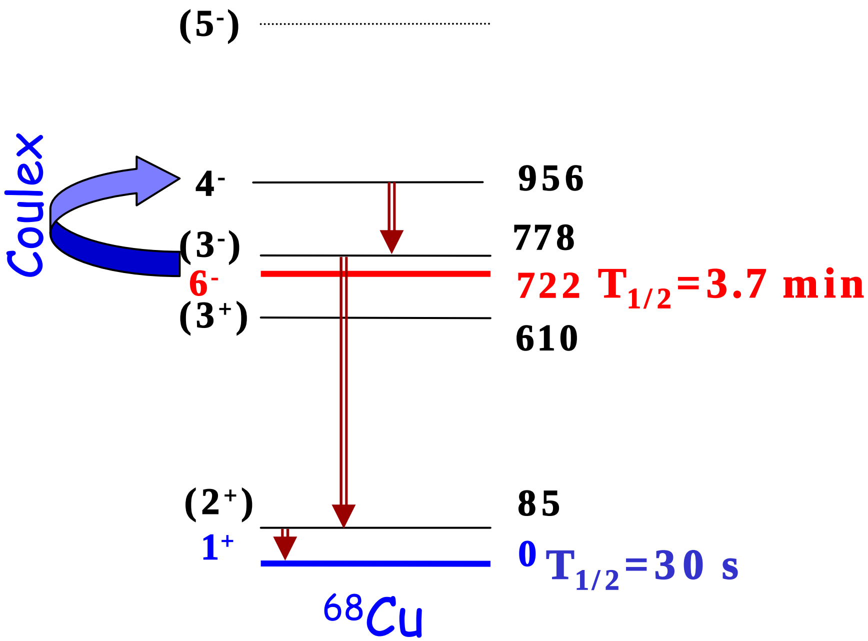


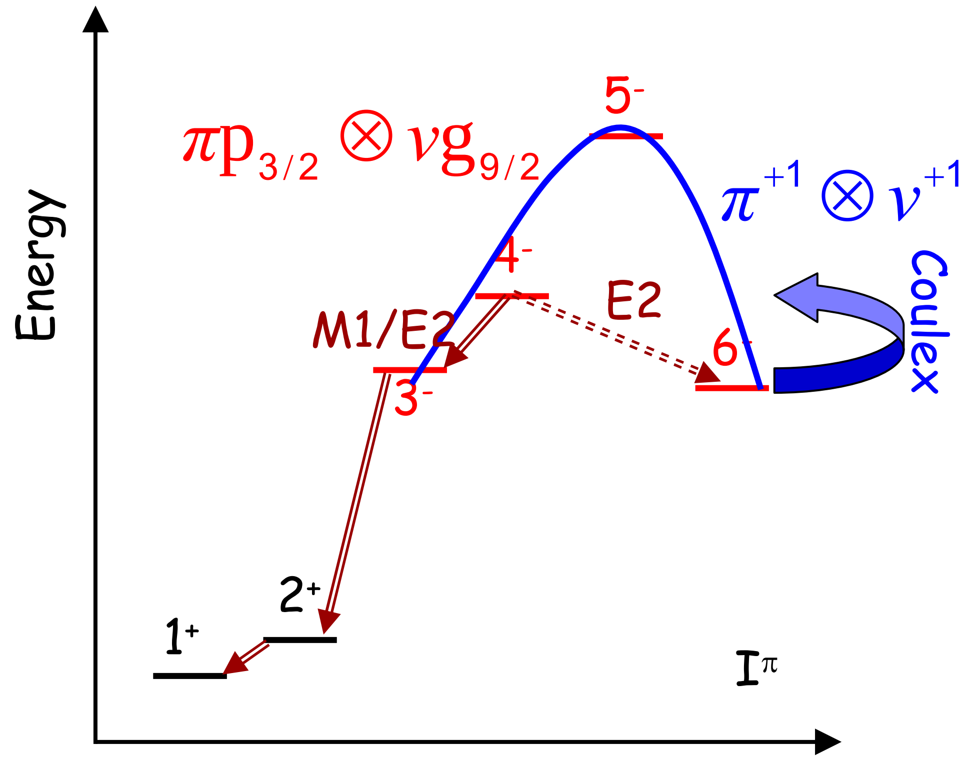
A. M. Oros-Peusquens and P. Mantica, NPA 669 (2000) 81.

Levels in the odd-A Cu nuclei described as single-particle or holes states coupled to the quadrupole or octupole vibrations of the underlying even-even core.

Energies of the excited states in the n-rich ^{69,71,73}Cu very well reproduced by the model. B(E2) values not available.

➢ Instantaneous depopulation of a nuclear isomer

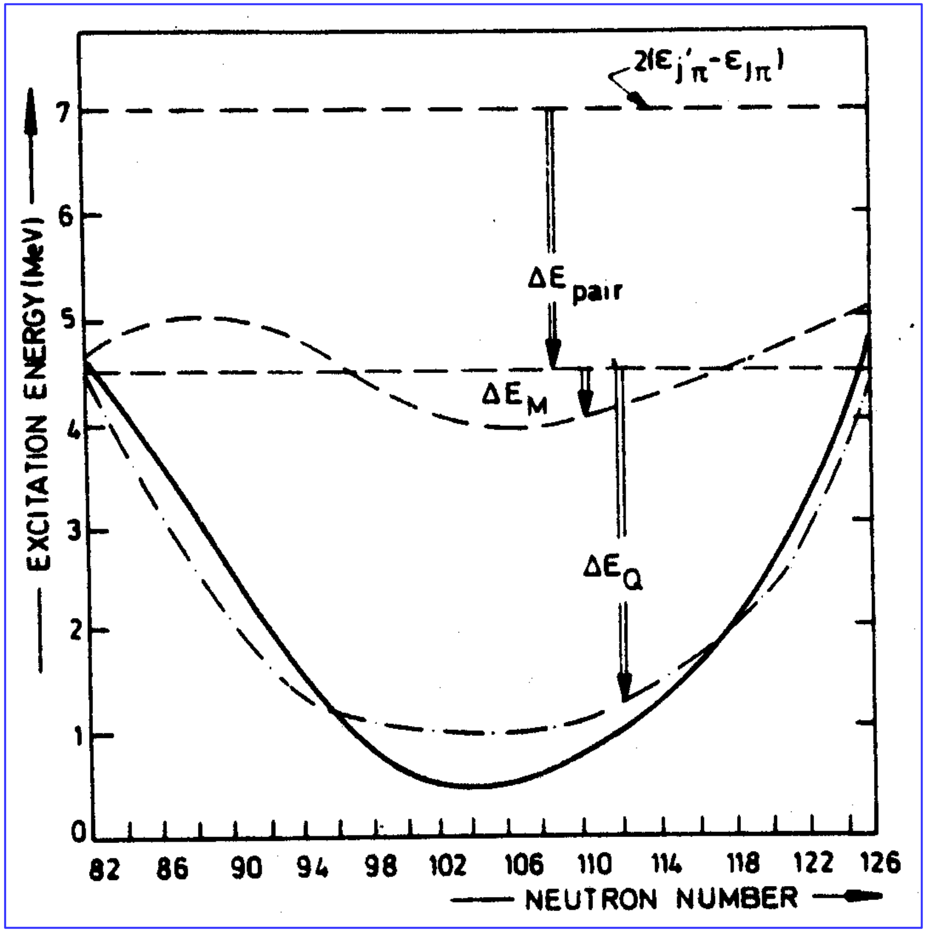


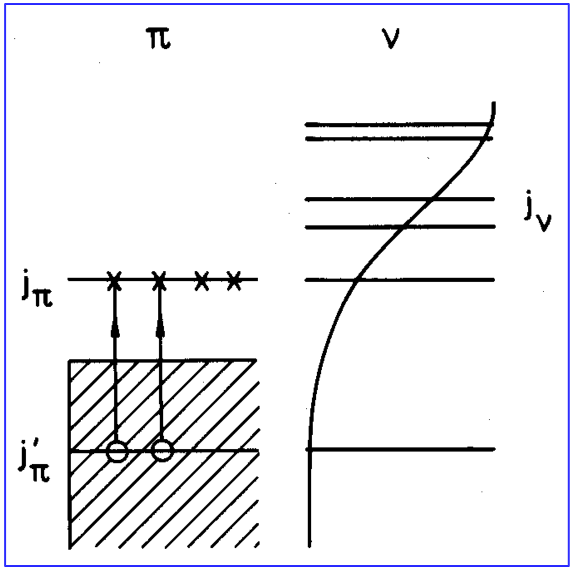


- Population via Coulex (E2)
- Decay through faster M1 transition
- "Paar" parabola: E2 excitation over the parabola's maximum

- Mechanism present in other odd-odd nuclei (e.g. ^{108,110}Ag) ?
- Energy is "released" and half life of the isotope is changed
  - interest for nucleosynthesis processes?

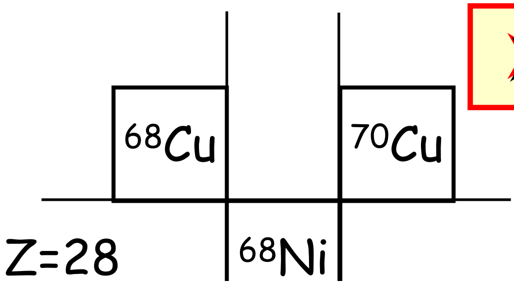
BriX





$$E_x(\pi : 1p-2h) = \left(\varepsilon_{j\pi} - \varepsilon'_{j'\pi}\right) - \Delta_{pairing} + \left\langle V_{\pi\nu} \right\rangle$$

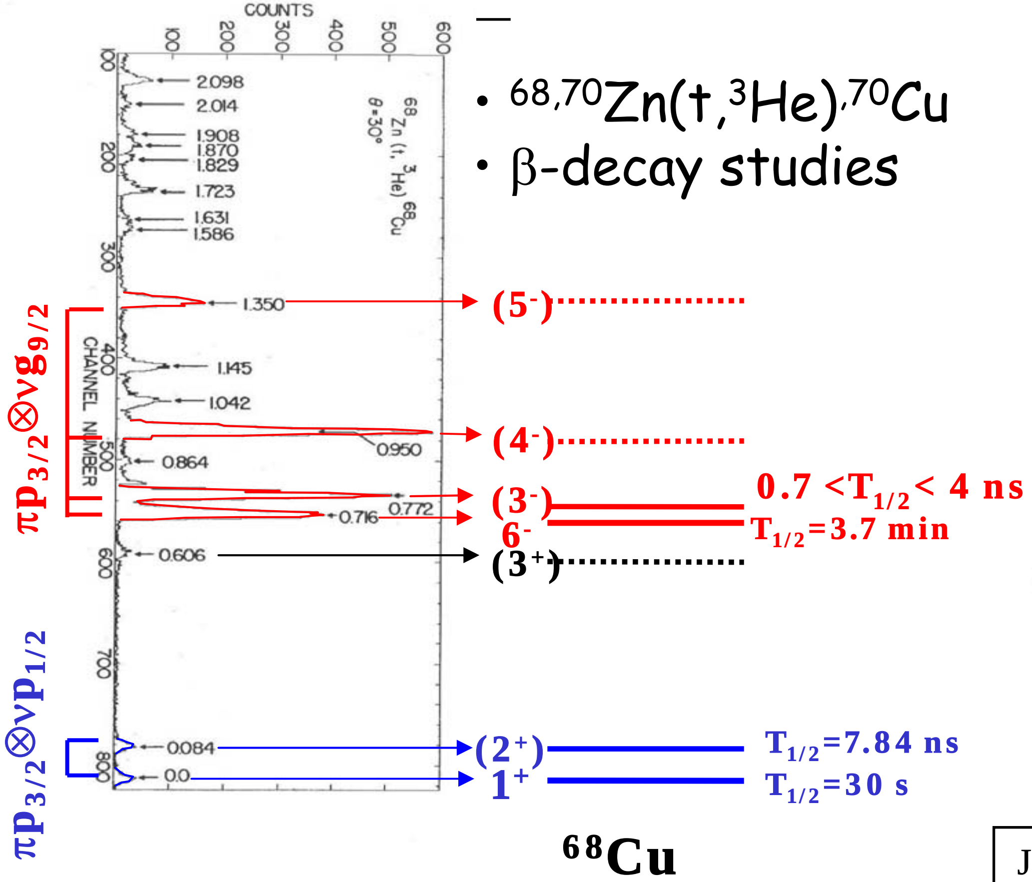
➢ Neutron-rich even-A Cu isotopes - $^{68,70}Cu$ -

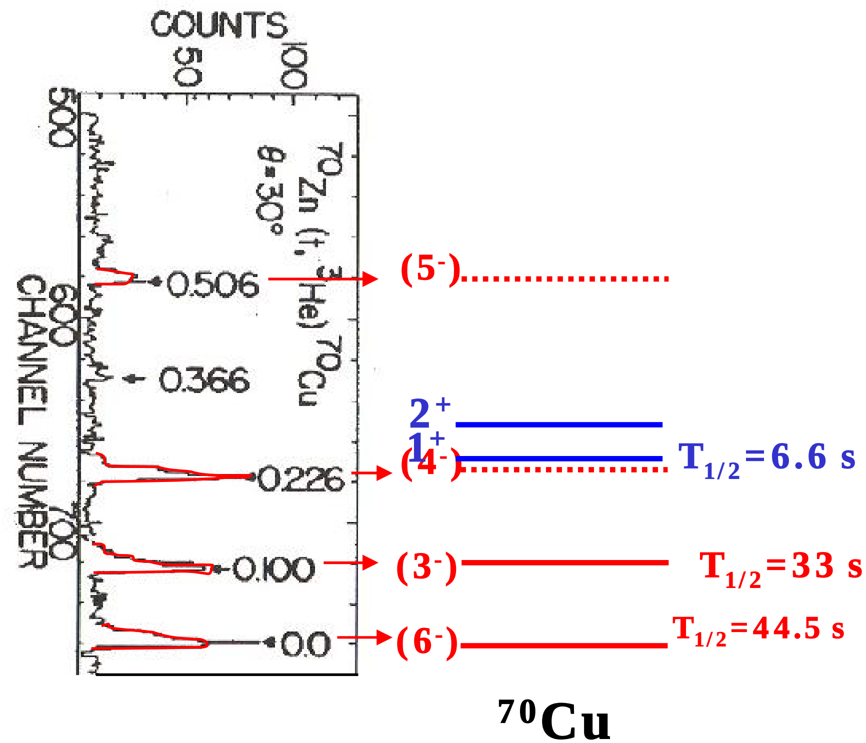


$\pi p_{3/2} \otimes \nu p_{1/2}$ ($J^{\pi}=1^{+}, 2^{+}$)

$\pi p_{3/2} \otimes \nu g_{9/2}$ ($J^{\pi}=3^{-}, 4^{-}, 5^{-}, 6^{-}$) ⇨ **Isomers**

- $^{68,70}Zn(t,{}^{3}He)^{,70}Cu$
- β-decay studies





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