Gamma-Spectroscopy into the Neutron-rich A~90 Region

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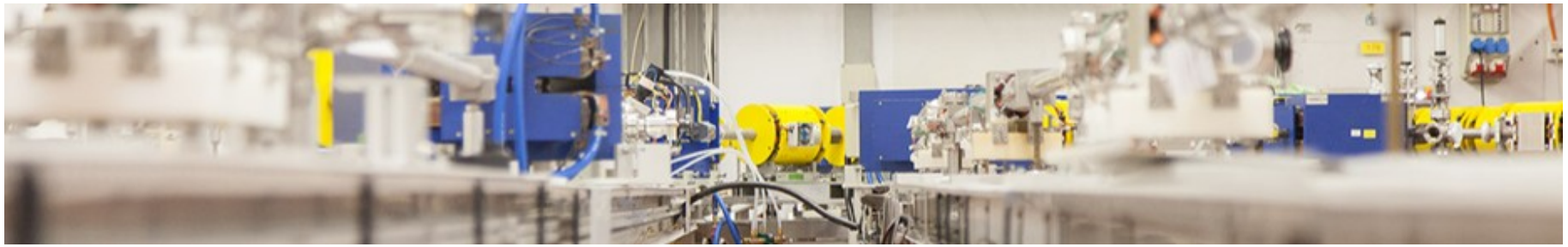
Volker Werner

Institut für Kernphysik, TU Darmstadt



MaRS
Matter and Radiation Science

HIC for FAIR
Helmholtz International Center

Bundesministerium für Bildung und Forschung
BMBF

Overview

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- **Introduction**
  - Basic shape evolution
  - Energy systematics A~90 region
- **Isomer Decay Spectroscopy**
  - New data on ^{92,94}Se
  - Complementary to in-beam SEASTAR
- **In-Beam Spectroscopy**
  - Ge Isotopes up to N=56
  - Discussion on triaxiality

$E(2_1^+)$ Systematics

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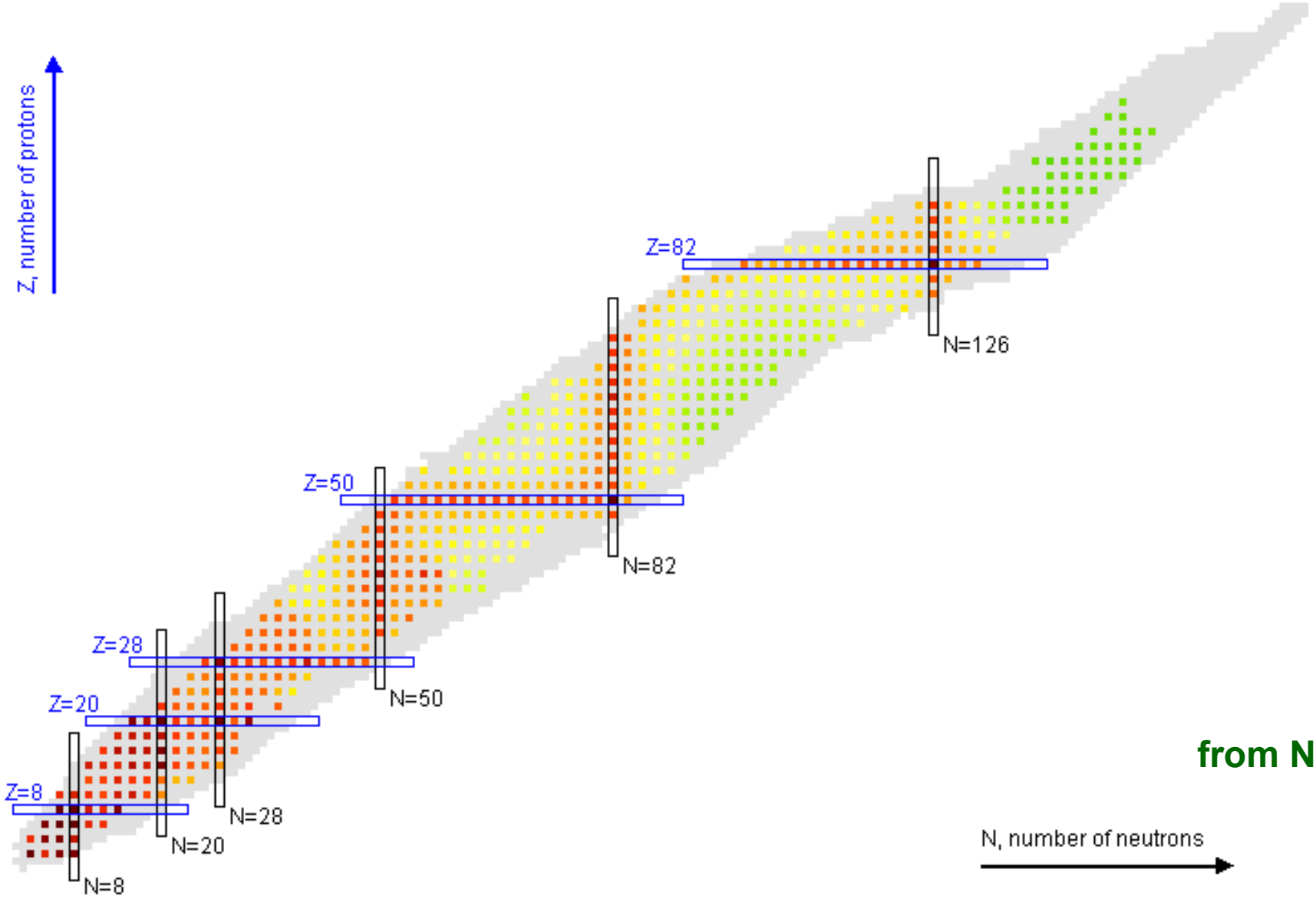

from NNDC

$E(2_1^+)$ Systematics

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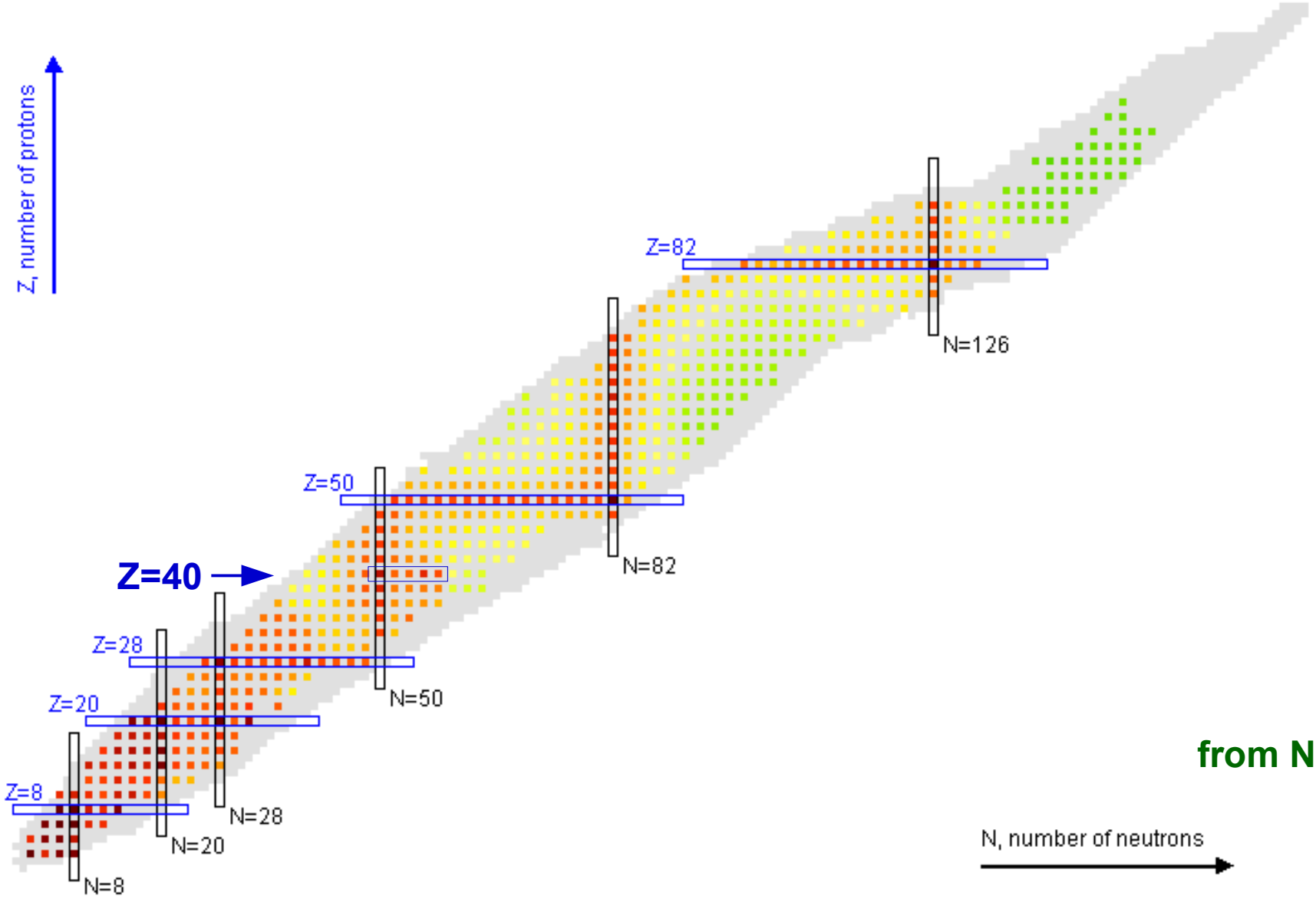

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$E(2_1^+)$ Systematics

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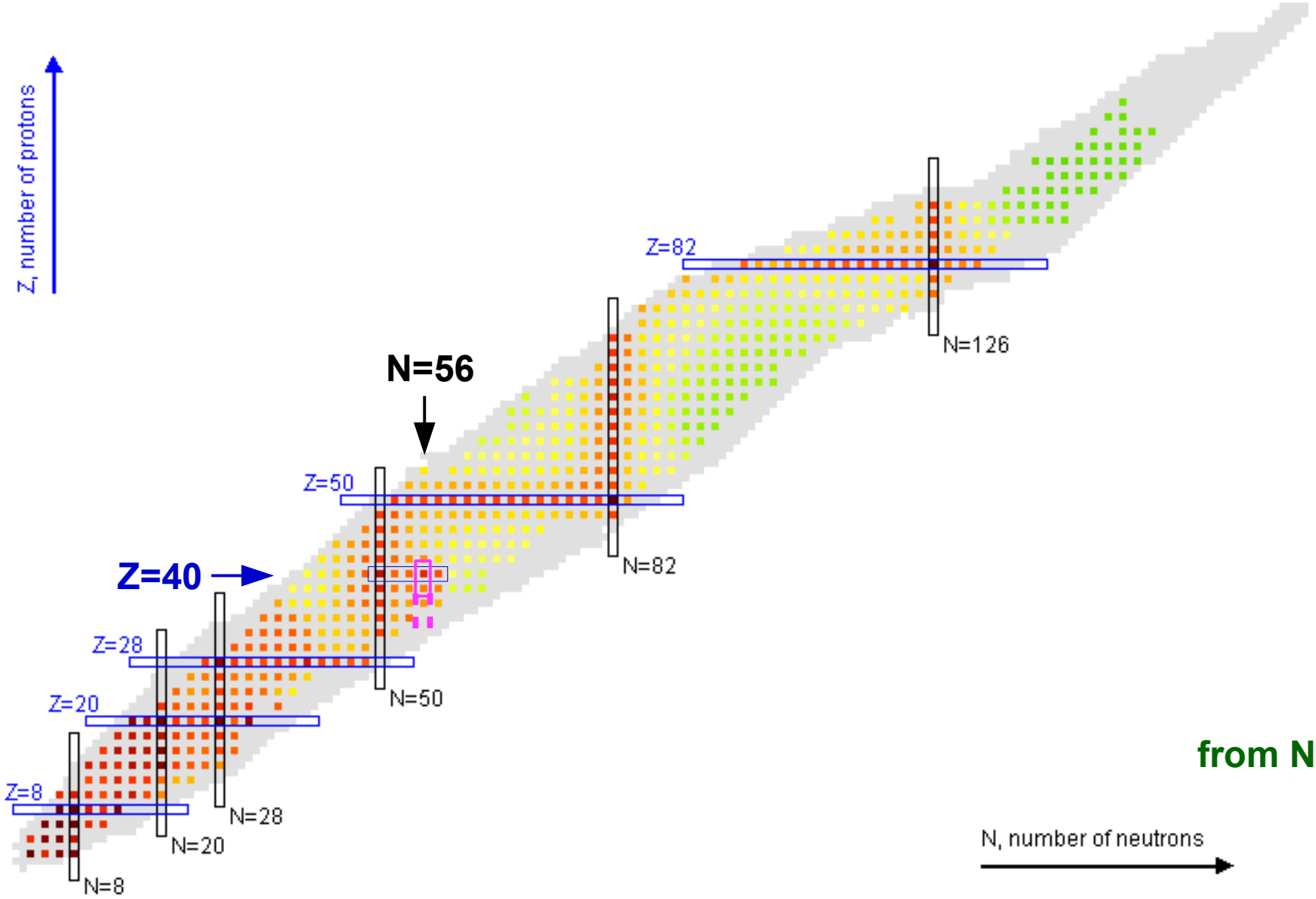

from NNDC

$E(2_1^+)$ Systematics

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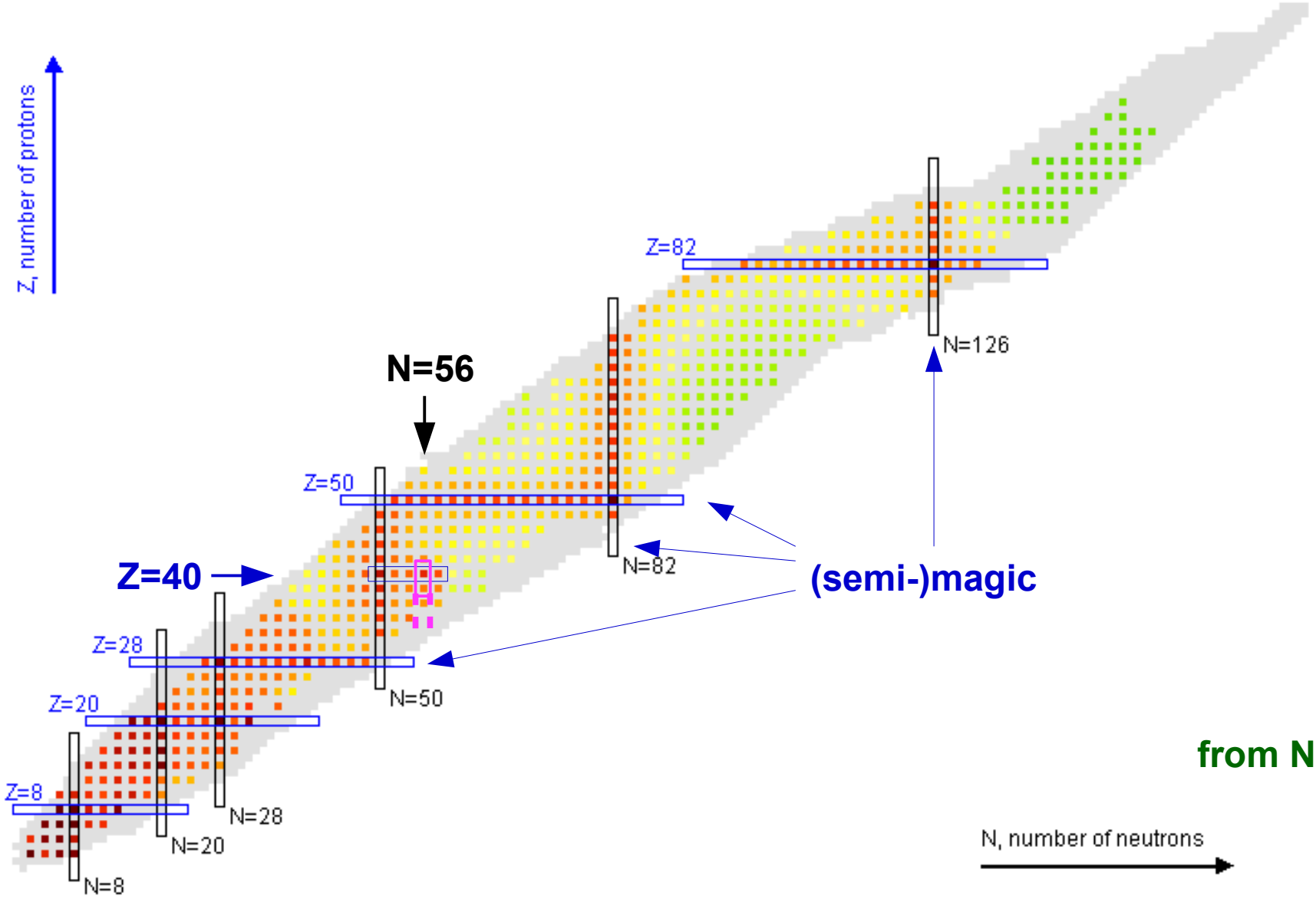

from NNDC

$E(2_1^+)$ Systematics

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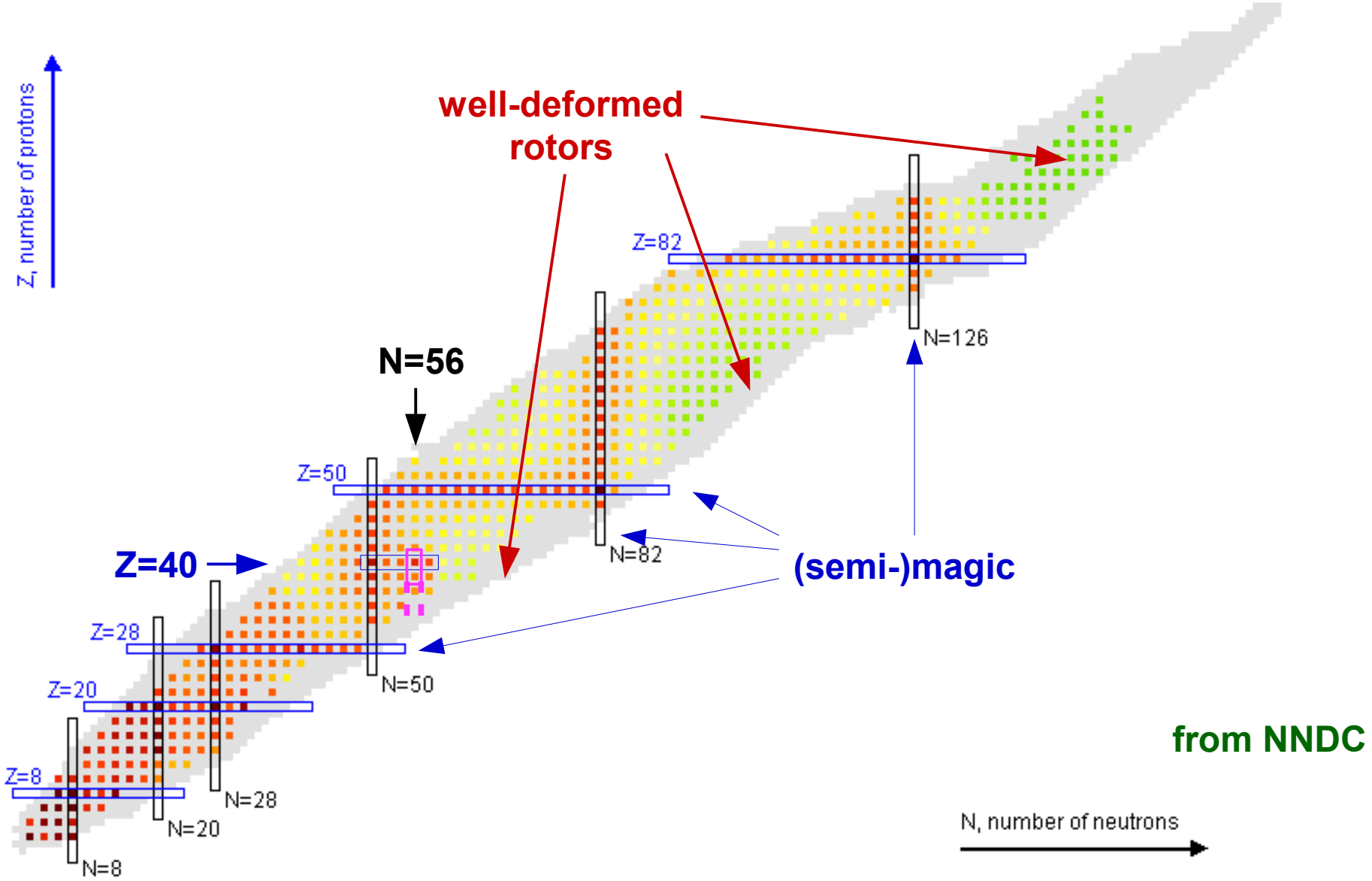

$E(2_1^+)$ Systematics

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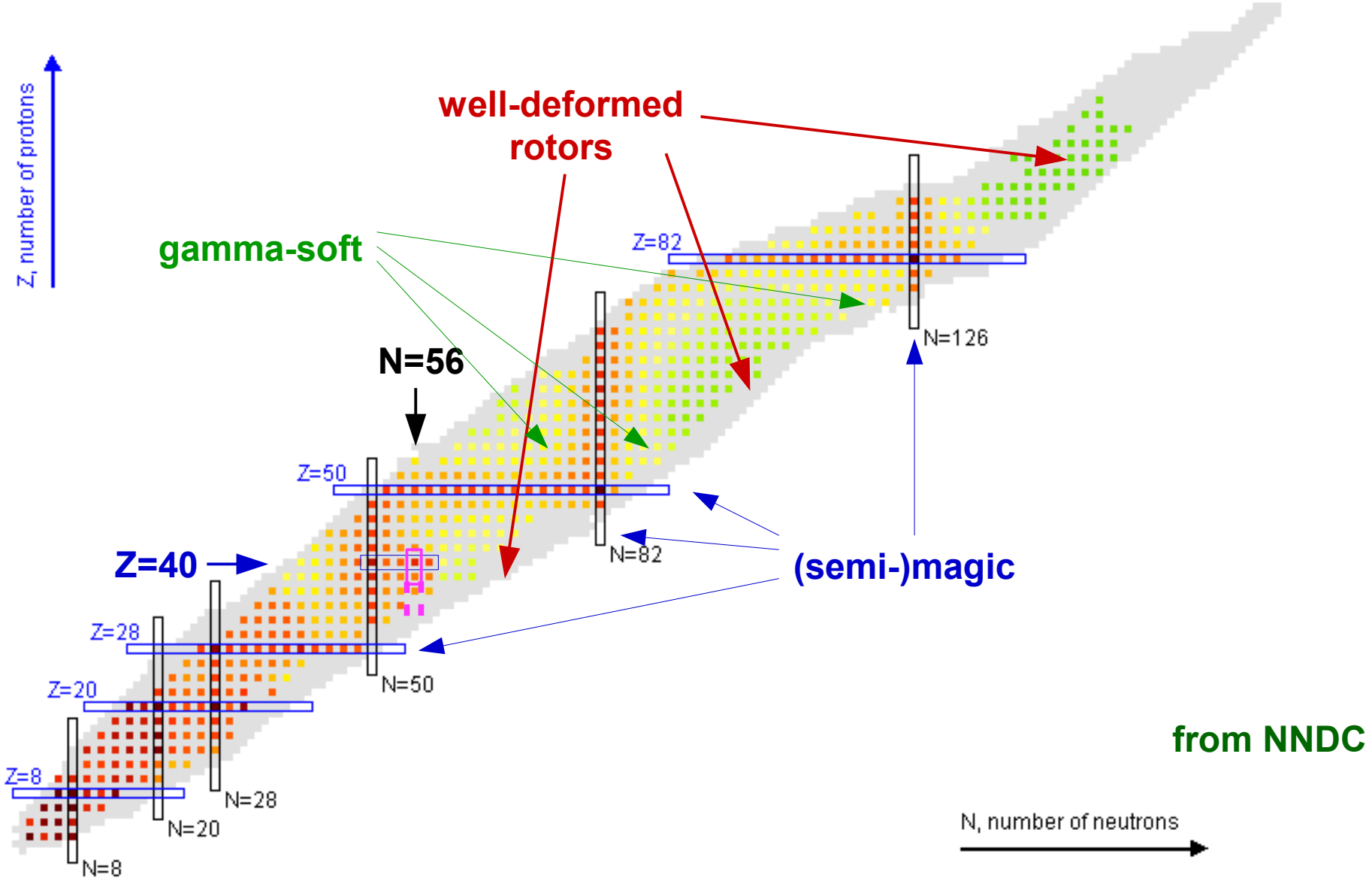

from NNDC

$E(2_1^+)$ Systematics

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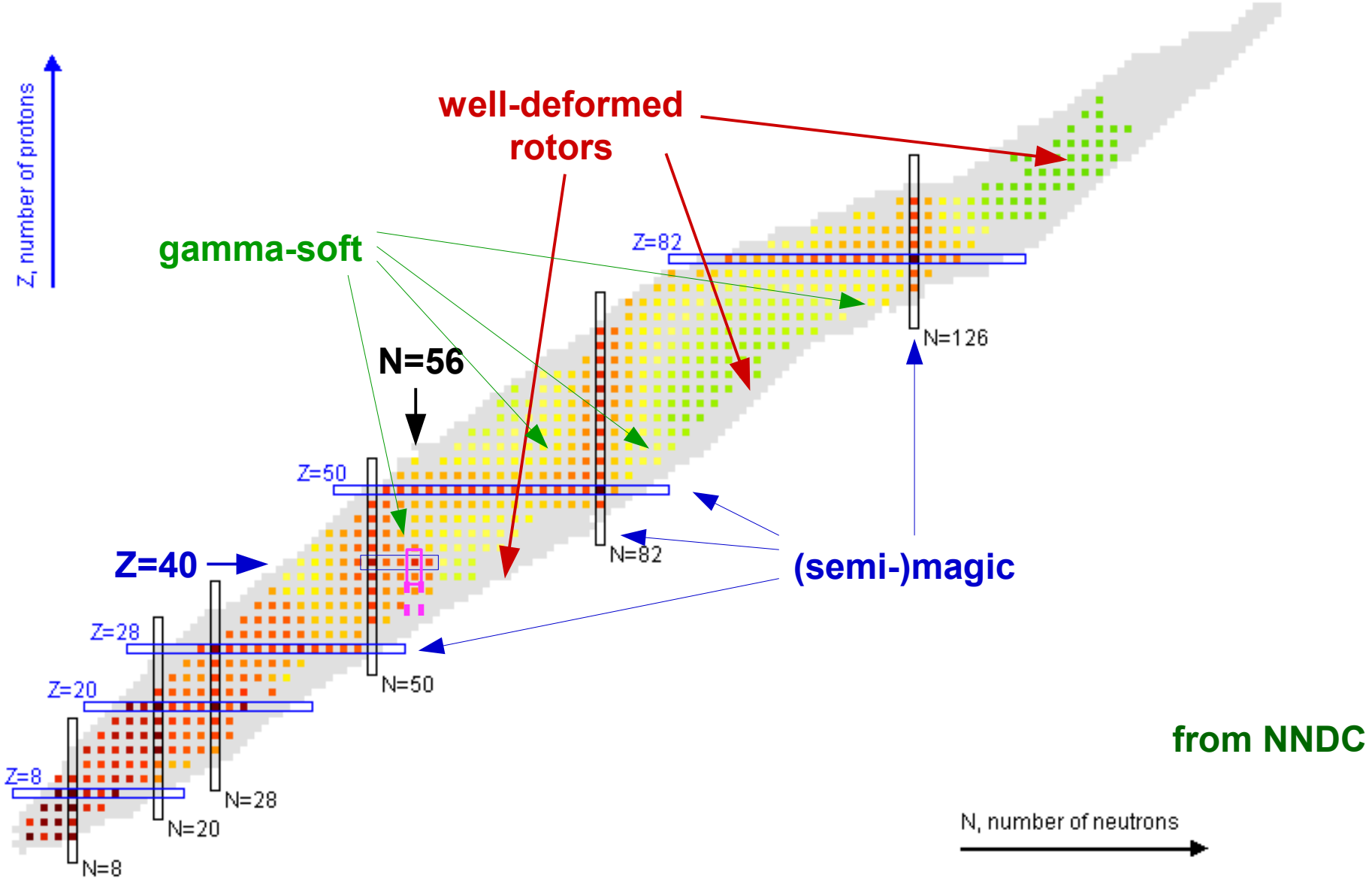

$E(2_1^+)$ Systematics

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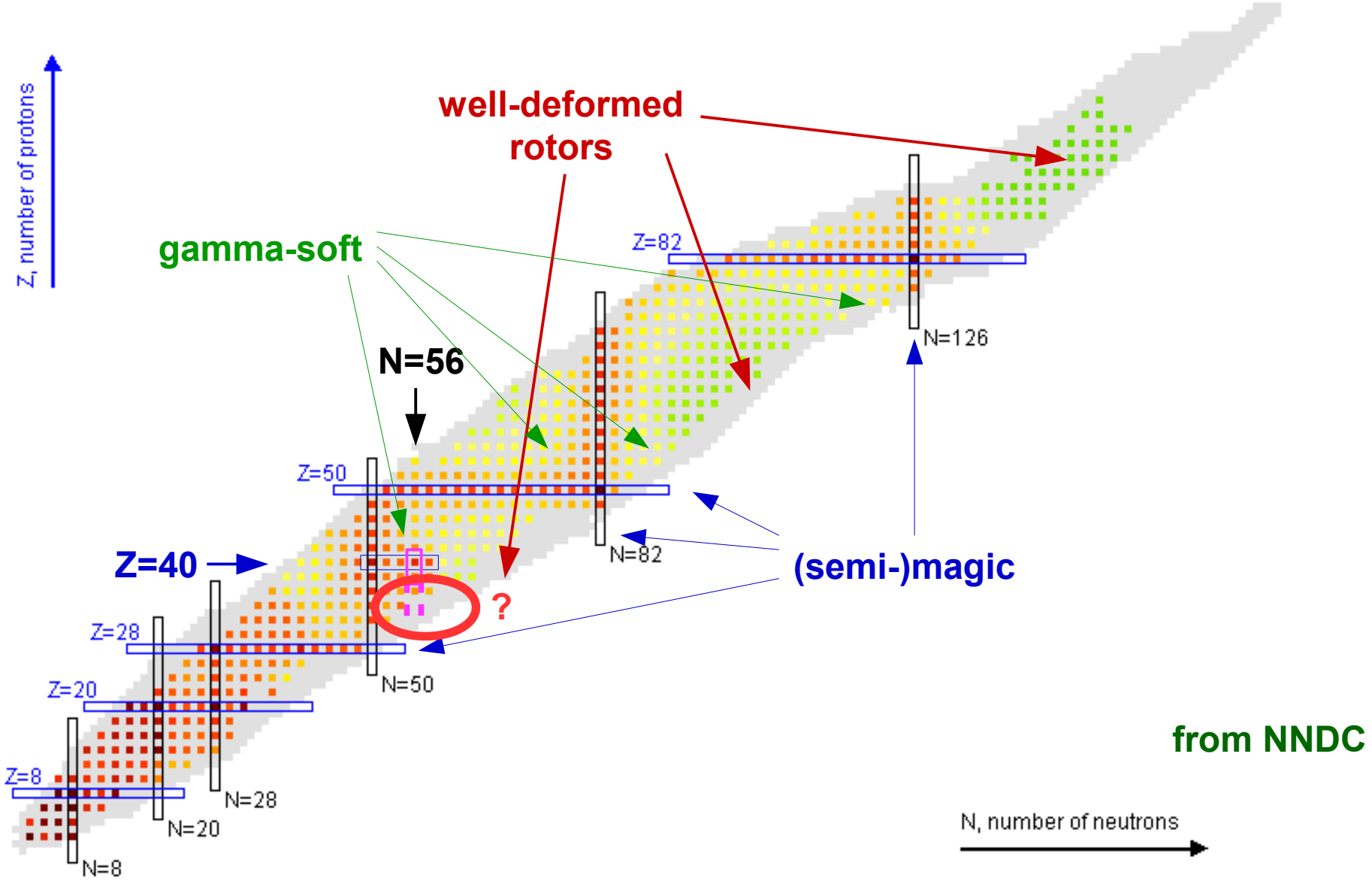
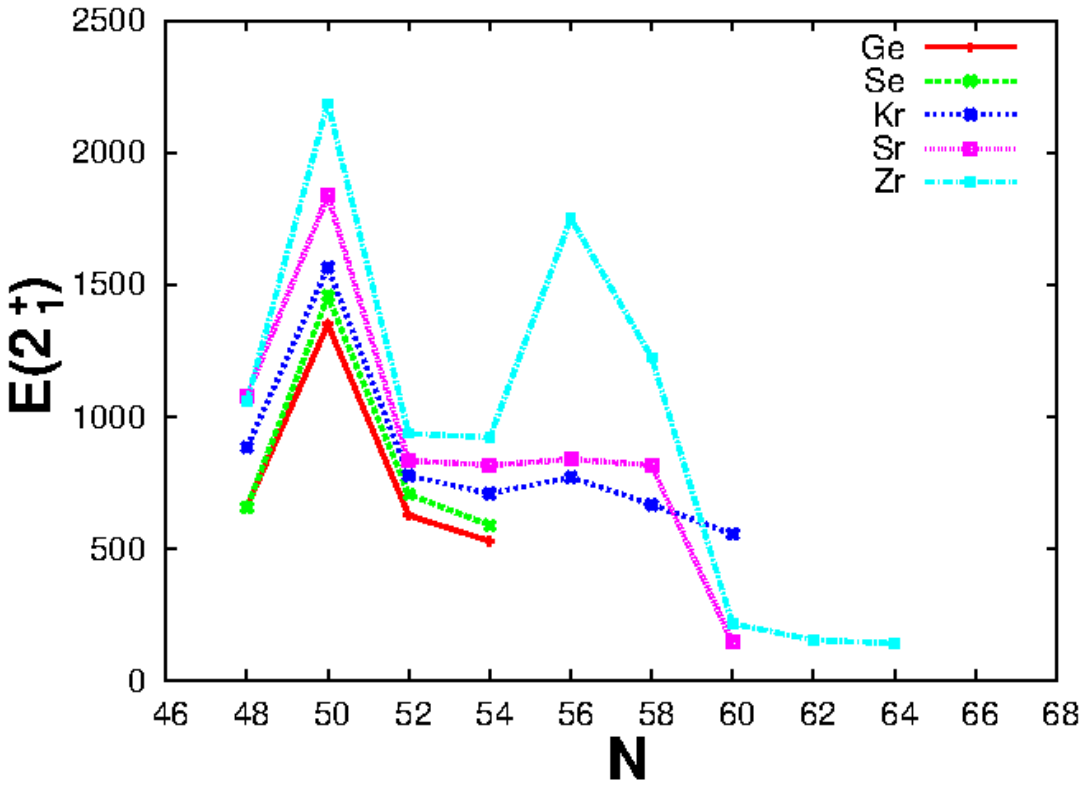


from NNDC

$E(2_1^+)$ Systematics at N=56-60



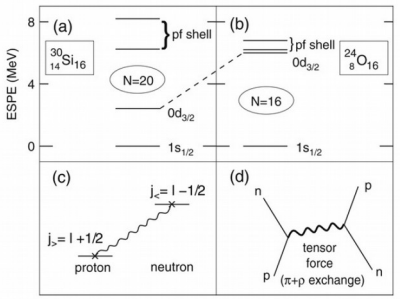
Zr: clear peak at N=56,*58* in Zr

Sr: „peak" N=56, drop *past 58*

Kr: small peak at 56, smooth after

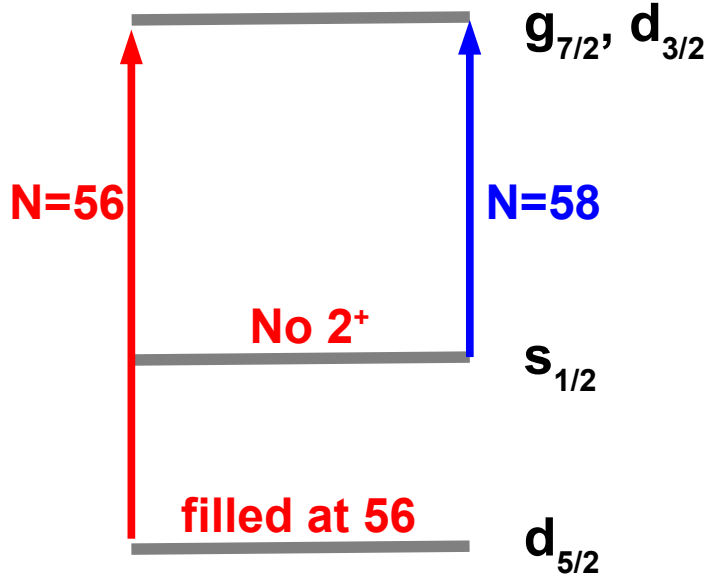
Se: ???

Ge: ???



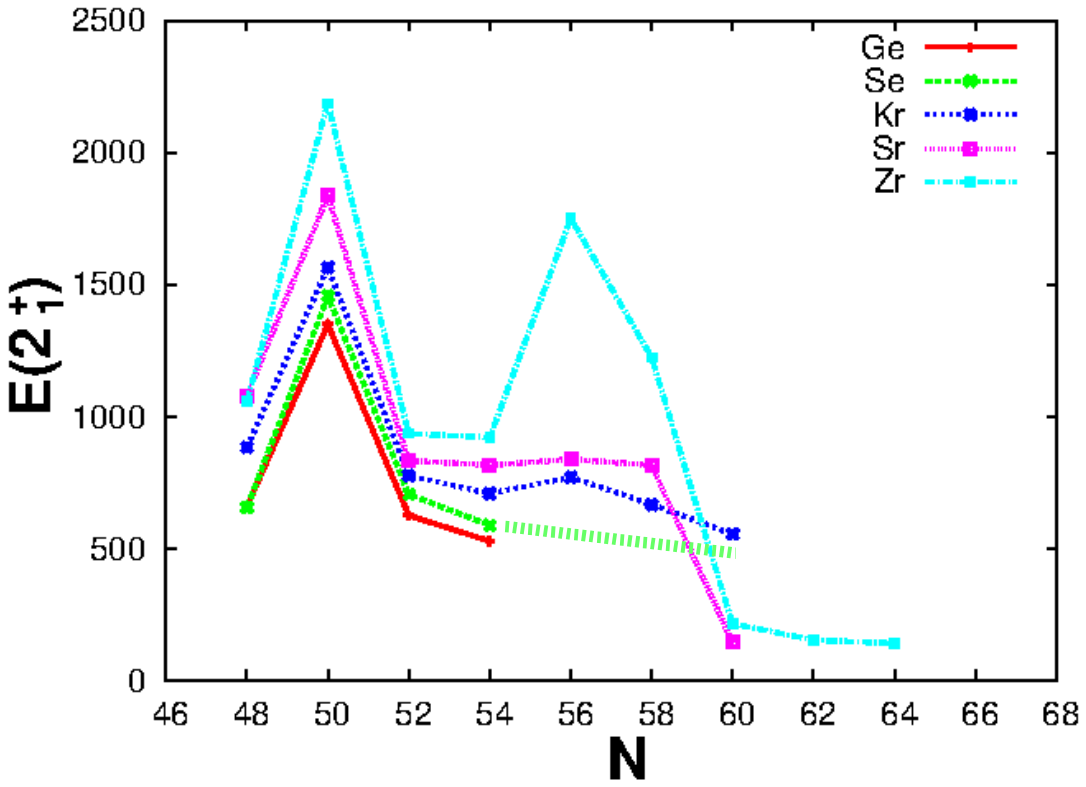
Weak coupling (p-n) was shown for Z~40, N<56 in prev. works

Assume it here -> $E(2_1^+)$ depends mainly on SPEs

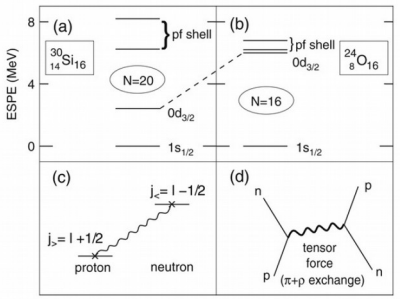


For Z>40 $\nu g_{7/2}$ fills and is lowered because of $\pi g_{9/2}$ -> gaps disappear

$E(2_1^+)$ Systematics at N=56-60



Zr: clear peak at N=56,*58* in Zr
Sr: „peak" N=56, drop *past 58*
Kr: small peak at 56, smooth after
Se: ??? slow drop → S. Chen
Ge: ???



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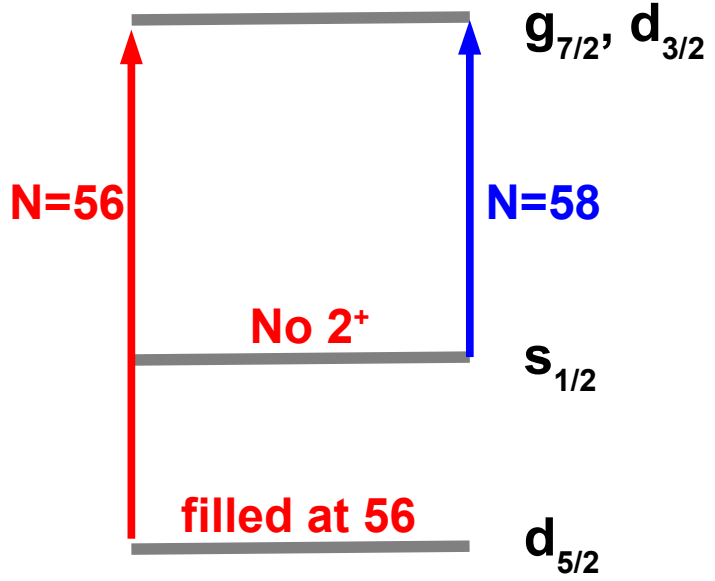

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RIKEN-RIBF Overview

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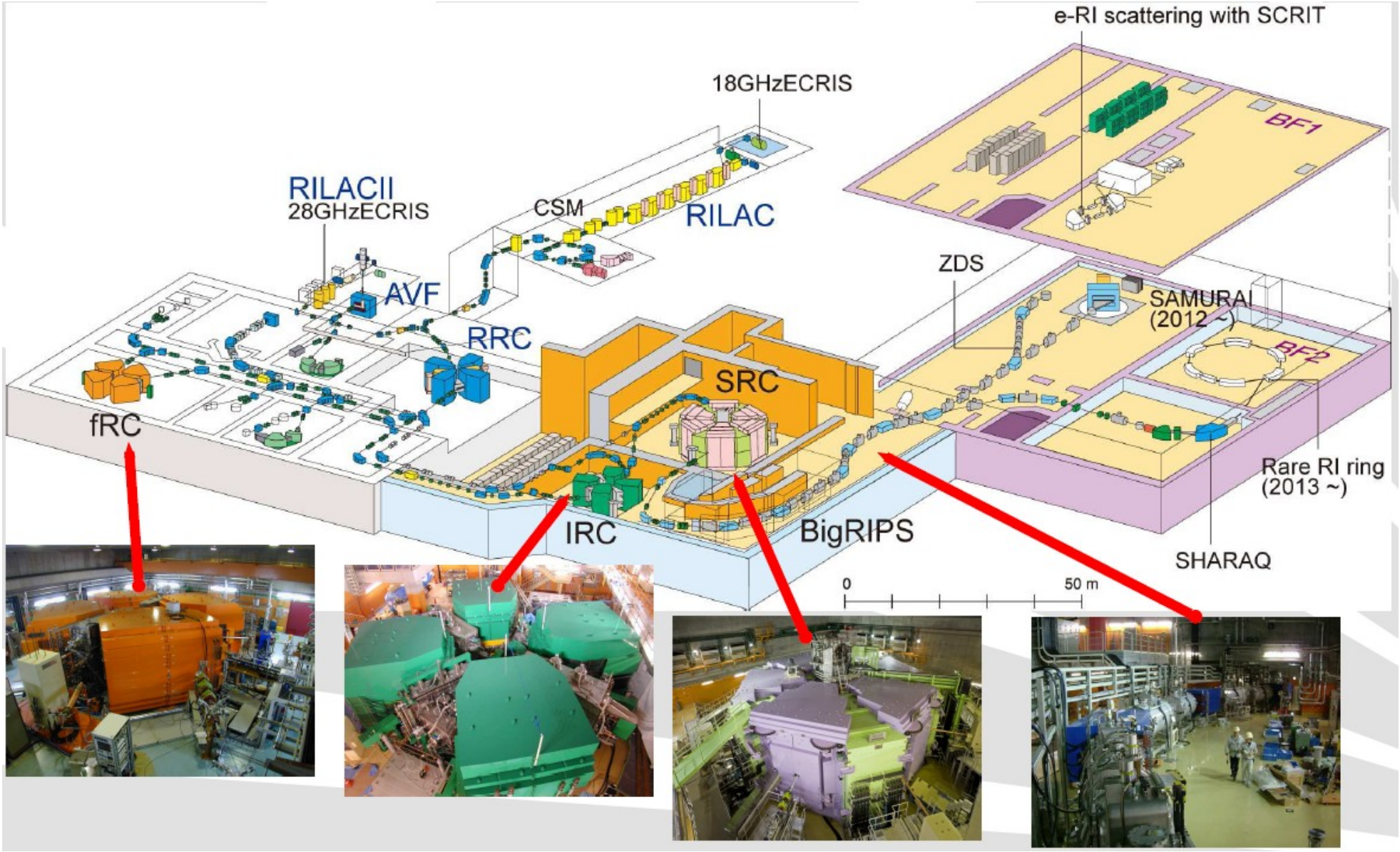

RIKEN-RIBF SEASTAR Setup

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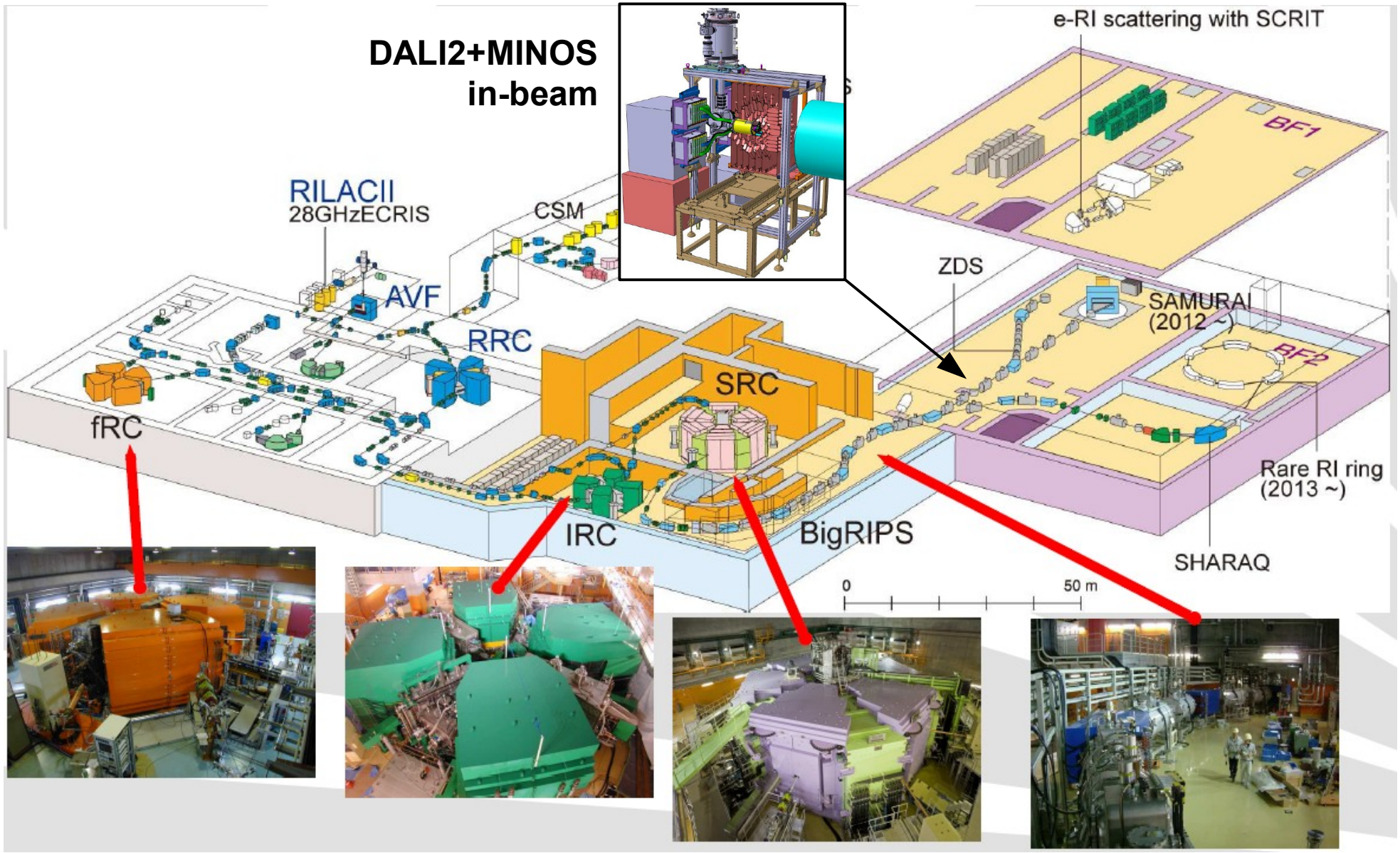

RIKEN-RIBF SEASTAR+EURICA

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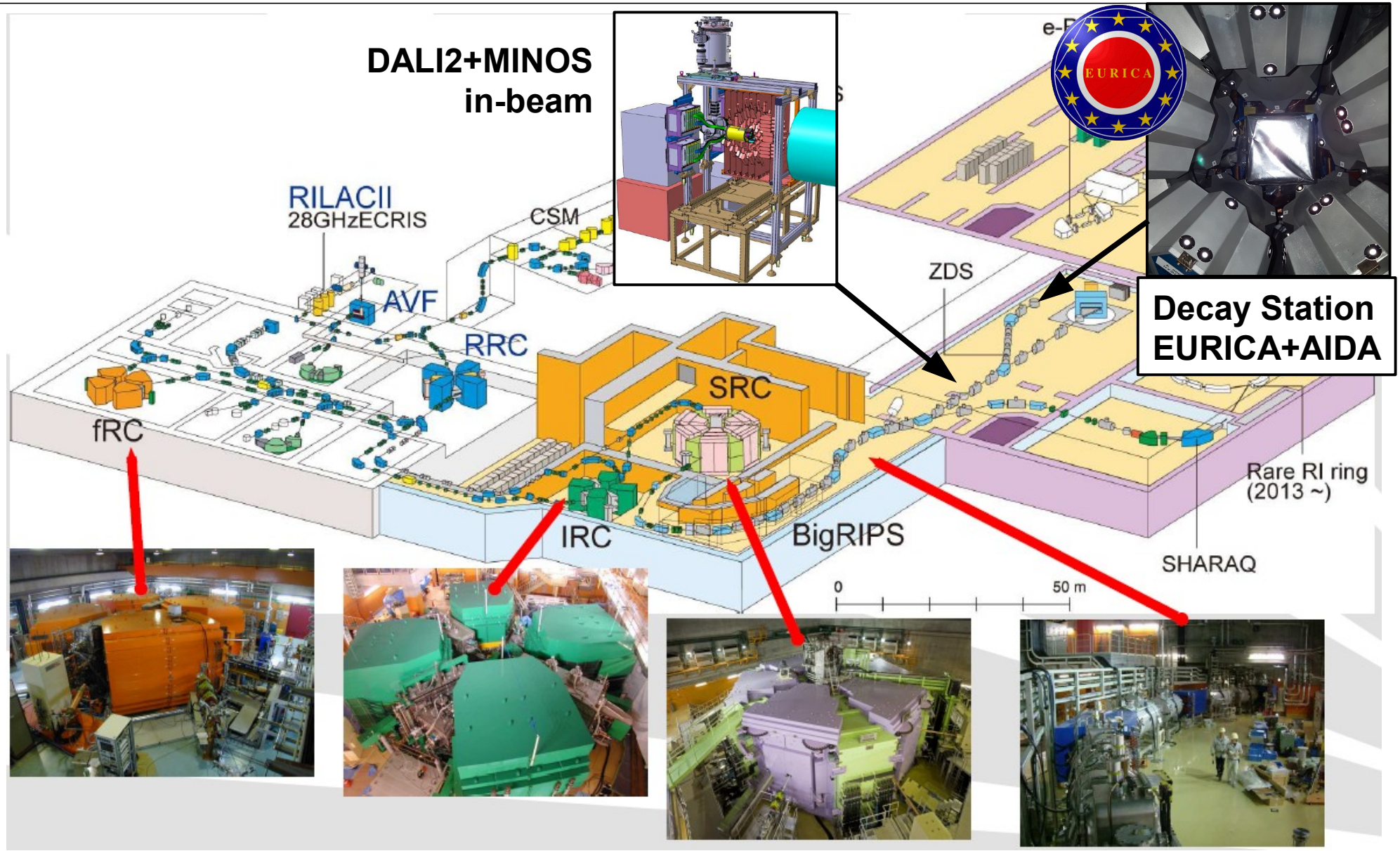

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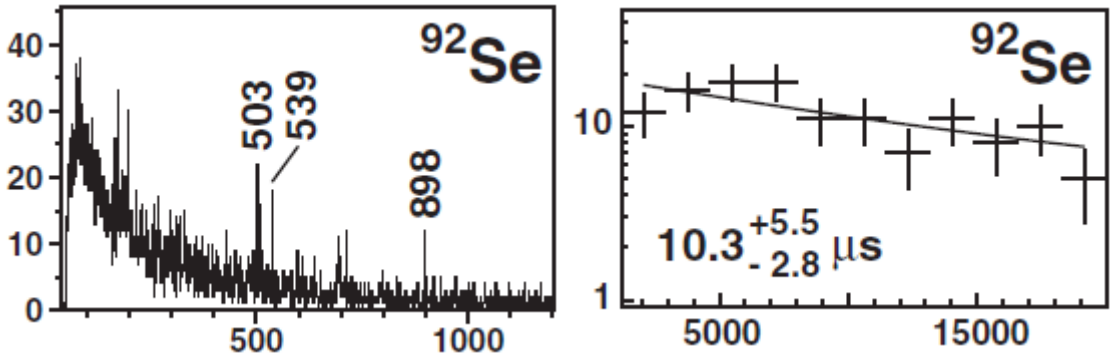
Se Isotopes

^{92}Se – EURICA Result

TECHNISCHE UNIVERSITÄT DARMSTADT

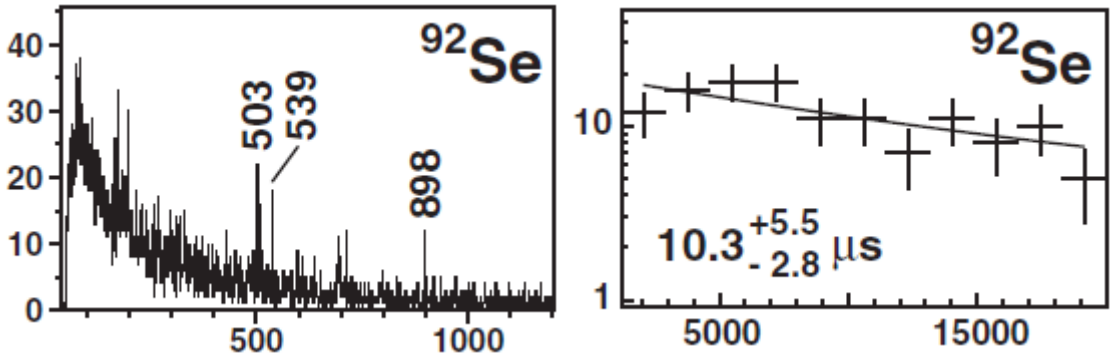
So far known from RIBF: **Kameda, PRC86, 054319 ('12)**

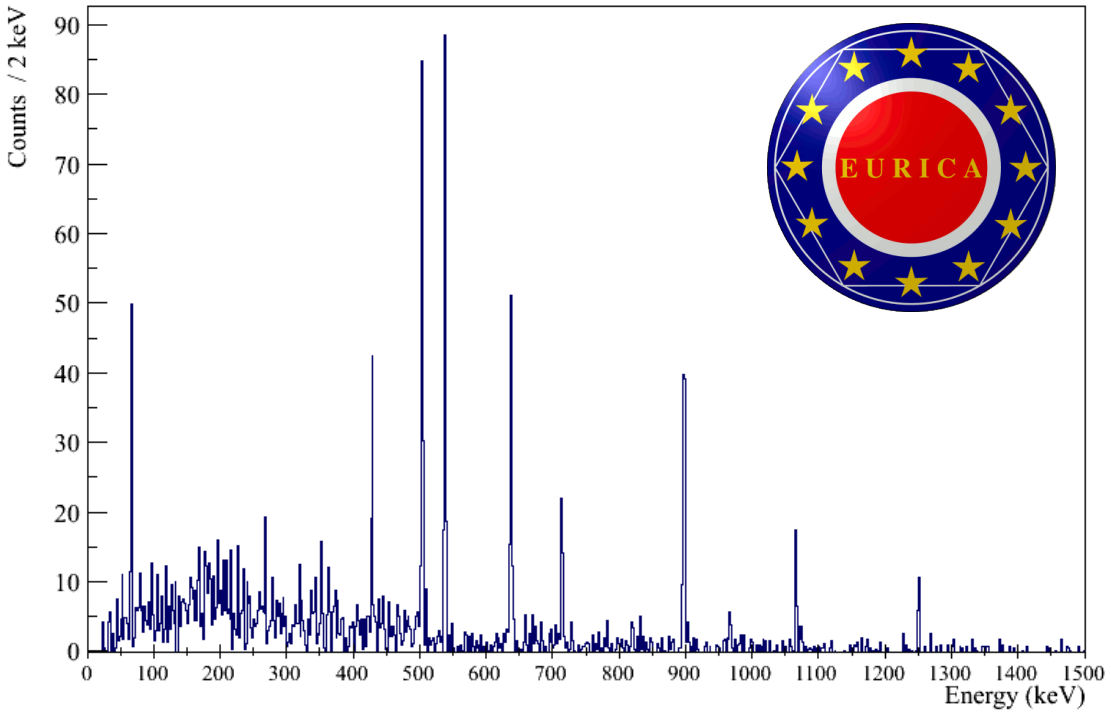


^{92}Se – EURICA Result

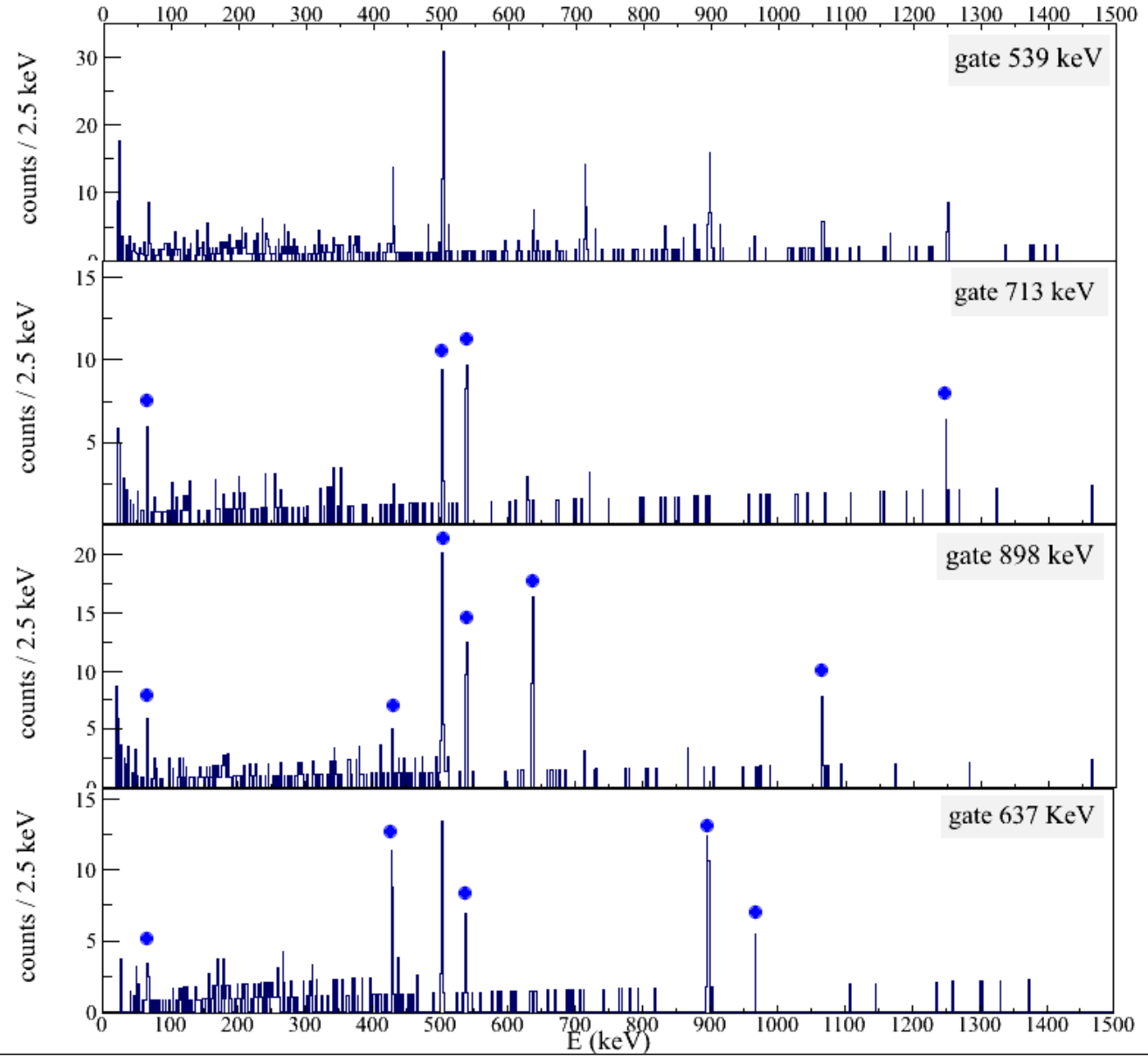
TECHNISCHE UNIVERSITÄT DARMSTADT

So far known from RIBF: Kameda, PRC86, 054319 ('12)





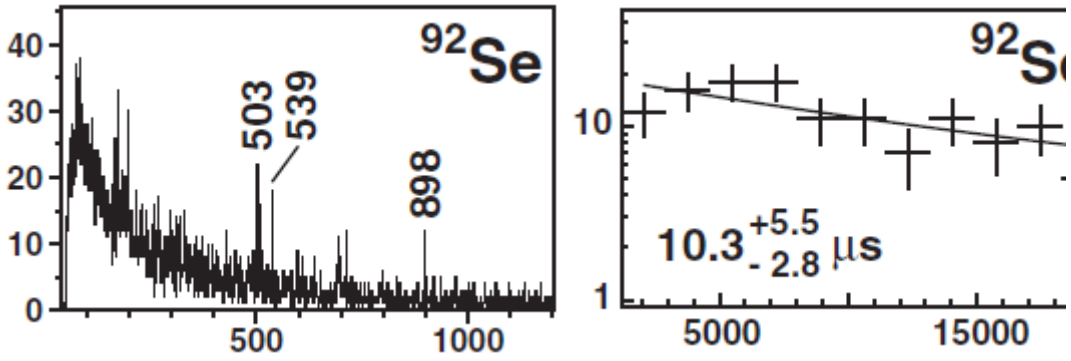
^{92}Se – EURICA Coincidences

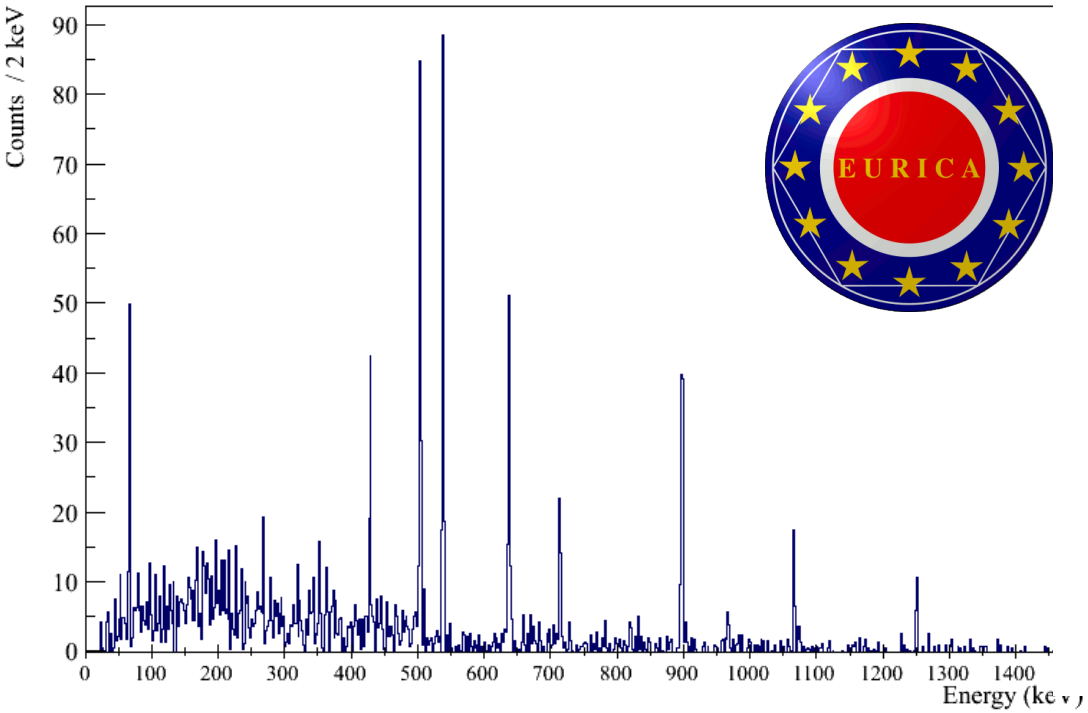


^{92}Se – EURICA Result

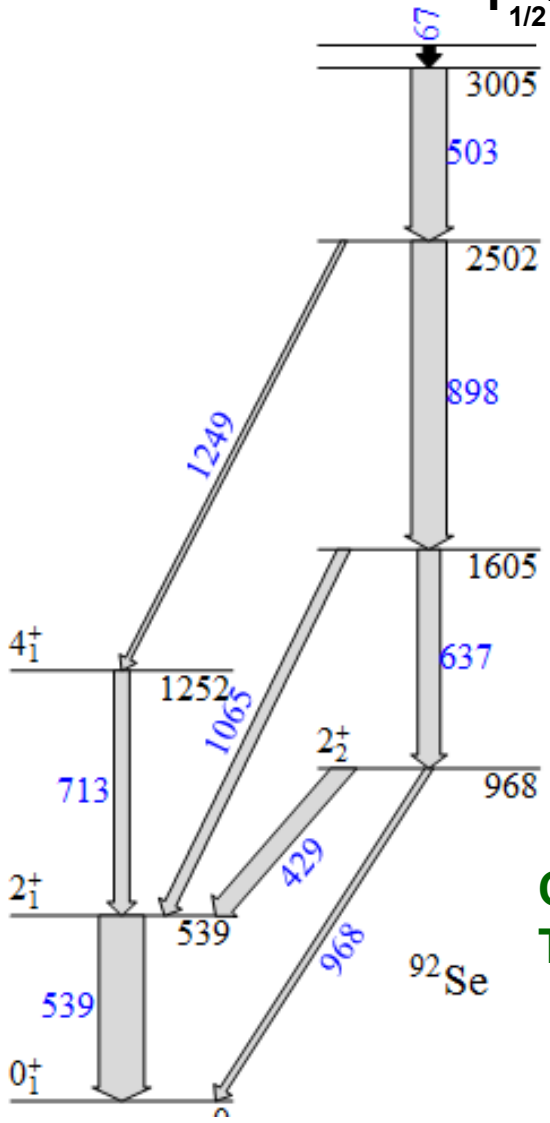
TECHNISCHE UNIVERSITÄT DARMSTADT

So far known from RIBF: Kameda, PRC86, 054319





$T_{1/2}$=15.0(1.3) µs



C. Lizarazo, TU Darmstadt

^{92}Se – EURICA/SEASTAR Result

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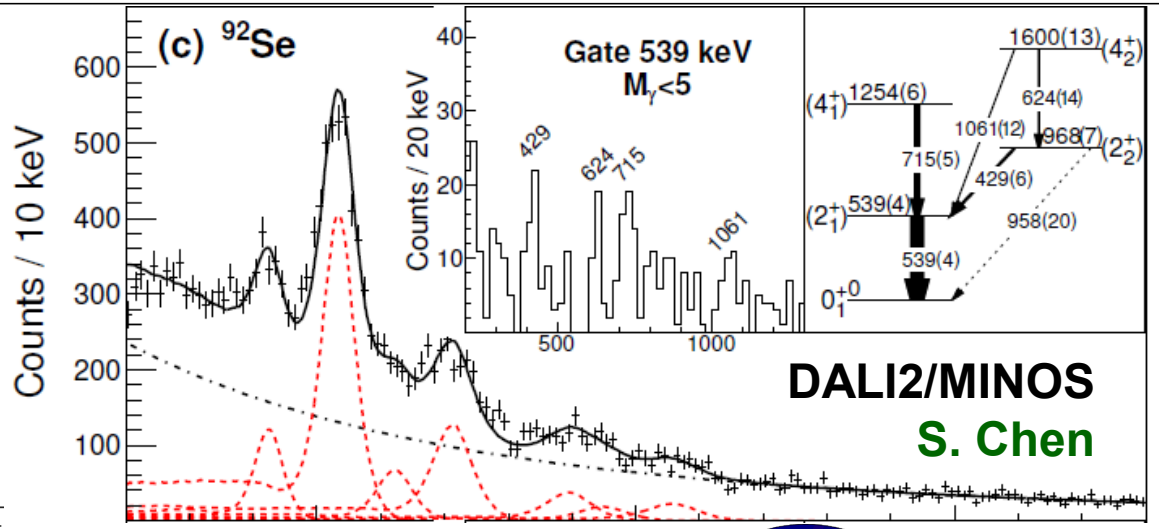
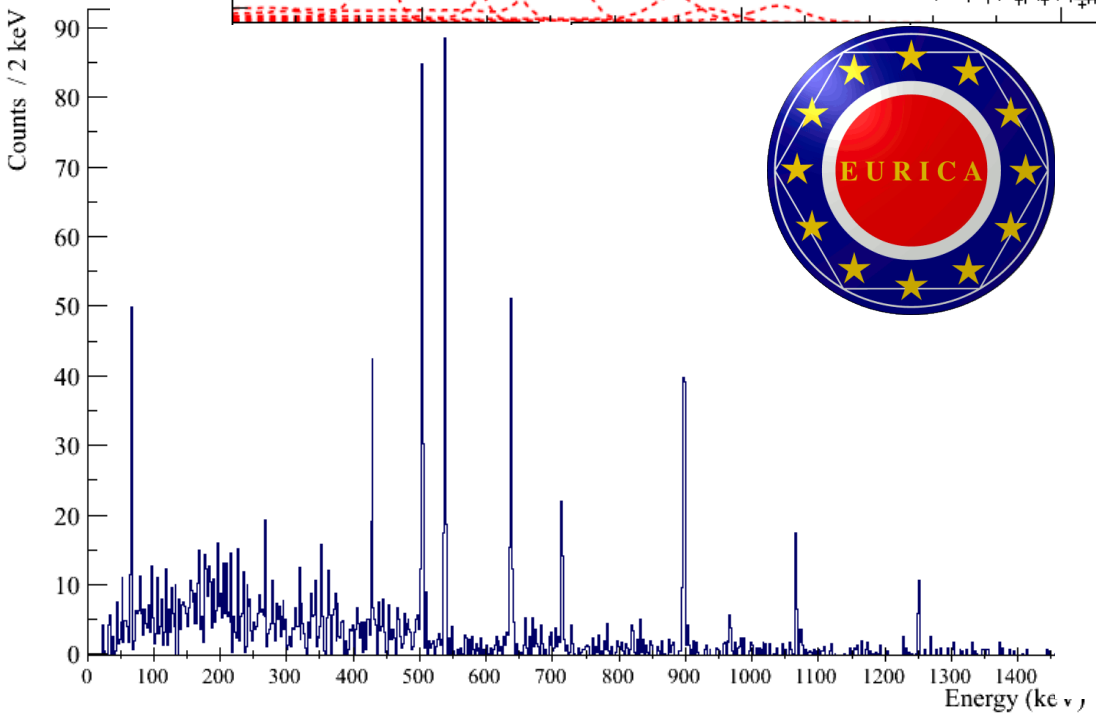
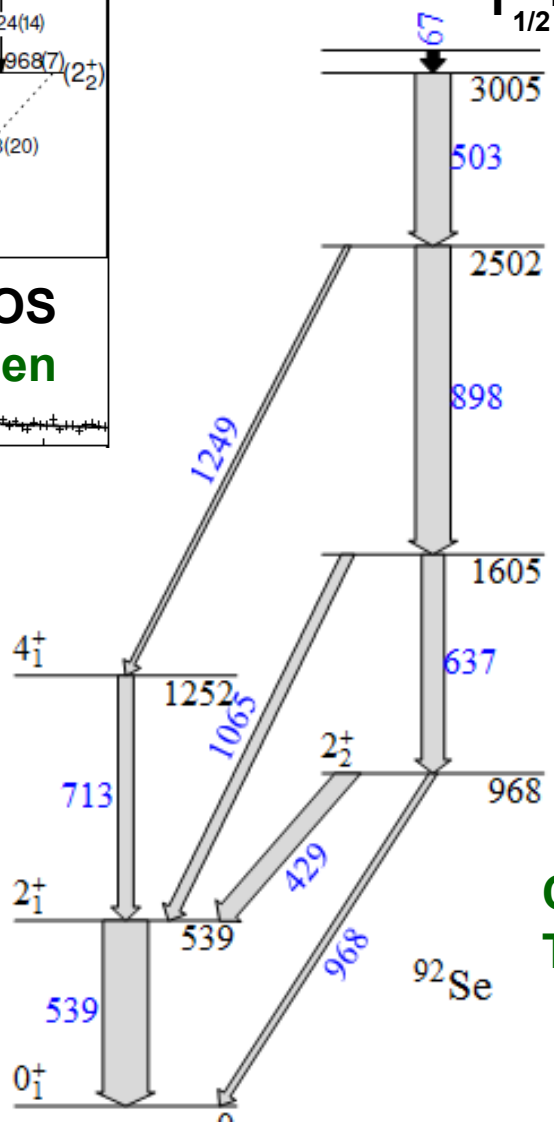




EURICA

$T_{1/2}$=15.0(1.3) µs



C. Lizarazo, TU Darmstadt

^{94}Se in the works

Ge Isotopes

Particle ID / Reaction Channels

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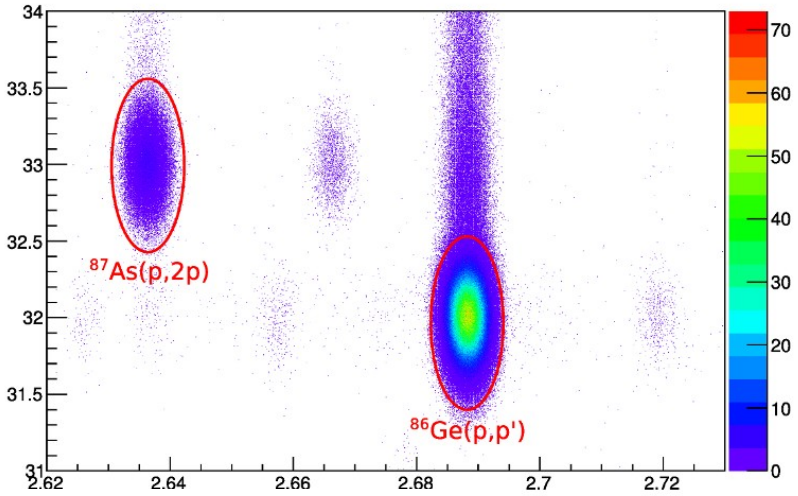
Gated on Reaction Product ^{8X}Ge

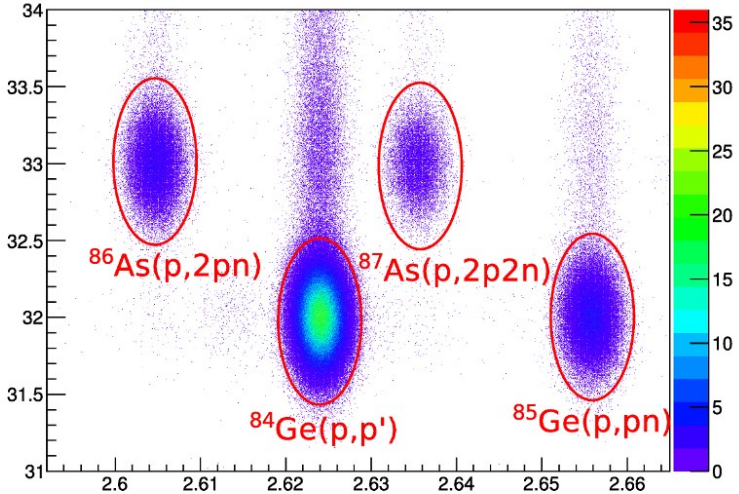
^{86}Ge



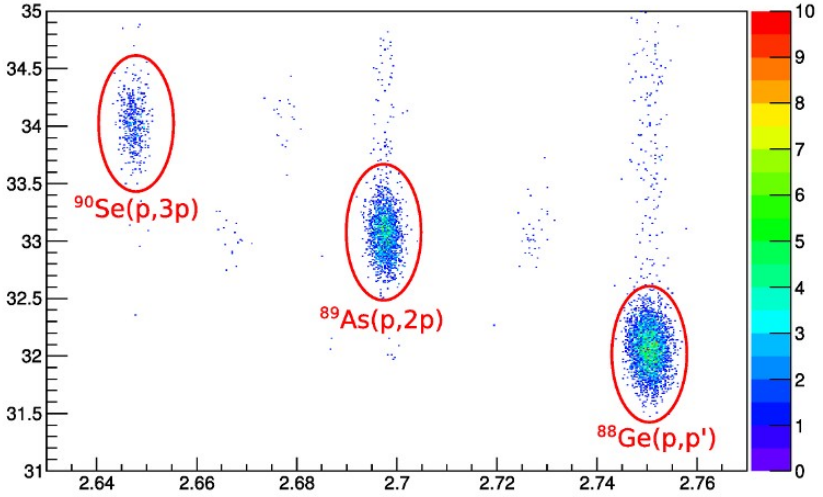
Through MINOS TPC
Gated out channels with outgoing high-E proton(s)

→ vertex reconstruction
→ good Doppler correction

^{84}Ge



^{88}Ge



Results ^{84}Ge

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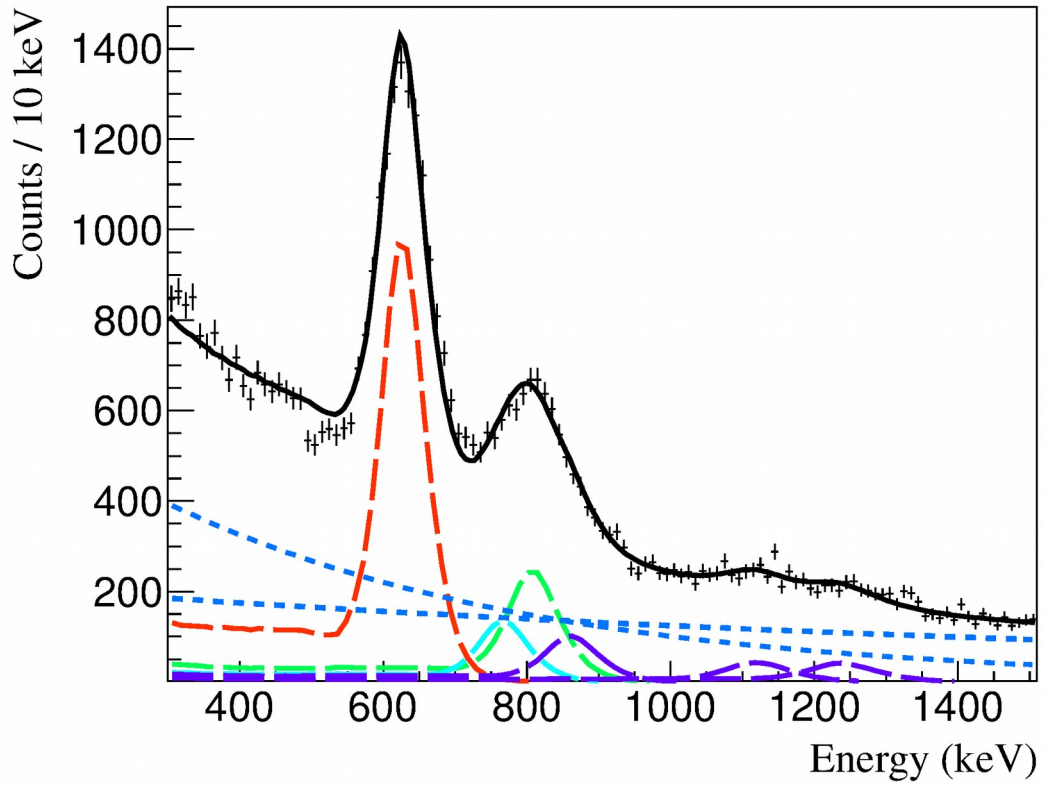
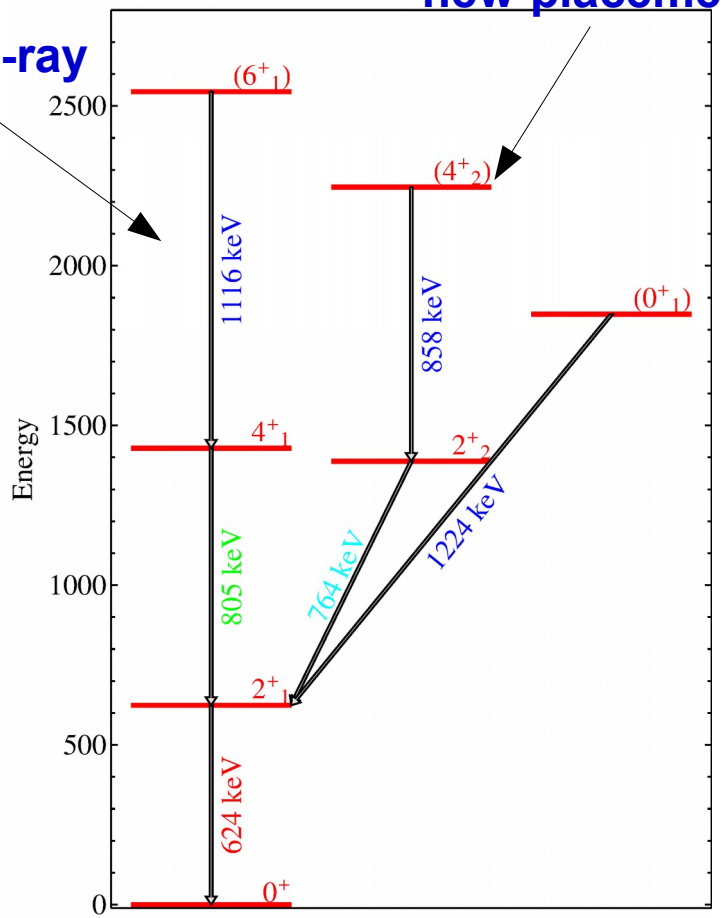
^{85}Ge (p,pn) ^{84}Ge



new placement

new γ-ray



Test case – much known from β-delayed spectroscopy

A. Korgul, PRC88, 044330 (2013)
K. Kolos, PRC88, 047301 (2013)

M. Lettmann, TU Darmstadt

Results ^{86}Ge

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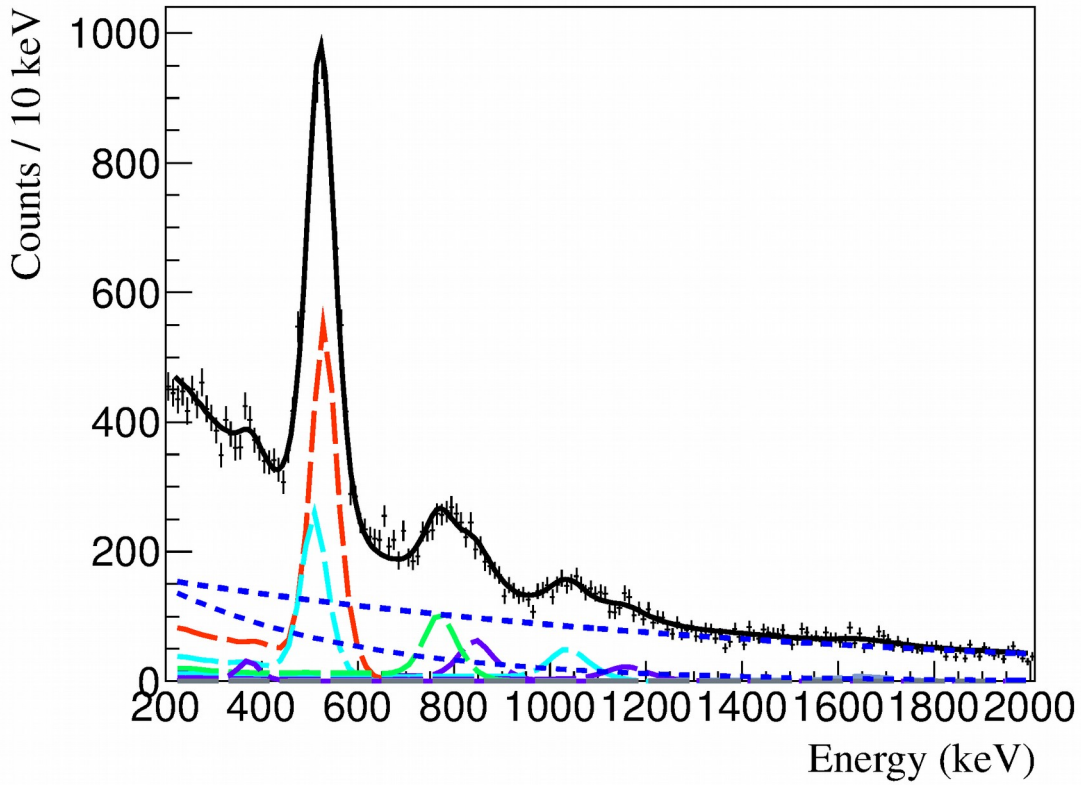
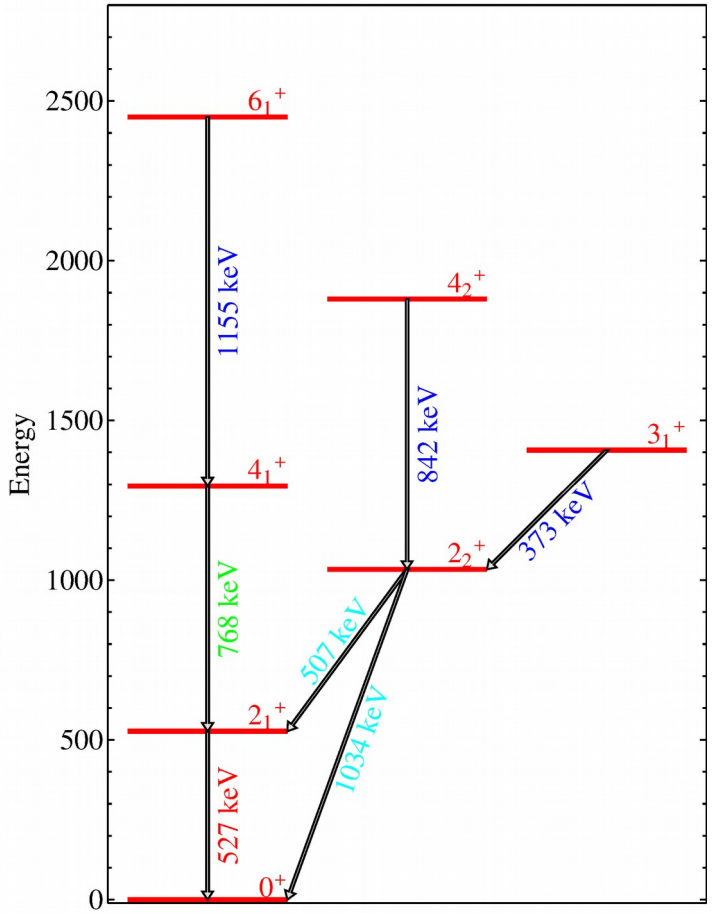
^{87}As (p,2p) ^{86}Ge





So far only 2_1^+ known

K. Miernik, PRL111, 132502 (2013)

M. Lettmann, TU Darmstadt

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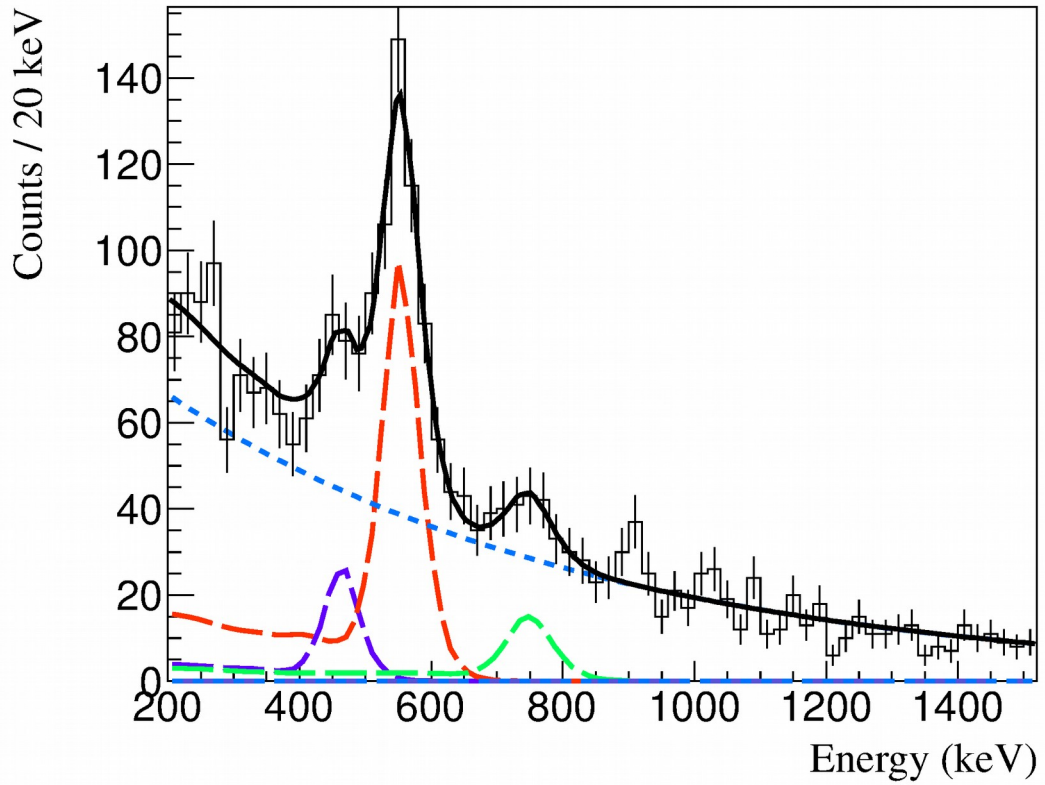
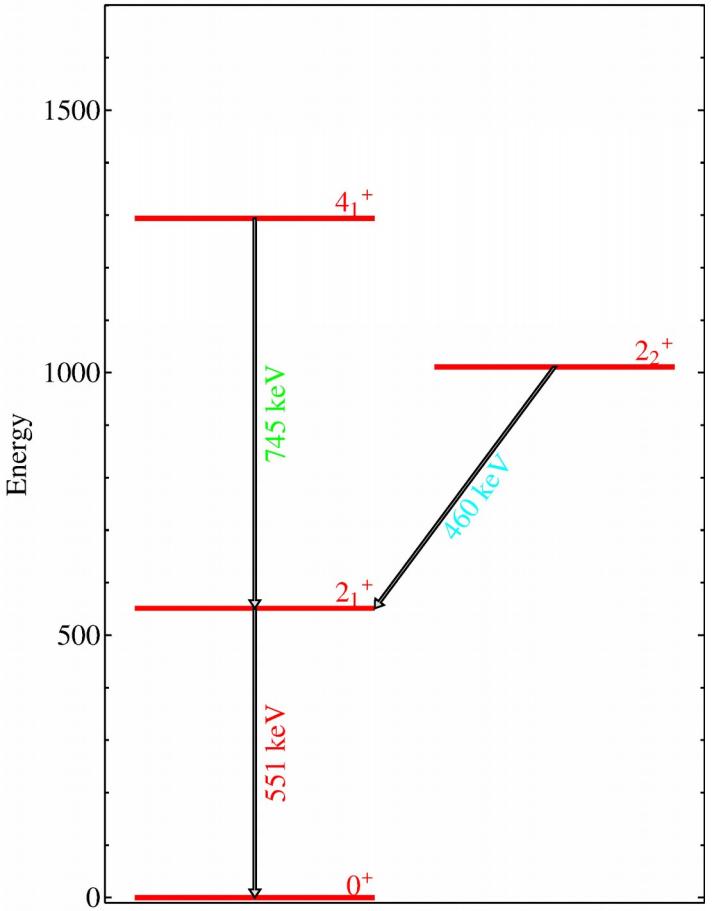
^{89}As (p,2p) ^{88}Ge





All New !

M. Lettmann, TU Darmstadt

$E(2^+)$, $E(4^+)$ & $R_{4/2}$ trends

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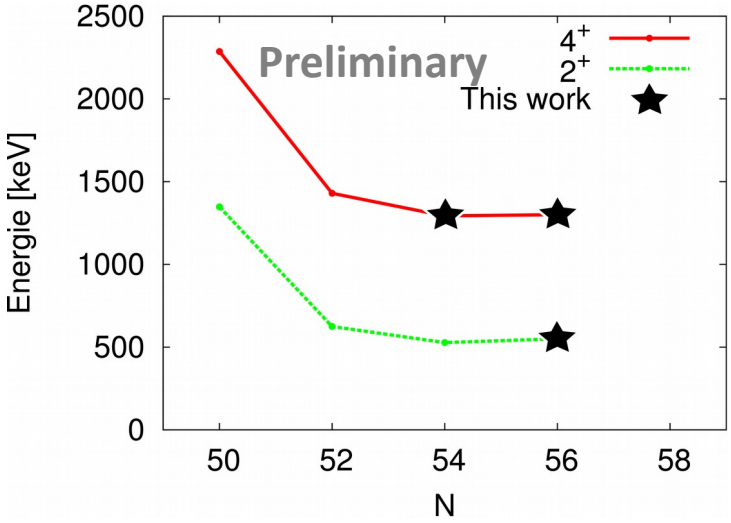
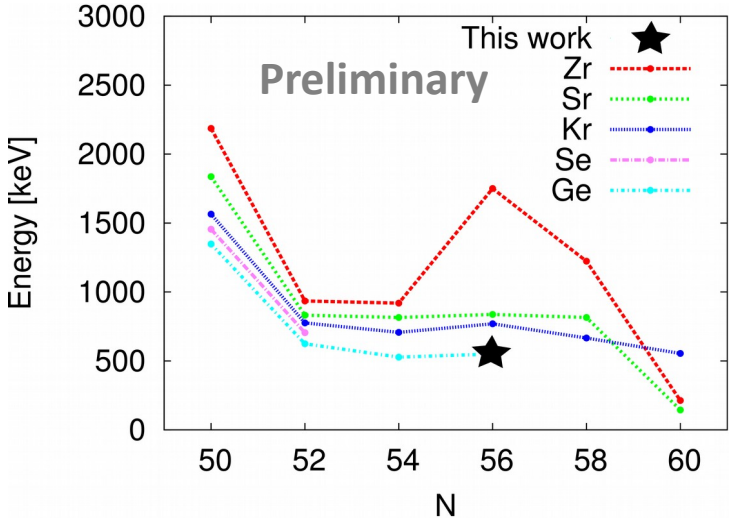
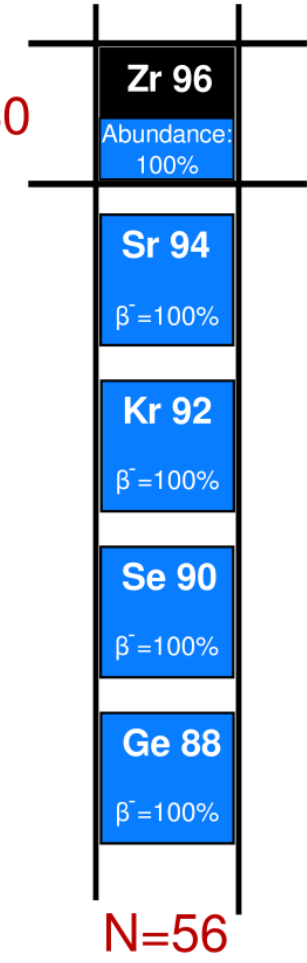
$E(2^+)$ & $E(4^+)$ behavior for Ge isotopes:



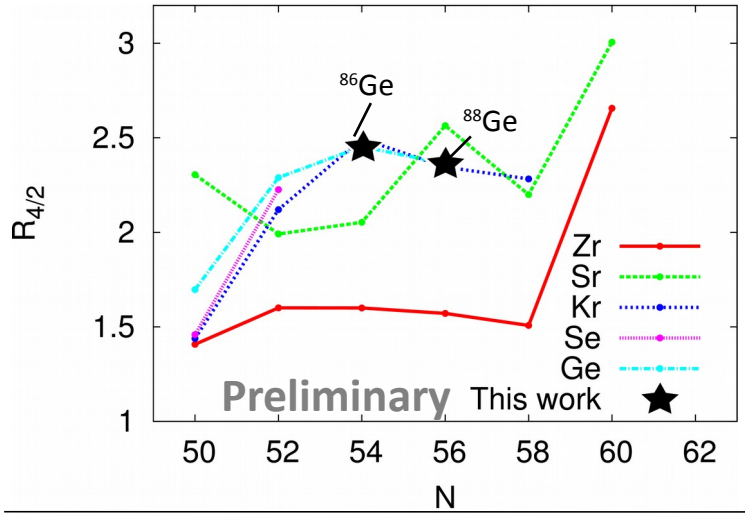
Trend of $E(2^+)$:



Z=40



Trend of $R_{4/2}$:



- Nearly constant $E(2^+)$ & $E(4^+)$ after N=52
- No strong N=56 sub-shell from $E(2^+)$
- No drop of $E(2^+)$ either → stabilized ?
- No systematic increase of deformation
- "γ-soft" $R_{4/2}$ ~ 2.5

Microscopic Models: Triaxiality

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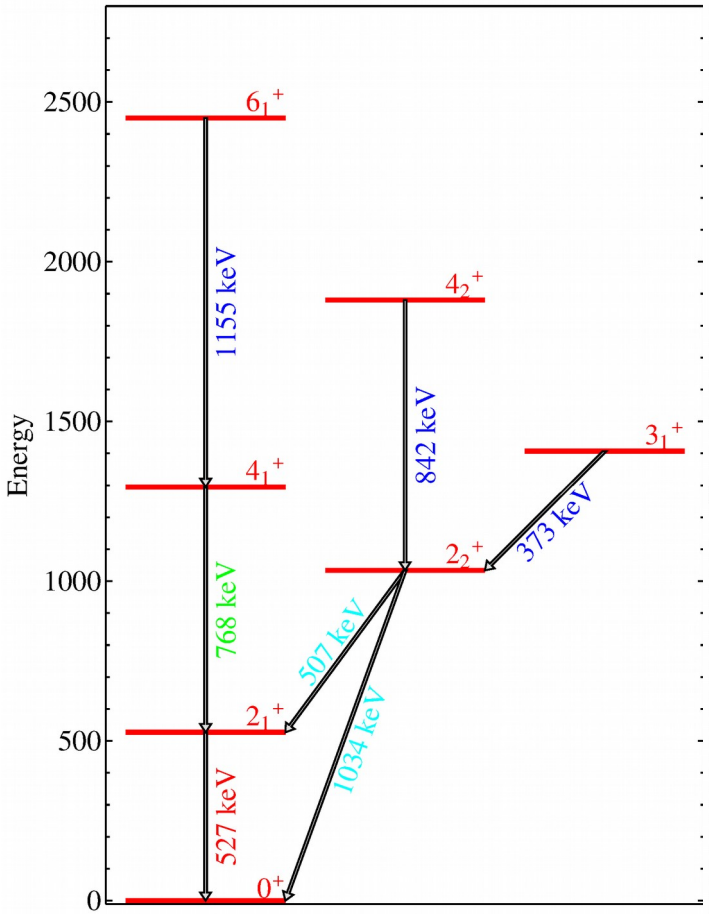
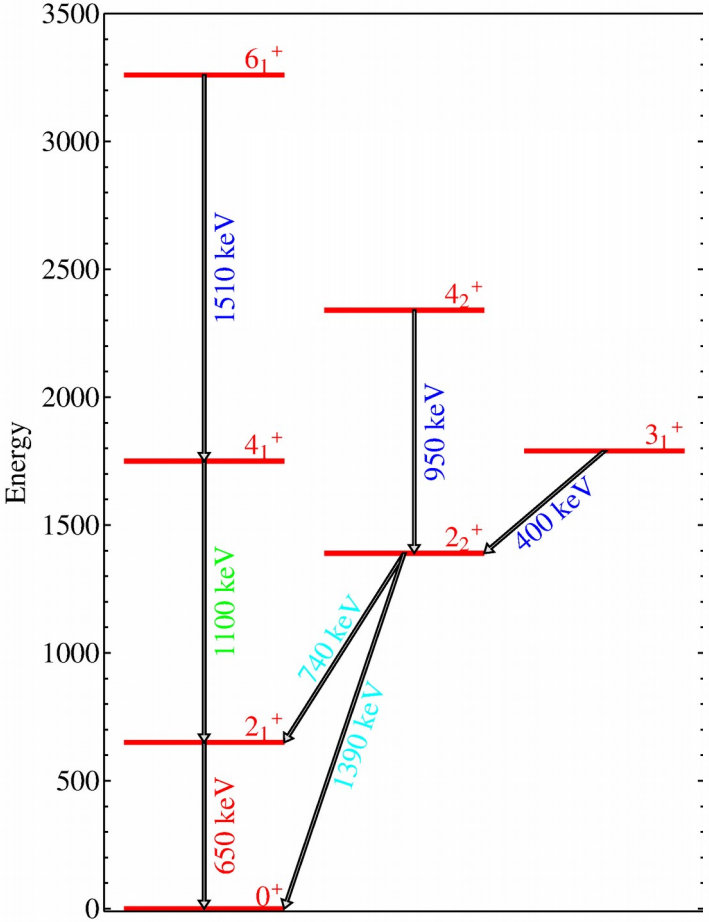
Tentative Level Scheme



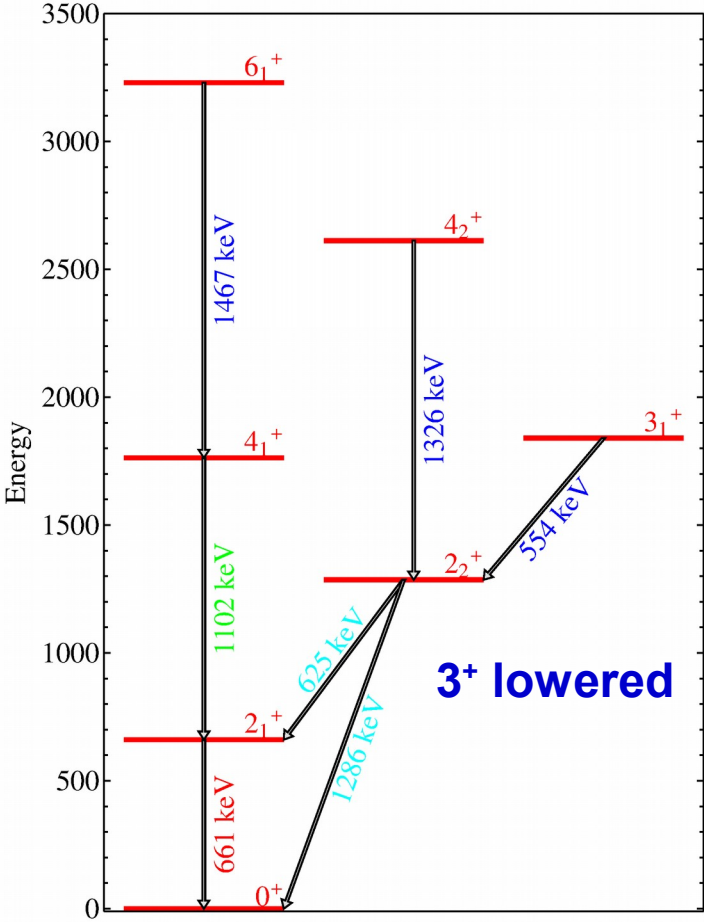
$R_{4/2}$ ~ 2.5
typical γ-soft

low-lying
γ-band

LSSM Sieja



Beyond-MF Rodriguez



- Energies somewhat high, good match overall
- Triaxiality at least in the γ-band

K. Sieja et al., PRC88, 034327 (2013)

Mean Field Potential, Wave Functions

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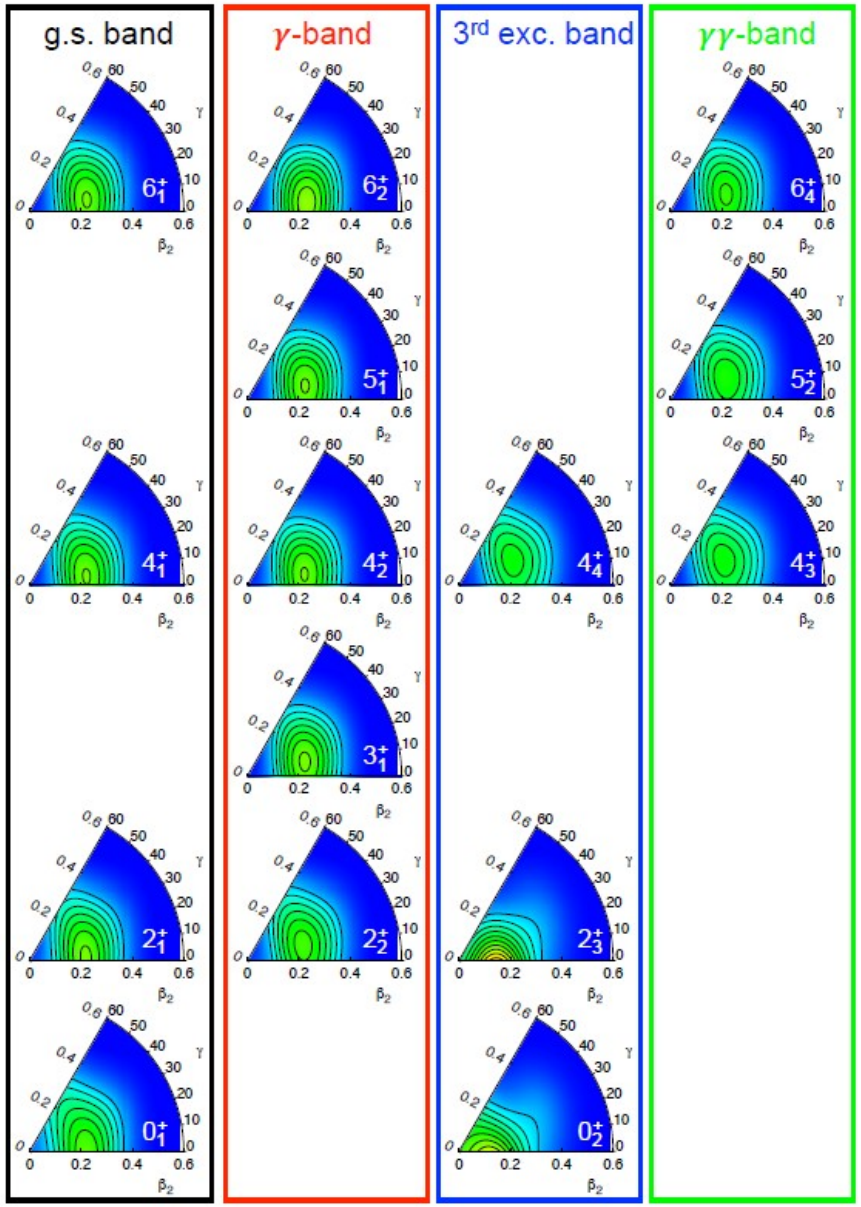
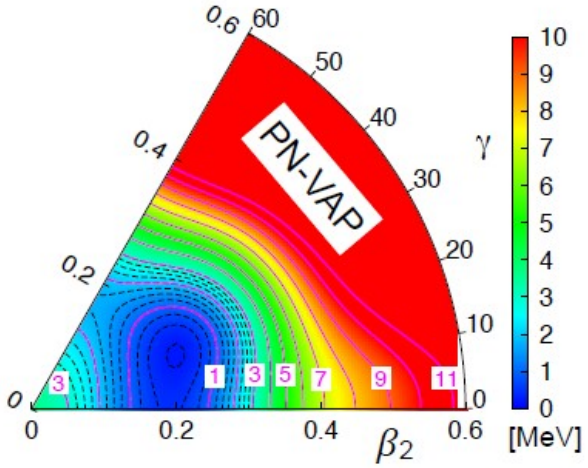
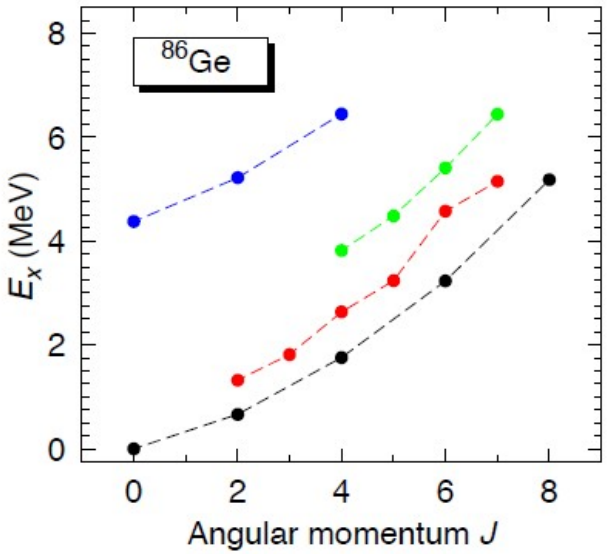




^{86}Ge

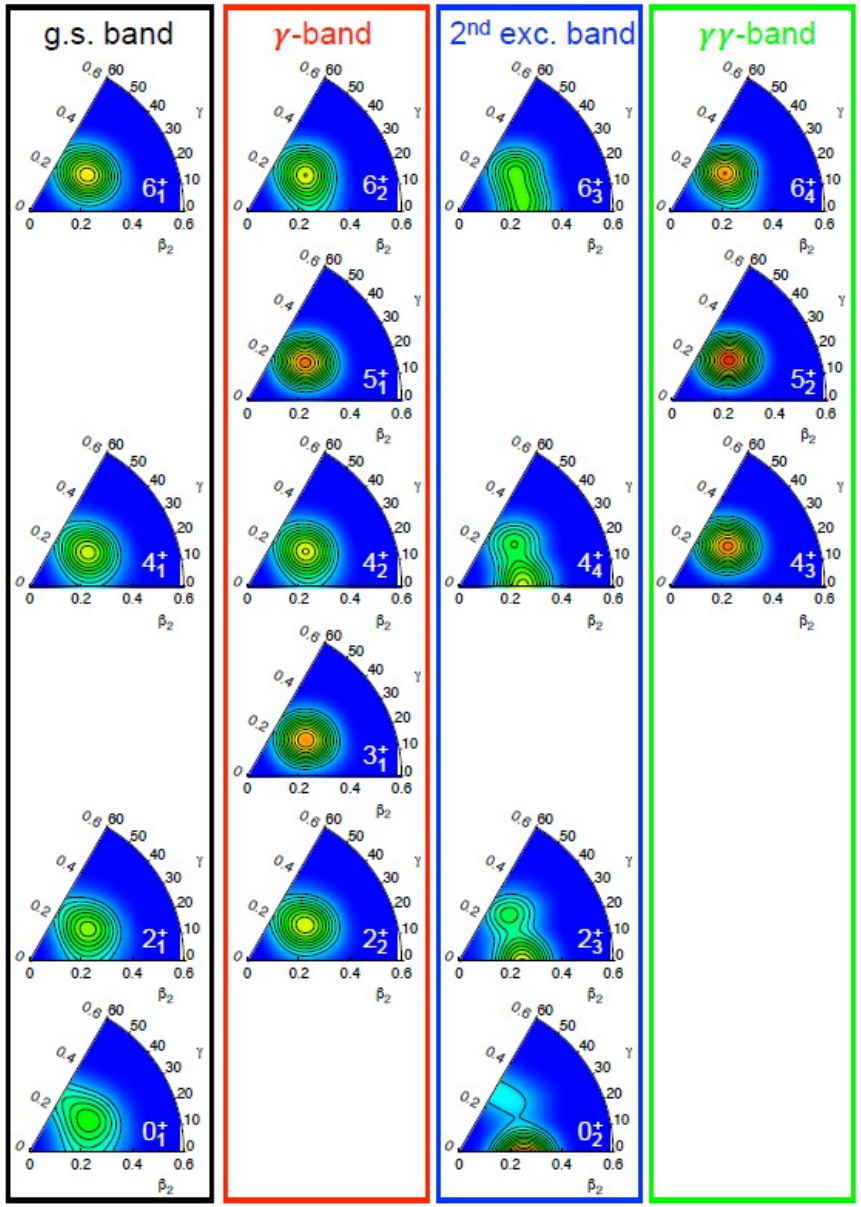
- **triaxial minimum**

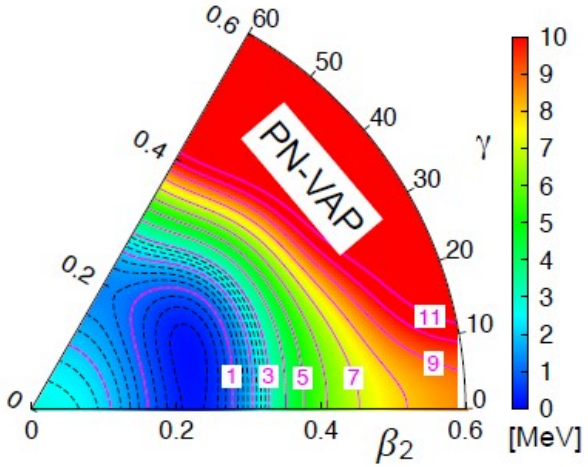


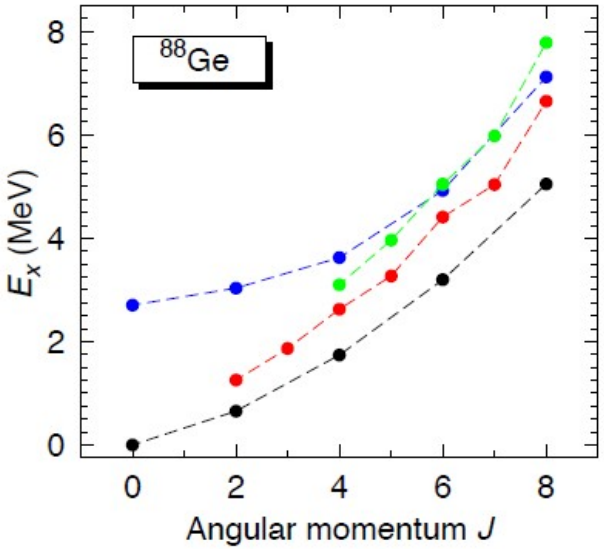
- **some γ-softness in wave functions**

T.R. Rodriguez, brandnew

Mean Field Potential, Wave Functions







^{88}Ge

- **triaxial minimum more pronounced**
- **wave functions more γ-rigid**

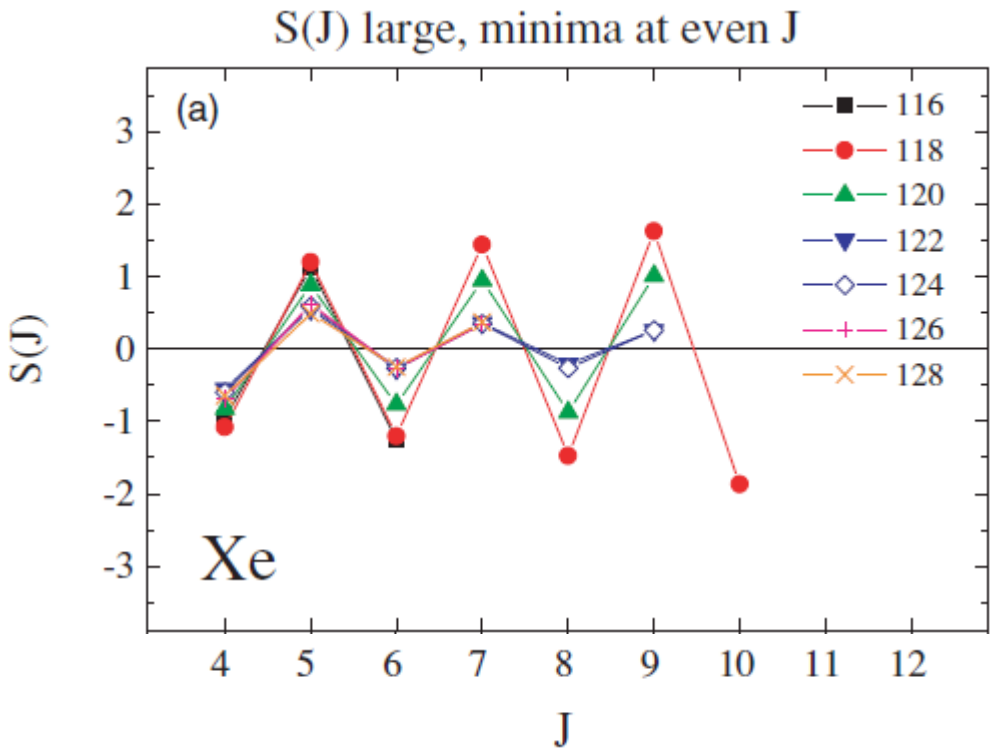
T.R. Rodriguez, brandnew

γ-Band Odd-Even Staggering

$$S(I) = \frac{[E(I) - E(I-1)] - [E(I-1) - E(I-2)]}{E(2_1^+)}$$

For example: **S(4) determines whether 3^+ is closer to 2^+ or 4^+**
S(4) < 0 → closer to 4^+ ; S(4) > 0 → closer to 2^+

Zamfir, Casten, PLB260, 265 (1991)



McCutchan, PRC76, 024306 (2007)

Typical γ-soft nuclei:
S(4) negative
then odd-even staggering

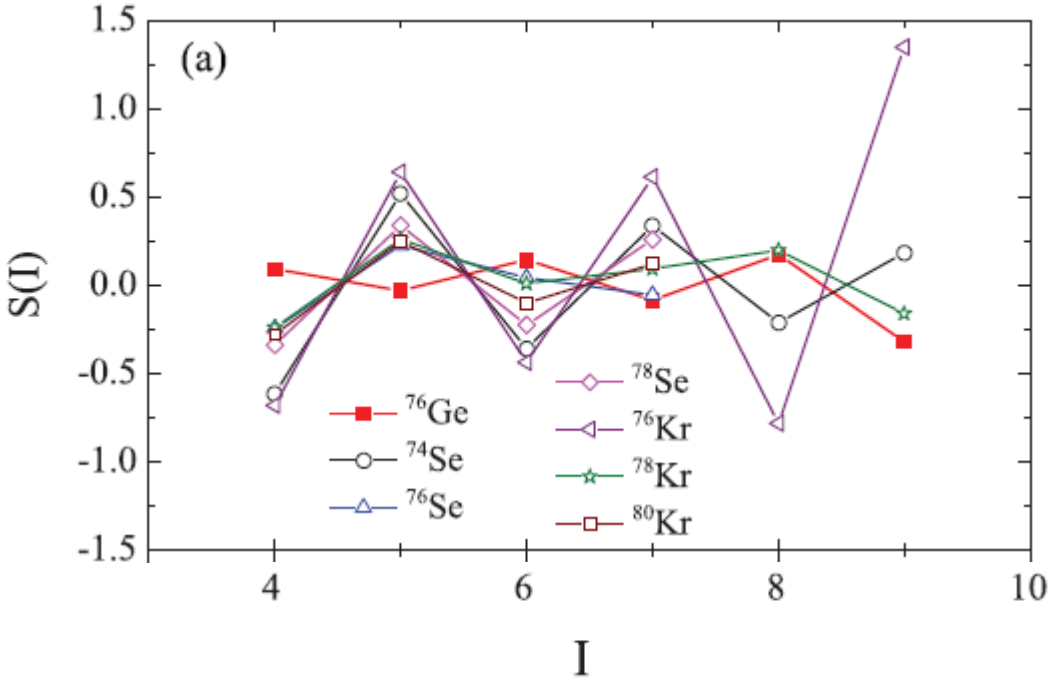
γ-Band Odd-Even Staggering

$$S(I) = \frac{[E(I) - E(I-1)] - [E(I-1) - E(I-2)]}{E(2_1^+)}$$

For example: **S(4) determines whether 3^+ is closer to 2^+ or 4^+**
S(4) < 0 → closer to 4^+ ; S(4) > 0 → closer to 2^+

^{76}Ge rigid triaxial, identified at Argonne

Zamfir, Casten, PLB260, 265 (1991)



Y. Toh, PRC87, 041304(R) (2013)

^{76}Ge:

- **staggering opposite to all others in the region**
- **S(4) = 0.09 > 0 → some rigid triaxiality**

^{86}Ge (this work):

- **S(4) = 0.18 > 0**

Thank You for your Attention !

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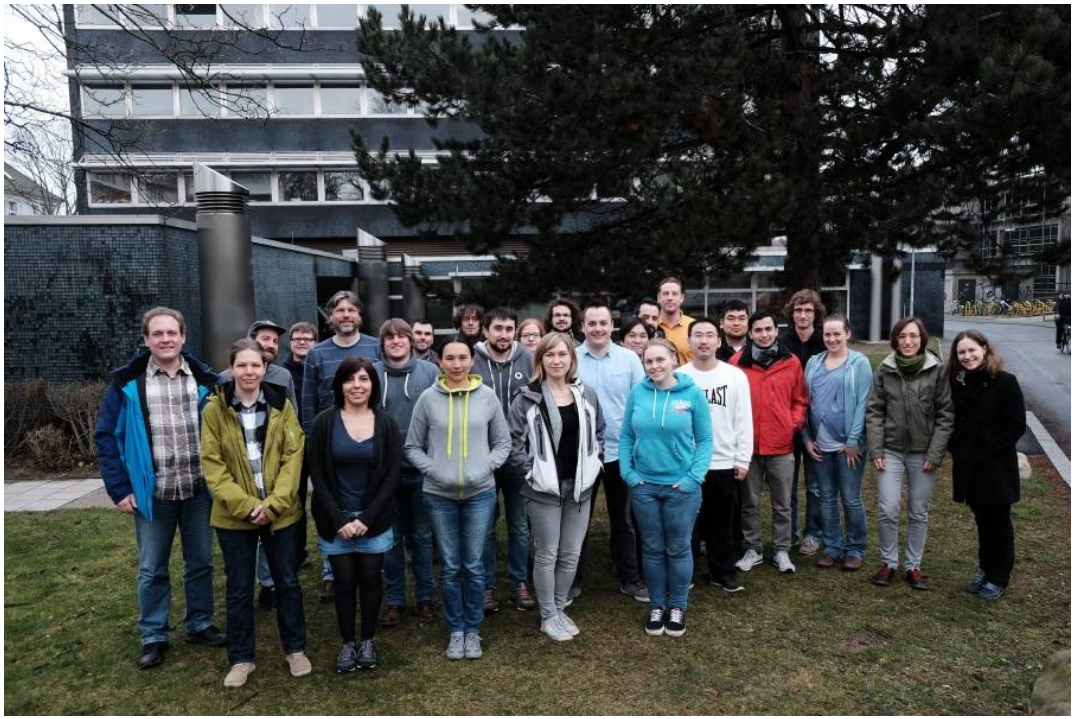
The SEASTAR Collaboration:

Riken Nishina Center: P. Doornenbal, H. Baba, S. Chen, T. Motobayashi, M. Niikura, H. Sakurai, D. Steppenbeck, R. Taniuchi, T. Uesaka, K. Wimmer, T. Ando, S. Momiyama, S. Nagamine, T. Saito, P.A. Söderström
CEA: A. Obertelli, G. Authelet, D. Calvet, F. Château, A. Corsi, A. Delbart, J.-M. Gheller, A. Giganon, A. Gillibert, V. Lapoux, N. Paul, J.-Y. Roussé, C. Santamaria
GSI: T. Arici, M. Górska, C. Lizarazo
Universität zu Köln: A. Blazhev, M. Dewald, K. Moschner
University of Brighton: F. Browne, A. Bruce, C. Nobs
University of Surry: R. Caroll, Z. Patel, Z. Podolyak, C. Shand, M. Rudigier
VAEC: L.X. Chung, B. Linh
TU Darmstadt: L. Cortés, M. Lettmann, V. Werner
Chinese Academy of Science: B. Ding, Z. Liu
Institute de Physique de Nucléaire Orsay: F. Flavigny, S. Franchoo, A. Gottardo, L. Olivier, I. Stefan
CSIC: A. Jungclaus, V. Vaquero
University of Hong Kong: J. Lee, J. Liu, Z. Xu
IFIN-HH: C. Nita
Japan Atomic Energy Agency: R. Orlandi, N. Nakatsuka



supported by Bundesministerium für Bildung und Forschung BMBF

Backups

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$R_{4/2}$ Systematics

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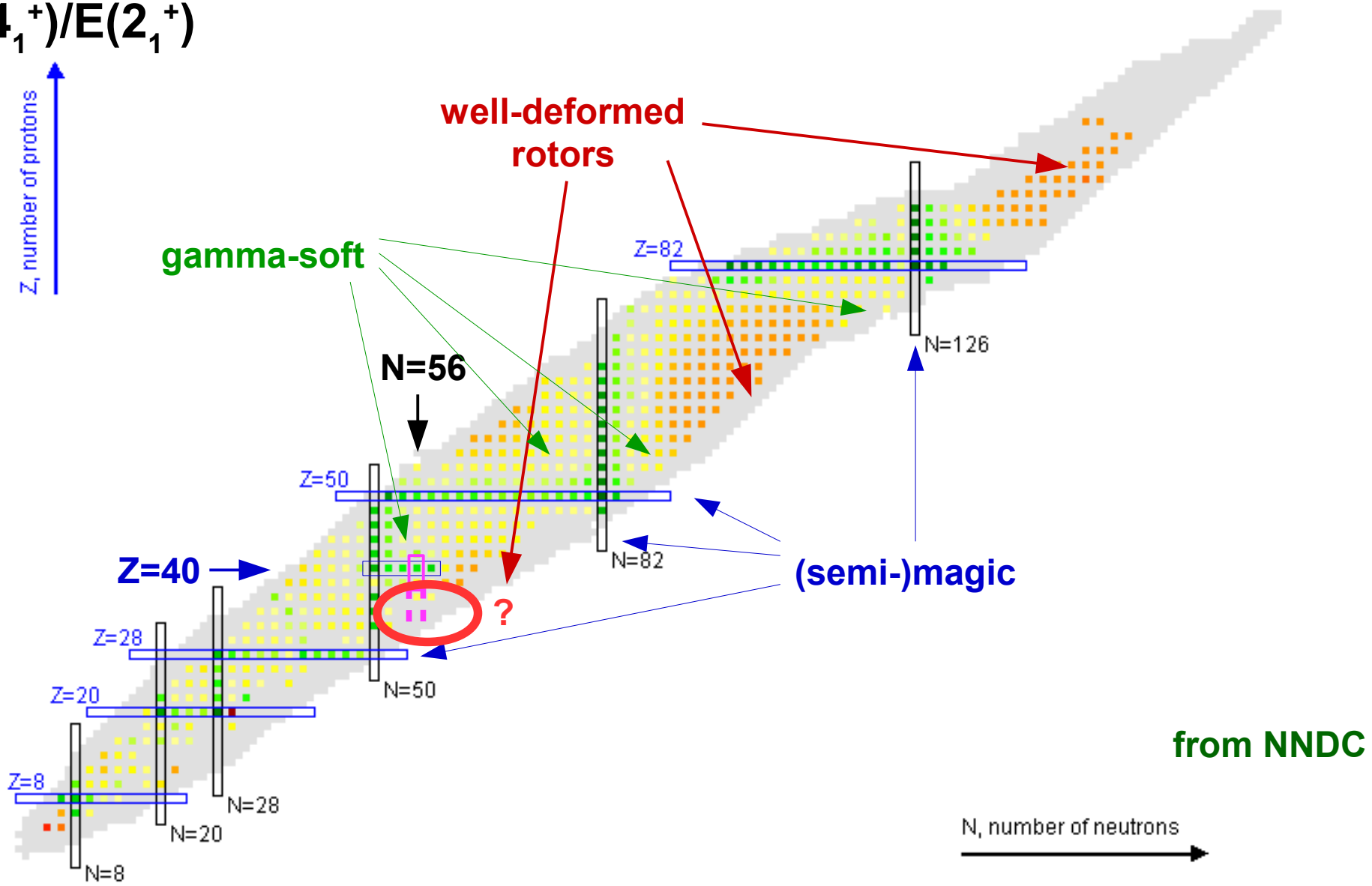
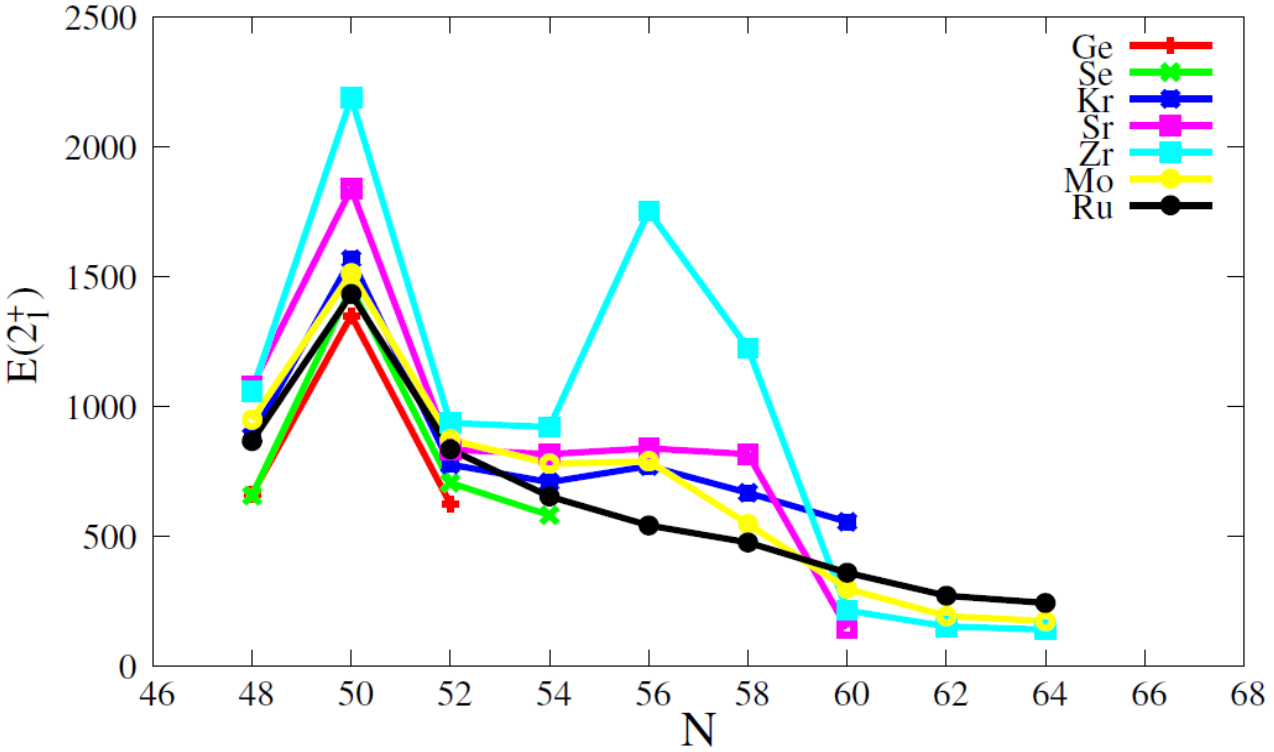
$E(4_1^+)/E(2_1^+)$



$E(2_1^+)$ Systematics at N=56-60



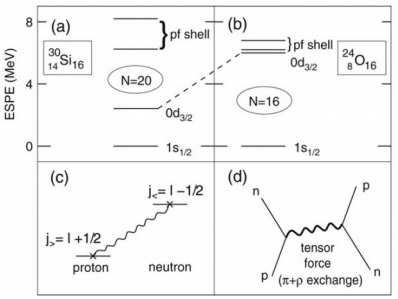
Ru: smooth drop

Mo: small peak at 56, moderate drop

Zr: clear peak at N=56,*58* in Zr

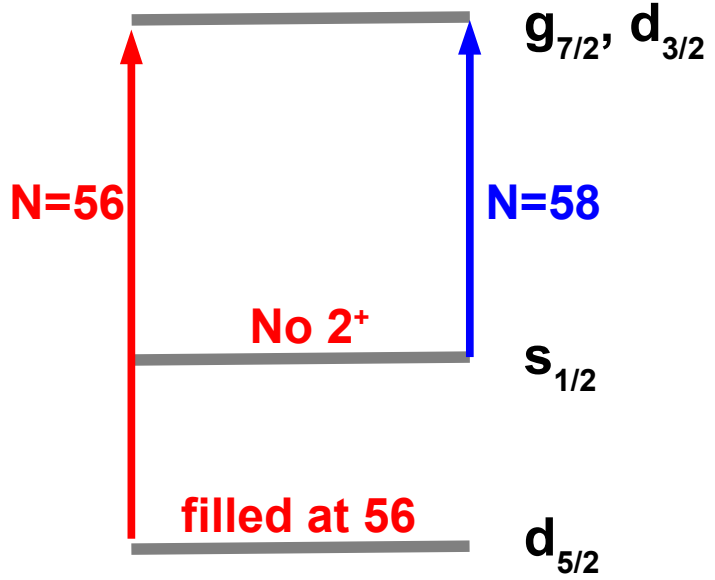
Sr: „peak" N=56, drop past *58*

Kr: small peak at 56, smooth after



Weak coupling (p-n) was shown for Z~40, N<56 in prev. works

Assume it here -> $E(2_1^+)$ depends mainly on SPEs



For Z>40 $\nu g_{7/2}$ fills and is lowered because of $\pi g_{9/2}$ -> gaps disappear

RIKEN-RIBF Overview

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Intensities of 345 MeV/u beams from the SRC

Nucleus	Beam Intensity / pnA		
	Goal	Achieved Max	Average
^{48}Ca	1000	415	>200
^{70}Zn	1000	123	100
^{78}Kr	1000	–	–
^{124}Xe	100	38	**30**
^{238}U	100	25	**15**

- $K = 2500$ MeV
- 8300 tons
- 5.36 m extraction radius
- 6 sector magnets
- four main RF cavities

MINOS + DALI2

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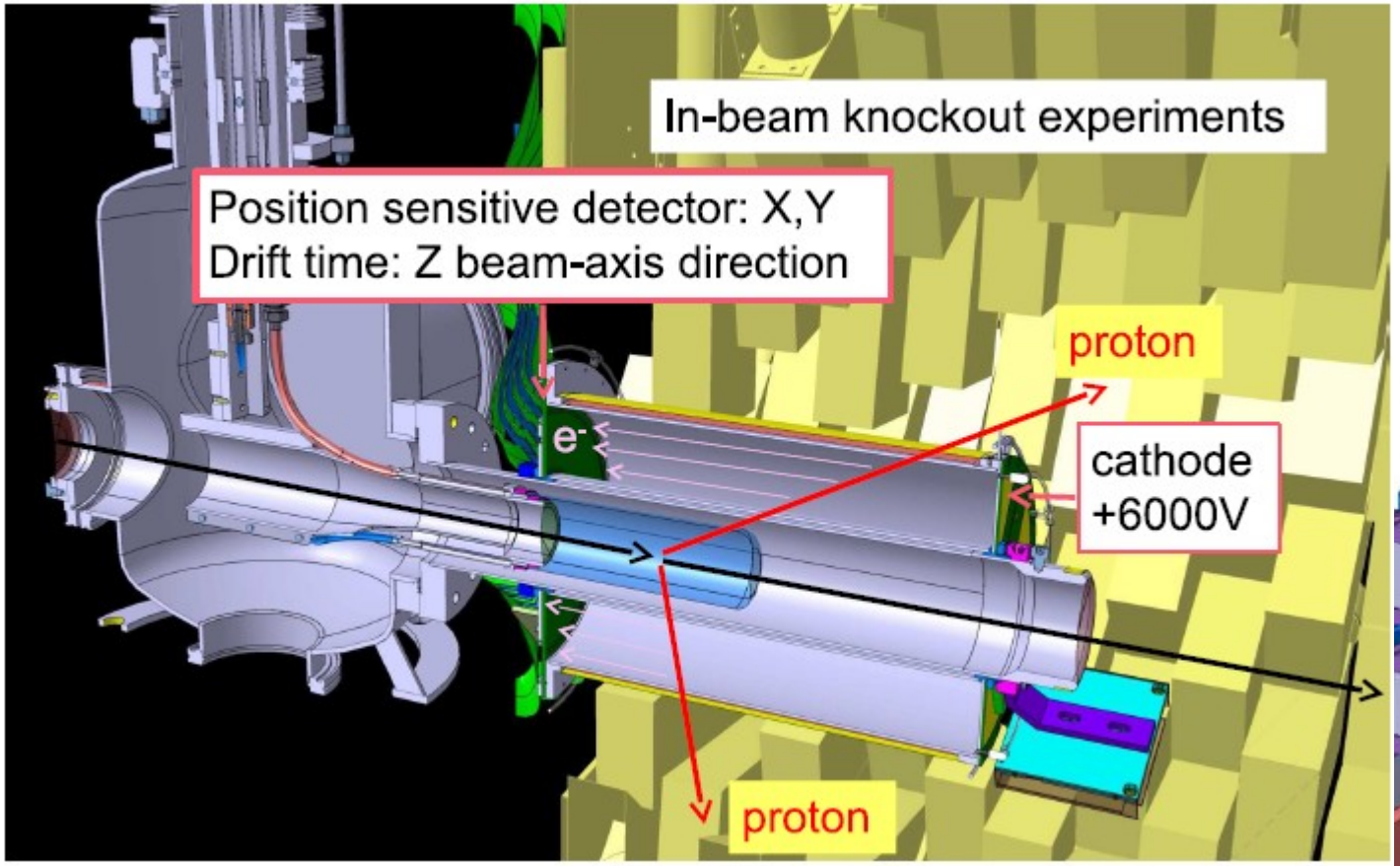

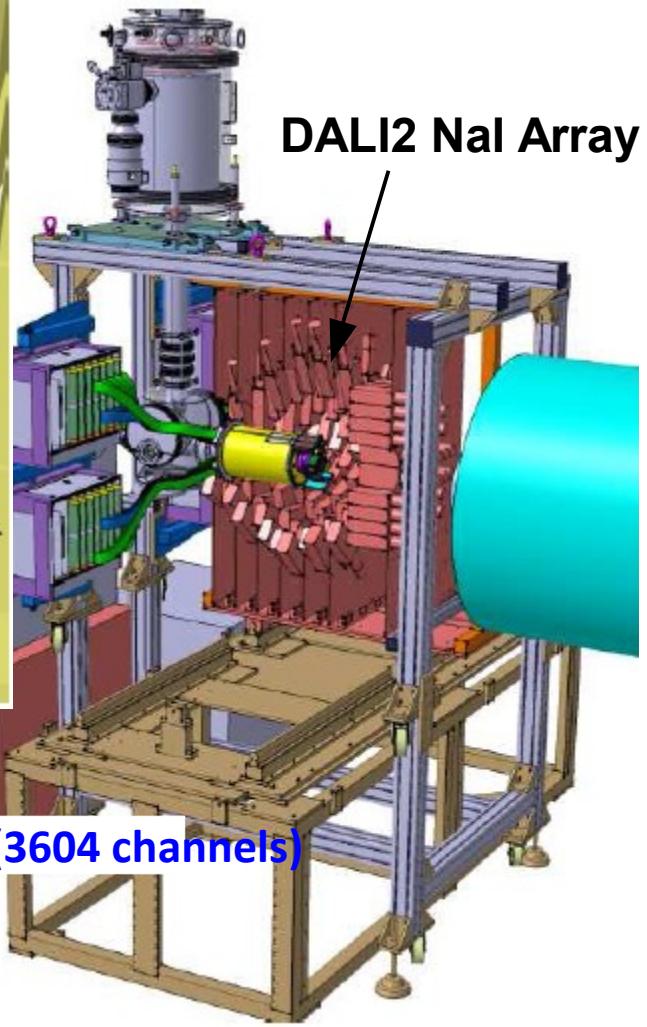

LH2 target length = 100 mm

Time Projection Chamber equipped with MicroMegas detector (3604 channels)

Settings duration : 22.7 hours for Cr, 26 hours for Fe

Intensities : $I(^{67}Mn) = 1.25, \quad I(^{73}Co) = 0.49$ pps/pnA

MINOS + DALI2

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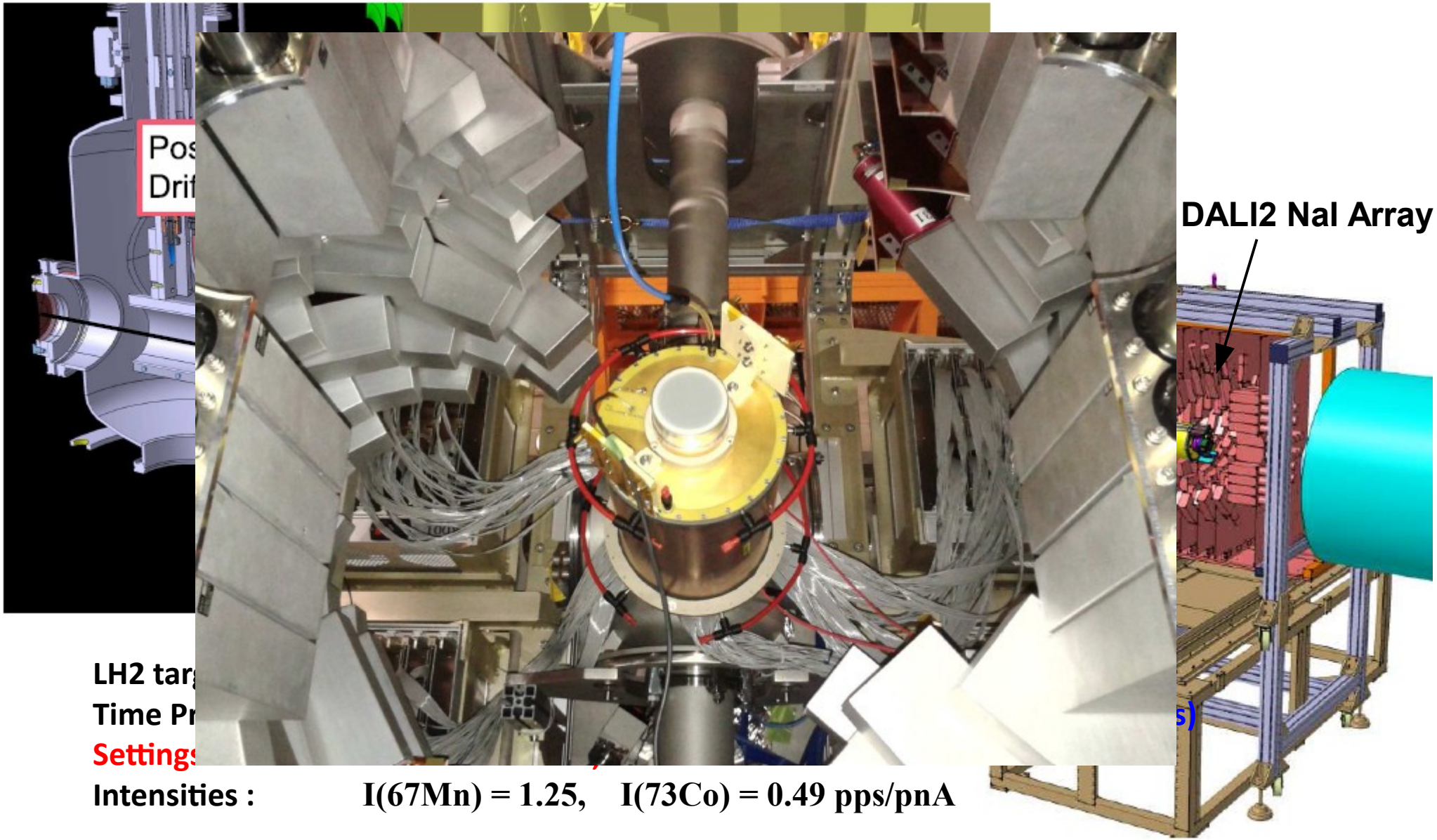

LH2 tar

Time Pr

Settings

Intensities : I(67Mn) = 1.25, I(73Co) = 0.49 pps/pnA

MINOS TPC

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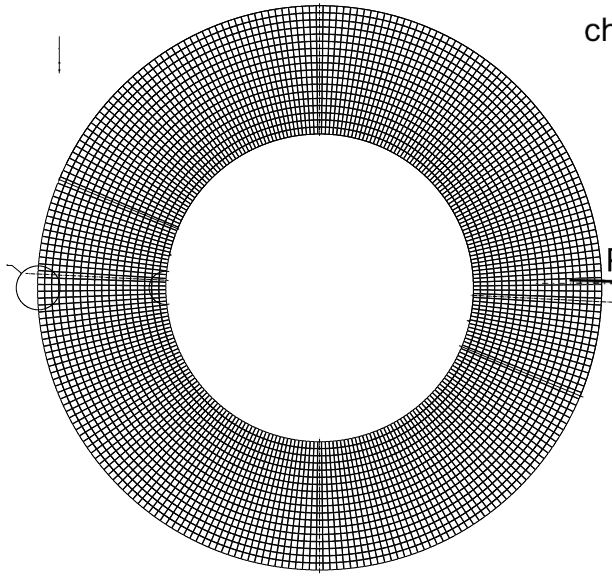
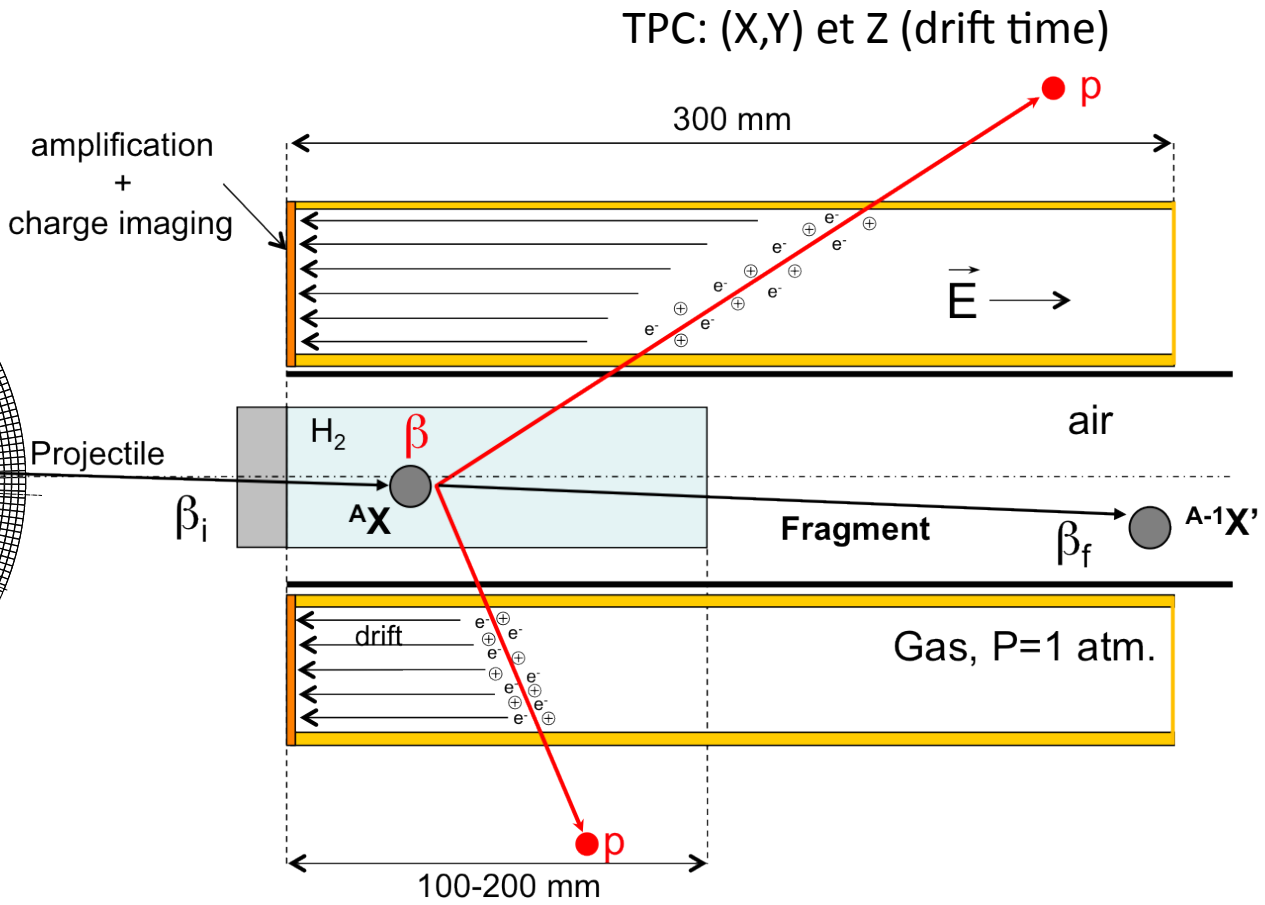
Micromegas



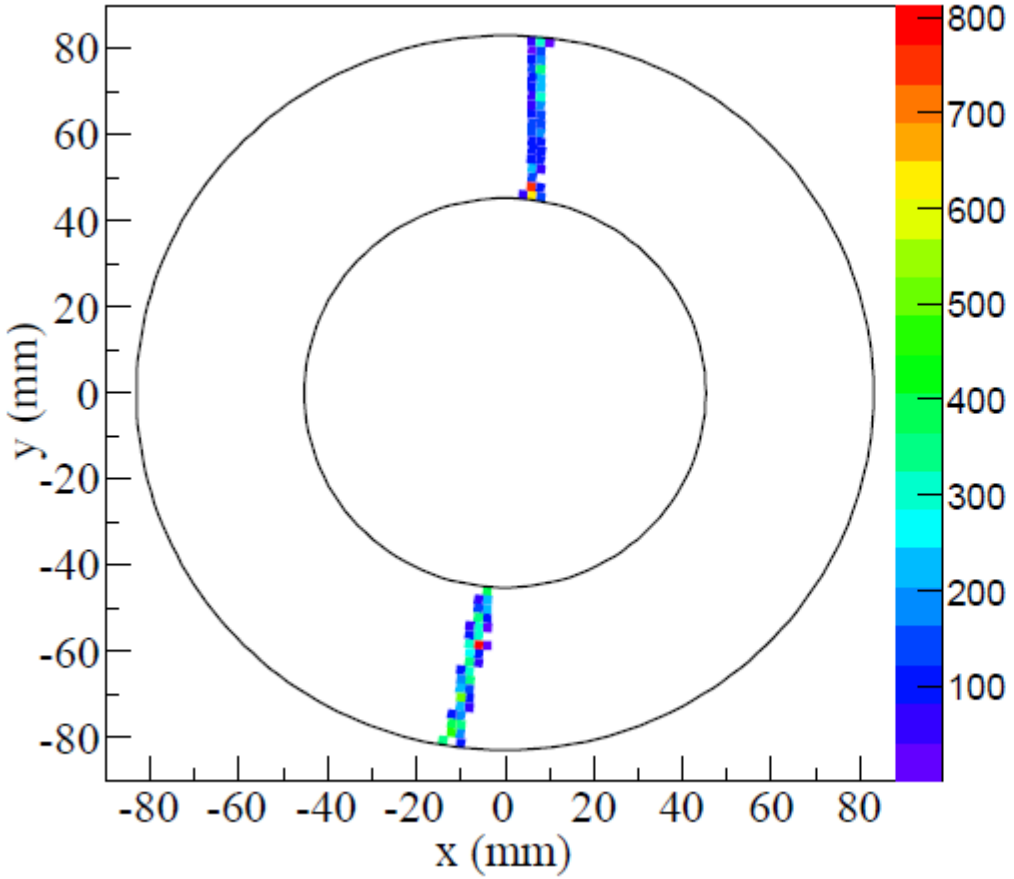
4608 pads
Area ≈ 2-4 mm2

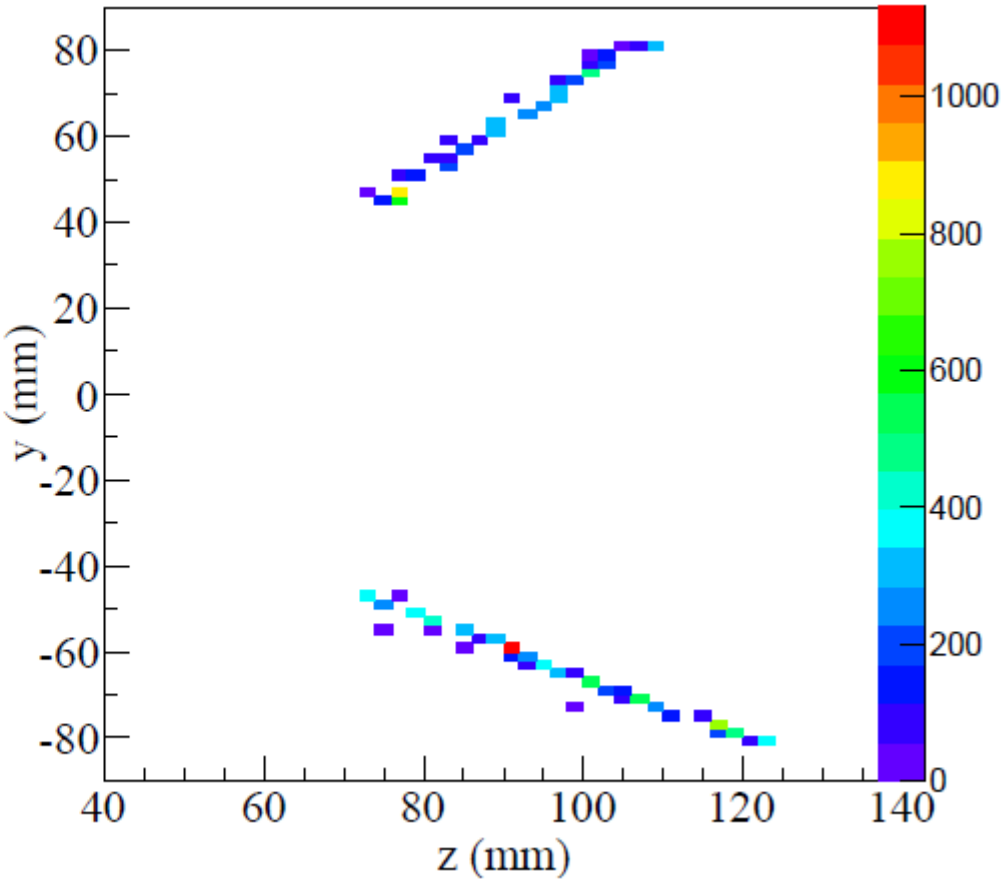


Initial goal: vertex resolution ~4 mm FWHM, detection efficiency > 80%

A. Obertelli et al., EPJA 50 (2014) 8

(p,2p) Event in MINOS





^{69}Co(p,2p)^{68}Fe @ 200 MeV/u
Proof of Principle

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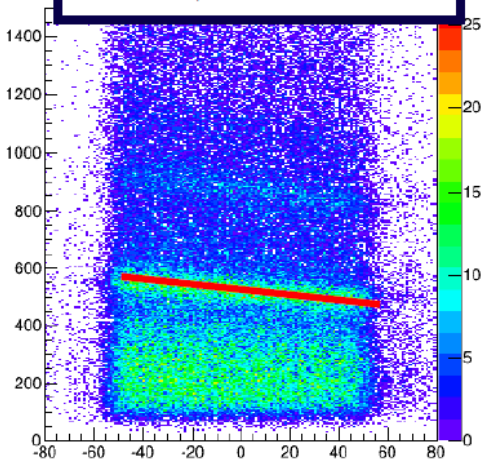
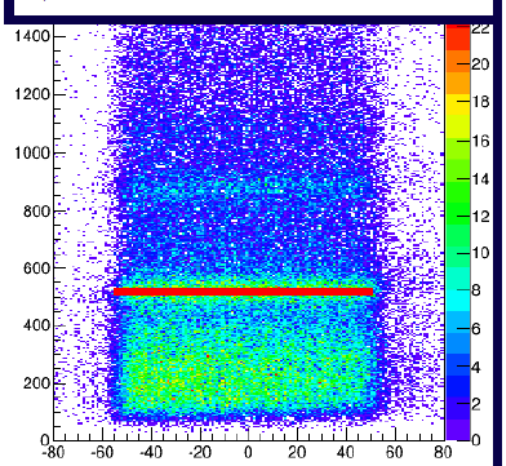
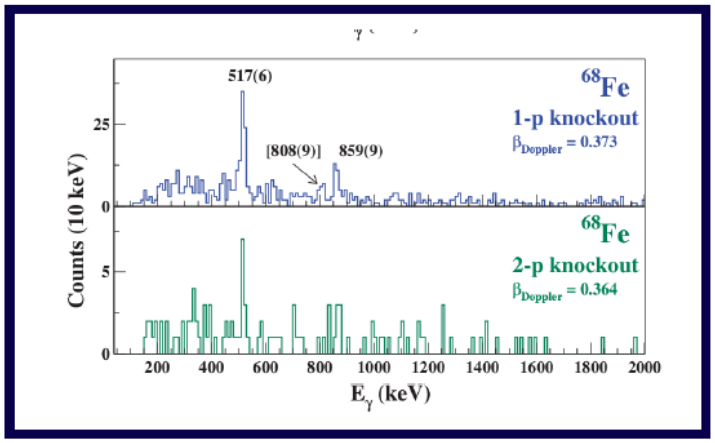
Fixed β and vertex



β and vertex with MINOS

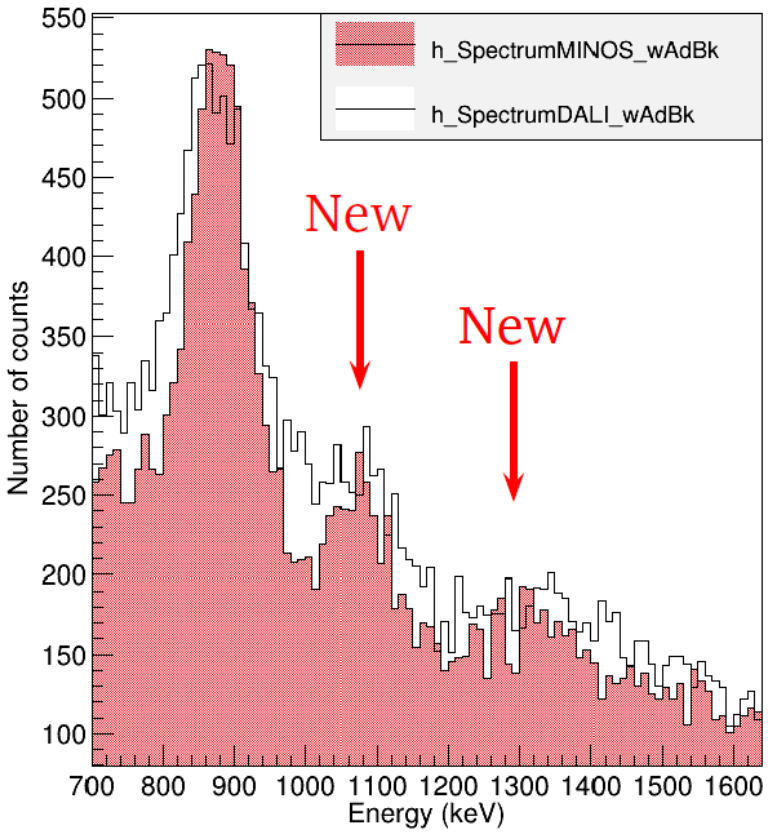


Beam axis Z (mm)



P. Adrich *et al.*, PRC 77, 054306 (2008).

BigRIPS setting on ^{67}Mn, 22 h of beam time



Successful 1st SEASTAR campaign. Physics results for ^{66}Cr, ^{70,72}Fe, ^{78}Ni and others available soon

Particle ID / Reaction Channels

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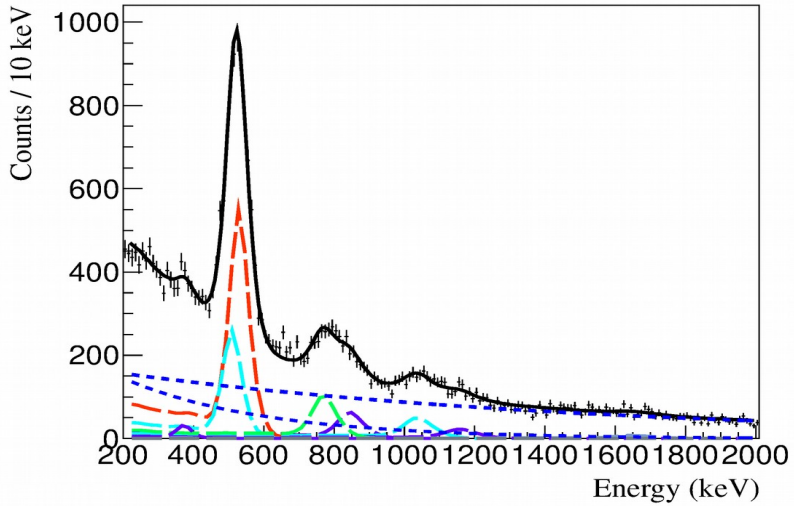
Gated on Reaction Product ^{8X}Ge

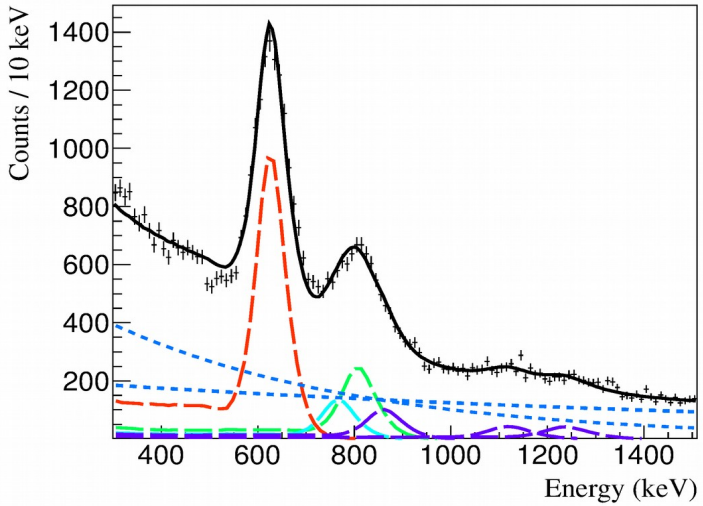
^{86}Ge



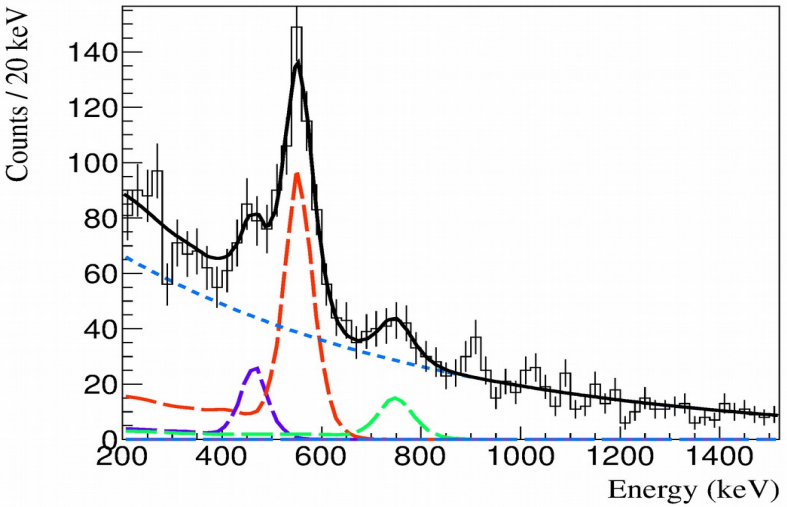
Through MINOS TPC
Gated out channels with outgoing high-E proton(s)

→ vertex reconstruction
→ good Doppler correction

^{84}Ge

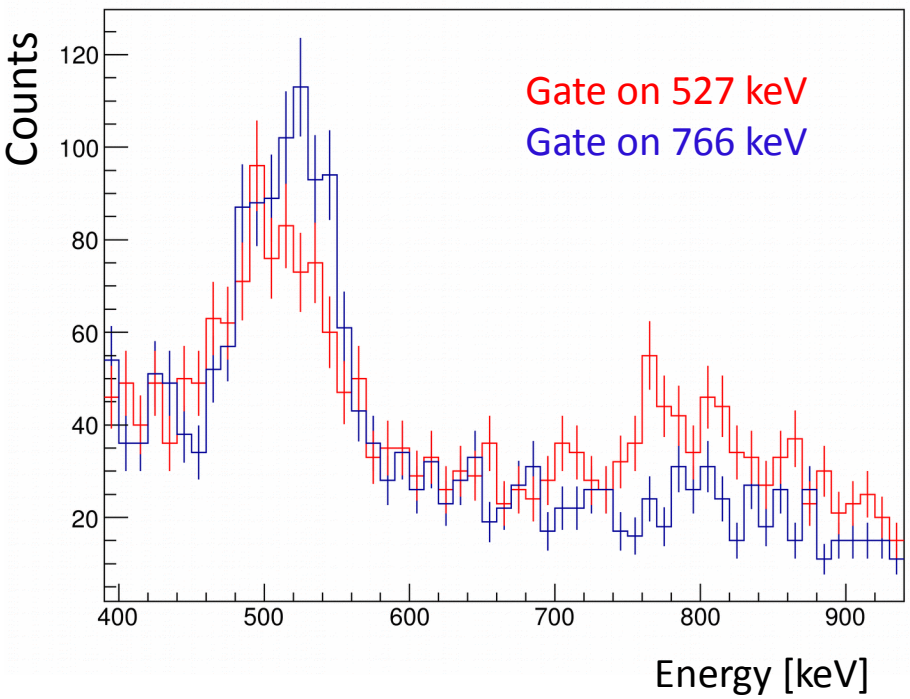


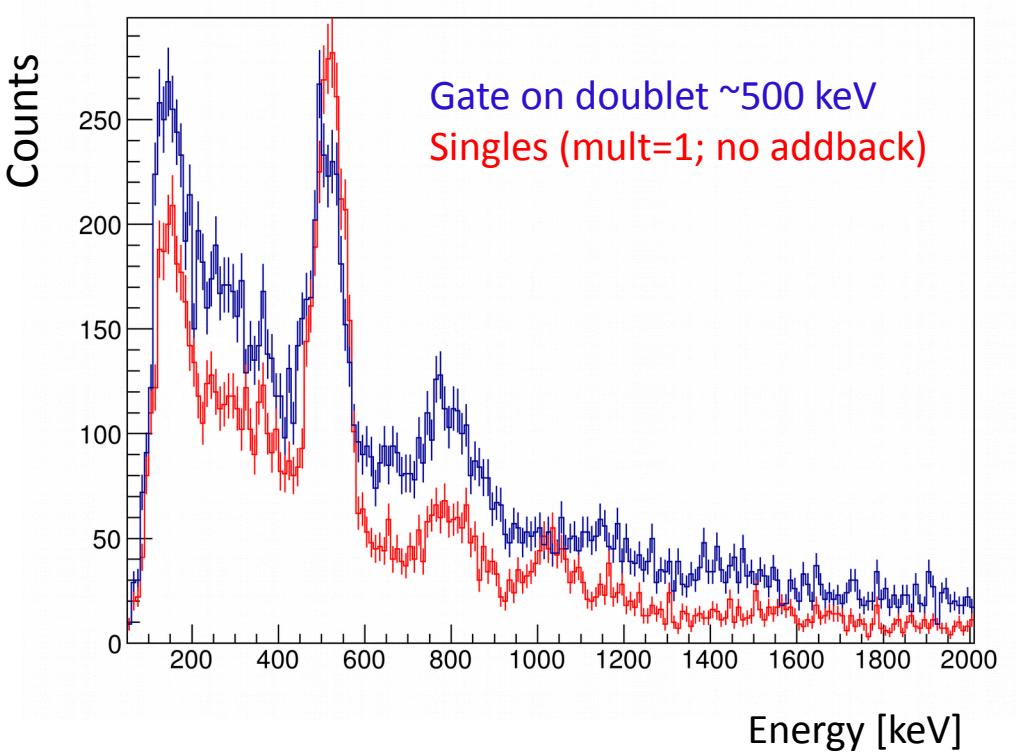
^{88}Ge



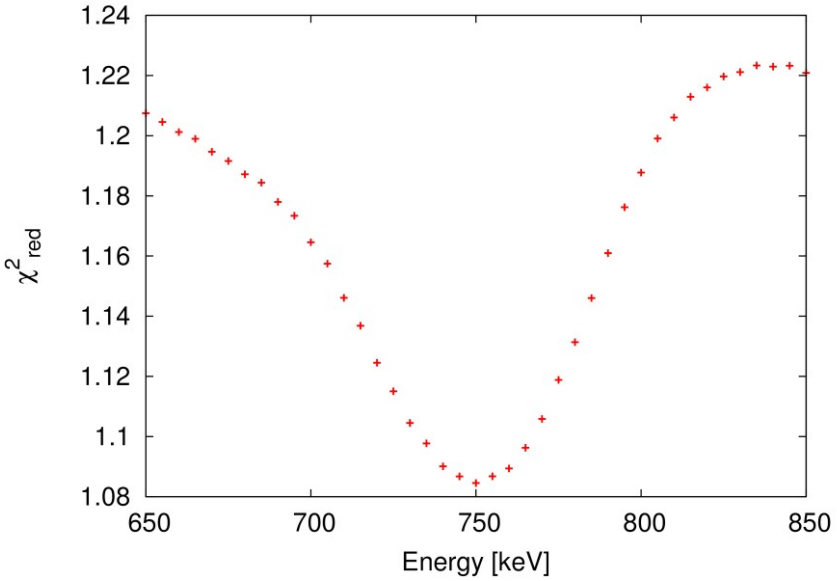
M. Lettmann, TU Darmstadt

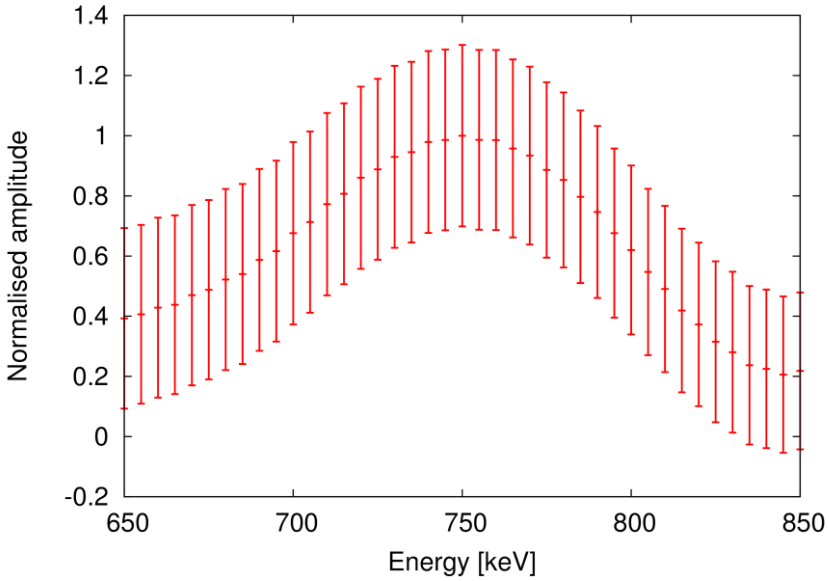
Coincidence spectra ^{86}Ge

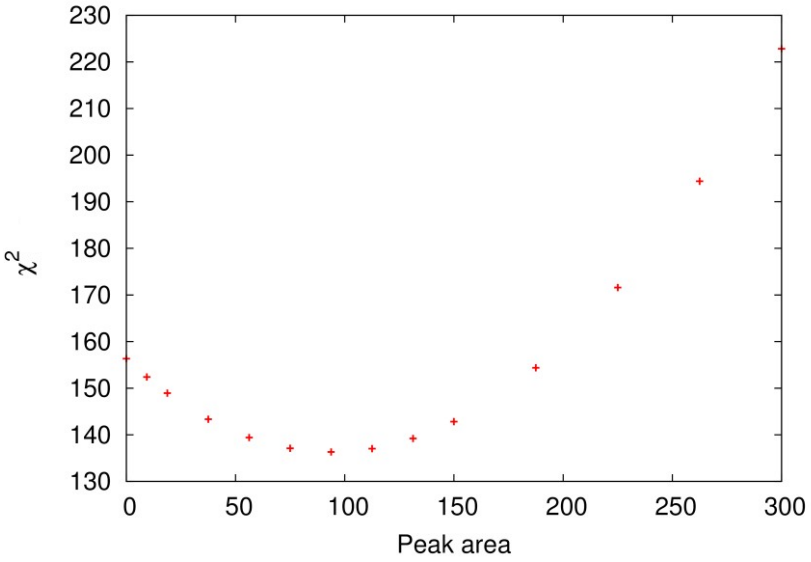




Significance of 4^+ in ^{88}Ge

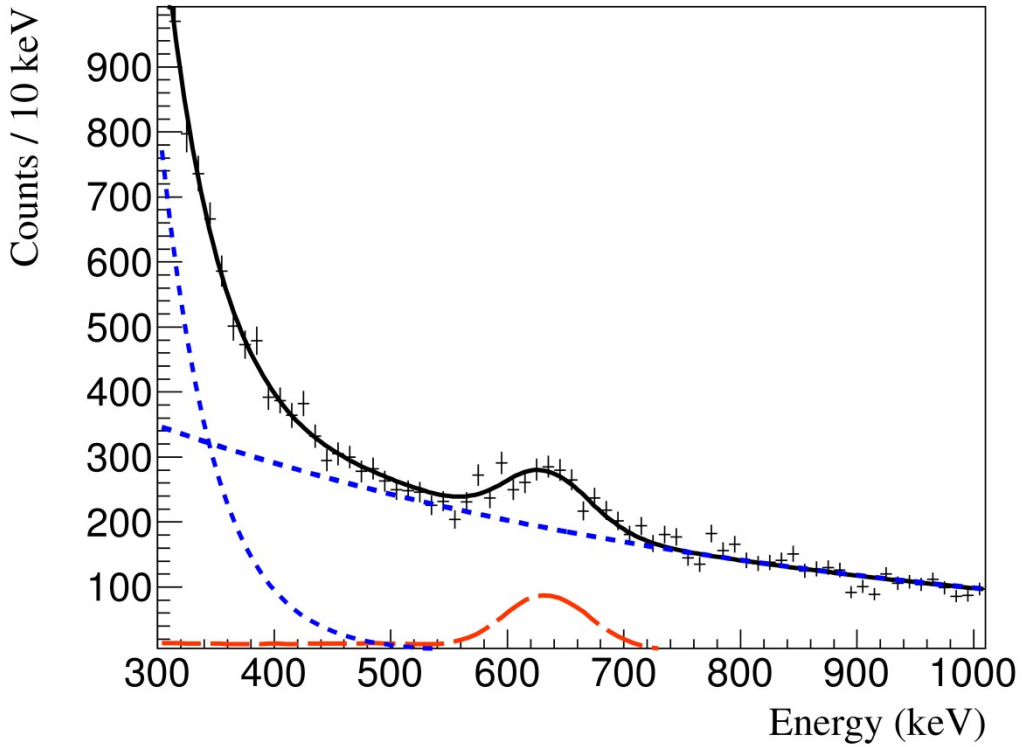


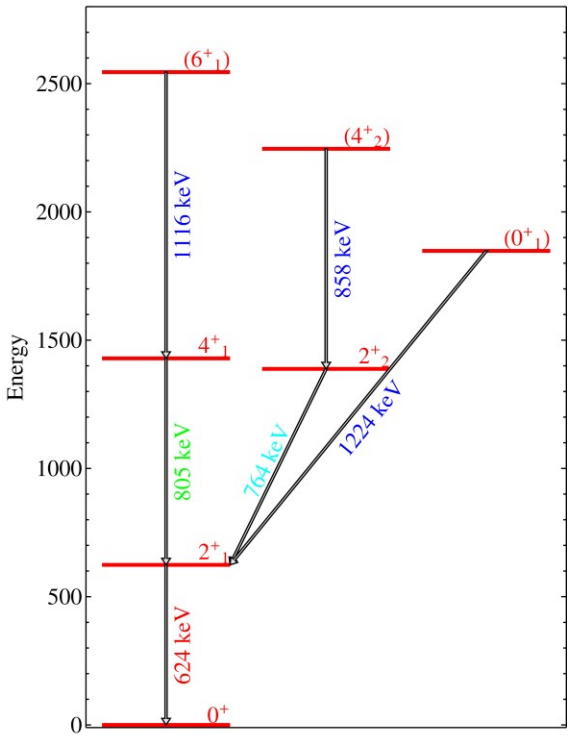




Results ^{84}Ge

^{84}Ge (p,p') ^{84}Ge





Results ^{84}Ge

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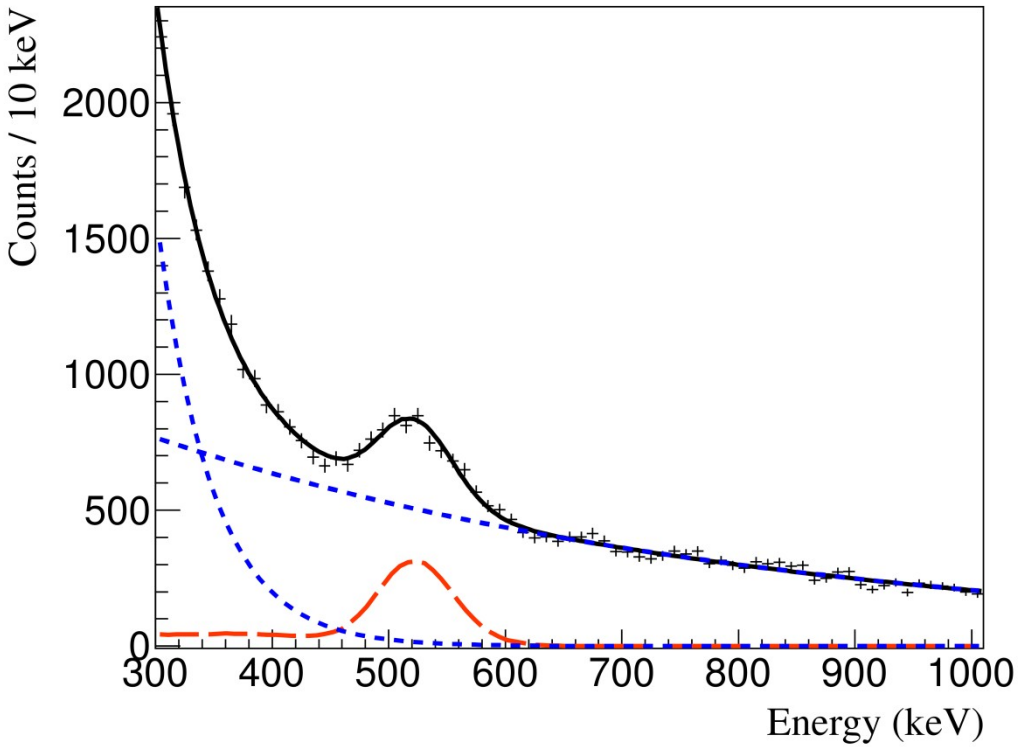
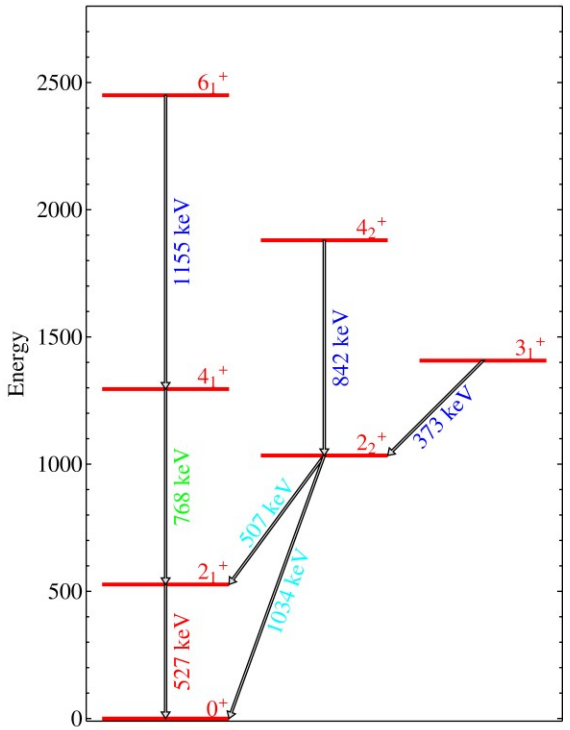
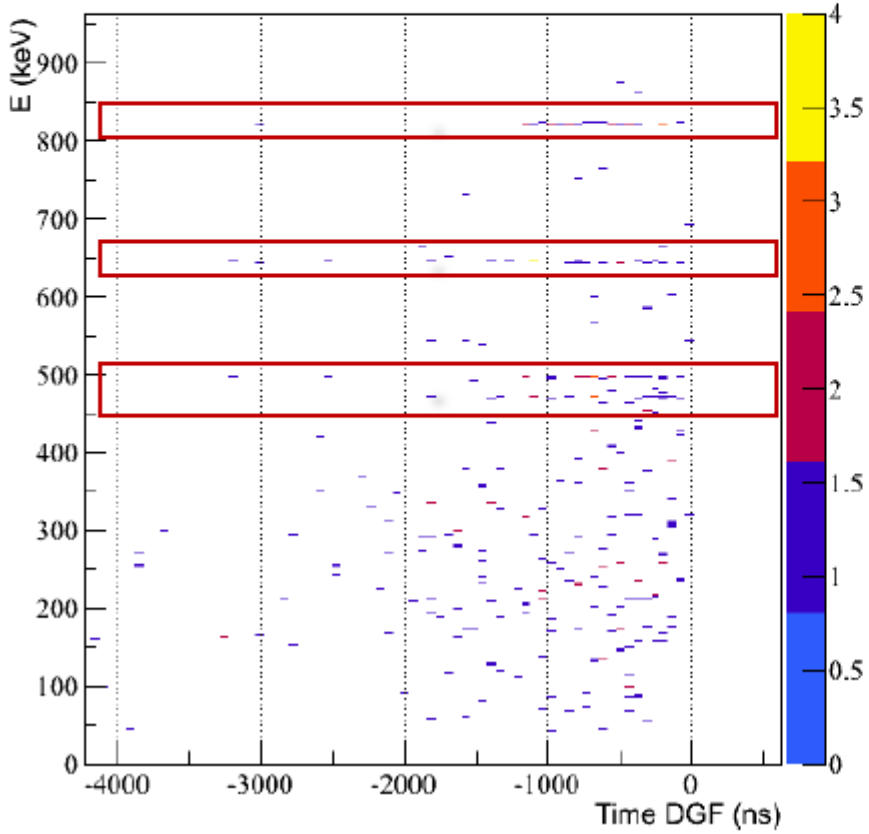
^{86}Ge (p,p') ^{86}Ge





Isomer in ^{94}Se

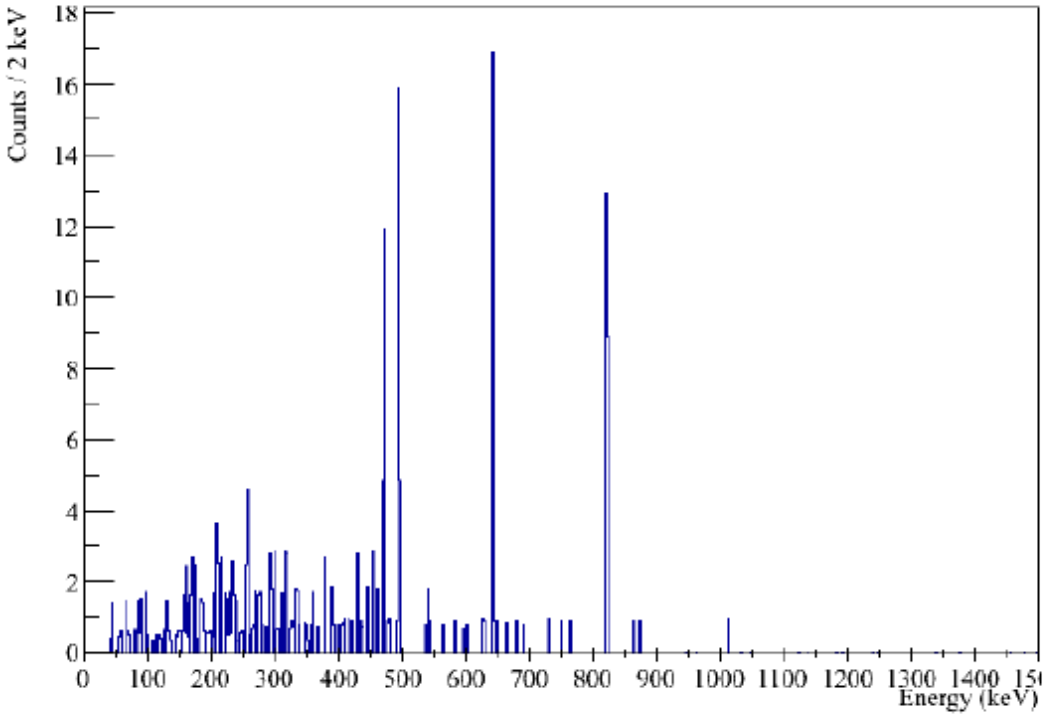
- No spectroscopy information reported for this before.
- Isomeric state observed for the first time in this work.
- Level-scheme not built yet: statistics of isomer decay data is significantly lower than **^{92}Se** (since $T_{1/2}$~0.5 μs, so most of the decays occur before it reaches AIDA, and the production of **^{94}Se** itself is lower)
- 4 transitions with similar life-time dependence and in coincidence between them were found:

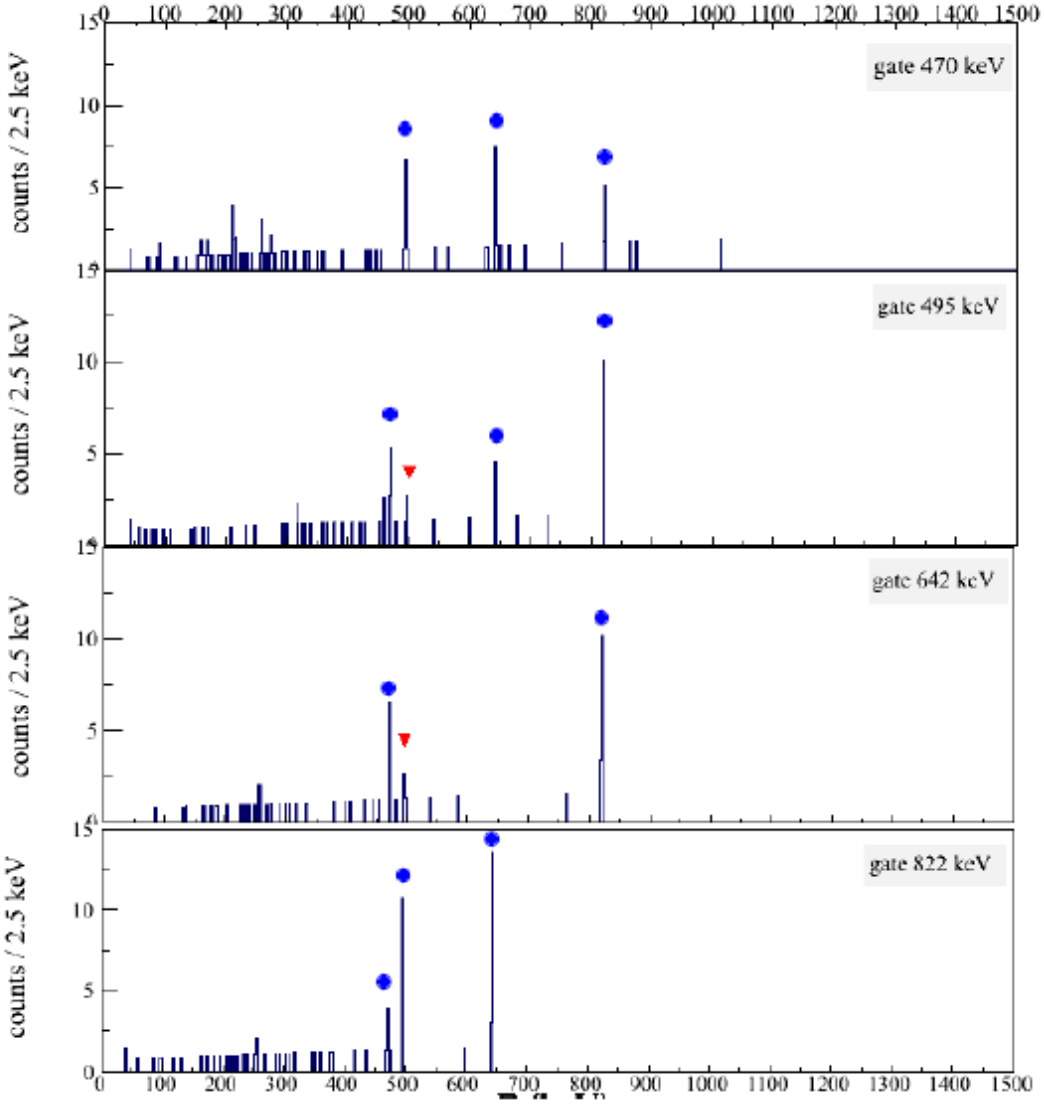


Transitions Observed with EURICA:

Energy (keV)	Observed on In-beam data
470	**X**
495	
642	**X**
822	

^{94}Se – Level Scheme to be decided





Triaxiality in ^{86}Ge ?

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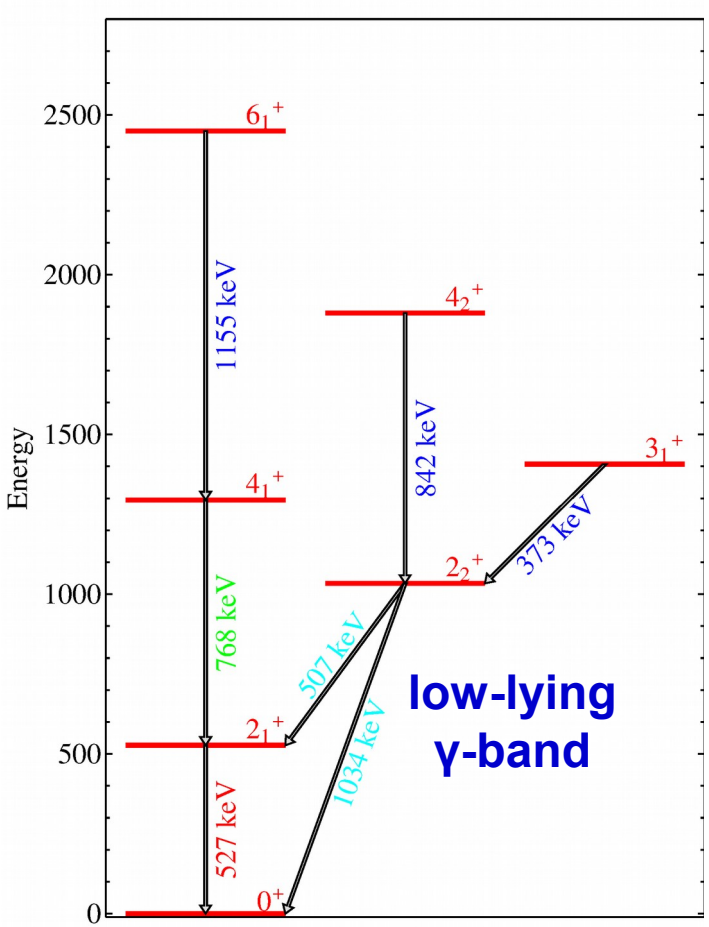
Tentative Level Scheme



$R_{4/2} \sim 2.5$

typical γ-soft

Triaxiality in ^{86}Ge ?

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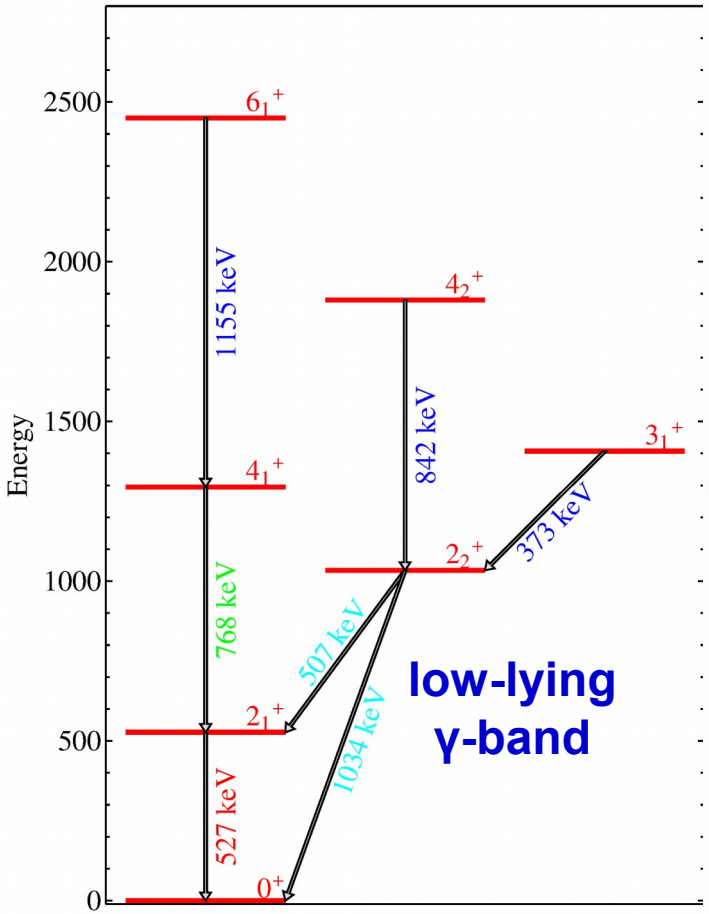
Tentative Level Scheme

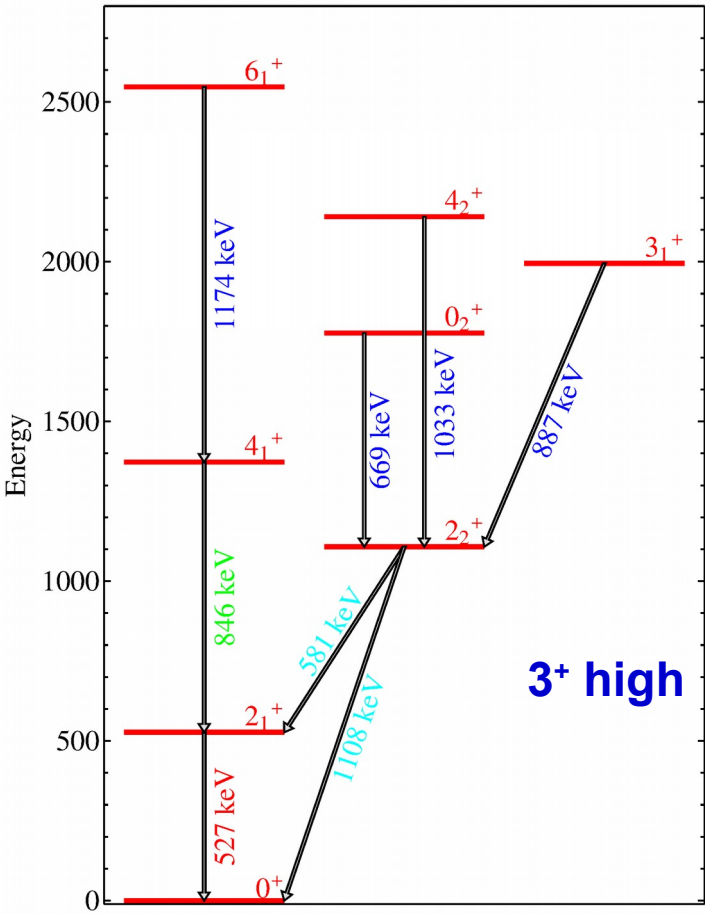


low-lying γ-band

$R_{4/2}$ ~ 2.5

typical γ-soft

IBM – γ-soft O(6)



3^+ high

Triaxiality in ^{86}Ge ?

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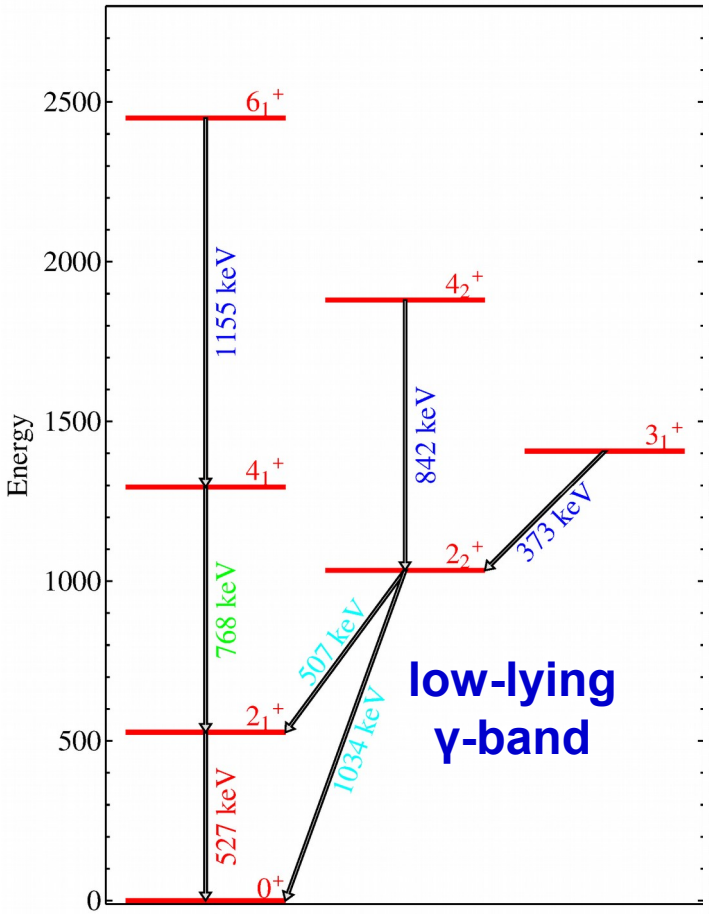
Tentative Level Scheme

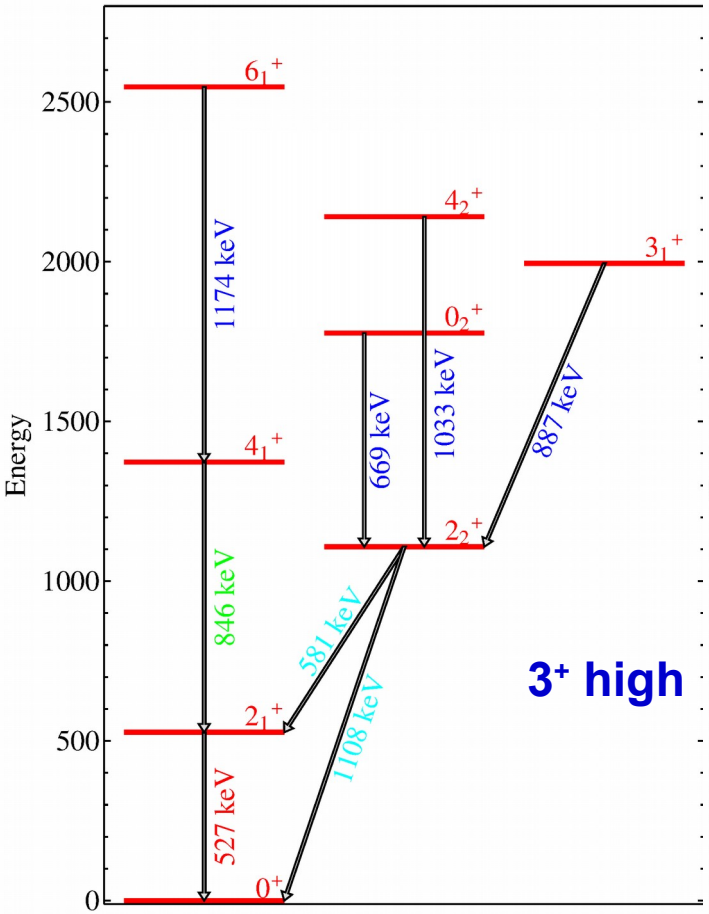


low-lying γ-band

$R_{4/2} \sim 2.5$

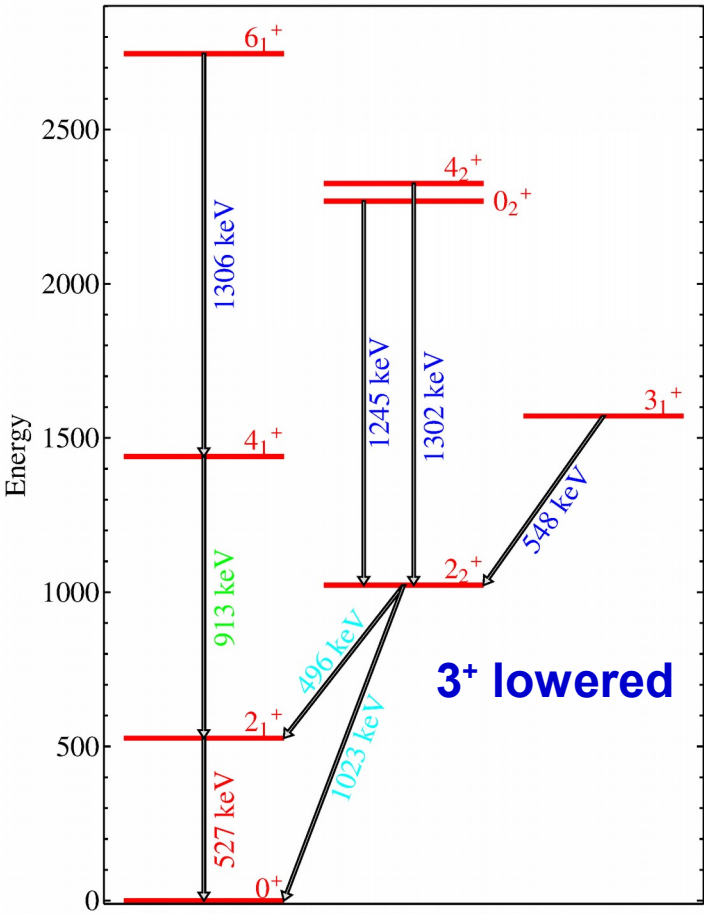
typical γ-soft

IBM – γ-soft O(6)



3^+ high

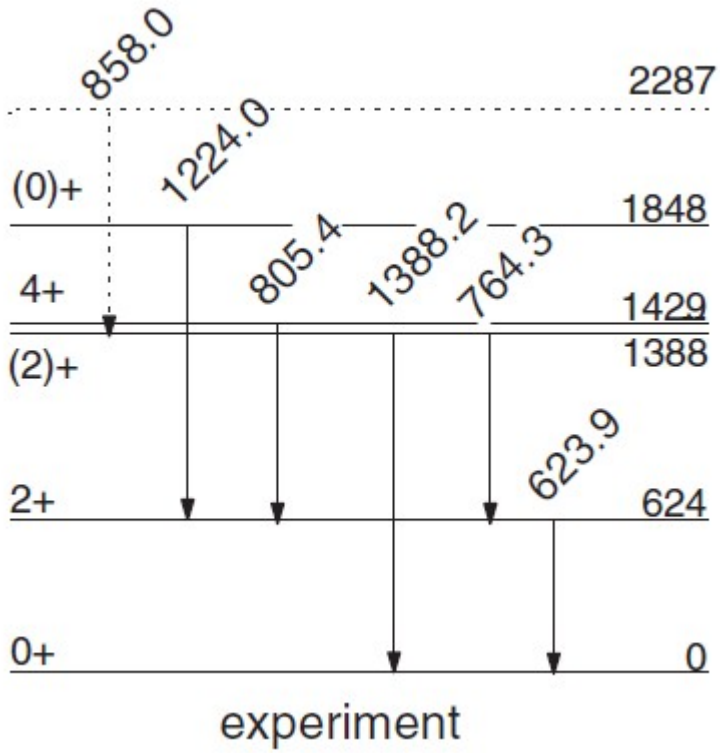
IBM-2 – γ-rigid "O(6)"



3^+ lowered

Gamma-Band odd-even staggering hints at rigid triaxiality !

^{84}Ge assignments b-delayed



A. Korgul, PRC88, 044330 (2013)