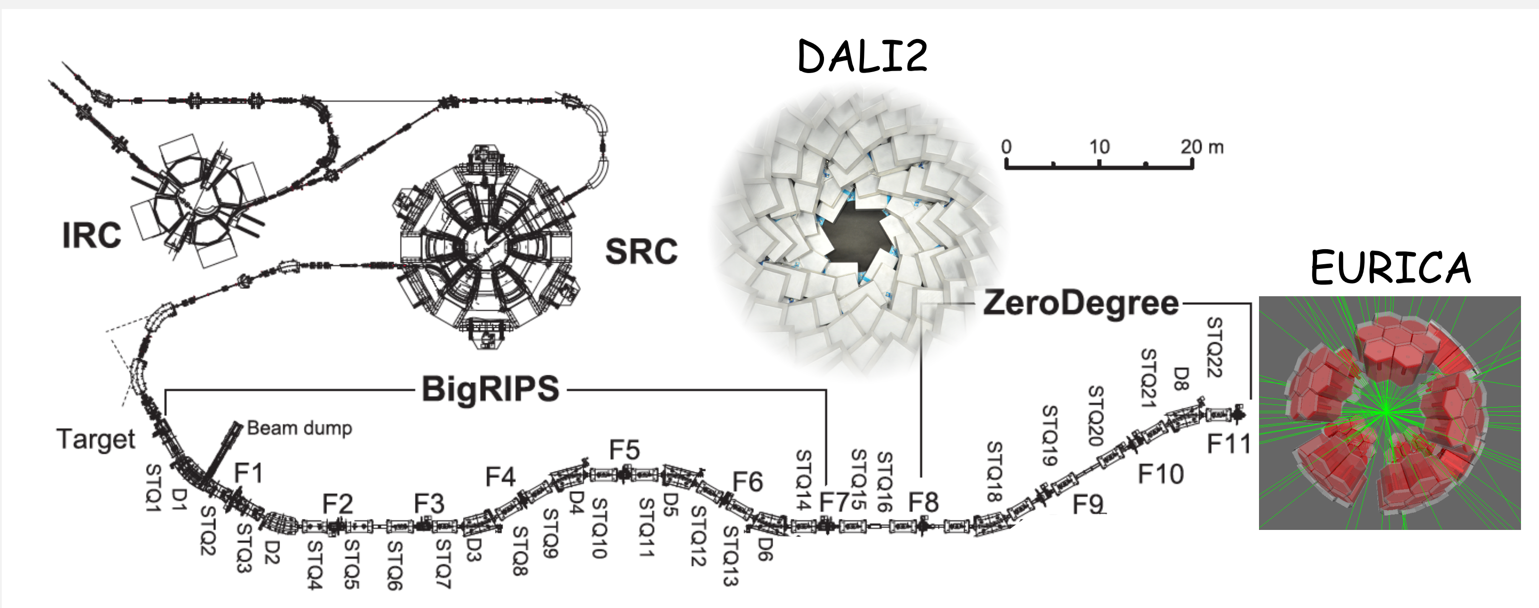
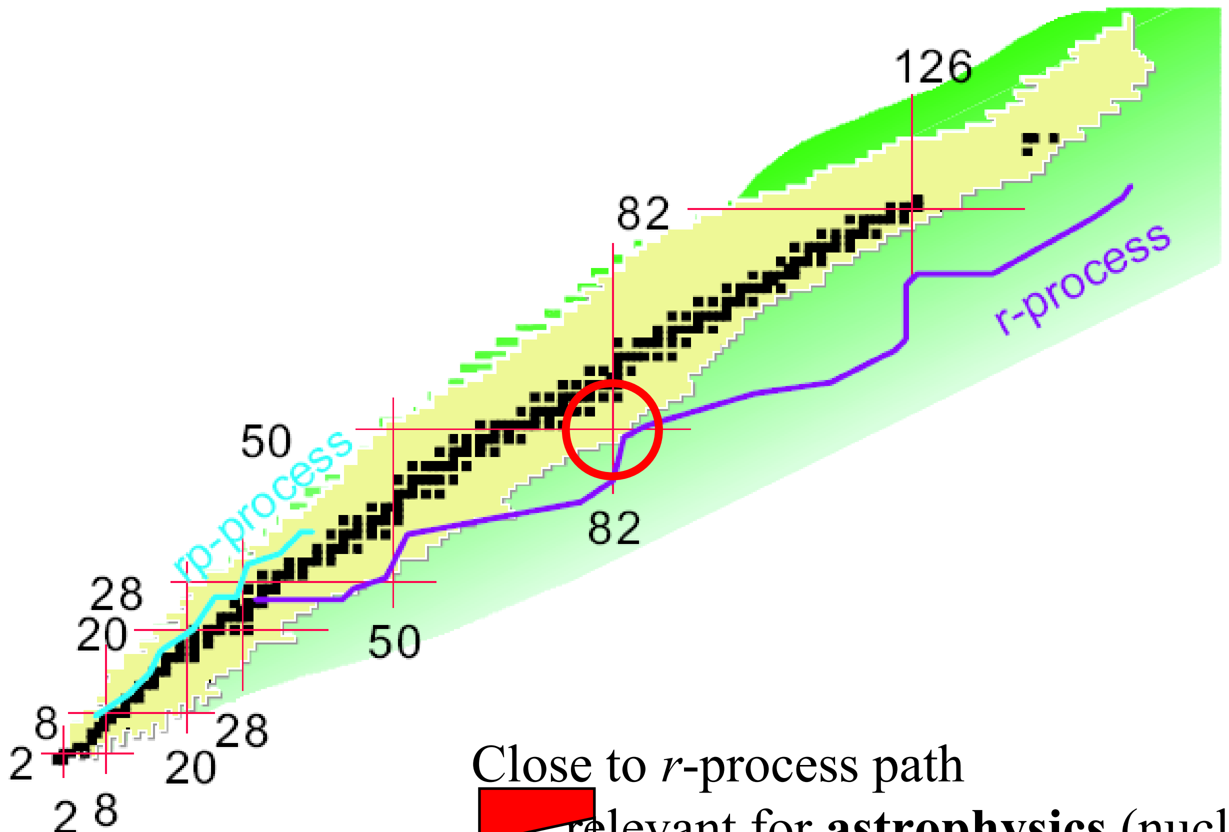
In-beam and decay B-ray spectroscopy in the 132Sn region at RIKEN

Andrea Jungclaus

Instituto de Estructura de la Materia, CSIC
Madrid - Spain



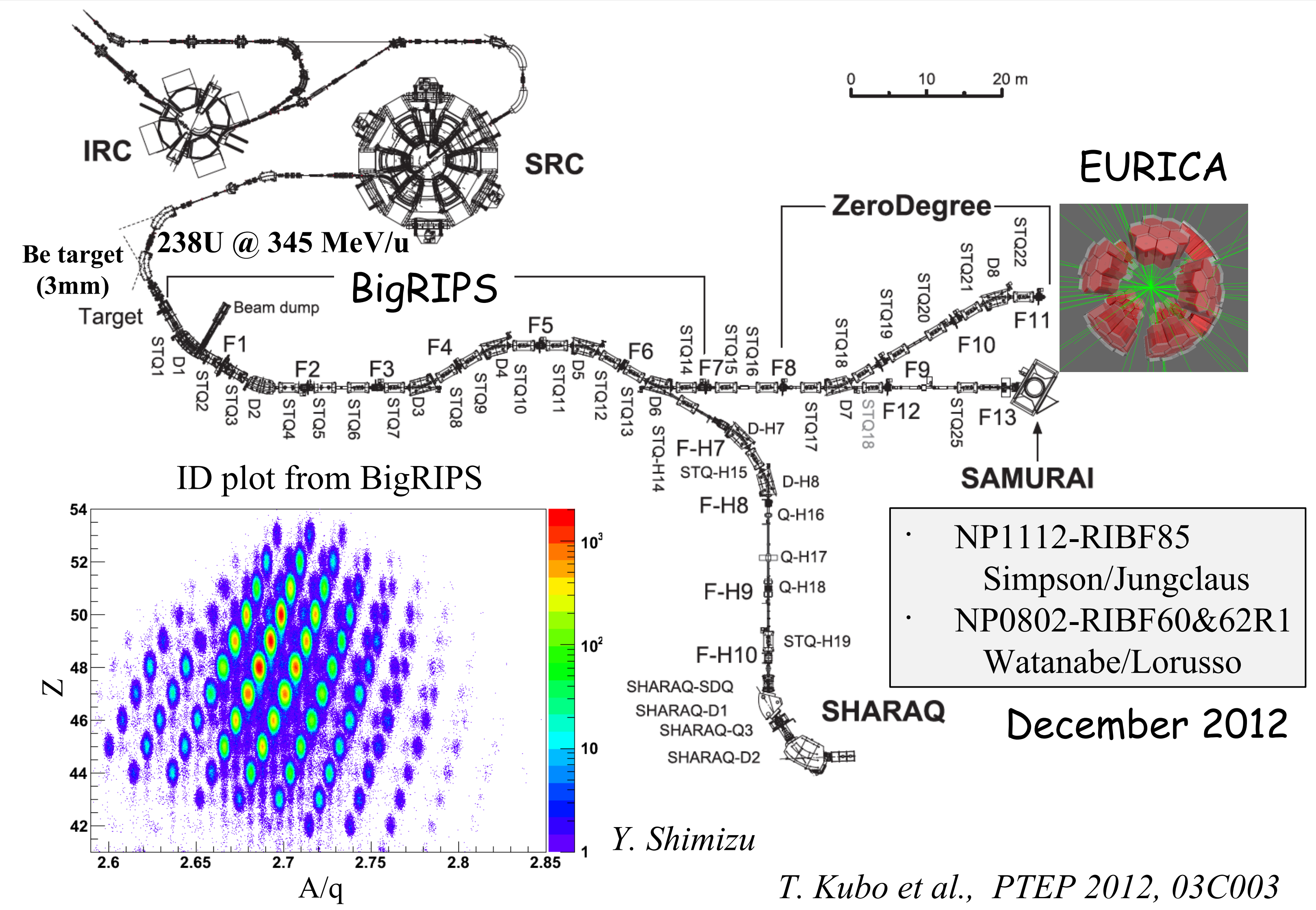
The region of interest around 132Sn



Close to *r*-process path
→ relevant for **astrophysics** (nucleosynthesis)

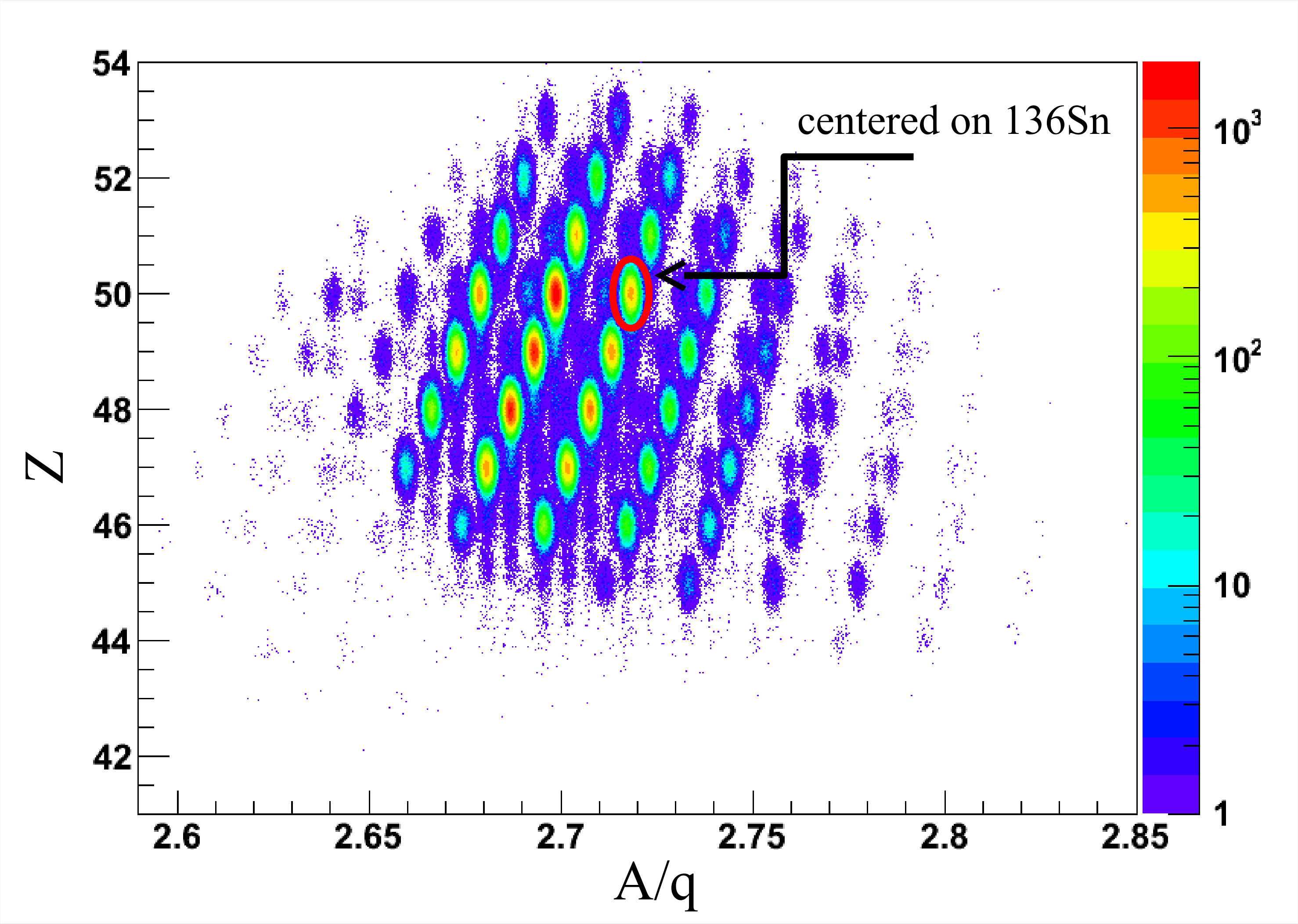
Heaviest accessible doubly-magic nucleus far-off stability
→ relevant for **nuclear structure** (shell model)

Decay spectroscopy: The EURICA project 2012-2016



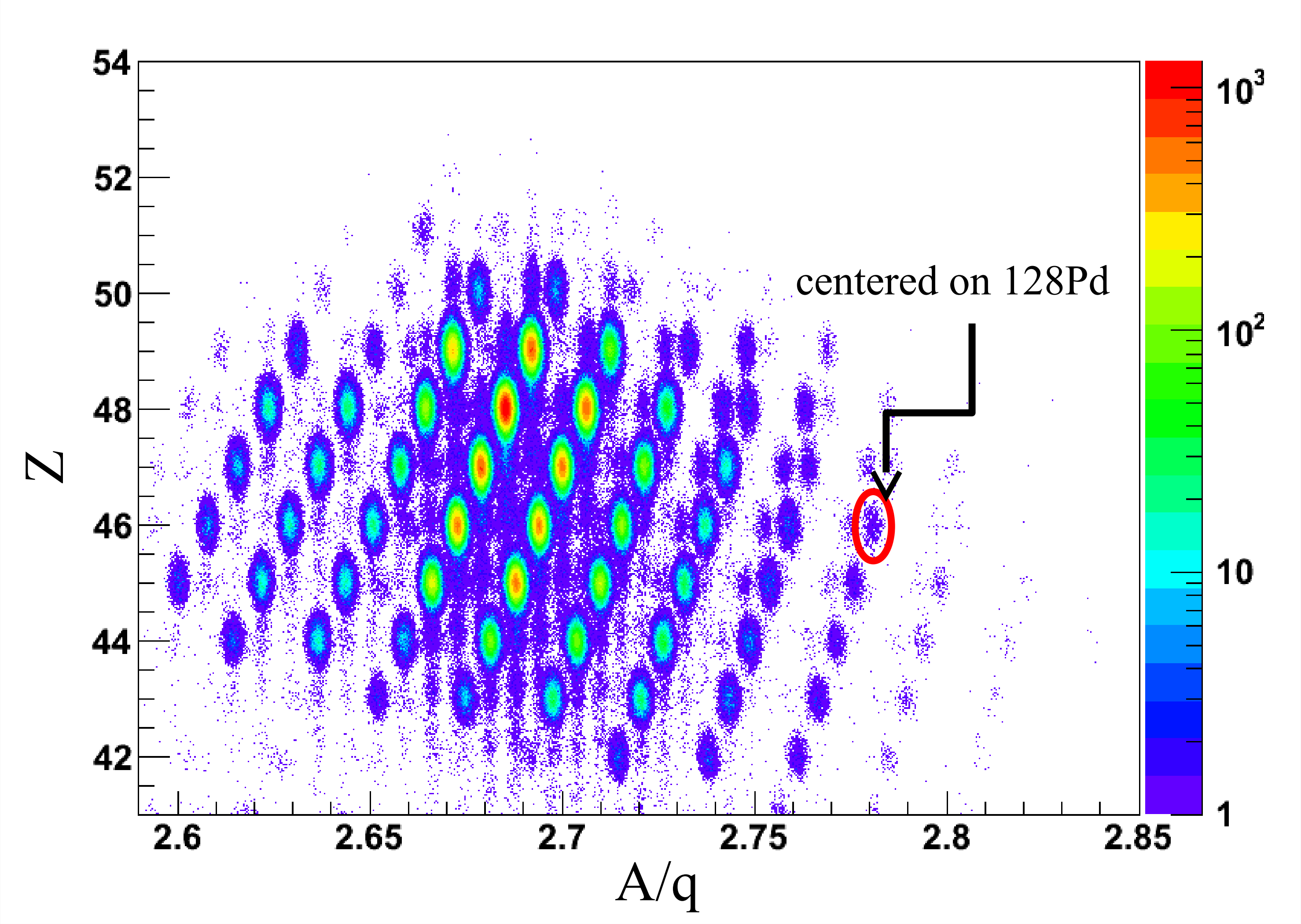
Ion identification plot from BigRIPS

NP1112-RIBF85 – Simpson/Jungclaus

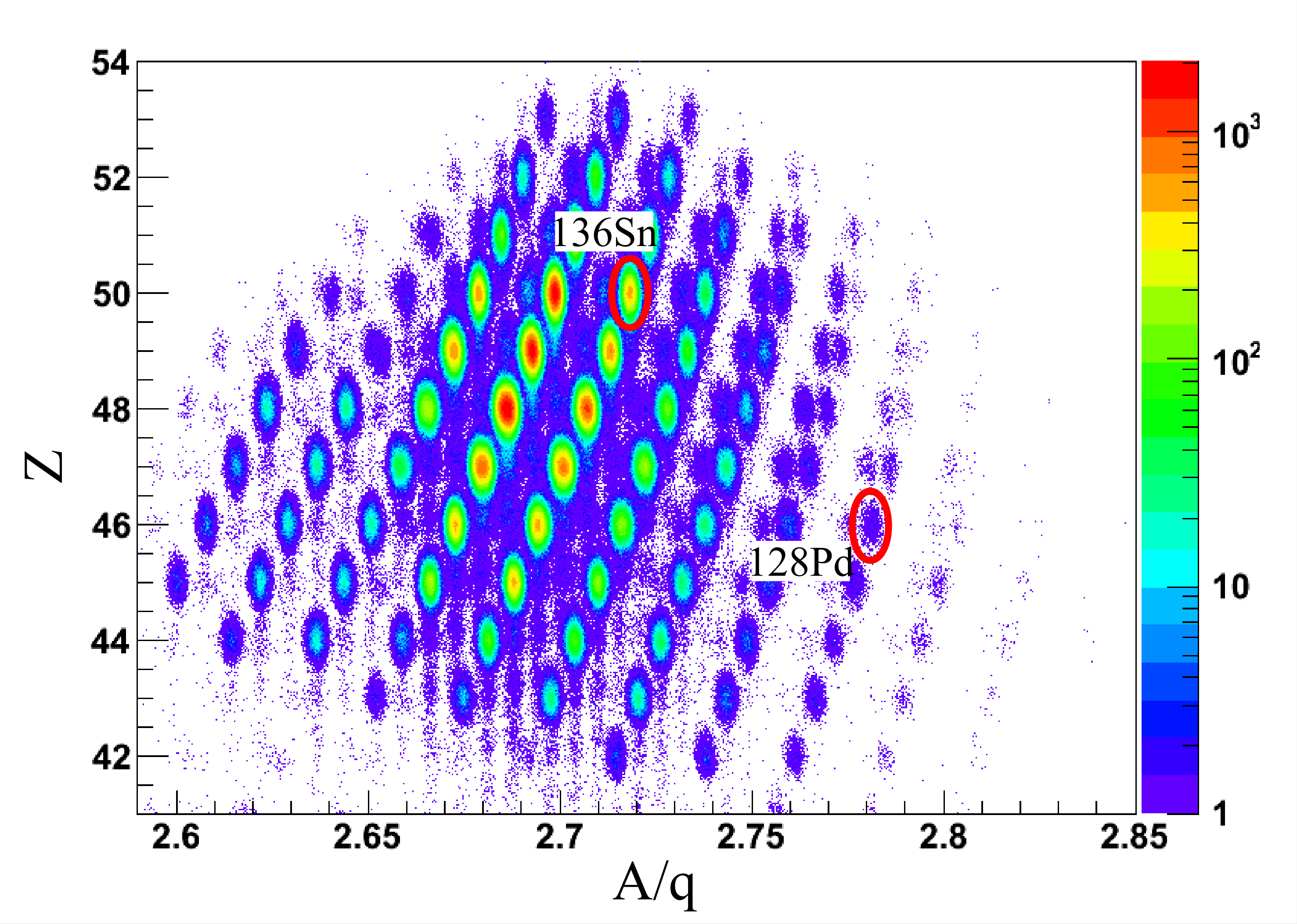


Ion identification plot from BigRIPS

NP0802-RIBF60&62R1 - Watanabe/Lorusso



BigRIPS ID plot: Sum of the two settings



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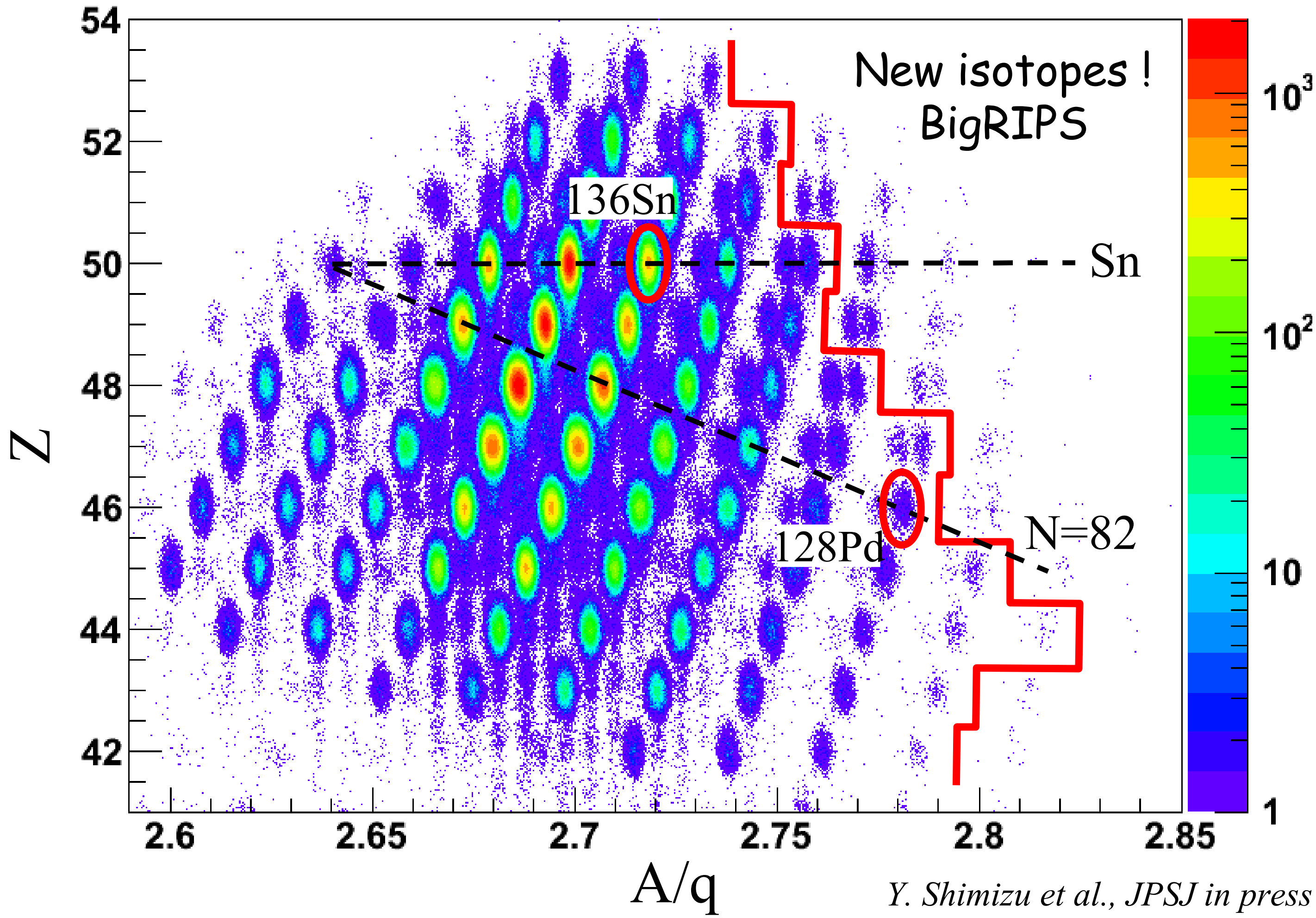
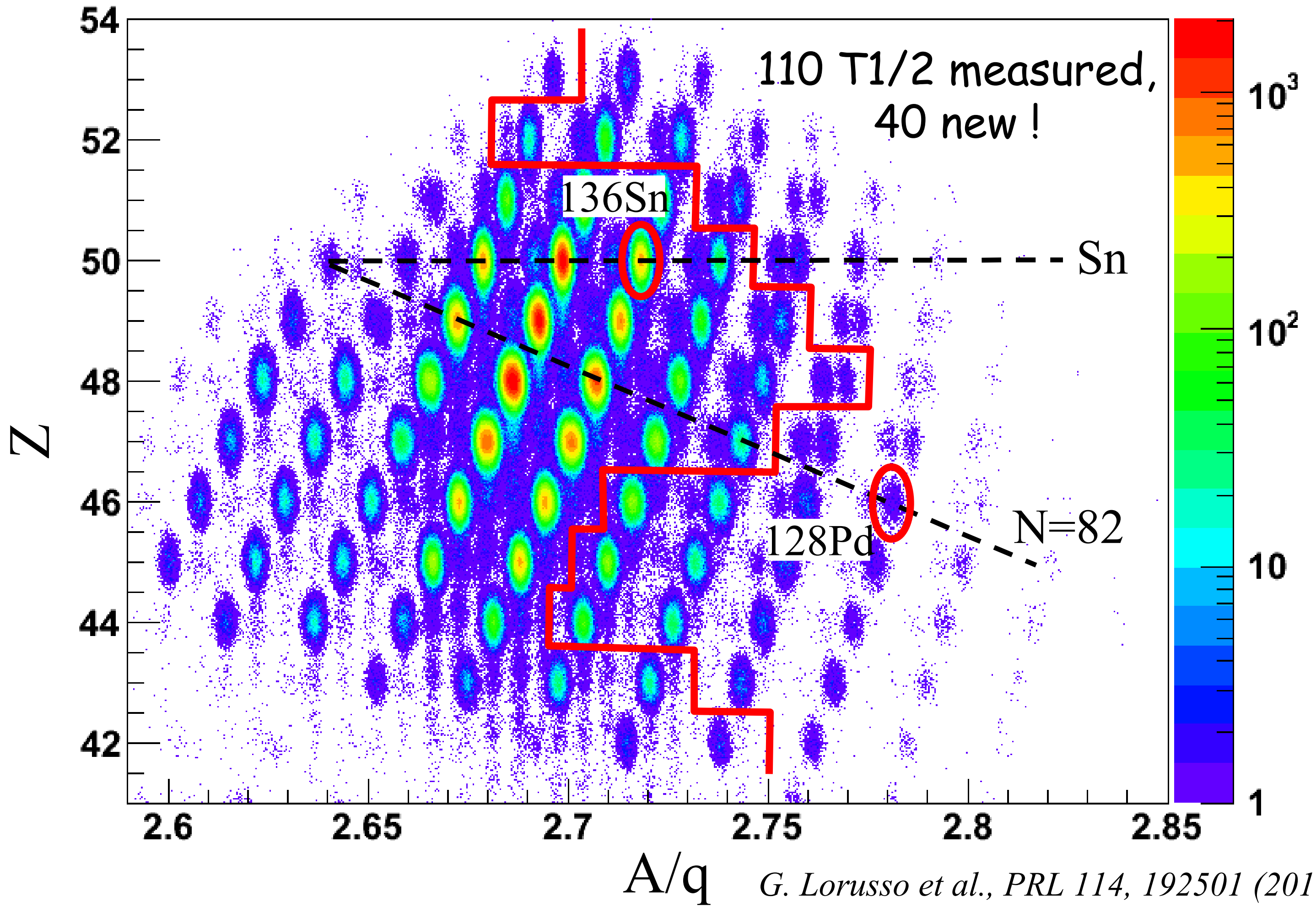


Y. Shimizu et al., JPSJ in press

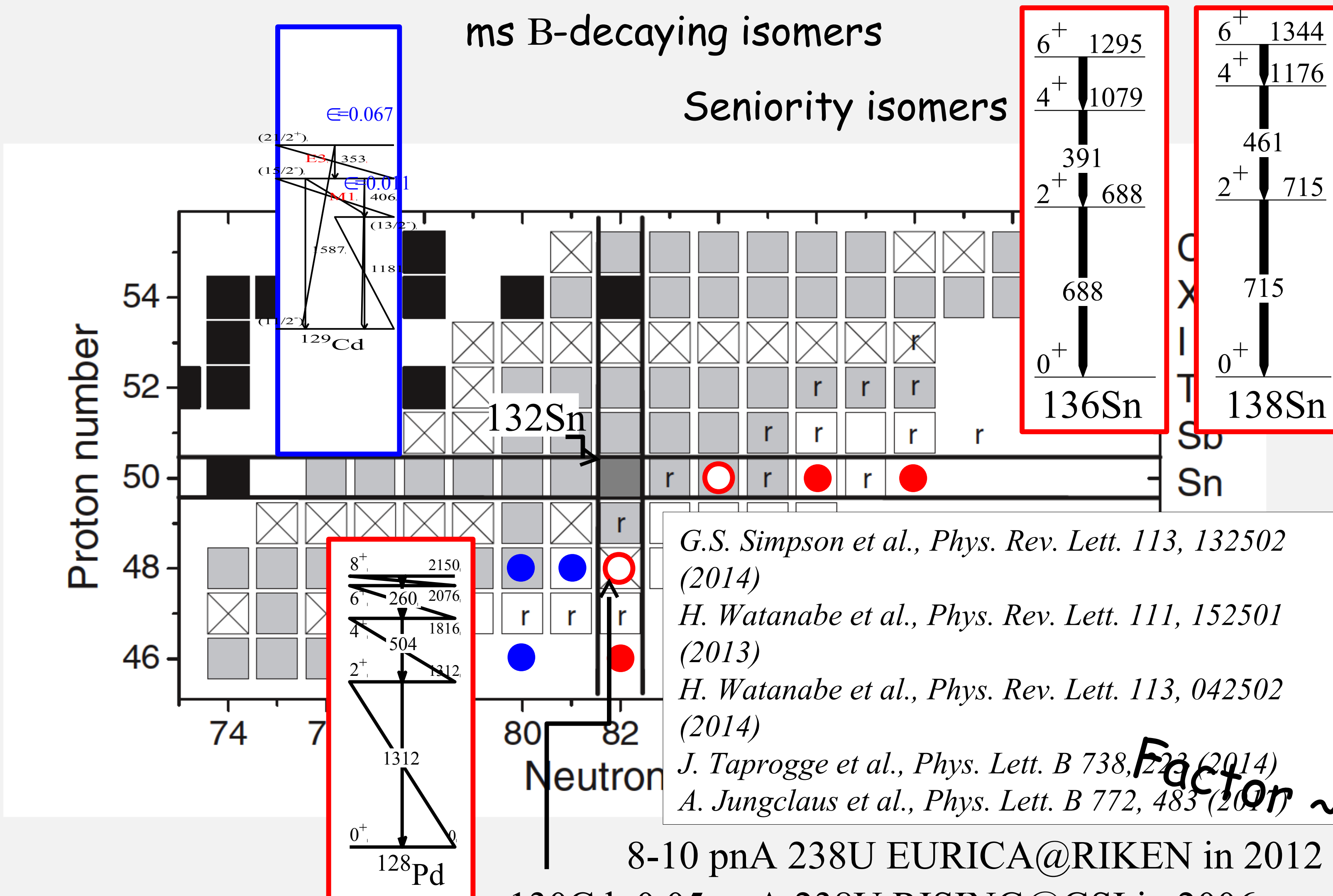
BigRIPS ID plot: Sum of the two settings



G. Lorusso et al., PRL 114, 192501 (2015)

Significant impact on r-process calculations !

EURICA information on isomers in the 132Sn region



G.S. Simpson et al., Phys. Rev. Lett. 113, 132502 (2014)
H. Watanabe et al., Phys. Rev. Lett. 111, 152501 (2013)
H. Watanabe et al., Phys. Rev. Lett. 113, 042502 (2014)
J. Taprogge et al., Phys. Lett. B 738, 223 (2014)
A. Jungclaus et al., Phys. Lett. B 772, 483 (2017)

Factor ~200 !

8-10 pnA 238U EURICA@RIKEN in 2012

130Cd: 0.05 pnA 238U RISING@GSI in 2006

A. Jungclaus et al., Phys. Rev. Lett. 99, 132501 (2007)

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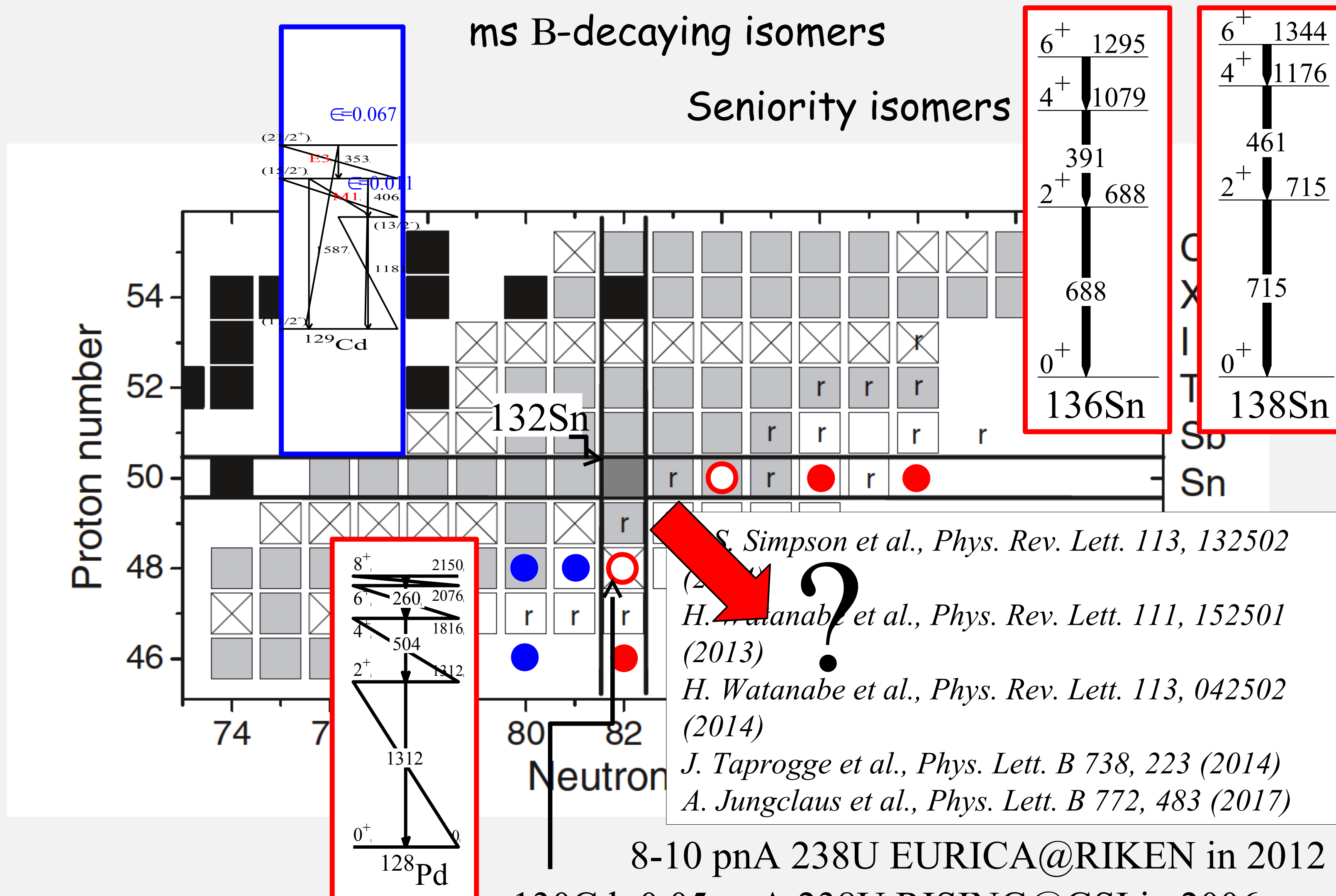

S. Simpson et al., Phys. Rev. Lett. 113, 132502 (2014)

H. Watanabe et al., Phys. Rev. Lett. 111, 152501 (2013)

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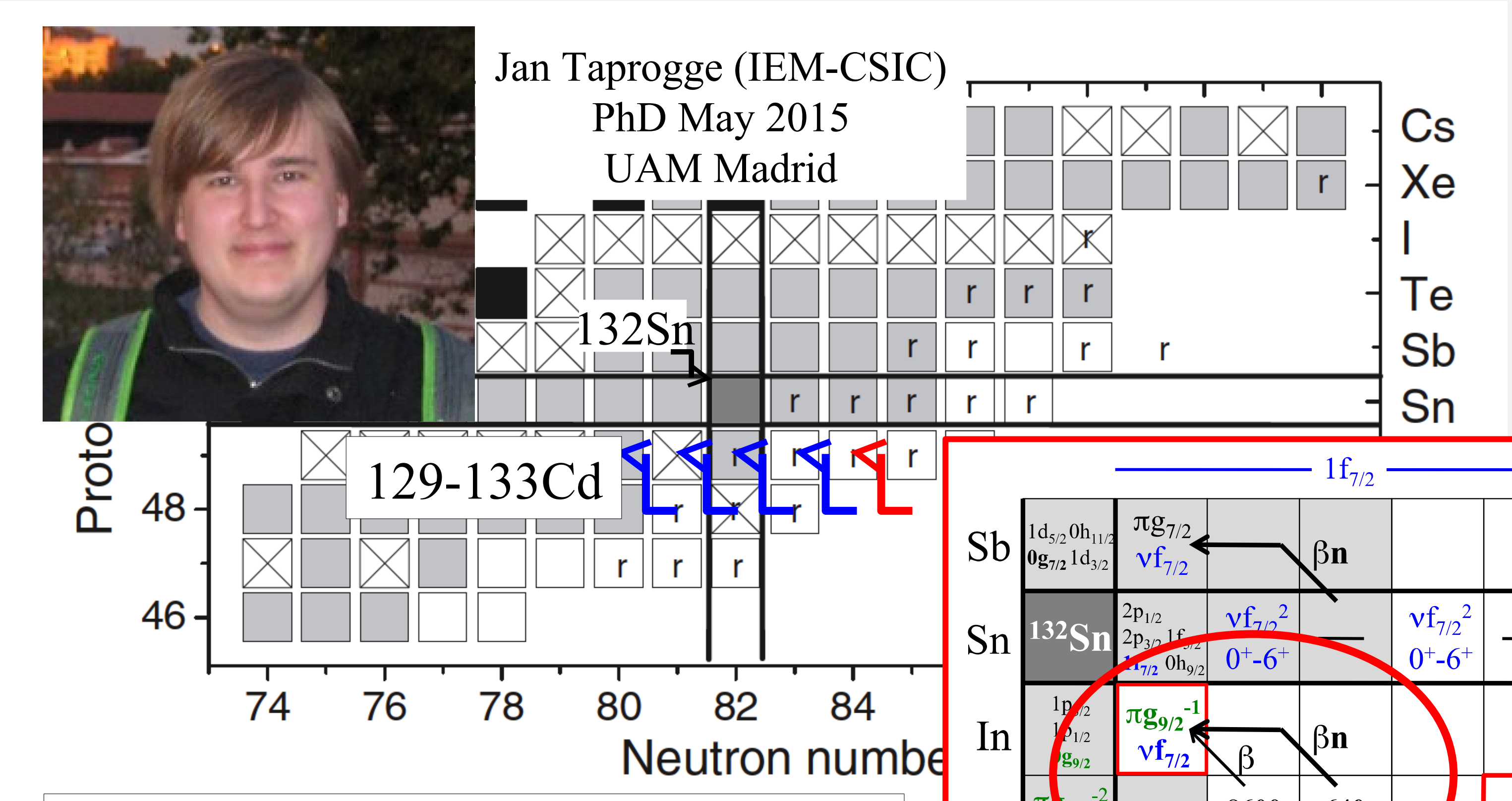
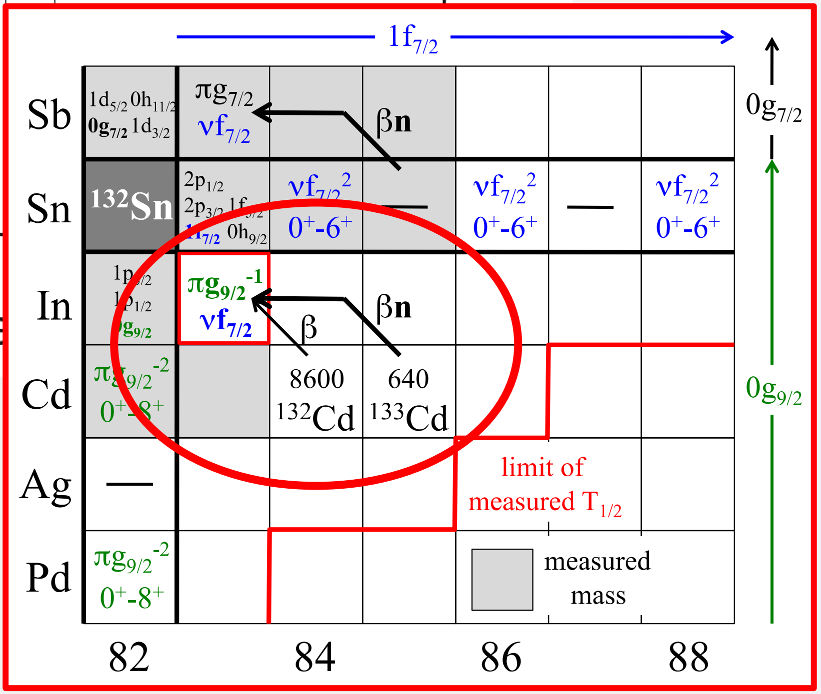
EURICA information on ∩ decays in the 132Sn region



8-10 pnA
238U in 2012

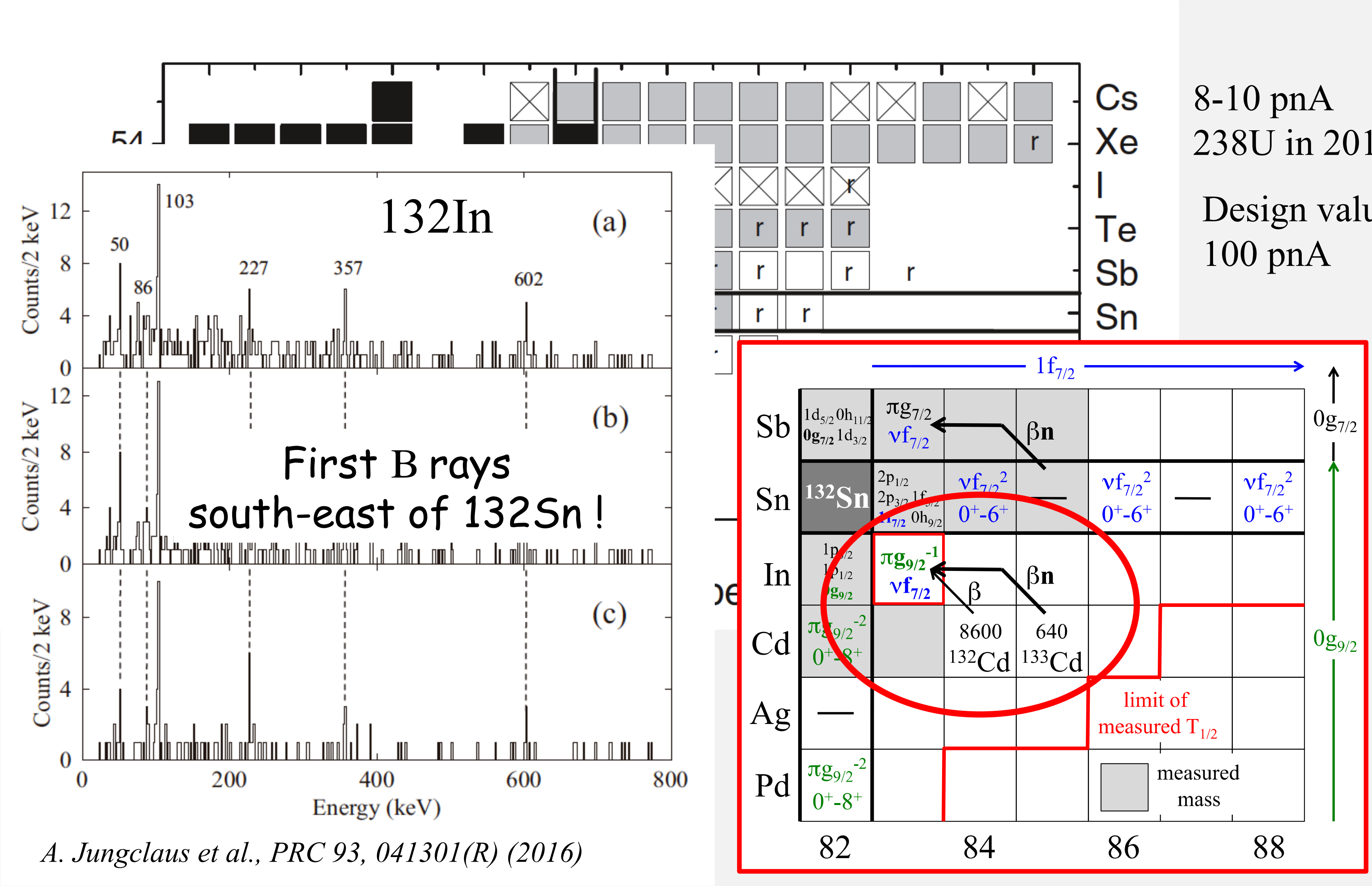
Design value:
100 pnA

J. Taprogge et al., Phys. Rev. Lett. 112, 132501 (2014)
J. Taprogge et al., Phys. Lett. B 738, 223 (2014)
J. Taprogge et al., Phys. Rev. C 91, 054324 (2015)
J. Taprogge et al., Eur. Phys. J. A 52, 347 (2016)
A. Jungclaus et al., Phys. Rev. C 93, 041301(R) (2016)
A. Jungclaus et al., Phys. Rev. C 94, 024303 (2016)
A. Jungclaus et al., Phys. Lett. B 772, 483 (2017)



Difficult to enter quadrant south-east of 132Sn via ∩ decay !

EURICA information on ∩ decays in the 132Sn region



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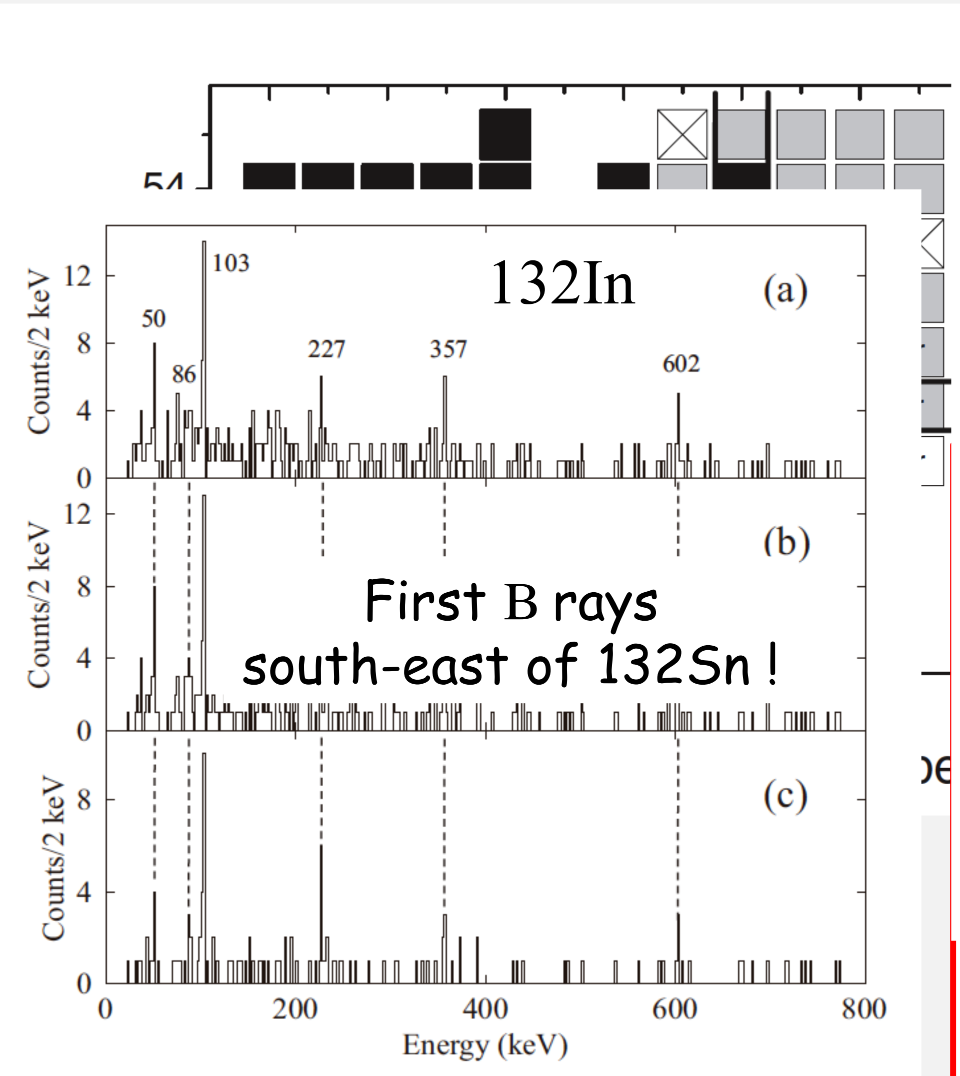
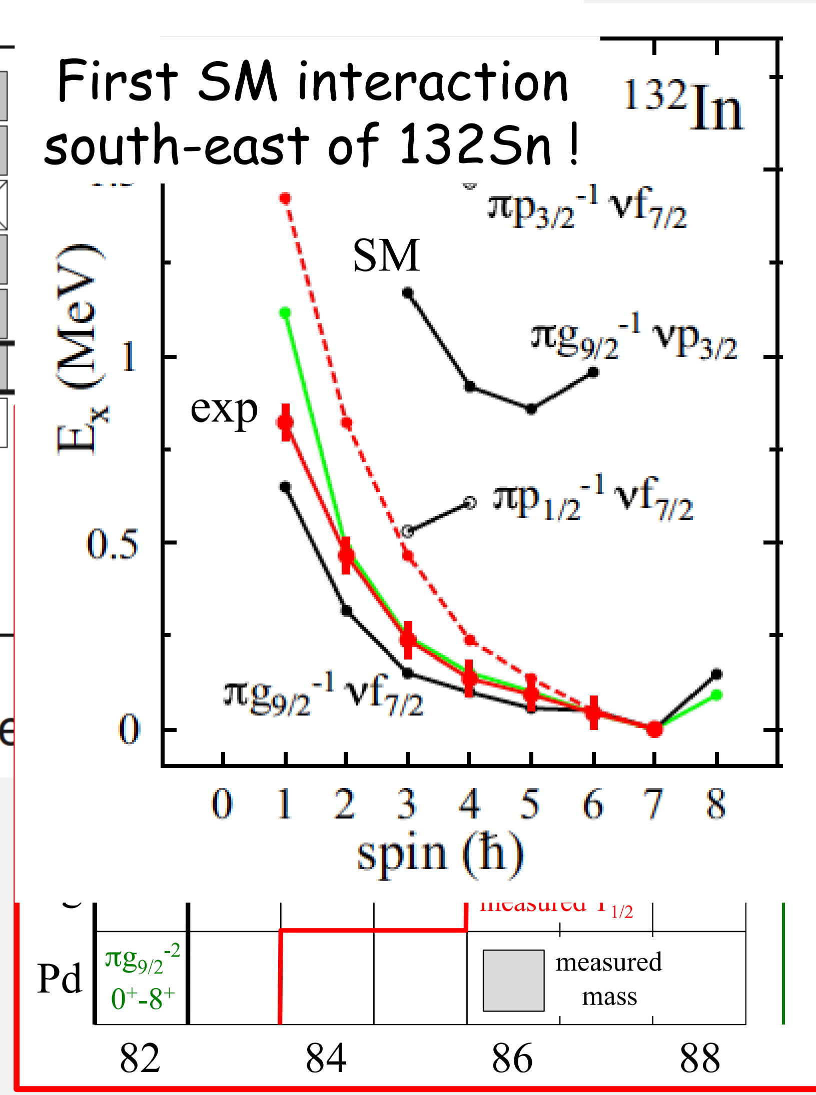


A. Jungclaus et al., PRC 93, 041301(R) (2016)



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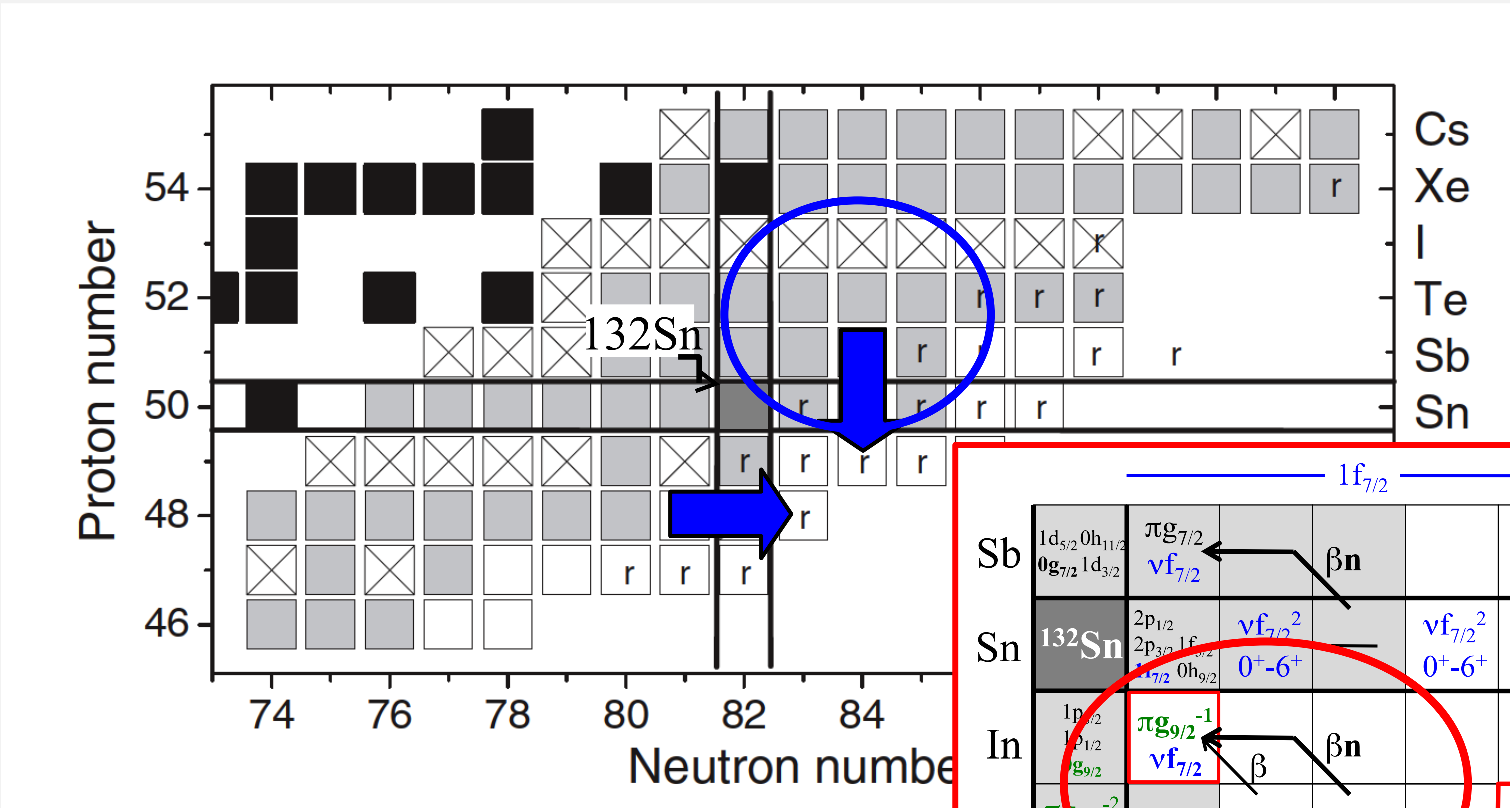

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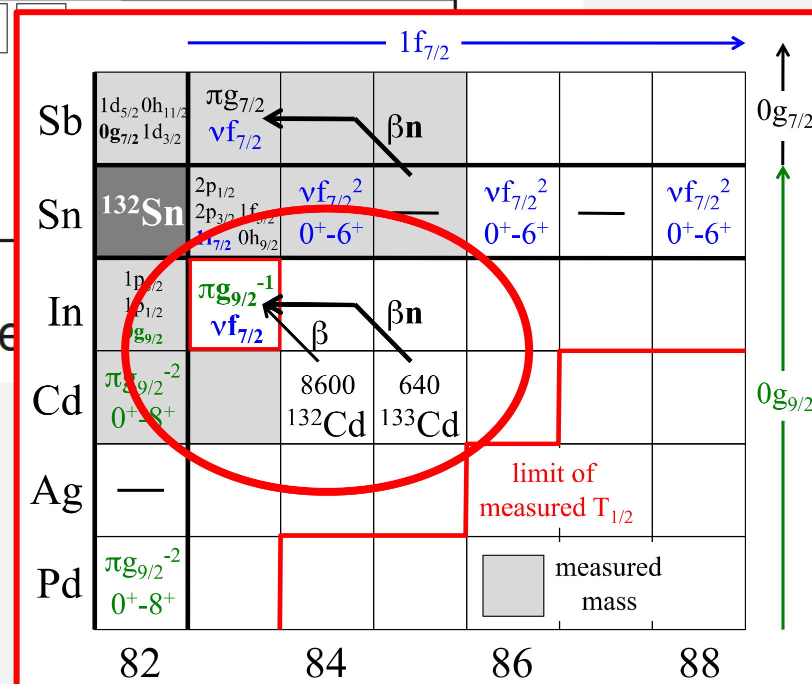
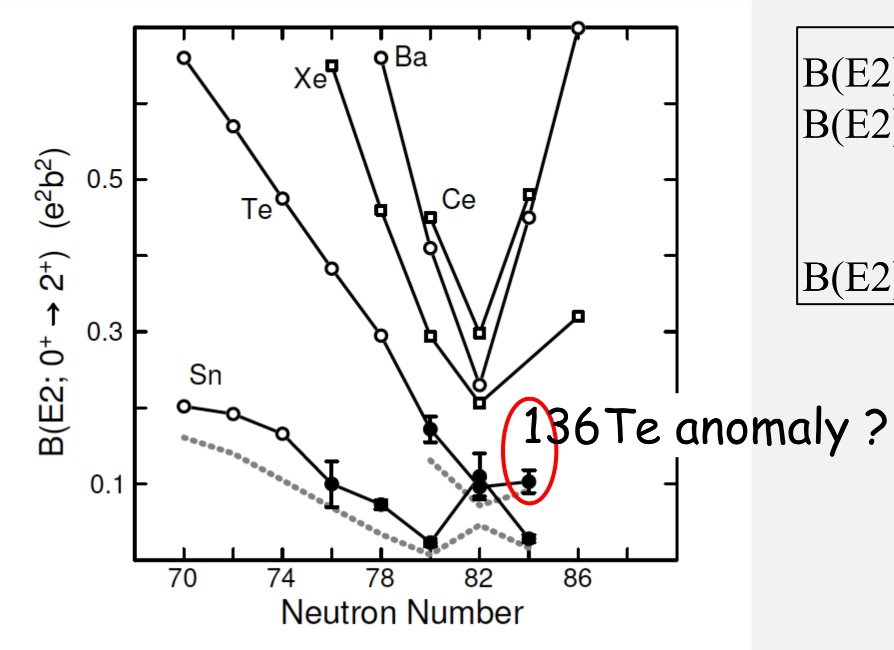


May it be easier using nuclear reactions ???

Difficult to enter quadrant south-east of 132Sn via ∩ decay !

RIKEN experiment NP1306-RIBF98R1: Coulex of 136Te



B(E2)up = 0.103(15) e2b2

B(E2)up = 0.122(18) e2b2 Coulex @ Oak Ridge

B(E2)up = 0.115(24) e2b2 fast timing @ ISOLDE

D.C. Radford et al., PRL 88, 222501 (2002)

M. Danchev et al., PRC 84, 061306(R) (2011)

L.M. Fraile et al., SSNET 2016

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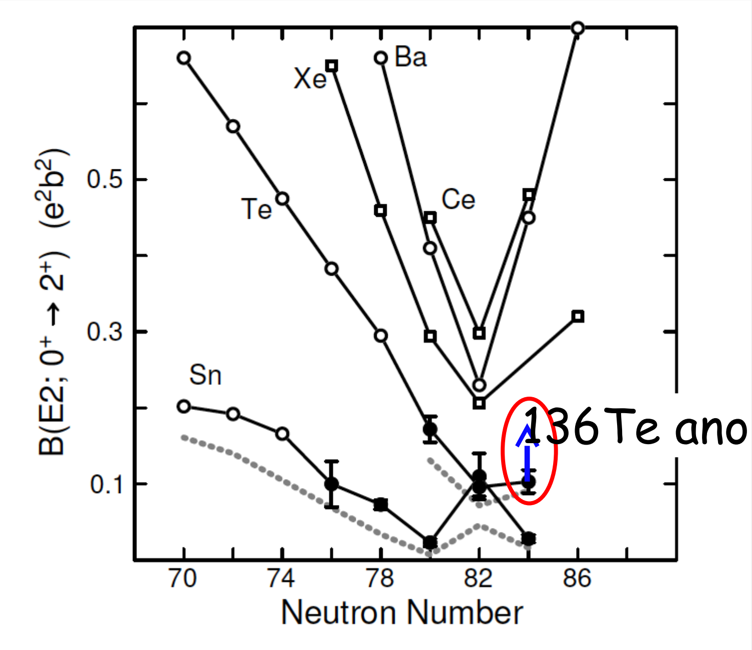


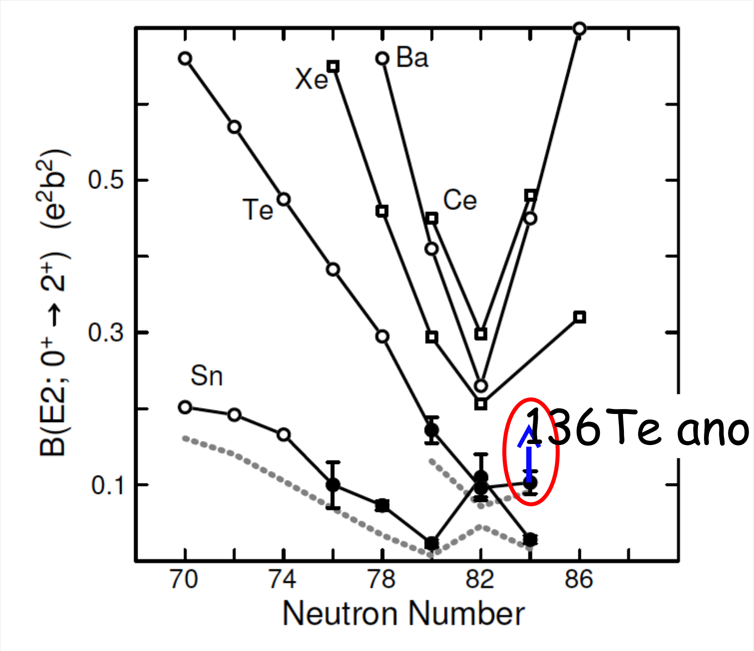
B(E2)up = 0.103(15) e2b2	
B(E2)up = 0.122(18) e2b2	Coulex @ Oak Ridge
B(E2)up = 0.181(15) e2b2	
B(E2)up = 0.115(24) e2b2	fast timing @ ISOLDE

D.C. Radford et al., PRL 88, 222501 (2002)
M. Danchev et al., PRC 84, 061306(R) (2011)
J.M. Allmond et al., PRL 118, 092503 (2017)

L.M. Fraile et al., SSNET 2016

Remeasure via Coulex at relativistic energies !

RIKEN experiment NP1306-RIBF98R1: Coulex of 136Te



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J.M. Allmond et al., PRL 118, 092503 (2017)

L.M. Fraile et al., SSNET 2016

Remeasure via Coulex at relativistic energies !

Interesting by-product: Search for decay of the mixed-symmetry 2+ state in 136Te

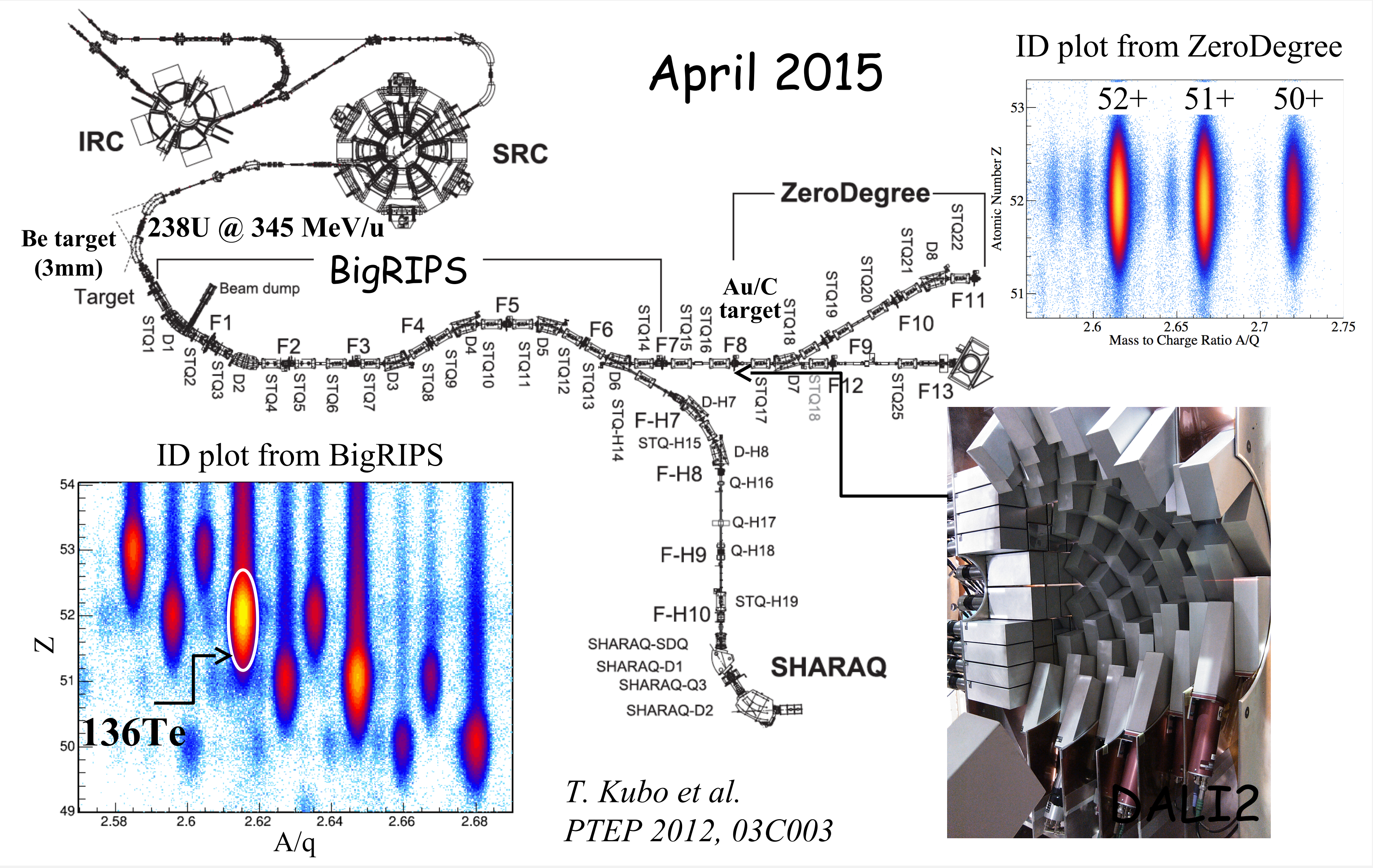
Theoretical predictions for B(E2) to the ms 2+ms in 136Te (Ex~1.5-2.0 MeV):

SM:	B(E2; 0+1 ! 2+ms) = 0.03 e2b2	0.20×B(E2)up
QRPA:	B(E2; 0+1! 2+ms) = 0.074 e2b2	0.66×B(E2)up

Note: At relativistic energies
Ois nearly independent on Ex !

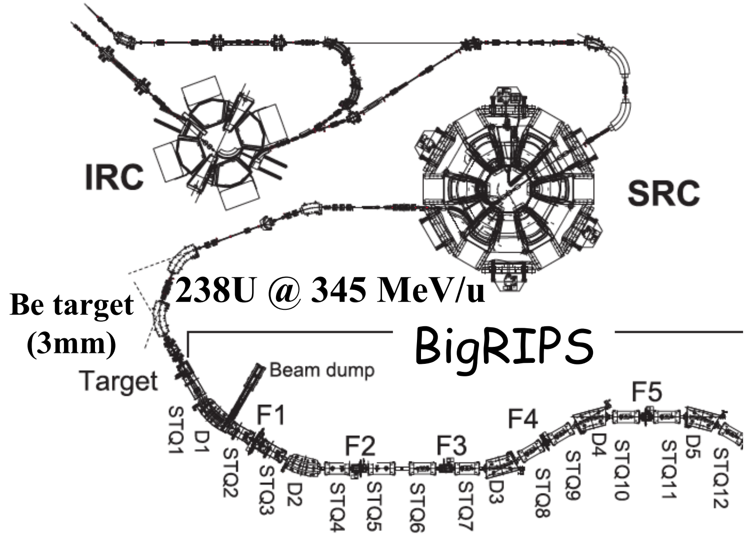
N. Shimizu et al., PRC 70, 054313 (2004)
A.P. Severyukhin et al., PRC 90, 011306(R) (2014)

RIKEN experiment NP1306-RIBF98R1: Coulex of 136Te



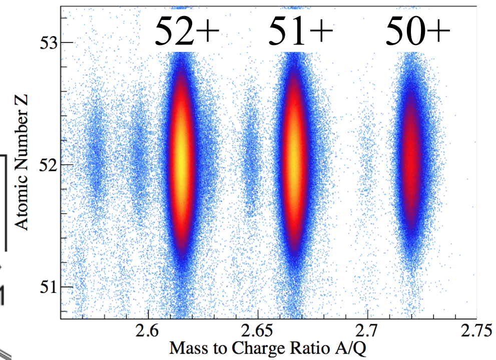
T. Kubo et al.
PTEP 2012, 03C003

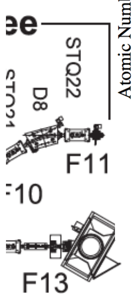
RIKEN experiment NP1306-RIBF98R1: Coulex of 136Te

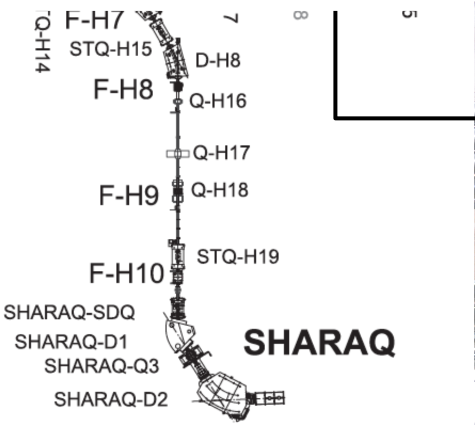


Víctor Vaquero

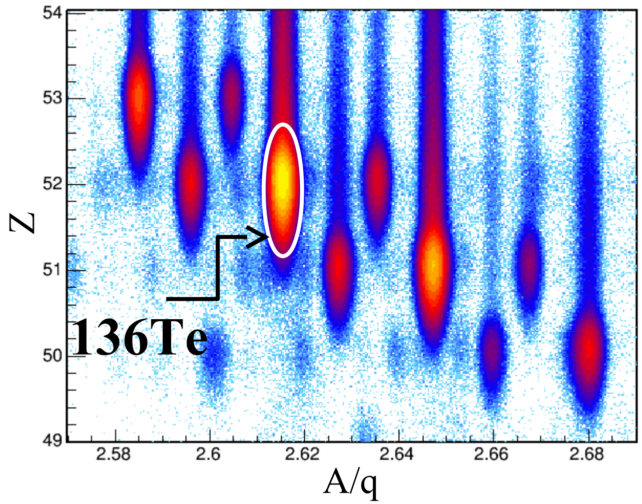
ID plot from ZeroDegree



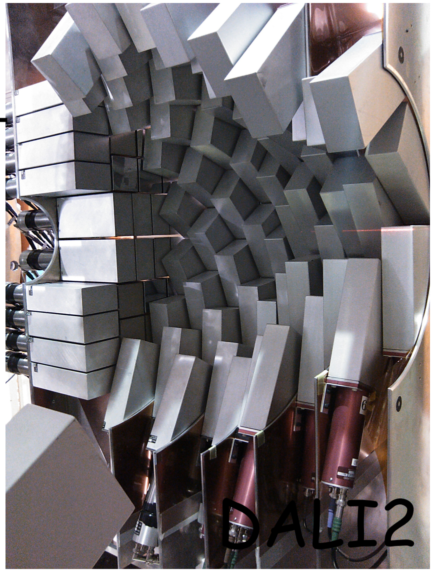




ID plot from BigRIPS



T. Kubo et al.
PTEP 2012, 03C003



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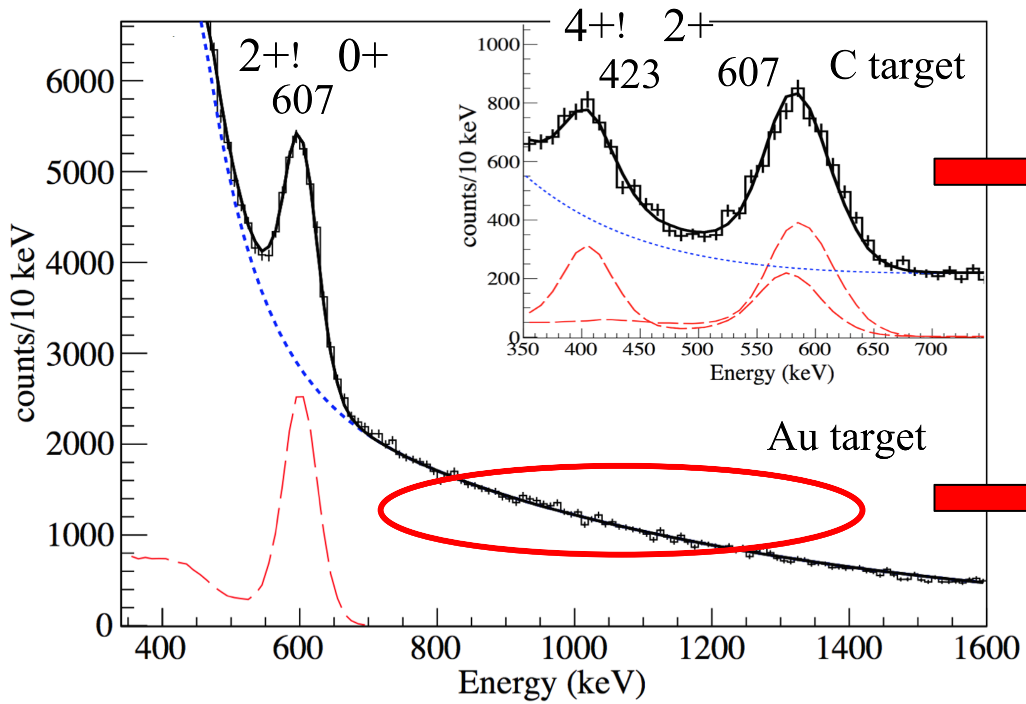


C target run to deduce the nuclear contribution to σAu:

σC = 21(3) mb

σAu = 260(9) mb

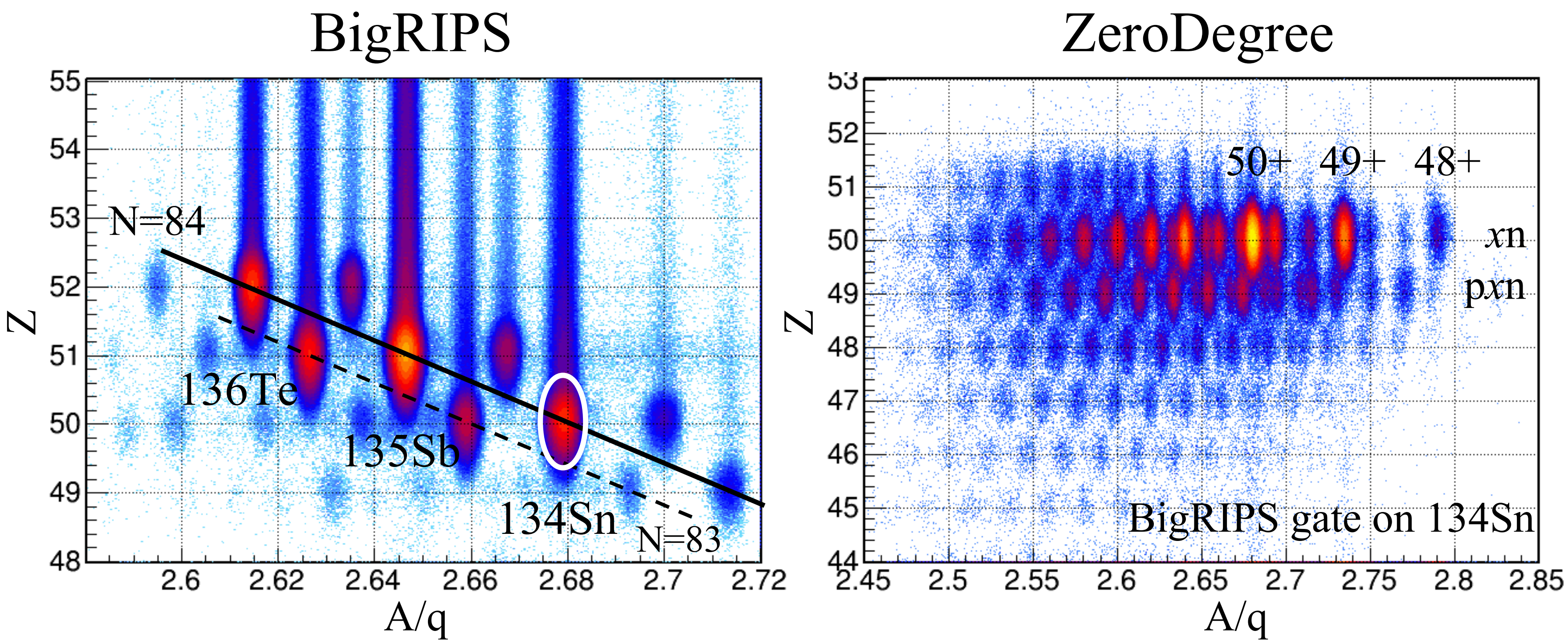
• (±2) = ?? e2b2

Still to be done:

Detailed consideration of feeding contributions, analysis of differential cross sections etc.

No indication for the decay of the 2+ms state ! Theoretical predictions off ...

Interesting by-product: Knockout reactions on C target

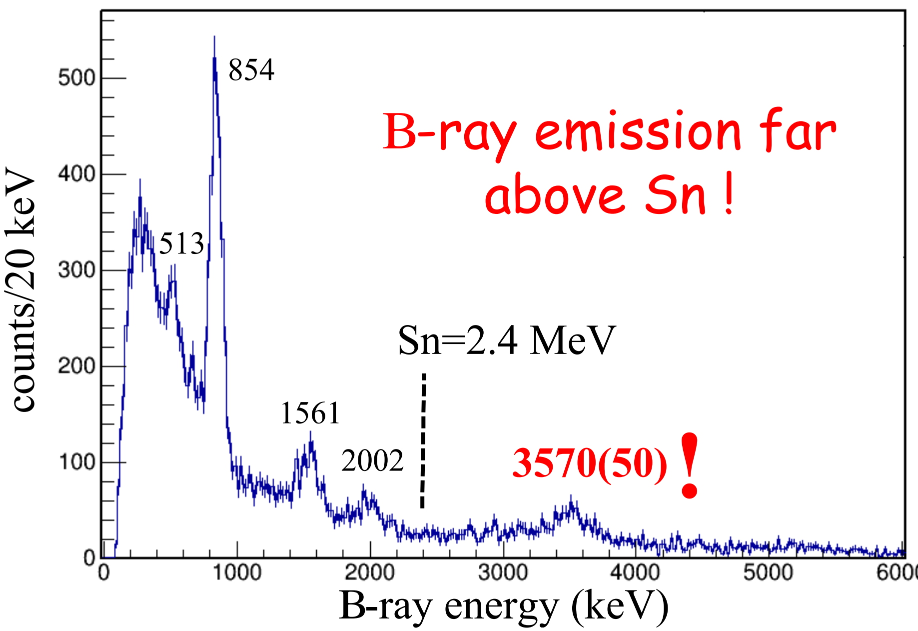


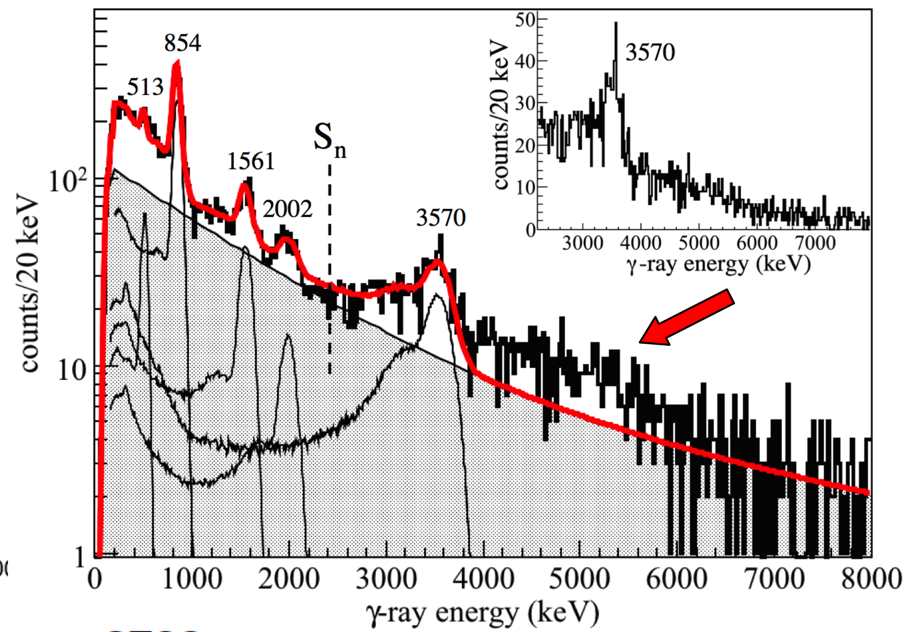
Allows to study systematics of *xn* knockout cross sections ...

Of course carefully taking into account ZD transmission, reaction losses in detector material along the beam line, C target properties etc.

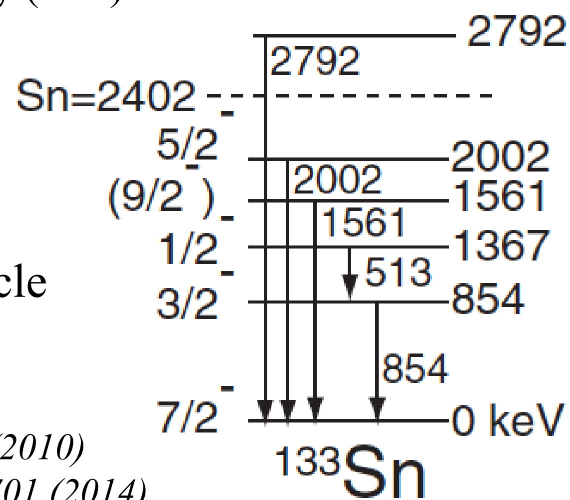
... and perform Β-ray spetroscopy of knockout residues !

133Sn populated via 1n knockout from 134Sn





513, 854, 1561, 2002 keV transitions from decay of known neutron single-particle states.



K.L. Jones et al., Nature 465, 454 (2010)
J.M. Allmond et al., PRL 112, 172701 (2014)

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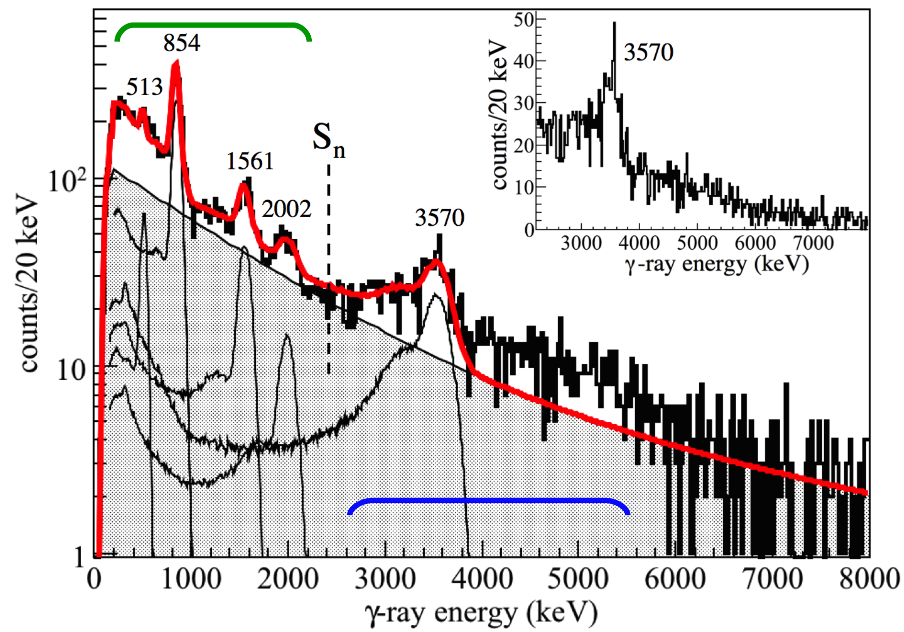
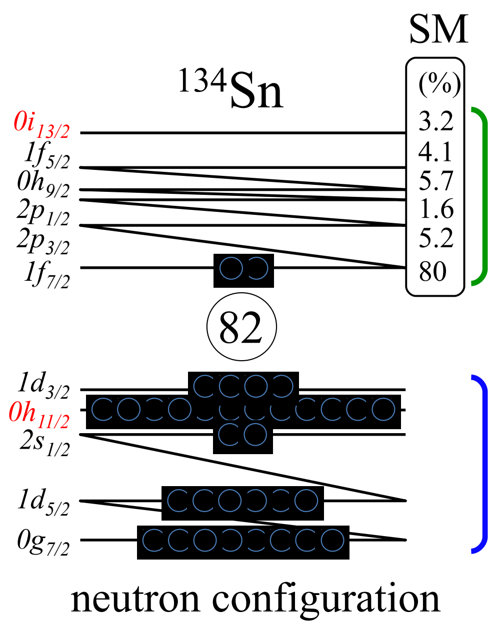




knockout from valence space
Oval

➡ **bound** single-particle states in 133Sn

knockout from N=82 core
Ocore

➡ **unbound** core-excited states in 133Sn

Why can B decay compete with neutron emission ?

Neutron vs. B competition above Sn in 133Sn

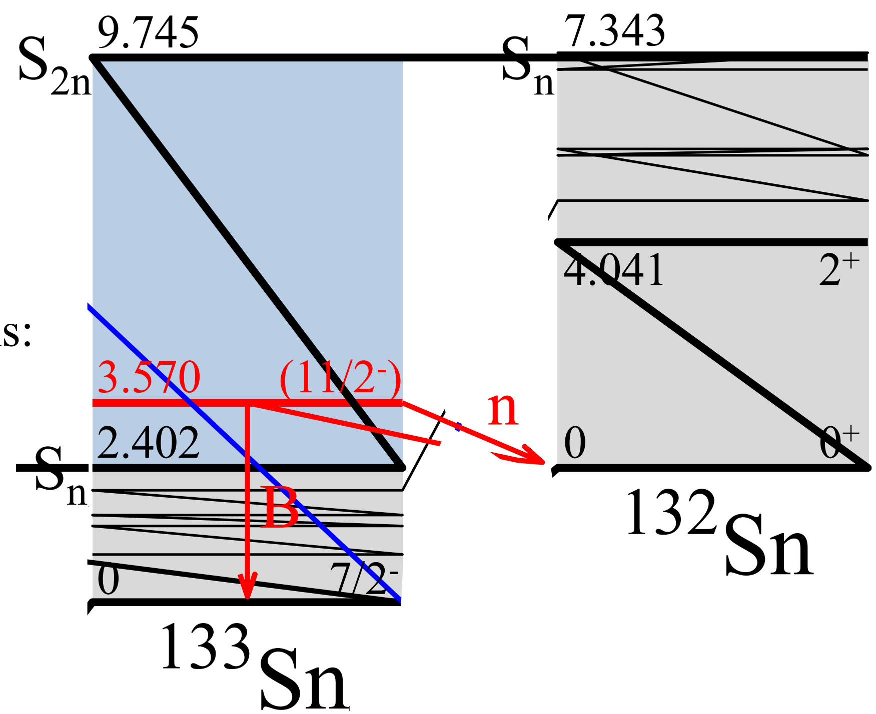
Up to Ex~6.4 MeV in 133Sn only neutron decay to the 132Sn g.s. is energetically possible.

In the case of knockout from h11/2

➡ neutron with ℓ =5 !

At the level of pure single-particle transitions:

neutron	**Π≈ 10-17 s**	[En=1.2 MeV]
E2 B-ray	**Π≈ 10-14 s**	[B(E2)=2 W.u.]



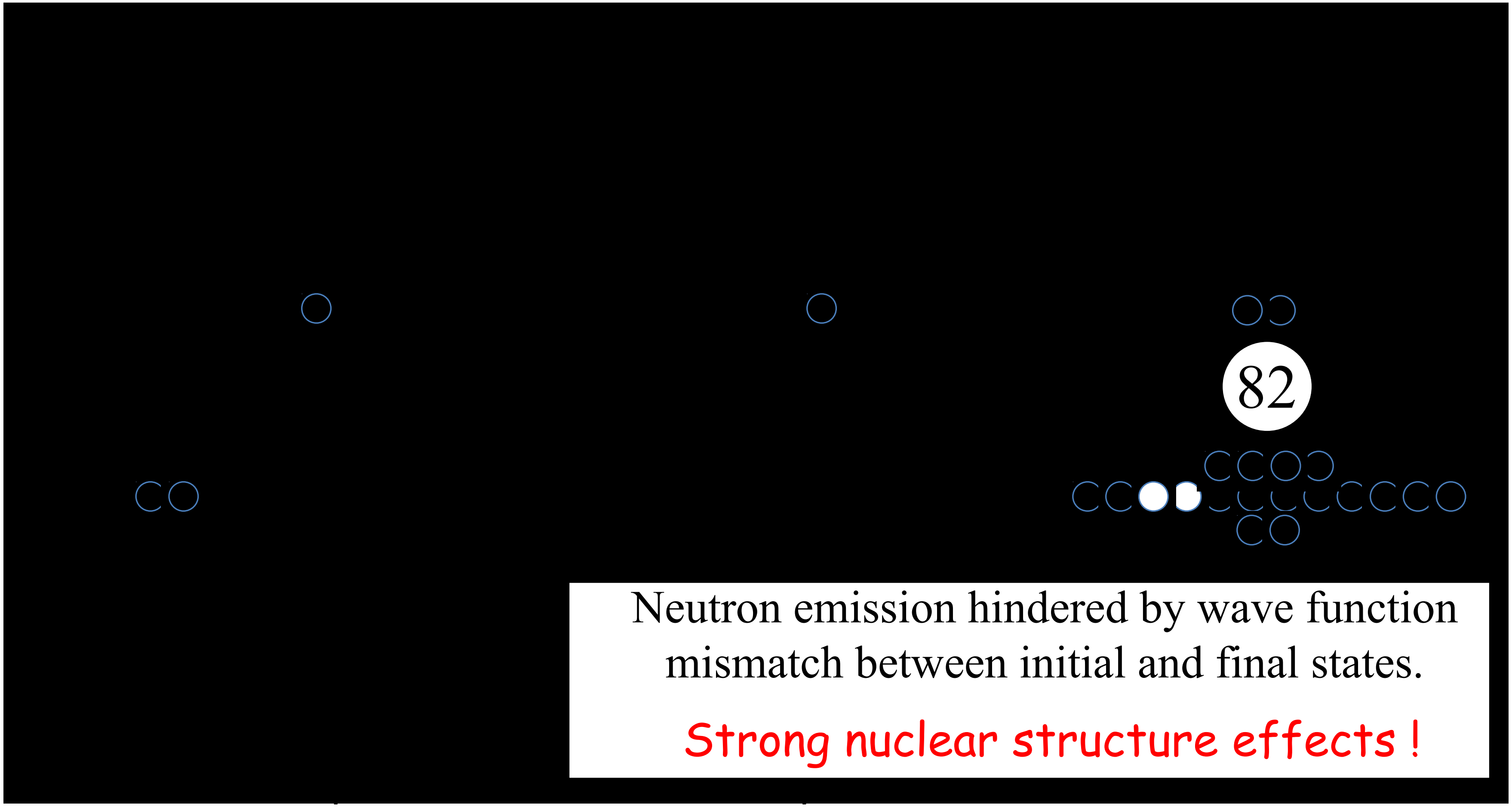
Neutron decay is expected to be roughly **three orders of magnitude faster** than E2 B decay to the 133Sn g.s. !

But ...

Neutron vs. B competition above S_n in ^{133}Sn

Neutron configuration after ...

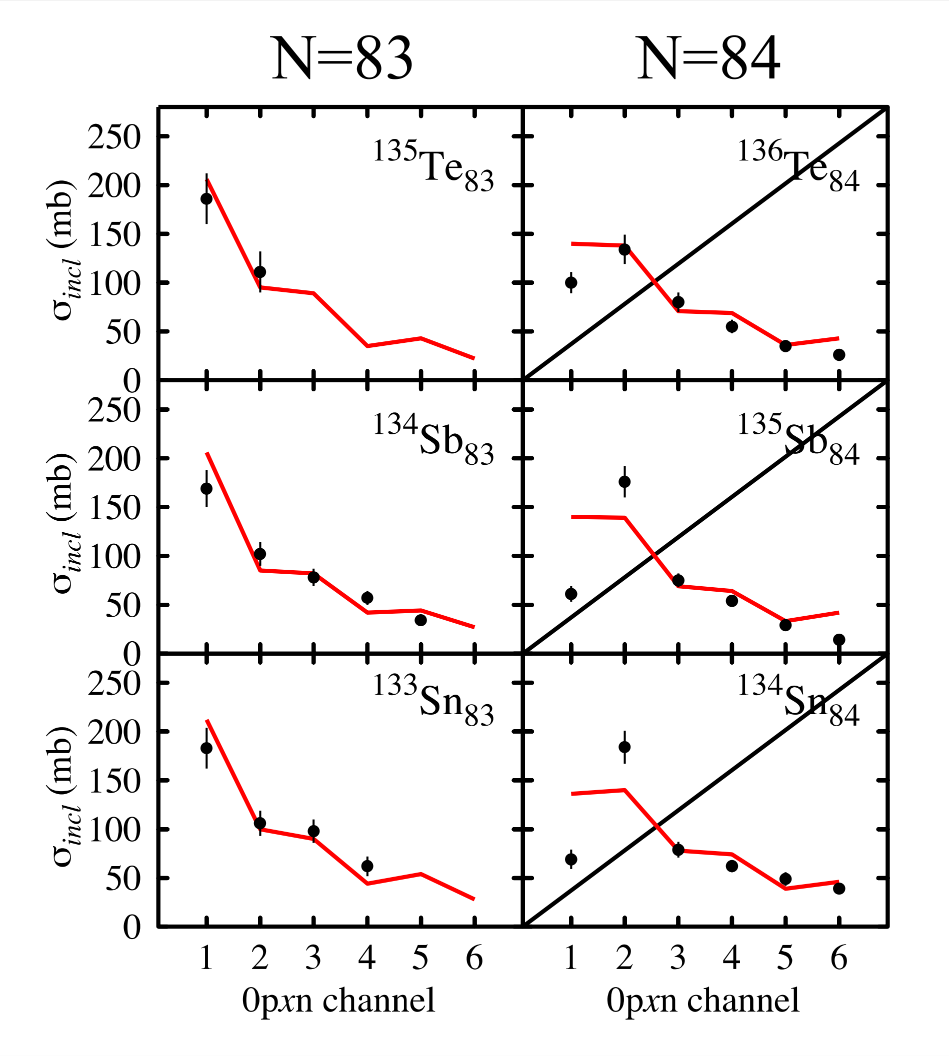
1n knockout followed by **B decay** or **n emission**



Neutron emission hindered by wave function mismatch between initial and final states.

Strong nuclear structure effects !

Systematics of inclusive *xn* knockout cross sections



INCL/ABLA07
Liège Intranuclear Cascade model
& statistical de-excitation model

A. Boudard et al., Phys. Rev. C 87, 014606(2013)
D. Mancusi et al., Phys. Rev. C 90, 054602(2014)

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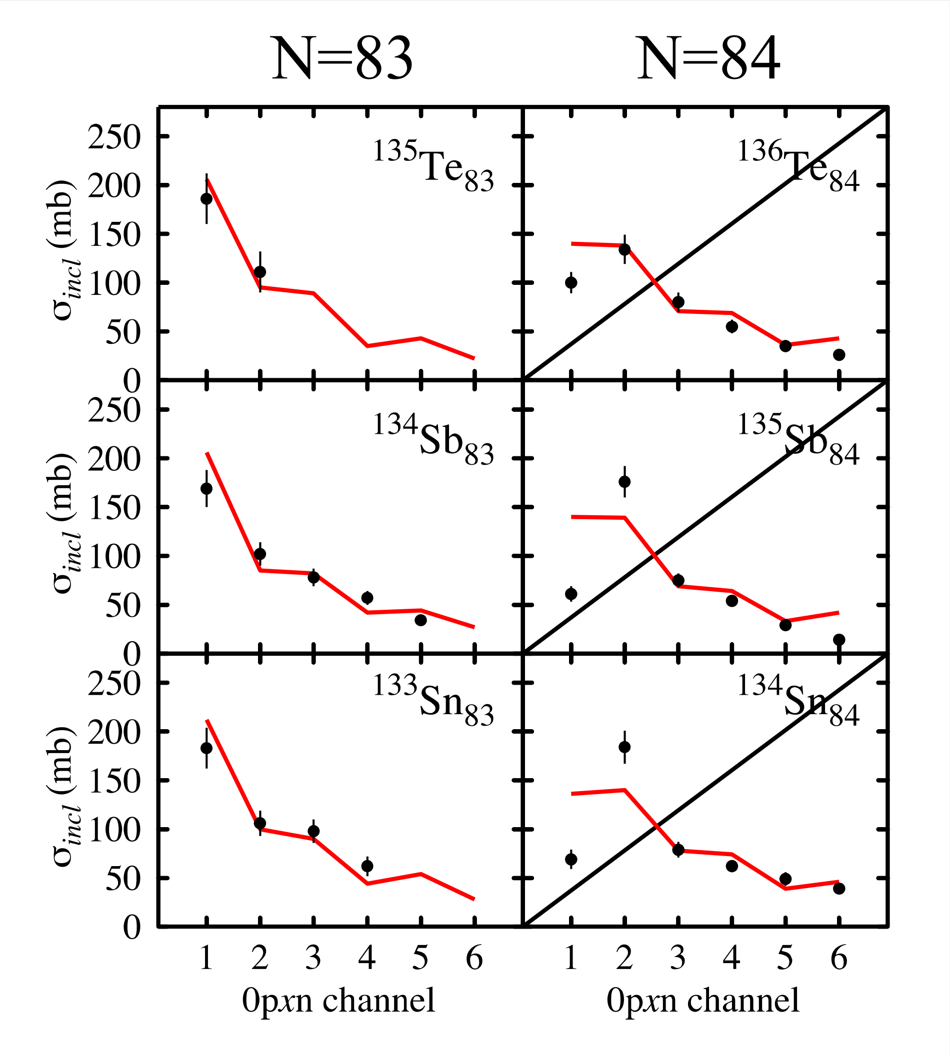

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In general nice agreement !

But ...

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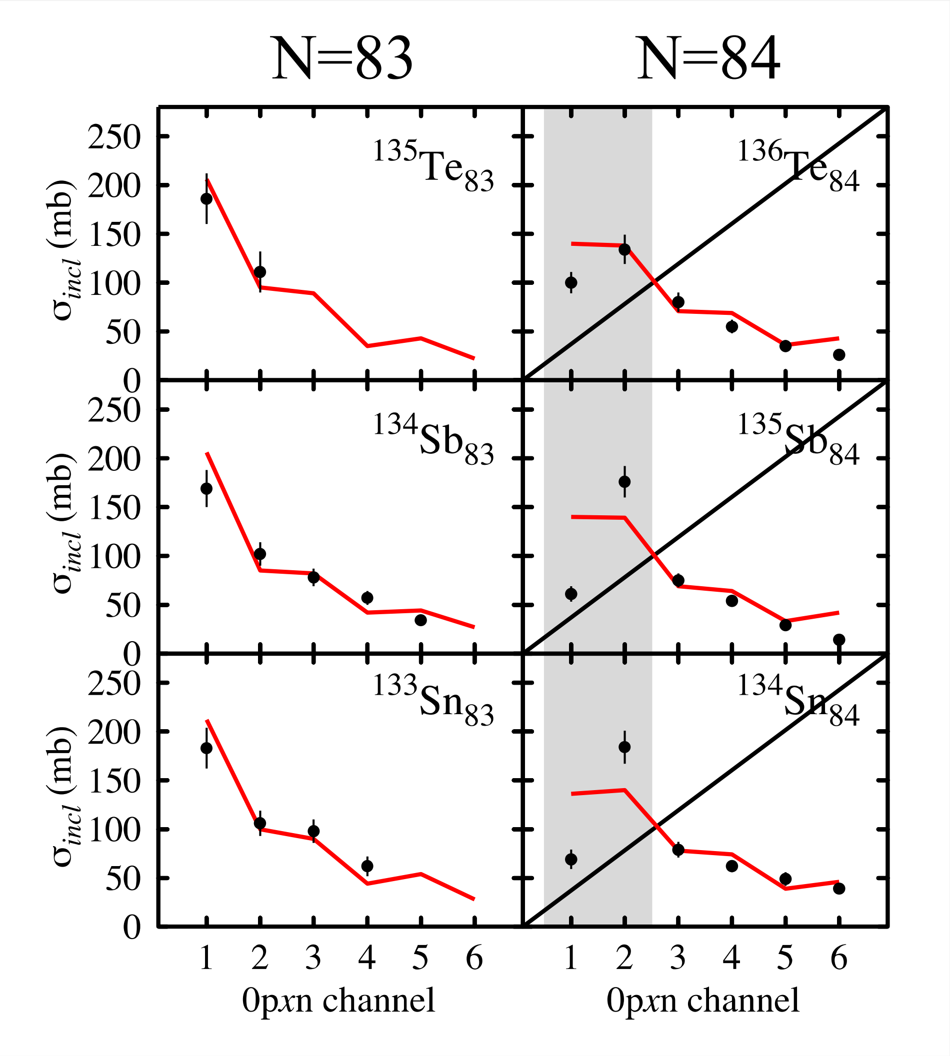

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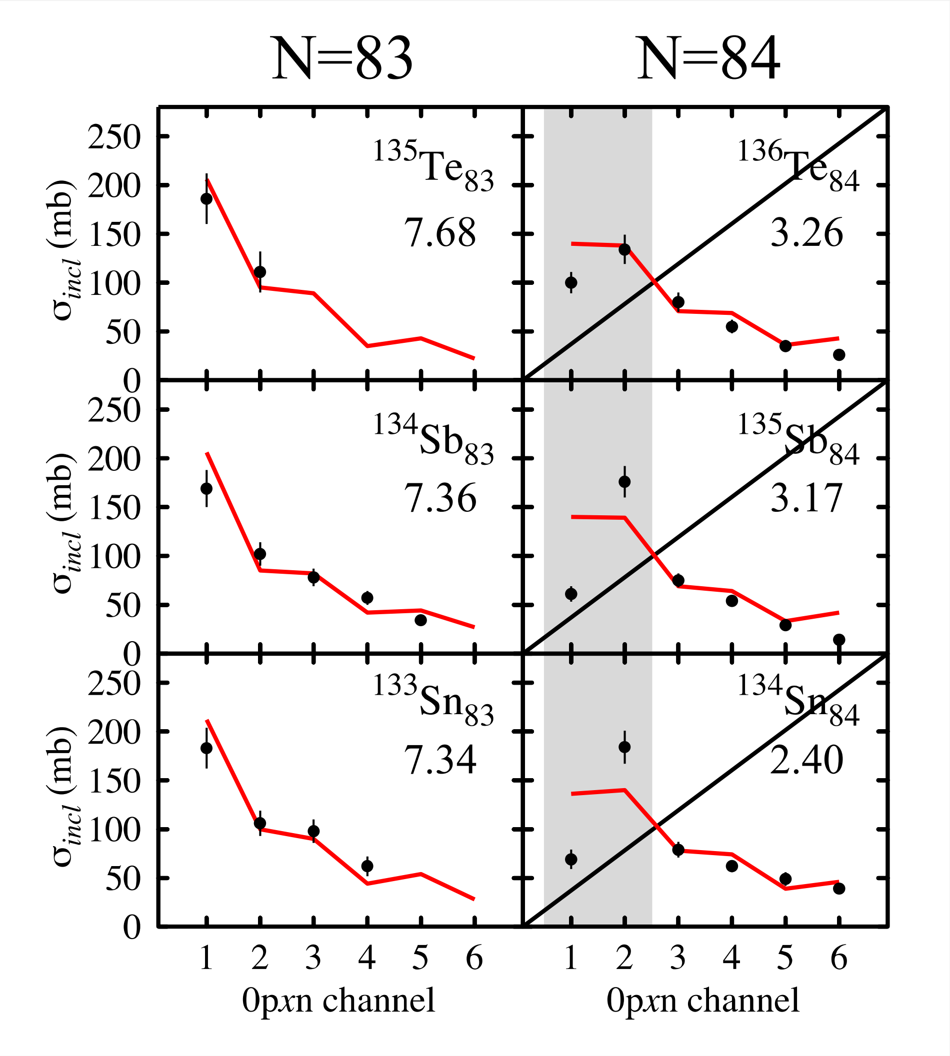

Sn (MeV) in 1n daughter

INCL/ABLA07
Liège Intranuclear Cascade model
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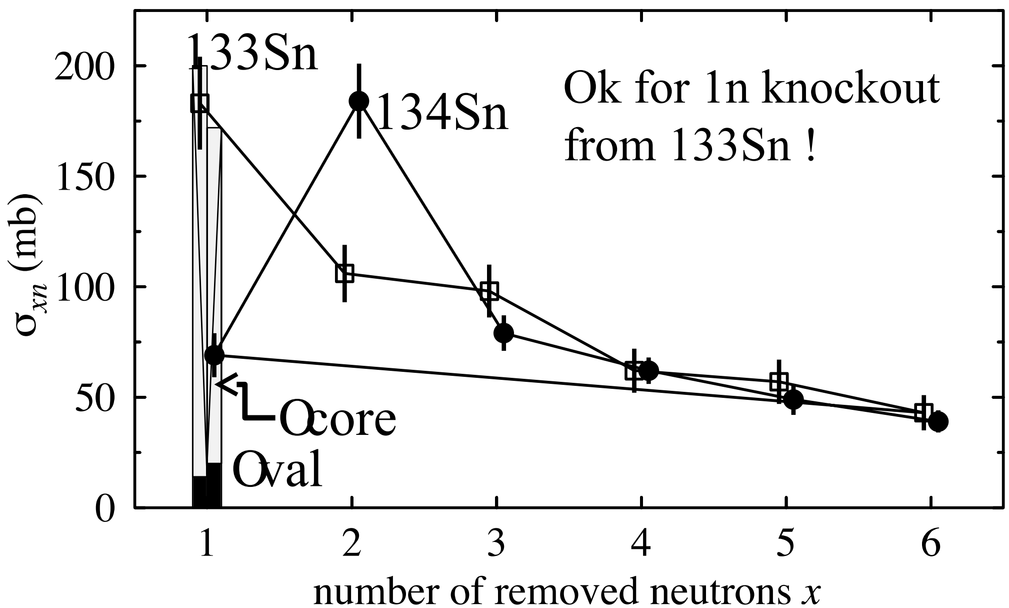
A. Boudard et al., Phys. Rev. C 87, 014606(2013)
D. Mancusi et al., Phys. Rev. C 90, 054602(2014)

In general nice agreement !

But ...

In case of neutron emission following 1n knockout, the product is identidied as -2n in the ZD spectrometer !

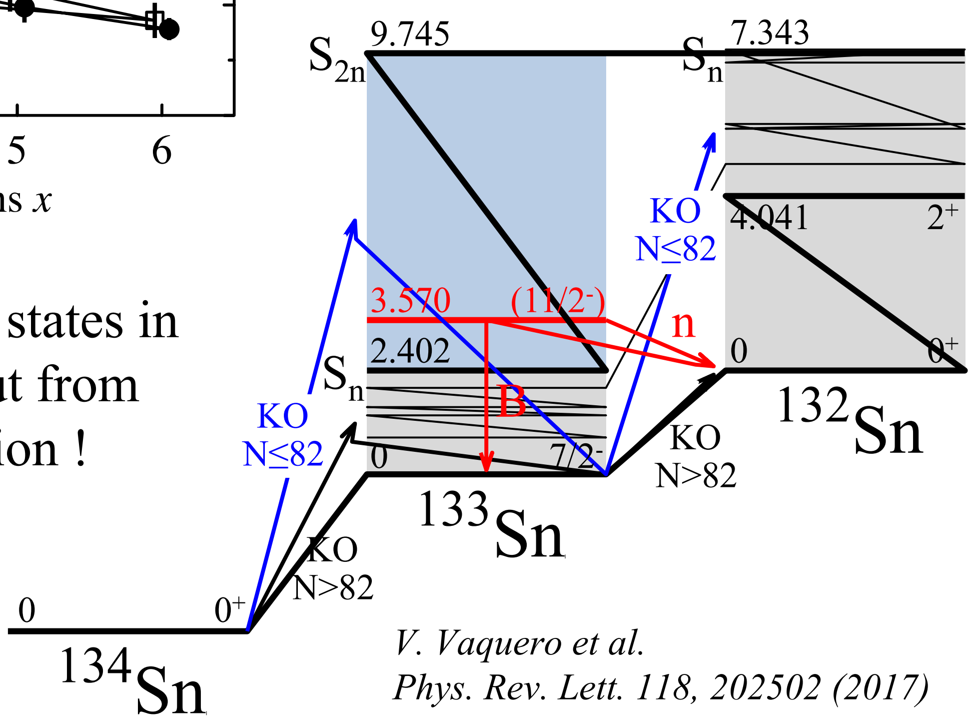
1n knockout from 133,134Sn: Comparison to theory



Oval, Ocore: Theoretical cross sections from eikonal reaction theory (Jeff Tostevin)

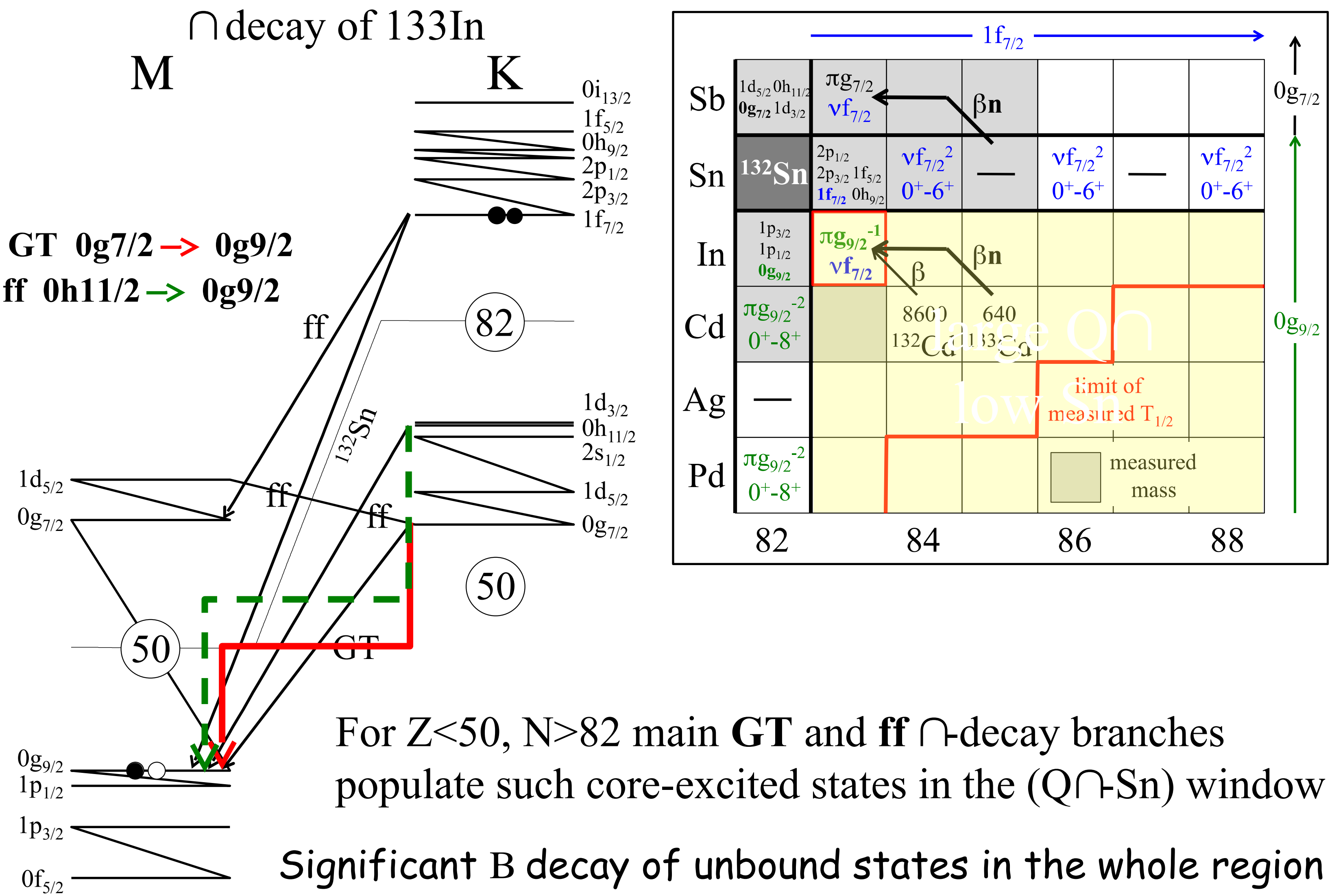
25-35% of the decay of unbound states in 133Sn, populated via 1n knockout from 134Sn, proceeds via B-ray emission !

Why is this relevant ?



V. Vaquero et al.
Phys. Rev. Lett. 118, 202502 (2017)

The ∩ decay south-east of 132Sn

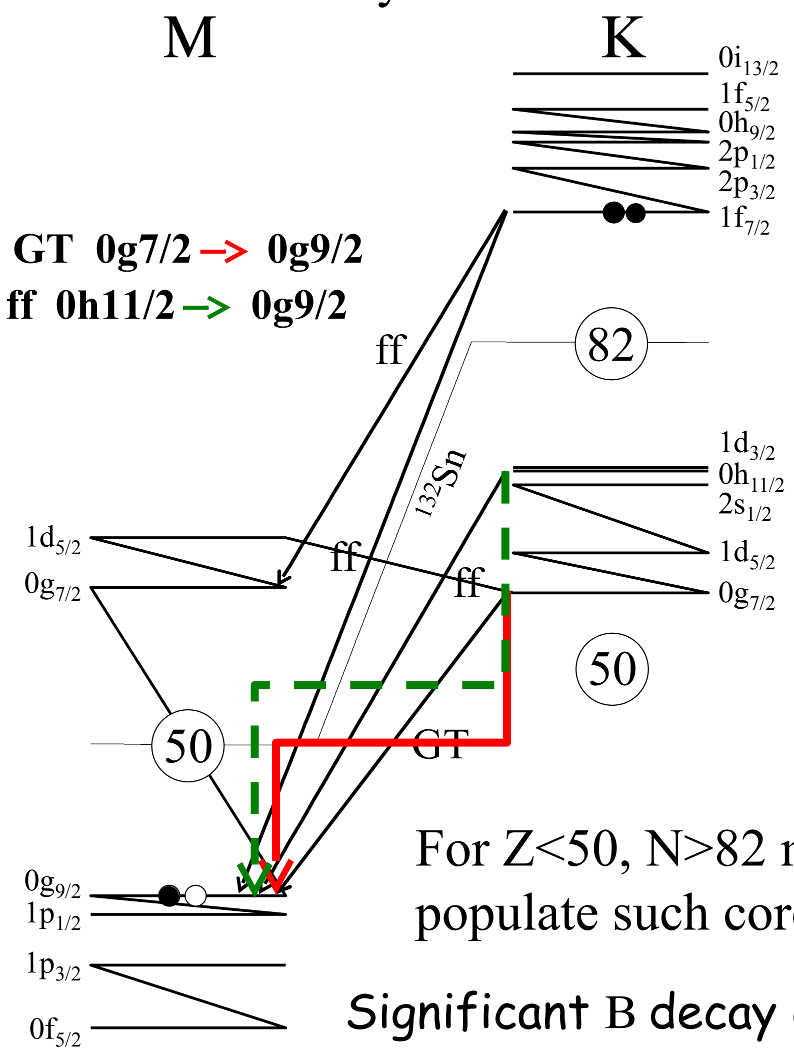


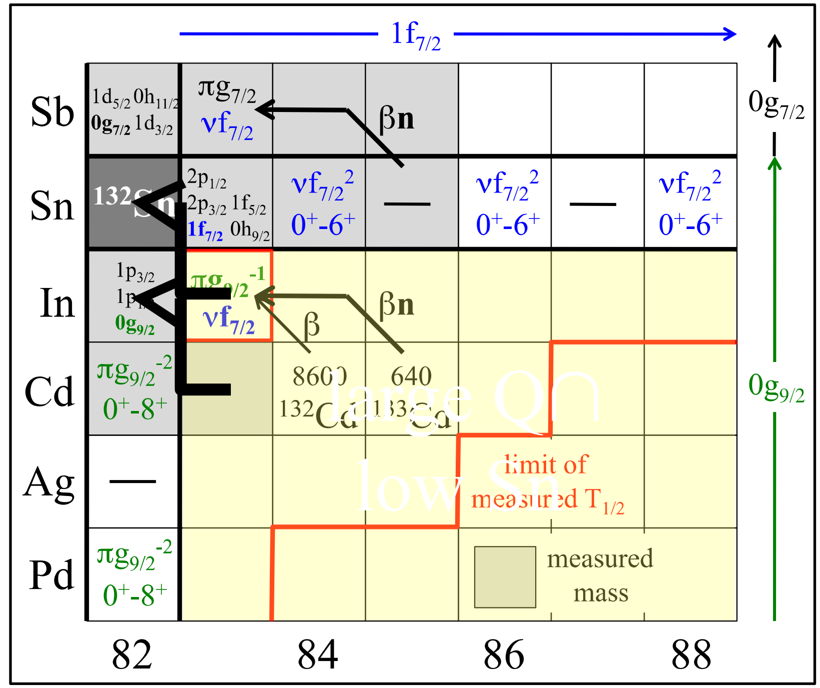
For Z<50, N>82 main **GT** and **ff** ∩-decay branches populate such core-excited states in the (Q∩-Sn) window !

Significant B decay of unbound states in the whole region ?

The ∩ decay south-east of 132Sn

∩decay of 133In





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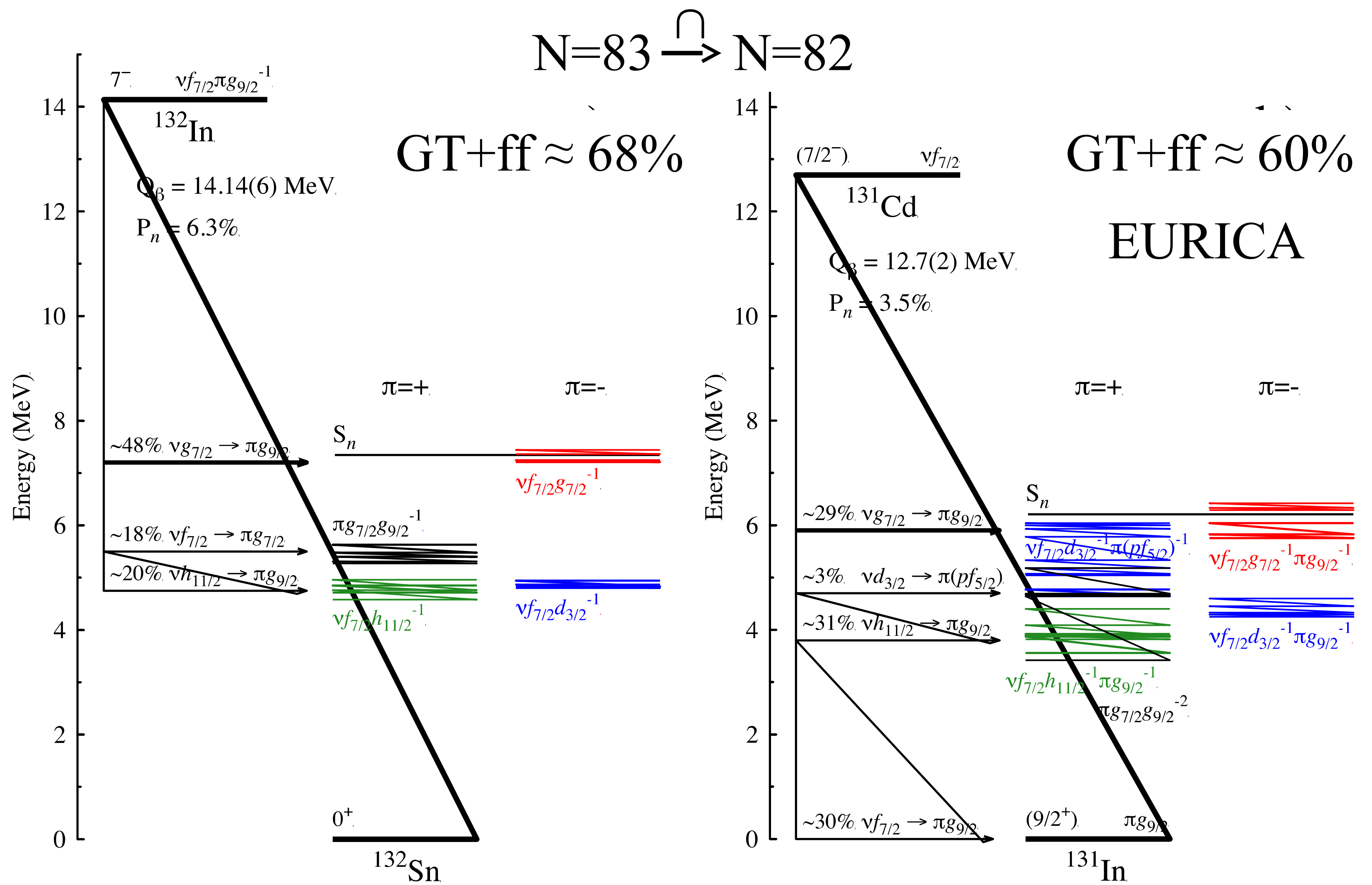
Significant Β decay of unbound states in the whole region ?

The β decay south-east of 132Sn

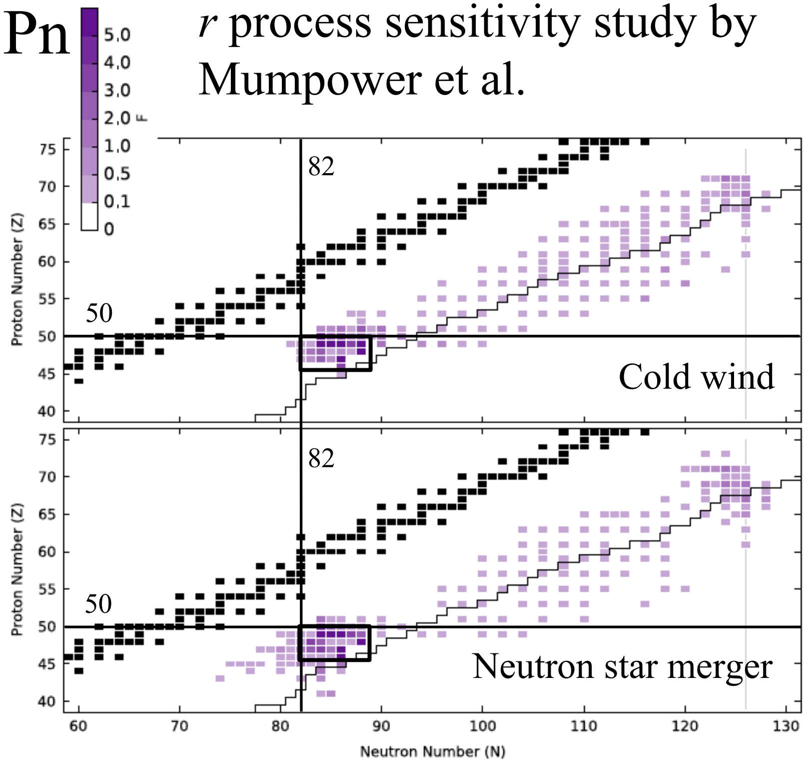


B. Fogelberg et al., Phys. Rev. Lett. 73, 2413 (1994) *J. Taprogge et al., Eur. Phys. J. A 52, 347 (2016)*

Importance of Pn values south-east of 132Sn

Pn

r process sensitivity study by Mumpower et al.



M.R. Mumpower et al.
Prog. Part. Nucl. Phys. 86, 86 (2016)

Pn values deduced from calculations of global ∩-decay properties.

Most recent example: *pn*-RQRPA

T. Marketin, L. Huther, G. Martínez-Pinedo
Phys. Rev. C 93, 025805 (2016)

Assumption:
Only neutron emission (no B !) above Sn !

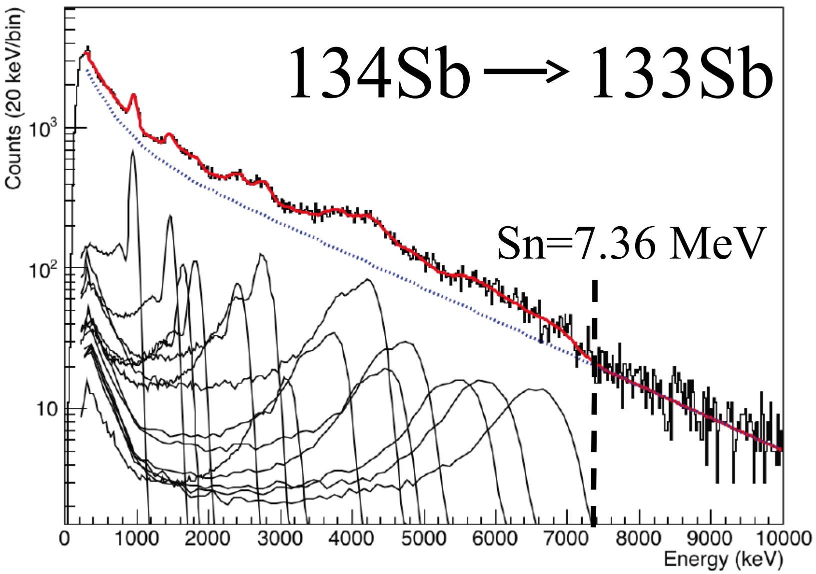
Complementary experimental information from high-resolution and total absorption (TAS) B-ray as well as neutron spectroscopy following ∩ decay required !

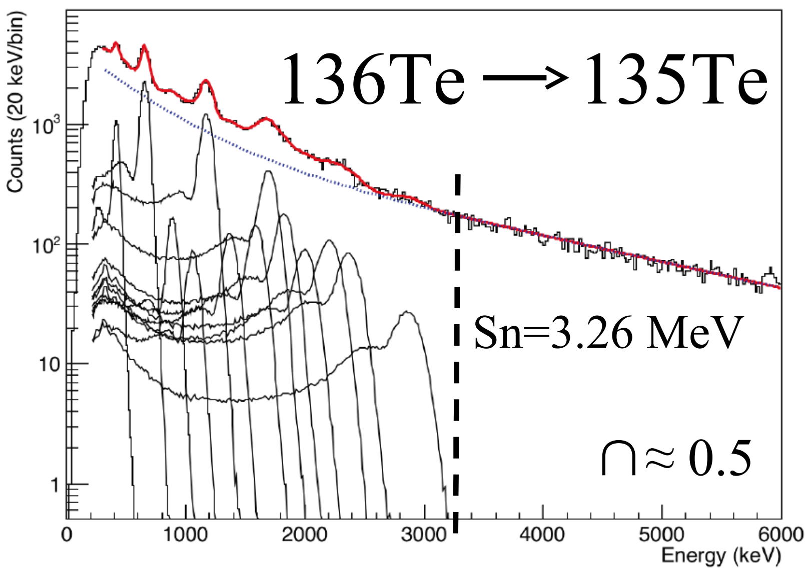
Need for SM calculations which include core excitations across N=82 and/or Z=50 !

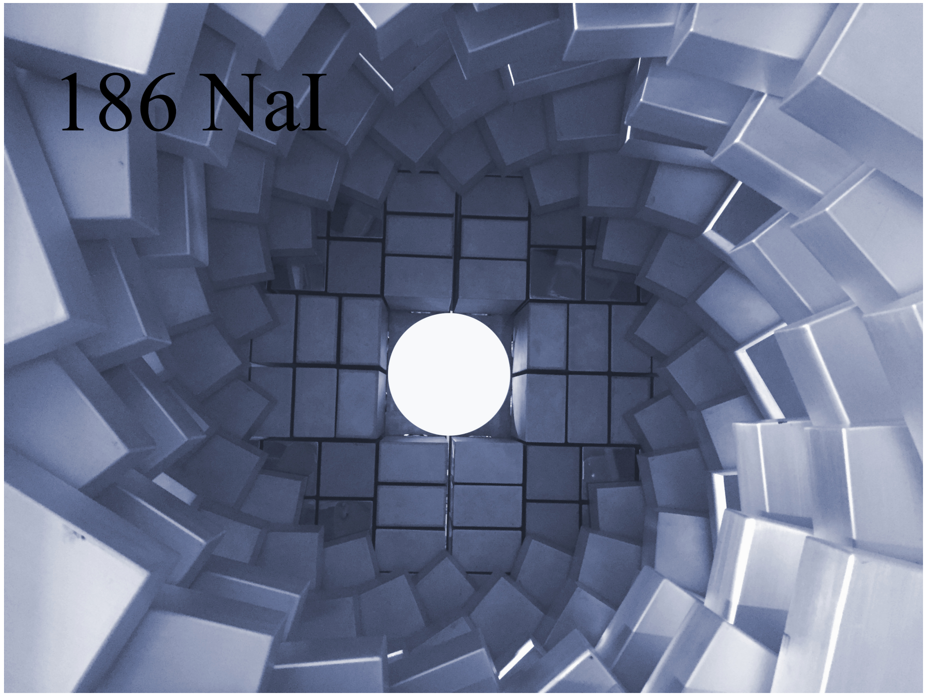
Conclusions and outlook

- Wealth of new information on isomeric and ∩ decays in the 132Sn region from the two EURICA experiments performed in December 2012. More to come ...
- In-beam B-ray spectroscopy at relativistic energies in this region with DALI2 is challenging, but possible !
- First results from April 2015 experiment out, more to come soon (136Te Coulex and B-ray spectroscopy of N=82-84 isotones following knockout reactions).

Touching the limits with DALI2 ...







Too high line density,

too bad energy resolution ...

Need B-ray tracking arrays !

Conclusions and outlook

- Wealth of new information on isomeric and ∩ decays in the 132Sn region from the two EURICA experiments performed in December 2012. More to come ...

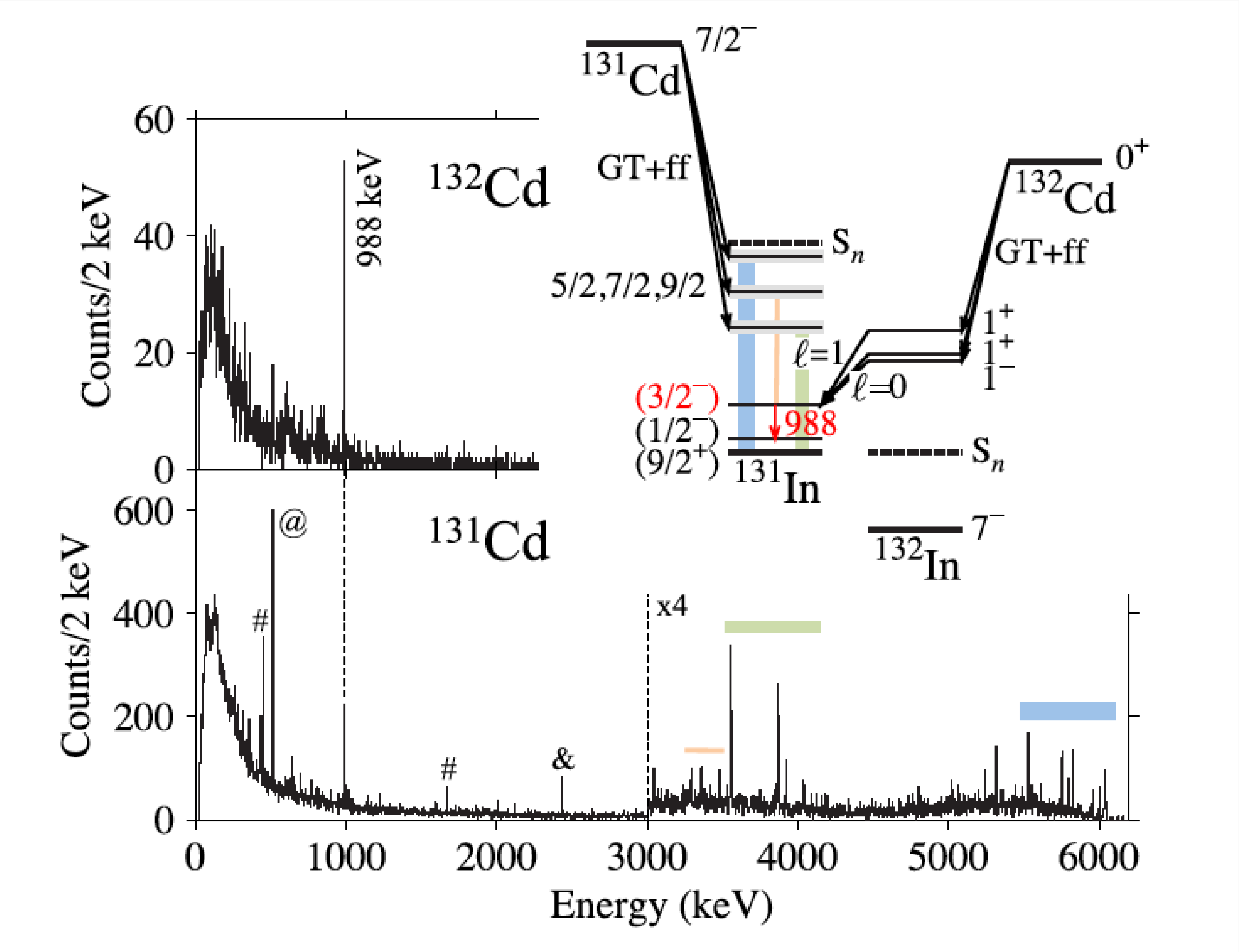
- In-beam B-ray spectroscopy at relativistic energies in this region with DALI2 is challenging, but possible !

- First results from April 2015 experiment out, more to come soon (136Te Coulex and B-ray spectroscopy of N=82-84 isotones following knockout reactions).

- New experiment in the 132Sn region, this time optimized for knockout, already approved by the RIKEN PAC in December 2016.

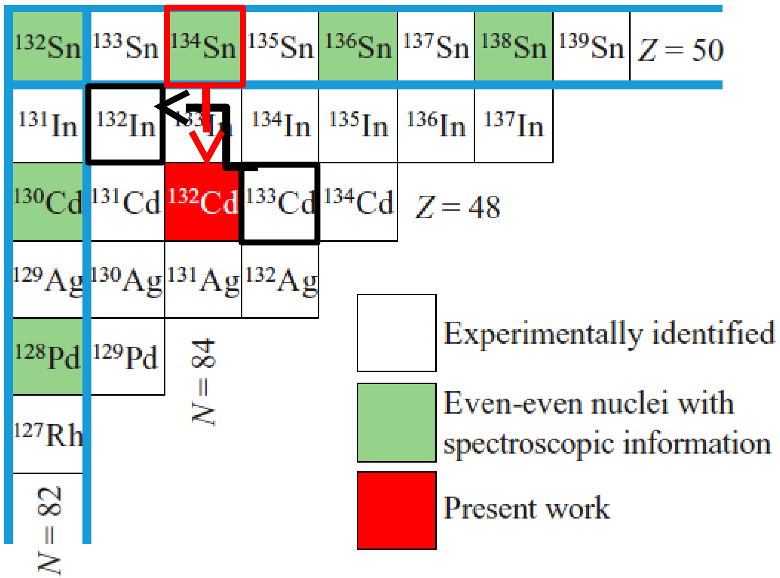
Special thanks to: NP1112-RIBF85 & NP1306-RIBF98R1 collaborations

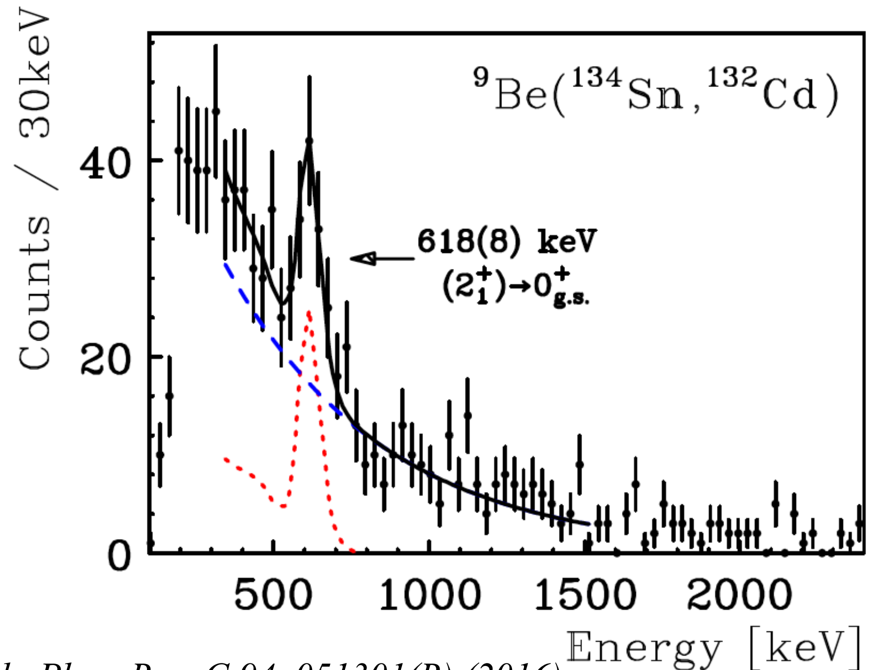
Jan Taprogge	Shunji Nishimura	Hubert Grawe
Victor Vaquero	Pieter Doornenbal	Angela Gargano
		Jeff Tostevin



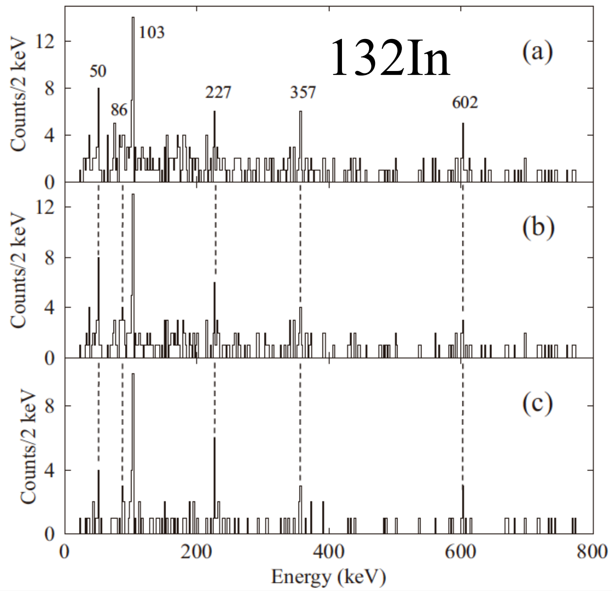
J. Taprogge et al., Phys. Rev. Lett. 112, 132501 (2014)

Is in-beam B-ray spectroscopy the better way ?





H. Wang et al., Phys. Rev. C 94, 051301(R) (2016)



- less exotic, higher intensity RIB
- secondary reaction cross section
- ∩≈0.5 and NaI resolution (DALI2)

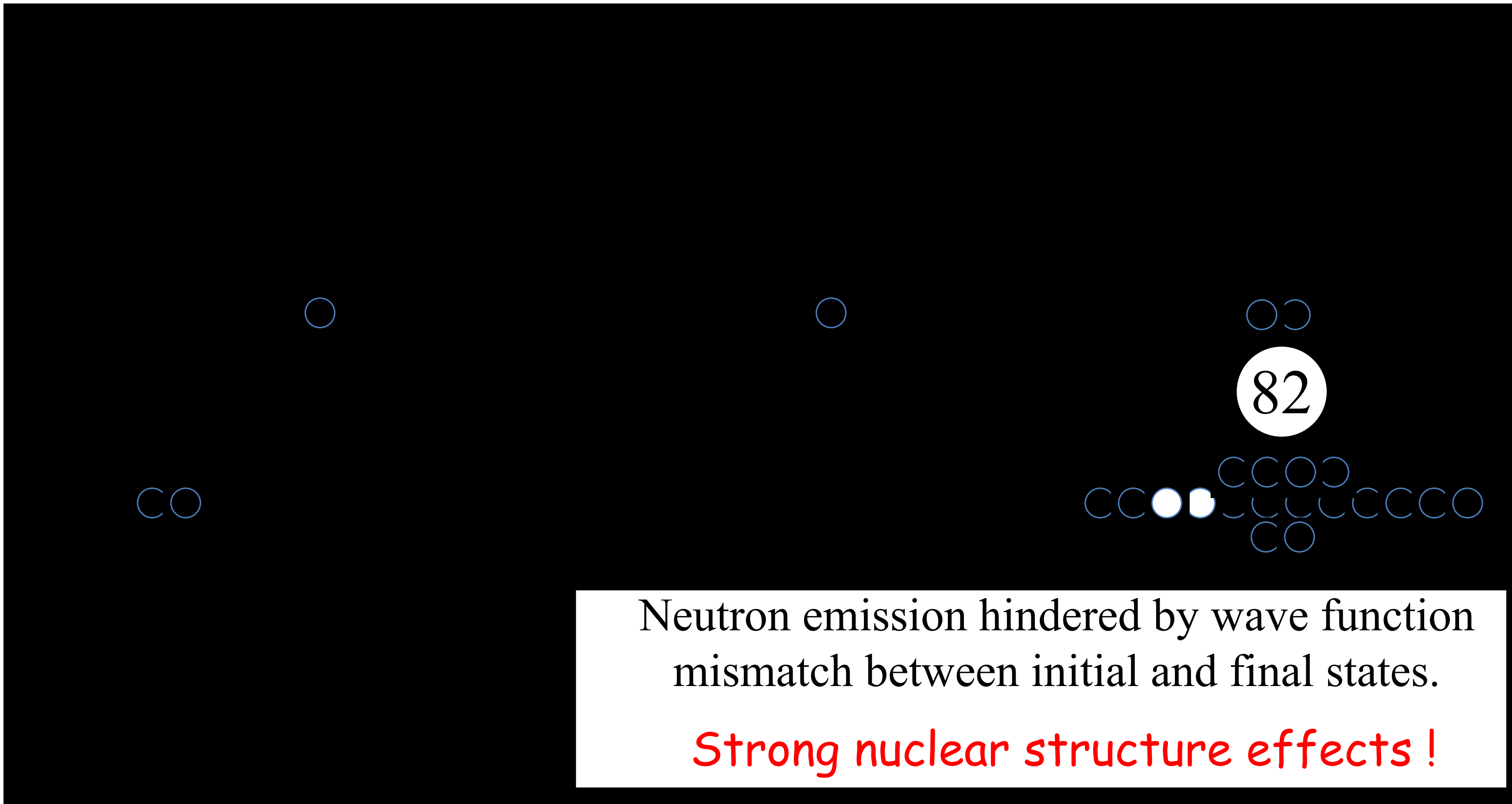
- Ge resolution (EURICA)
- large Pn values
- more exotic, lower intensity RIB

A. Jungclaus et al., Phys. Rev. C 93, 041301(R) (2016)

Neutron vs. B competition above Sn in 133Sn

Neutron configuration after ...

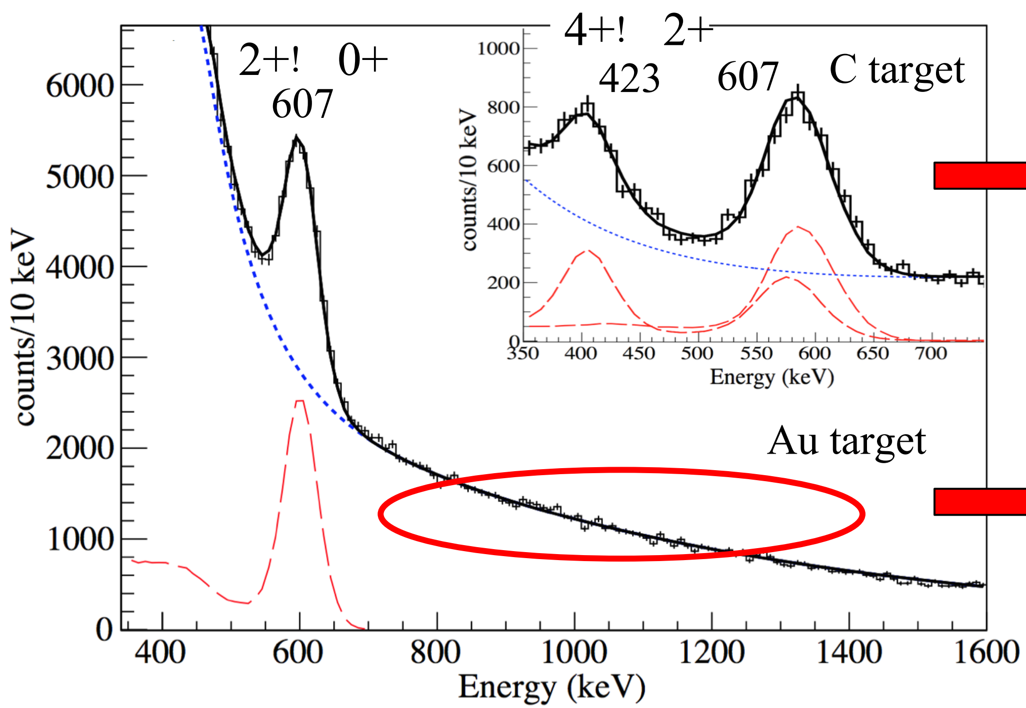
1n knockout followed by **B decay** or **n emission**



Neutron emission hindered by wave function mismatch between initial and final states.

Strong nuclear structure effects !

RIKEN experiment NP1306-RIBF98R1: Coulex of 136Te



C target run to deduce the nuclear contribution to OAu:

OC = 21(3) mb

OAu = 260(9) mb

• (±2) = ?? mb

No indication for the decay of the 2ms+ state !

Theoretical predictions off ...

<u>Still to be done:</u>

Detailed consideration of feeding contributions, analysis of differential cross sections etc.

Neutron vs. B competition above Sn in 133Sn

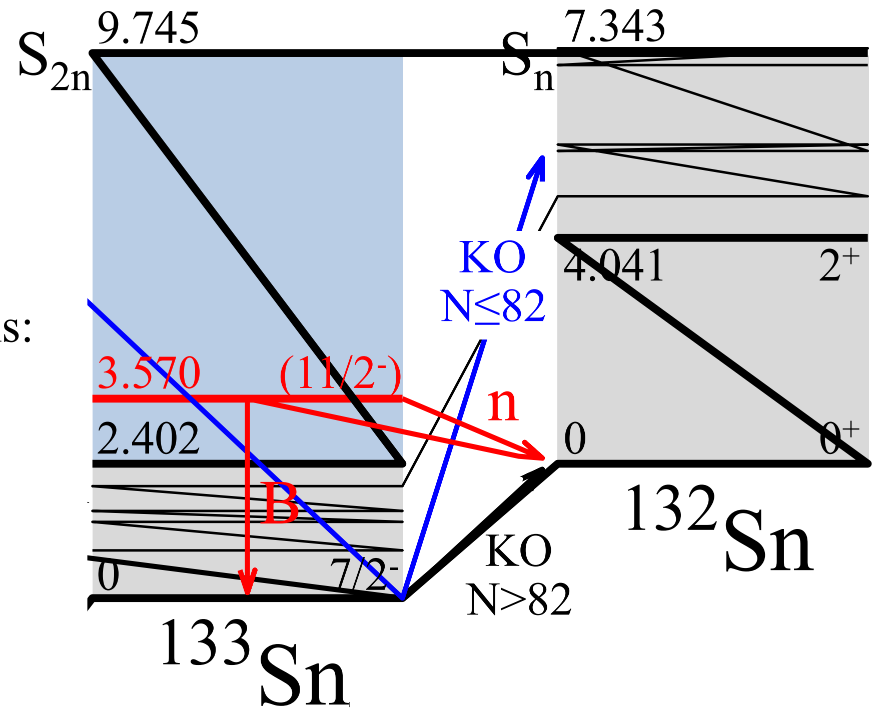
Up to Ex~6.4 MeV in 133Sn only neutron decay to the 132Sn g.s. is energetically possible.

In the case of knockout from h11/2

➡ neutron with ℓ =5 !

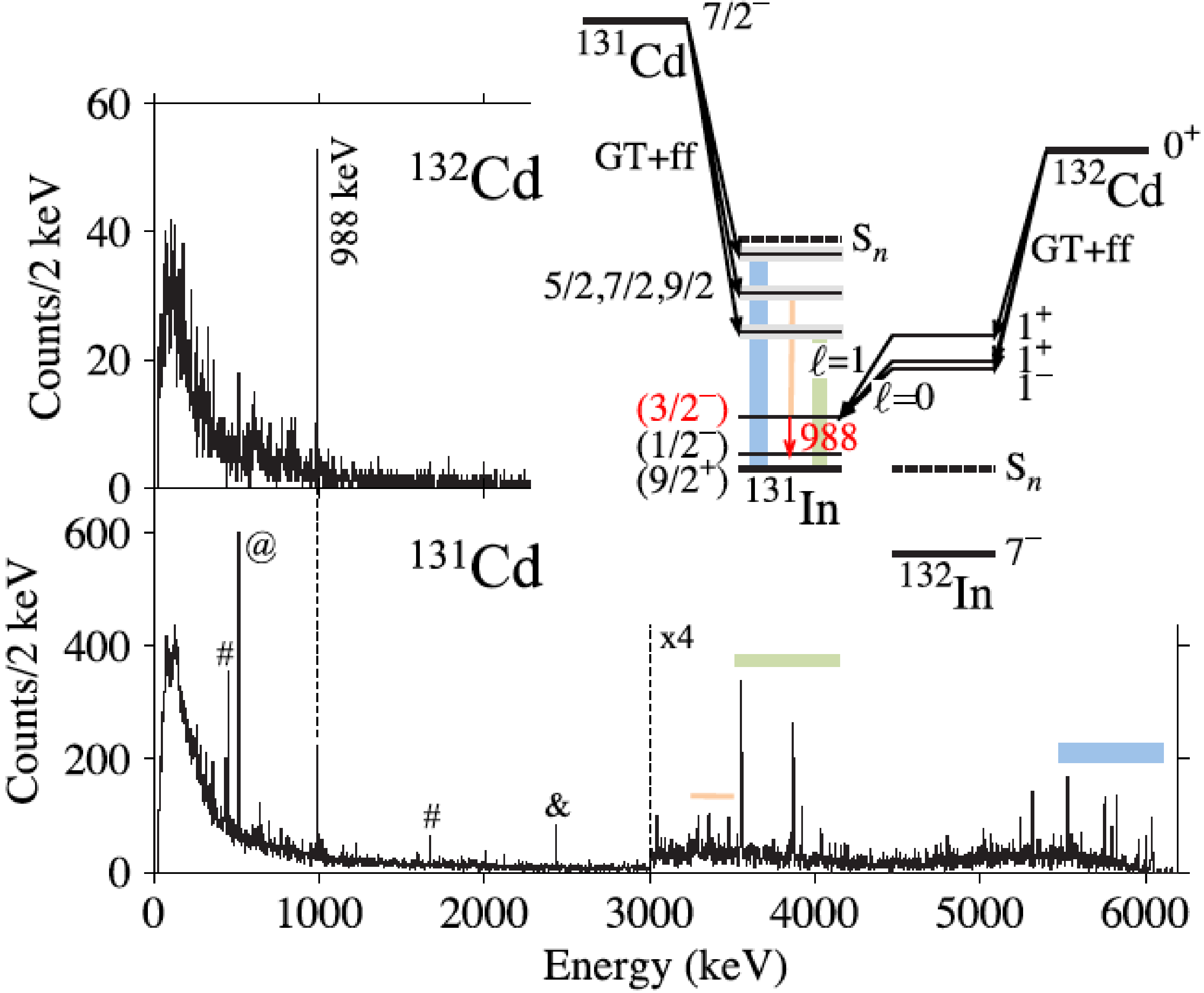
At the level of pure single-particle transitions:

neutron	**Π≈ 10-17 s**	[En=1.2 MeV]
E2 B-ray	**Π≈ 10-14 s**	[B(E2)=2 W.u.]



Neutron decay is expected to be roughly **three orders of magnitude faster** than E2 B decay to the 133Sn g.s. !

But ...



J. Taprogge et al., Phys. Rev. Lett. 112, 132501 (2014)