
RIKEN
NISHINA
CENTER

Recent Results and Perspectives of Gamma-ray Spectroscopy at the RIBF

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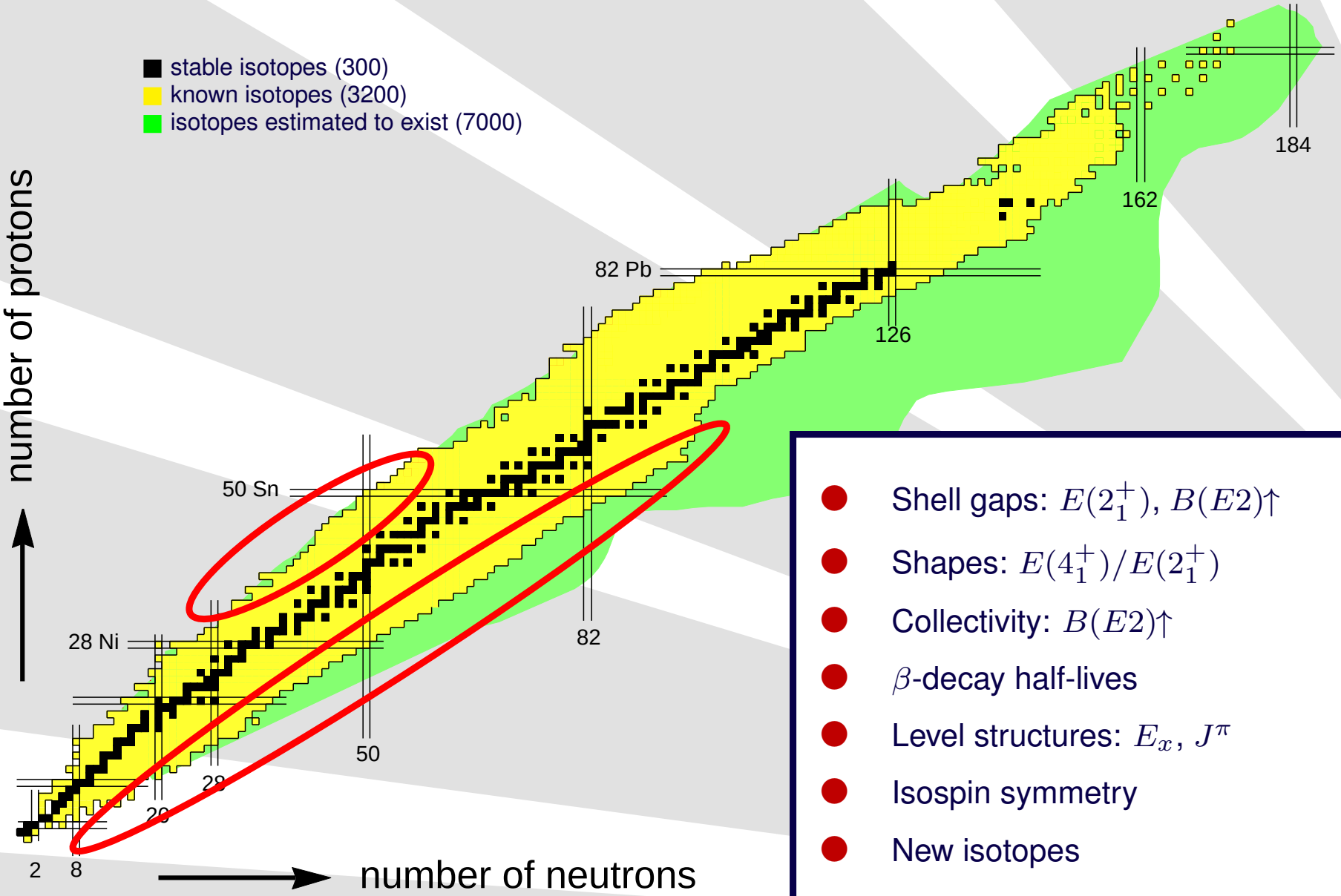
ピーター　ドルネンバル

Outline

- Physics case
- Setup
  - DALI2 for in-beam spectroscopy
  - EURICA for decay and isomer spectroscopy
- Selected results
- Conclusions and perspectives

Physics Case

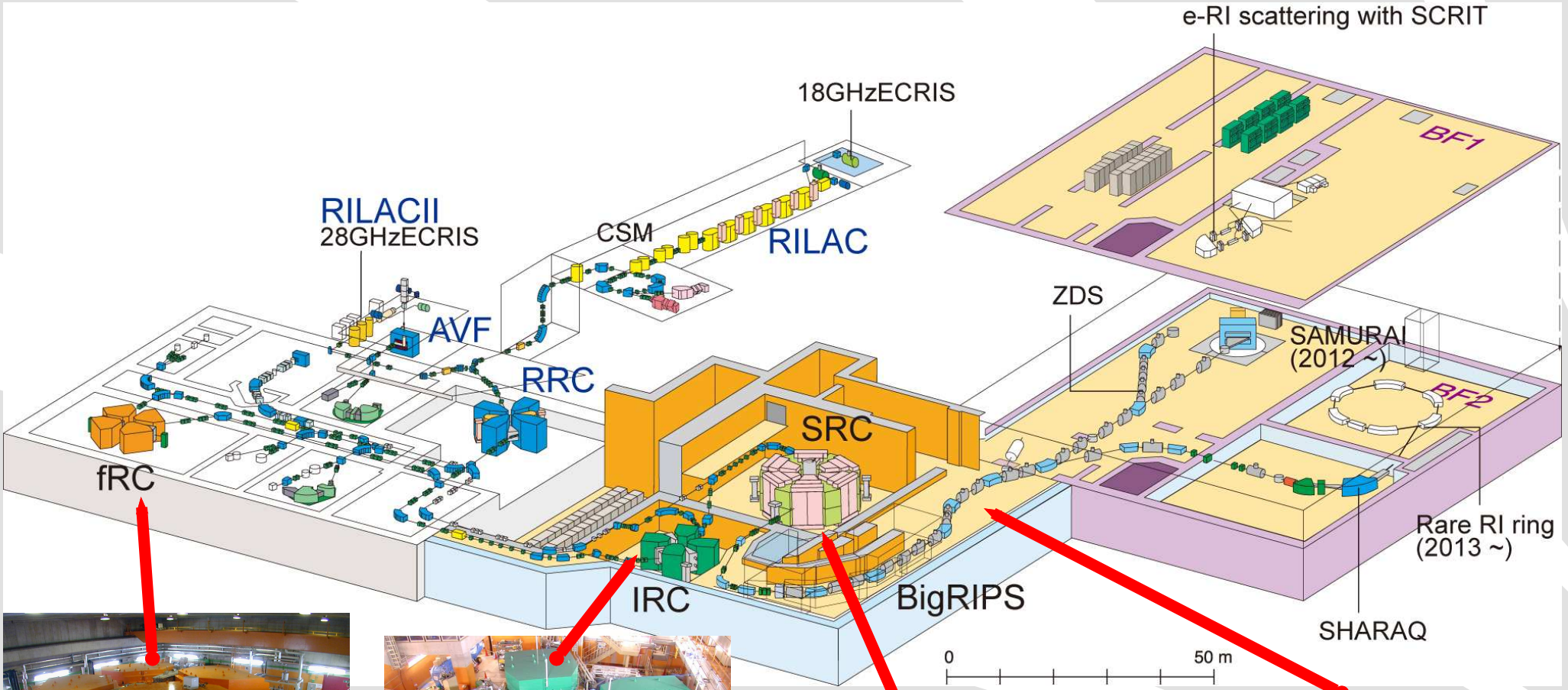
Regions of Interest

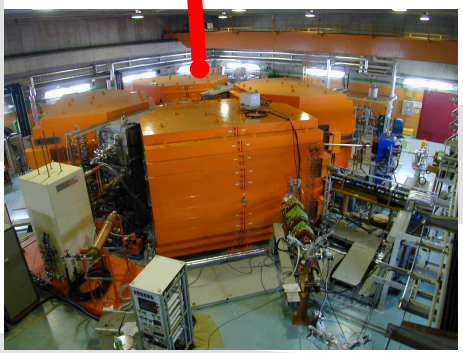


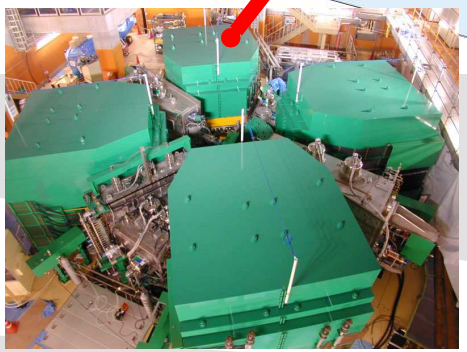
- Shell gaps: $E(2_1^+)$, $B(E2)\uparrow$
- Shapes: $E(4_1^+)/E(2_1^+)$
- Collectivity: $B(E2)\uparrow$
- β-decay half-lives
- Level structures: E_x, J^π
- Isospin symmetry
- New isotopes

Experimental Setup

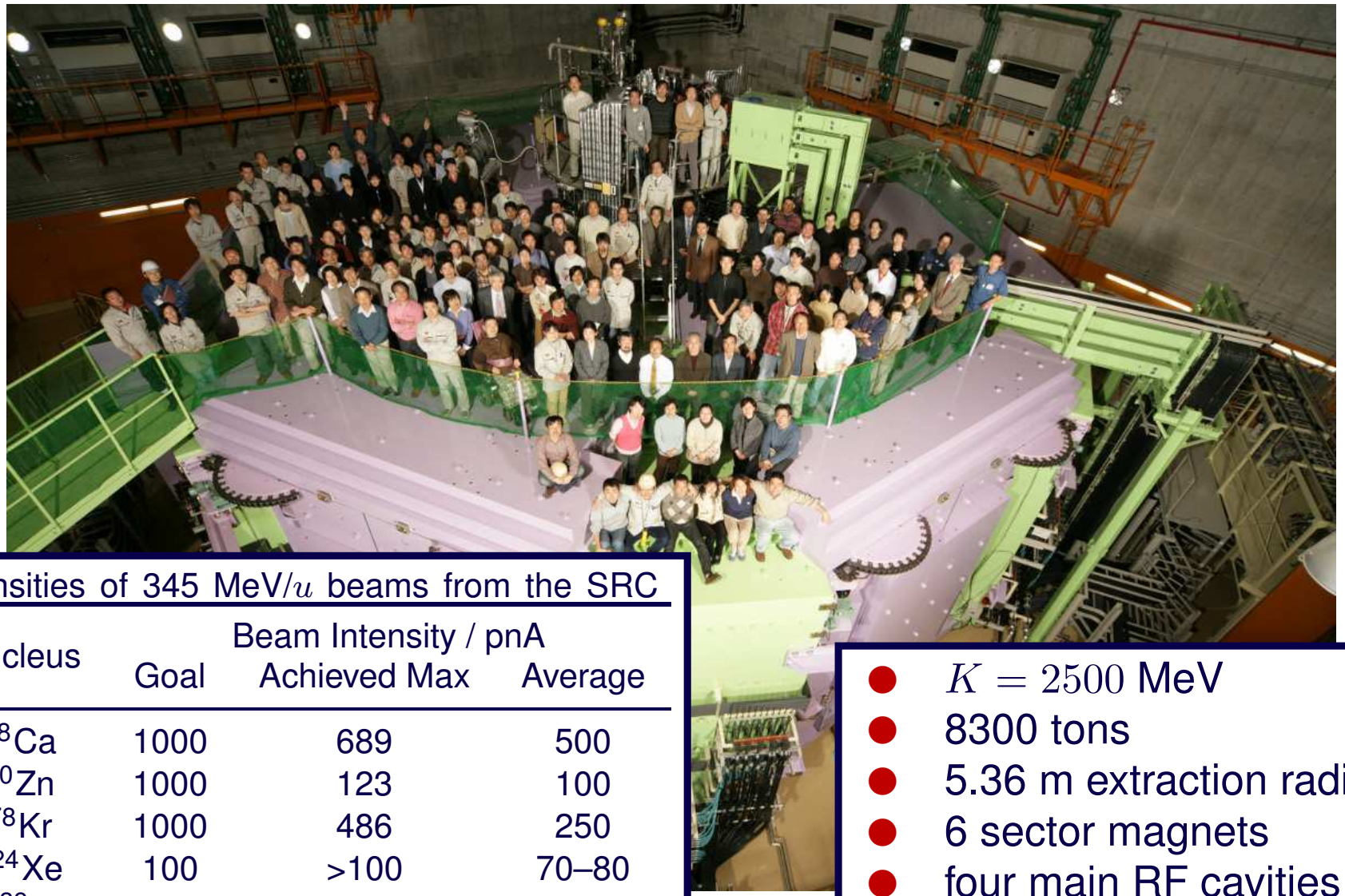
RIBF Overview







Superconducting Ring Cyclotron (SRC)

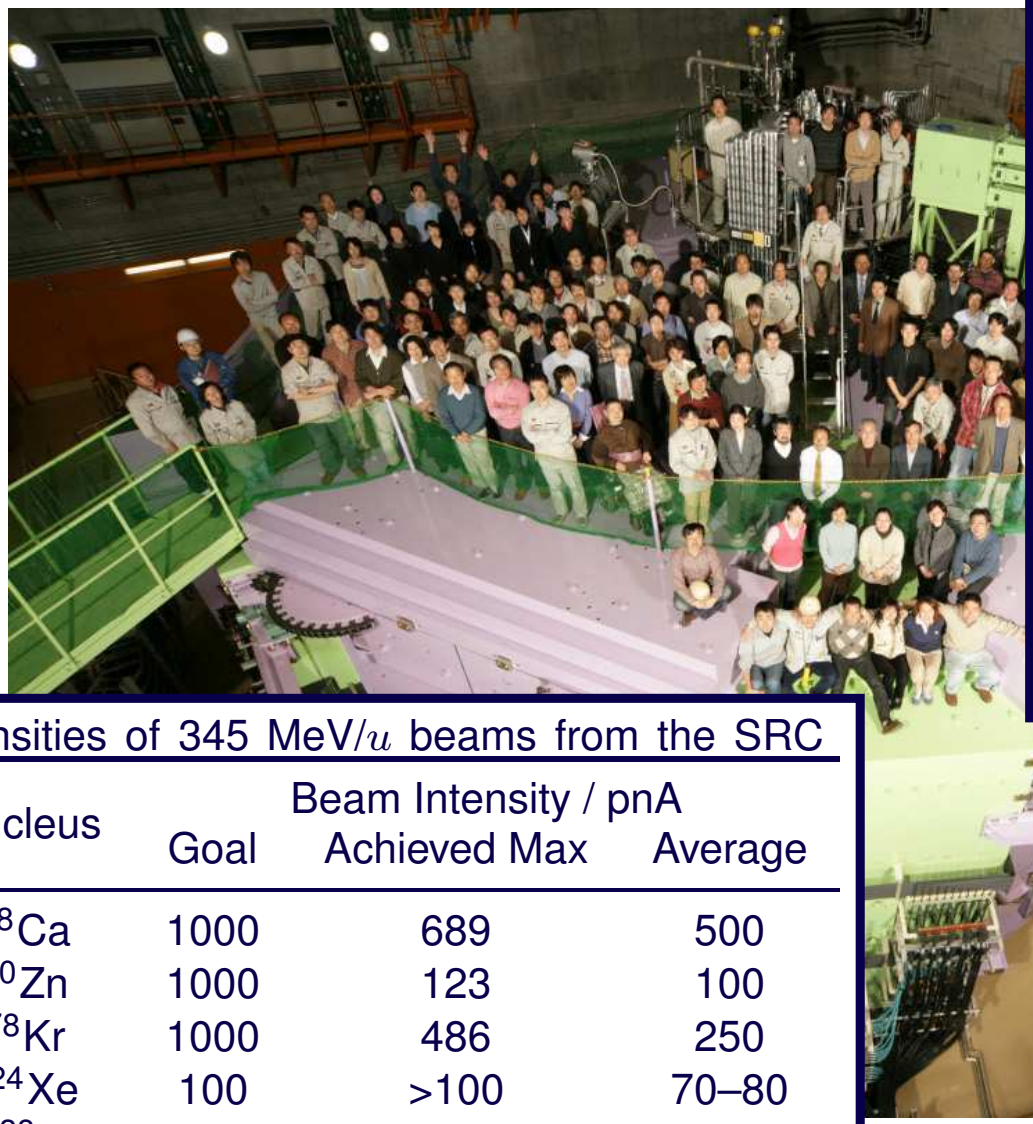


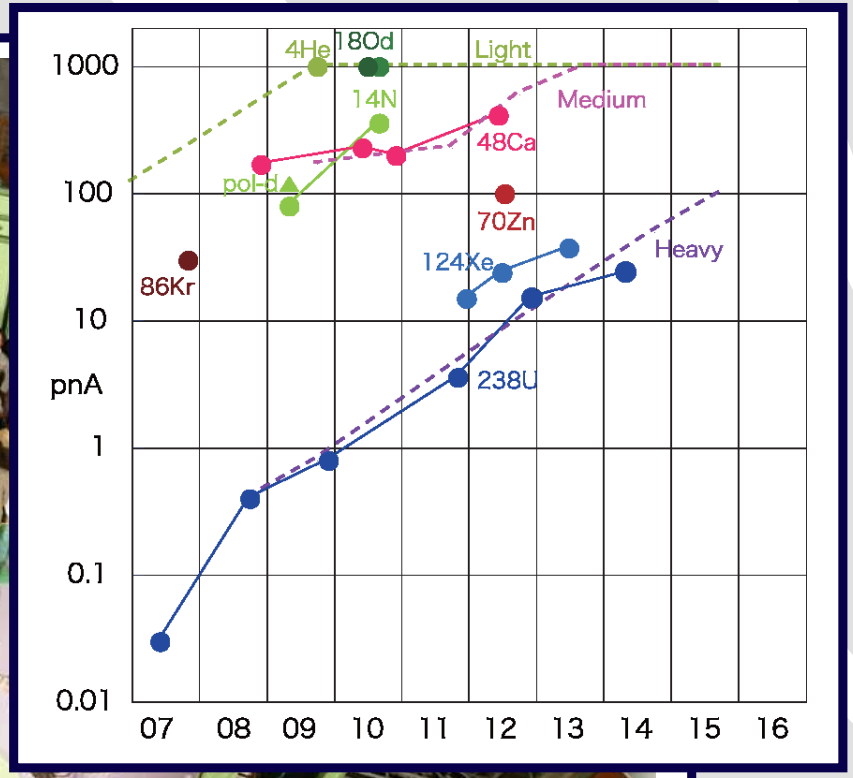
Intensities of 345 MeV/u beams from the SRC

Nucleus	Beam Intensity / pnA		
	Goal	Achieved Max	Average
^{48}Ca	1000	689	500
^{70}Zn	1000	123	100
^{78}Kr	1000	486	250
^{124}Xe	100	>100	70–80
^{238}U	100	49	40

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

Superconducting Ring Cyclotron (SRC)





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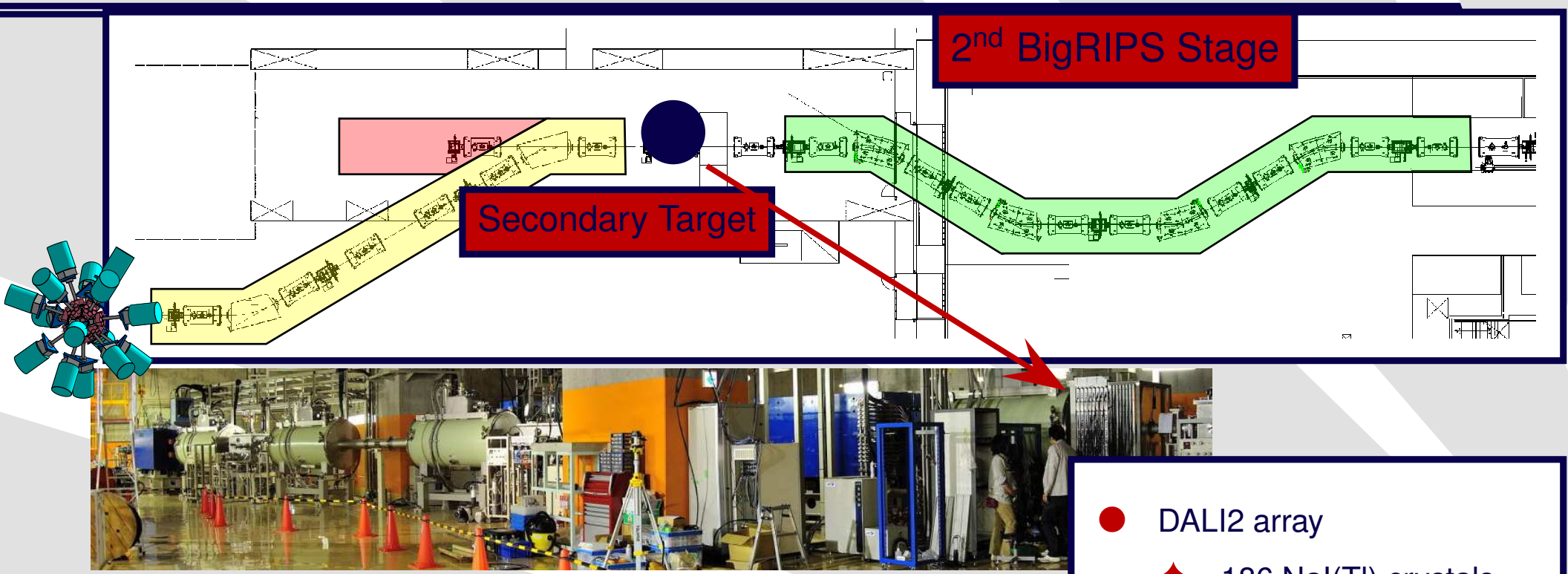
ZeroDegree Spectrometer



- DALI2 array
  - 186 NaI(Tl) crystals
  - 4π coverage
  - 20 % efficiency
  - 10 % resolution
- $E_{\mathrm{beam}} \sim 150 - 250$ MeV/u

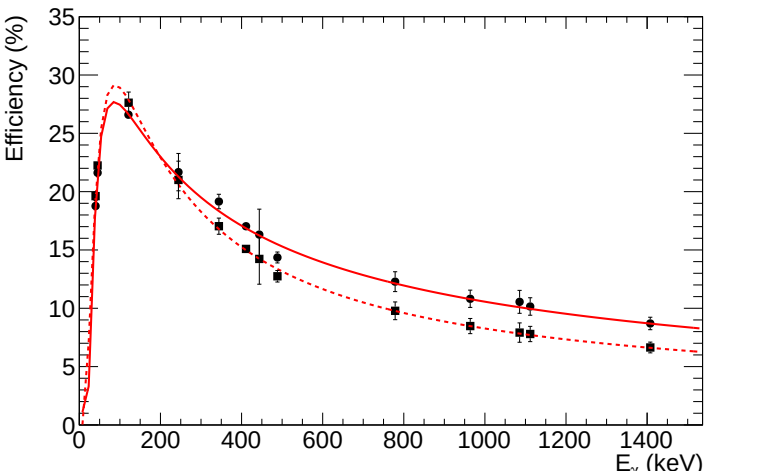
0° Spectrometer ZeroDegree

- **Particle ID** after secondary target
- Fragment momentum distribution
- Various modes of operation

mode	$p/\Delta p$	Δp	Ang. Accep.
Large Accep.	**1240**	± 3**%**	± 45 **mrad(H)** ± 30 **mrad(V)**
High res.(achrom)	2120	± 3%	± 20 mrad(H) ± 30 mrad(V)
Dispersive	4130	± 2%	± 20 mrad(H) ± 30 mrad(V)

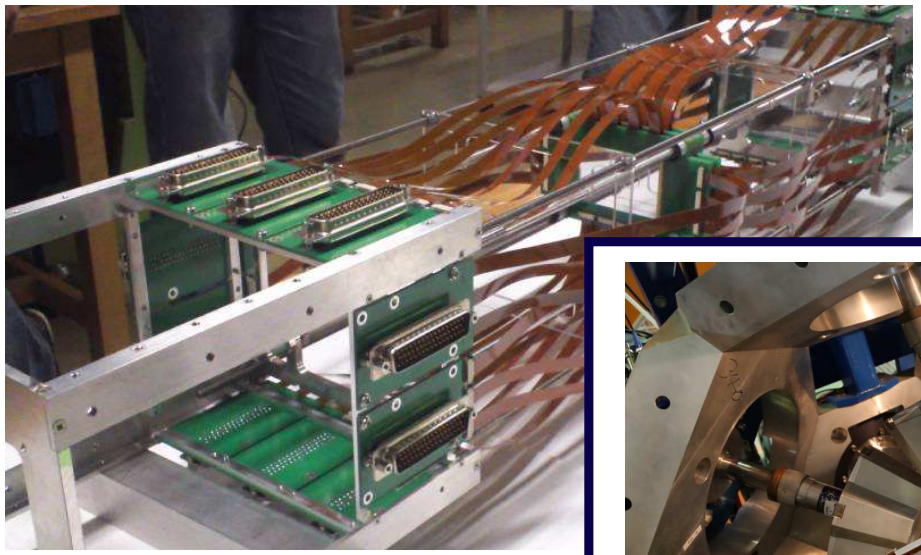
EURICA (EUroball-RIken Cluster Array)

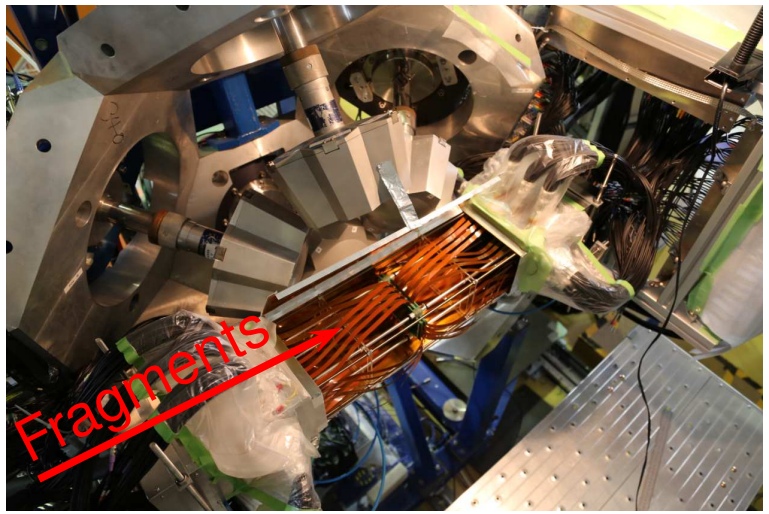
- 12 EUROBALL Cluster detectors
  - 84 crystals
    - Arranged in 12 Clusters of 7 crystals
    - High granularity
    - 10 % efficiency at 1 MeV
- Located at the Final focus of ZeroDegree
- Ancillary Si, $LaBr_3$, plastic detectors
- At RIKEN since 2012, this year back to GSI



WAS3ABi

Wide-range
Active
Silicon-
Strip
Stopper
Array for
Beta and
ion detection





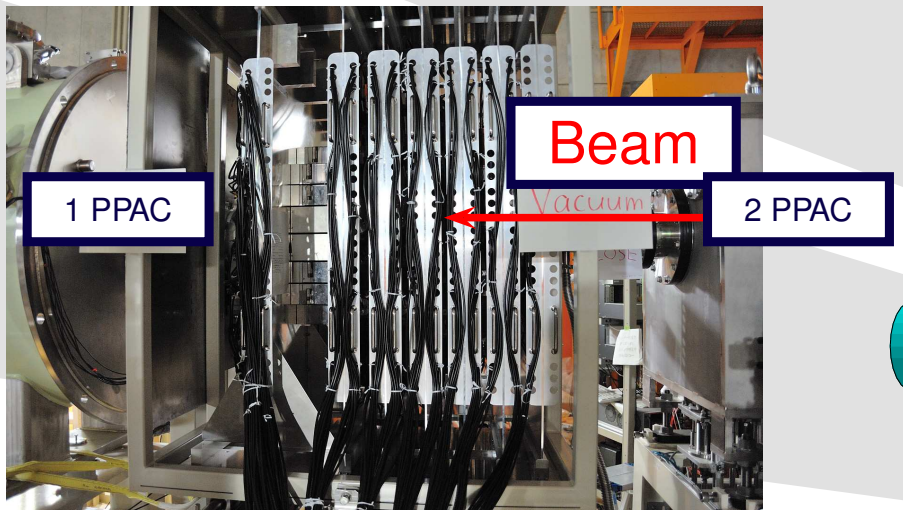
- Up to 8 layers of DSSSDs
- 40 $\times$ 60 strips, 1 mm width
- Developed and owned by RIKEN/IBS/TU München
- 20 keV threshold, 20 keV energy resolution
- 100-200 pps maximum implantation rate
- Provides β-decay trigger for EURICA spectrometer

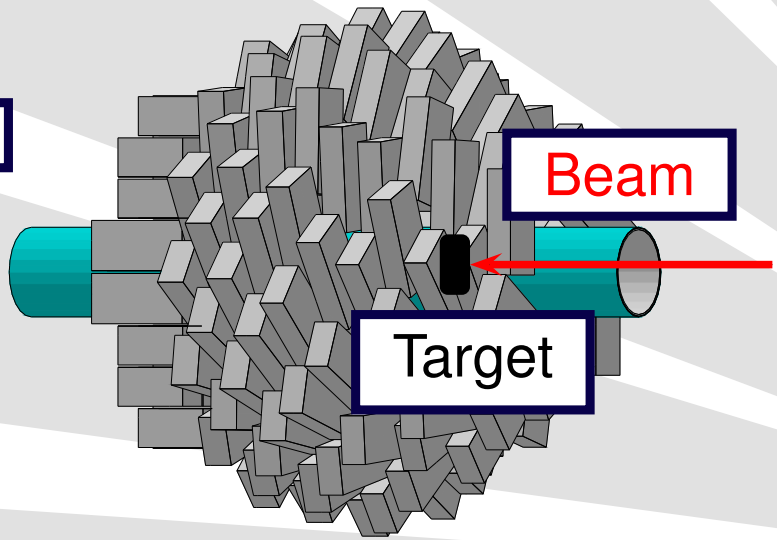
Performed Experiments EURICA

Date	Spokesperson	Primary	Used Days
April 2012	S. Nishimura, P. Doornenbal	^{18}O	4
June 2012	P. Boutachkov	^{124}Xe	6
November 2012	S. Nishimura	^{238}U	7.5
November 2012	H. Watanabe, G. Lorusso	^{238}U	6
November 2012	G. Simpson, A. Jungclaus	^{238}U	5
December 2012	H. Watanabe, G. Lorusso	^{238}U	3.7
December 2012	M. Niikura	^{238}U	5.5
April 2013	A. Odahara, R. Lozeva, C. Moon	^{238}U	4.5
May 2013	T. Sumikama	^{238}U	9.5
May 2013	E. Ideguchi	^{238}U	5.5
May 2013	G. Benzoni	^{238}U	5.7
June 2013	M. Lewitowicz	^{124}Xe	12
June 2013	G. Lorusso	^{124}Xe	3
November 2014	H. Watanabe, P.A. Söderström	^{238}U	5.5
June 2015	B. Blank	^{78}Kr	5
June 2015	Y. Fujita, W. Gelletly, B. Rubio	^{78}Kr	5
June 2015	G. de Angelis, A. Algora, F. Recchia, B. Rubio	^{78}Kr	5
June 2016	A. Estrade	^{238}U	5
June 2016	F. Recchia	^{238}U	3.5
	19 Experiments	TOTAL	106.9

DALI2 (2010–to Present)

- Forward-wall configuration
- 186 NaI(Tl) detectors
- ϑ coverage 11° to 165°
- 7 % intrinsic resolution at 1 MeV
- $\Delta E/E \approx$**10(11) % at 100(250) MeV**/u
- **20% efficiency @ 1 MeV w/o add-back**
- Simplified target holder and beam pipe
- **3 PPAC for beam tracking, σ_ϑ = 5 mrad**
- 1mm Pb (+1mm Sn) shielding





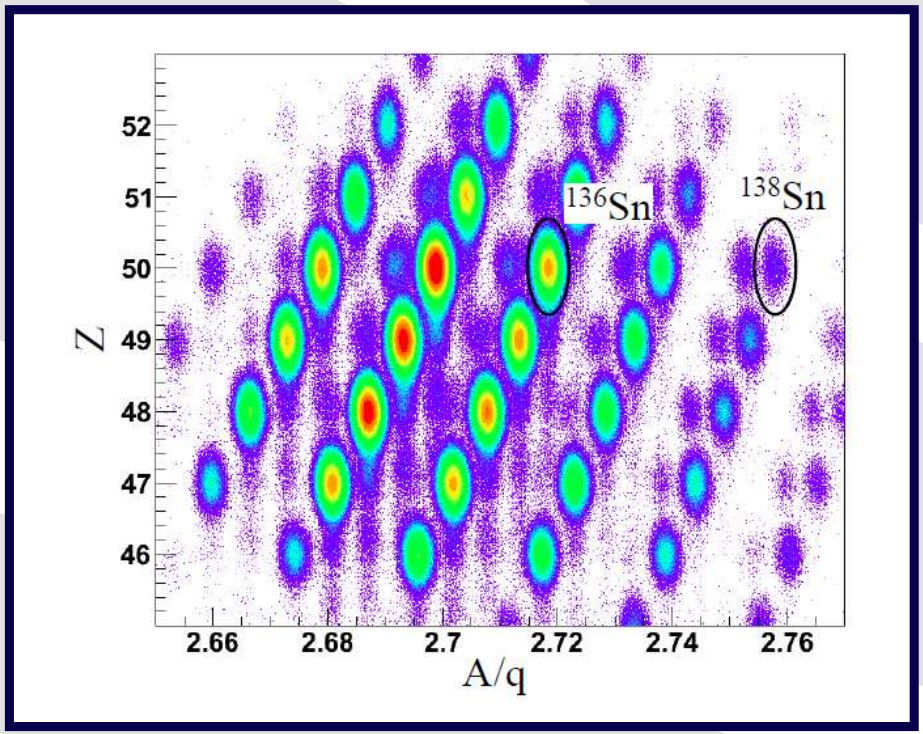
S. Takeuchi *et al.*, NIMA 763, 596 (2014).

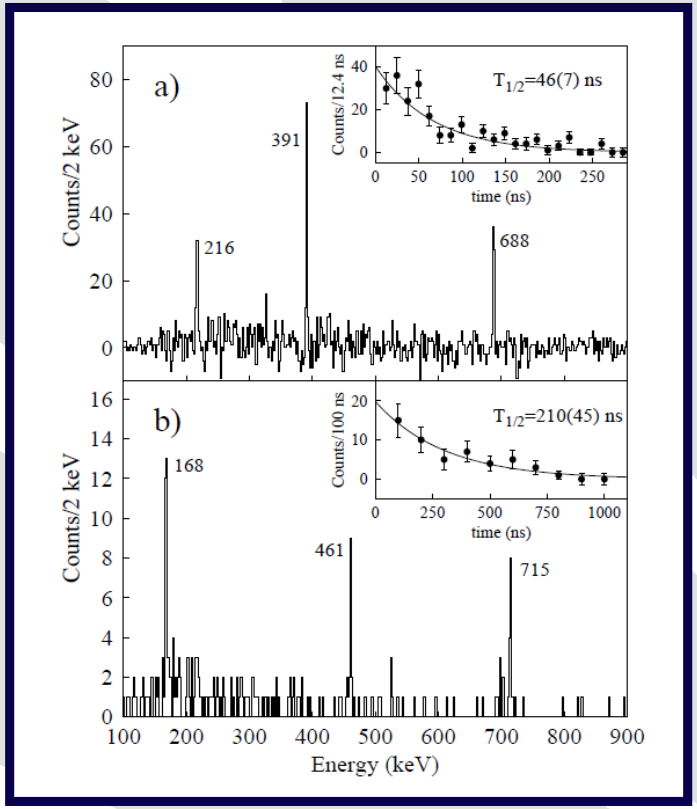
Performed Experiments ZDS(+DALI2)

Date	Spokesperson	Primary	Used Days	Nuclei	Method
December 2008	H. Scheit	^{48}Ca	0.5	^{32}Ne	knock-out
December 2008	T. Nakamura	^{48}Ca	2.5	^{20,22}C, ^{31}Ne	knockout, Coul. diss
December 2009	H. Scheit	^{48}Ca	–	^{32}Mg	Coulex
December 2010	S. Takeuchi	^{48}Ca	3.4	^{38,40,42}Si	knock-out
December 2010	H. Scheit	^{48}Ca	3	^{30}Ne, ^{36,38}Mg	knockout, Coulex
December 2010	D. Bazin	^{48}Ca	4	^{33}Mg	knockout
December 2010	P. Fallon	^{48}Ca	1	^{40}Mg	knockout
December 2010	T. Nakamura	^{48}Ca	4.5	n-rich Mg, Si	knockout, Coul. diss.
November 2011	K. Yoneda	^{238}U	10	^{78}Ni	knockout
December 2011	N. Aoi	^{238}U	3	^{122,124,126}Pd, ^{132}Cd, ^{136}Mg	knockout
June 2012	P. Doornenbal, A. Obertelli	^{124}Xe	5	^{102,104,112}Sn	knockout, Coulex
July 2012	D. Steppenbeck, S. Takeuchi	^{70}Zn	3	^{54}Ca	knockout
May 2013	G. de Angelis	^{238}U	parasitic	$^{73–75}$Ni	Coulex
April 2014	H. Wang, N. Aoi	^{238}U	3.5	^{130}Cd	Coulex
May 2014	P. Doornenbal, A. Obertelli	^{238}U	10	^{66}Cr, ^{70,72}Fe, ^{78}Ni	knockout
November 2014	T. Aumann	^{238}U	4.5	^{128,132}Sn	pygmy, inel.
November 2014	O. Wieland	^{238}U	2	^{70}Ni	pygmy, inel.
November 2014	H. Baba	^{48}Ca	7.5	^{20,22,24}O	pygmy, inel.
April 2015	E. Sahin	^{238}U	5	^{73,77}Cu	Coulex
April 2015	A. Jungclaus	^{238}U	3	^{136}Te	Coulex
May 2015	P. Doornenbal, A. Obertelli	^{238}U	9	many	knockout
May 2015	W. Korten	^{78}Kr	6	^{70,72}Kr	Coulex, knockout
	22 Experiments	TOTAL	90.4		

Selected EURICA Results

6^+ *seniority isomers of* ^{136,138}Sn

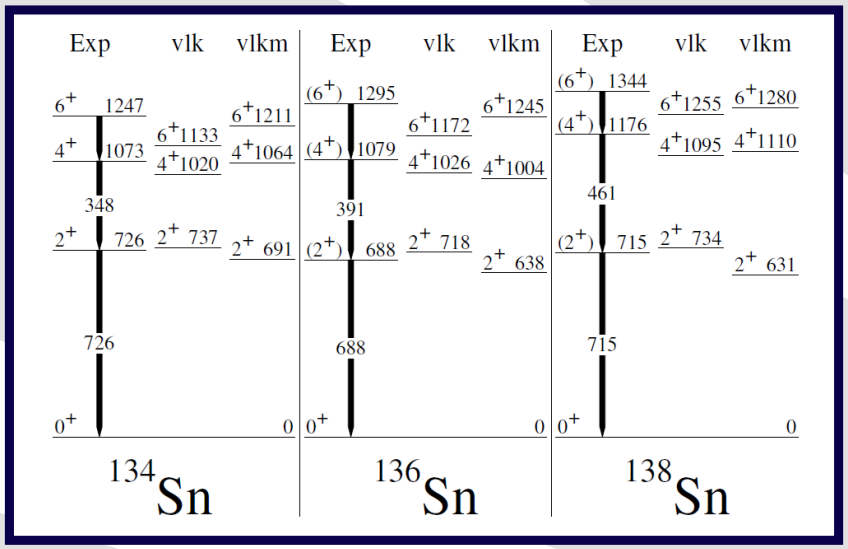


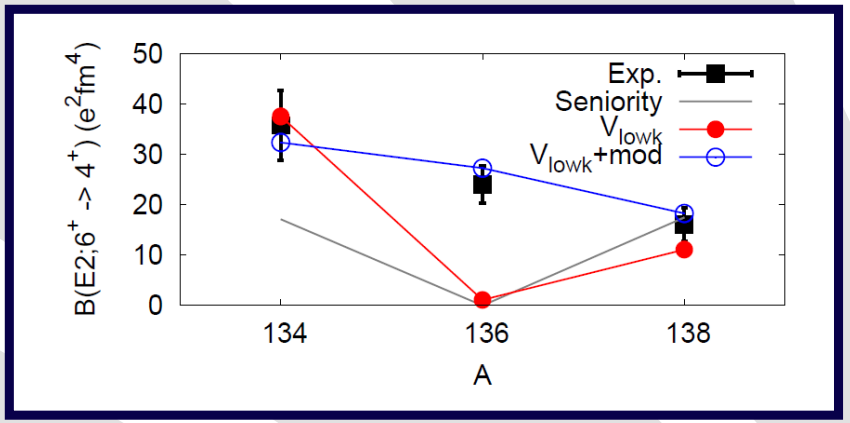


- To investigate in detail the neutron-neutron part of nucleon-nucleon effective interactions in semi-magic Sn nuclei which have simple structures.
- A 6^+ isomer is known in ^{134}Sn and the same isomer should be present in ^{136,138}Sn.

G.S. Simpson *et al.*, Phys. Rev. Lett. 113, 262502 (2014)

6^+ *seniority isomers of* ^{136,138}Sn

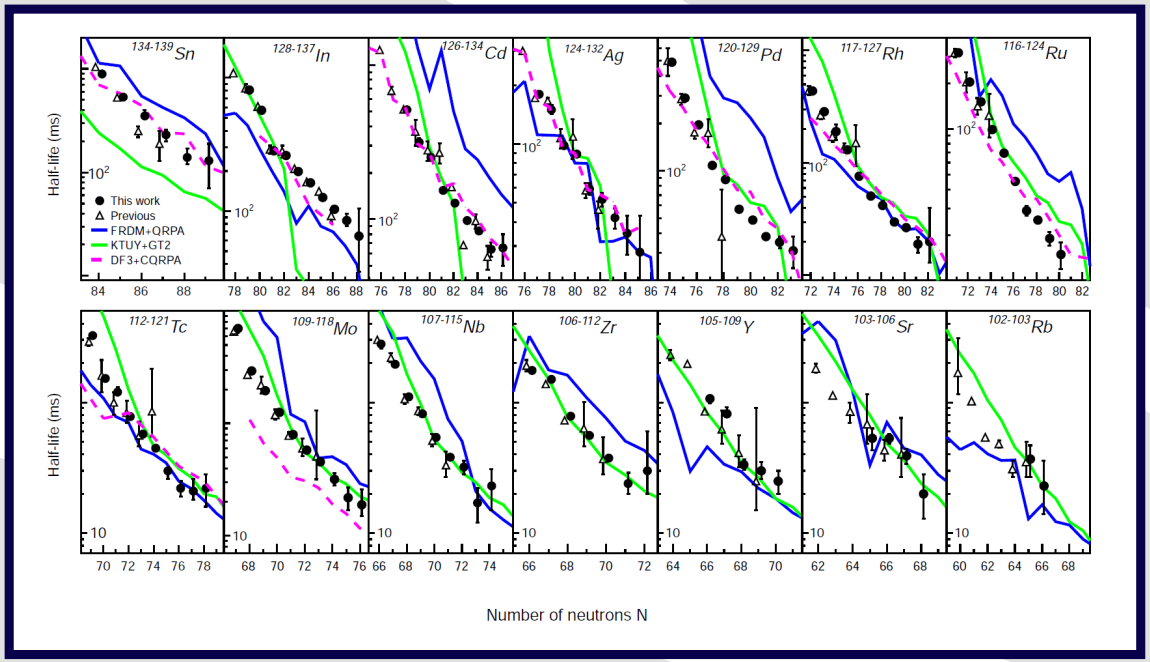


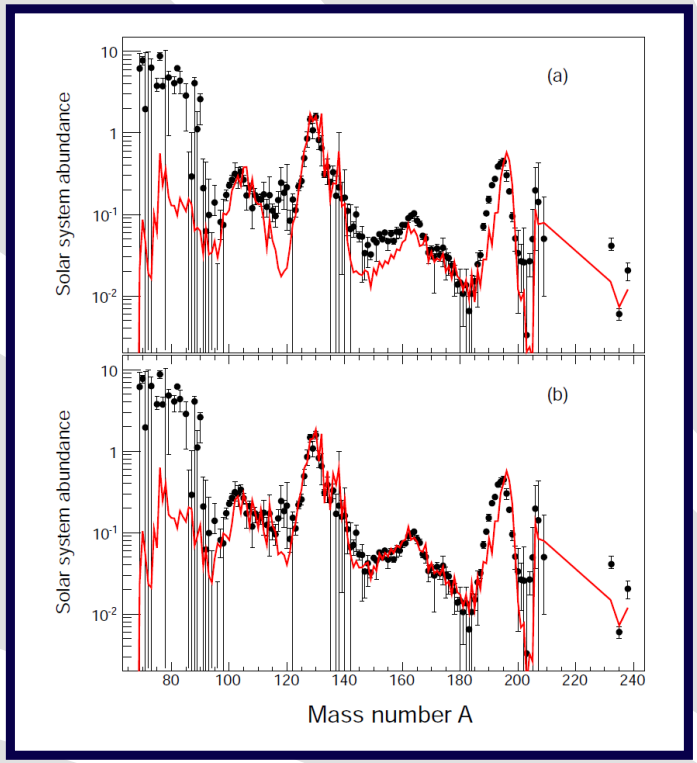


- Nearly constant energies of the 2^+, 4^+, 6^+ levels
- Seniority 2 excitations, mostly $\nu f_{7/2}^2$
- $6^+ \rightarrow 4^+$ B(E2) in ^{136}Sn not in agreement
- $\rightarrow$ reduce the $\nu f_{7/2}^2$ matrix elements
- Almost equal contribution of seniority 2 and 4

G.S. Simpson *et al.*, Phys. Rev. Lett. 113, 262502 (2014)

Measured Half-Lives in ^{132}Sn Region

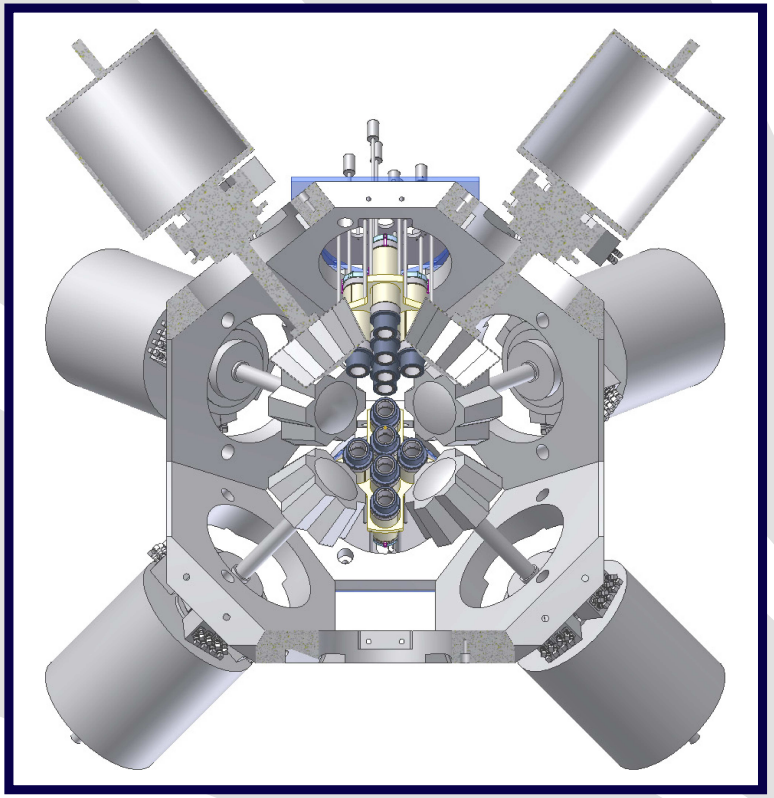




- 108 Half-Lives (re)-measured
- Direct impact on r-process calculations
- Hot r-process abundance drastically improved

G. Lorusso *et al.*, Phys. Rev. Lett. 114, 192501 (2015)

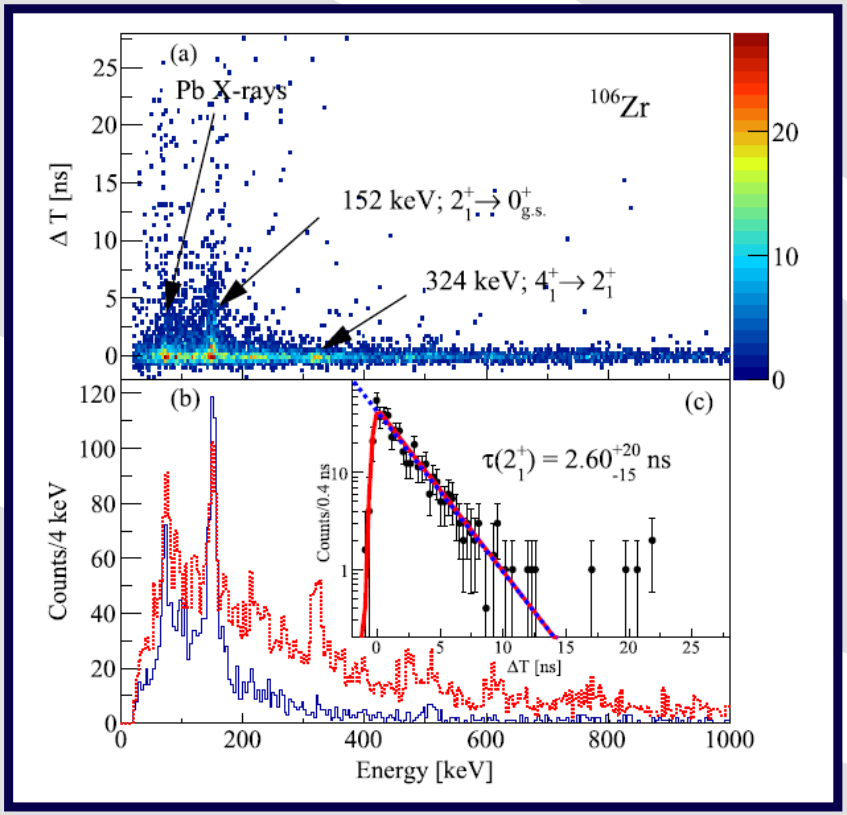
A Fast Timing Array together with EURICA

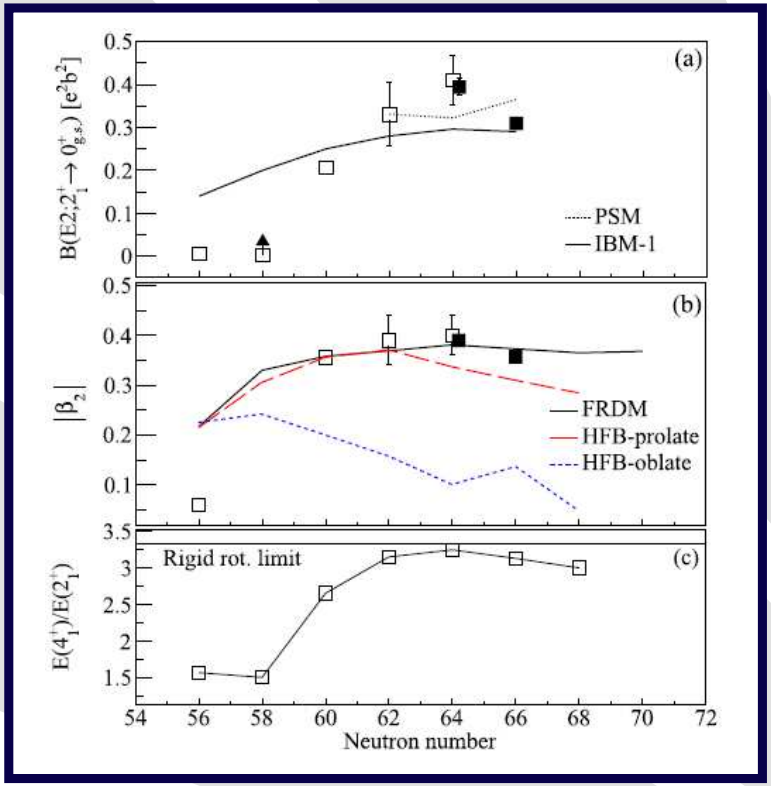


- 18 $LaBr_3$ detectors provided by UK
- $\beta\gamma$-coincidence with fast plastic scintillator
- First time this technique is used in-flight with RI Beams
- Life-time capability down to ~ 100 ps

Z. Patel *et al.*, RIKEN Accel. Prog. Rep. 47, 13 (2014)

Life-time of 2_1^+ states in ^{104,106}Zr



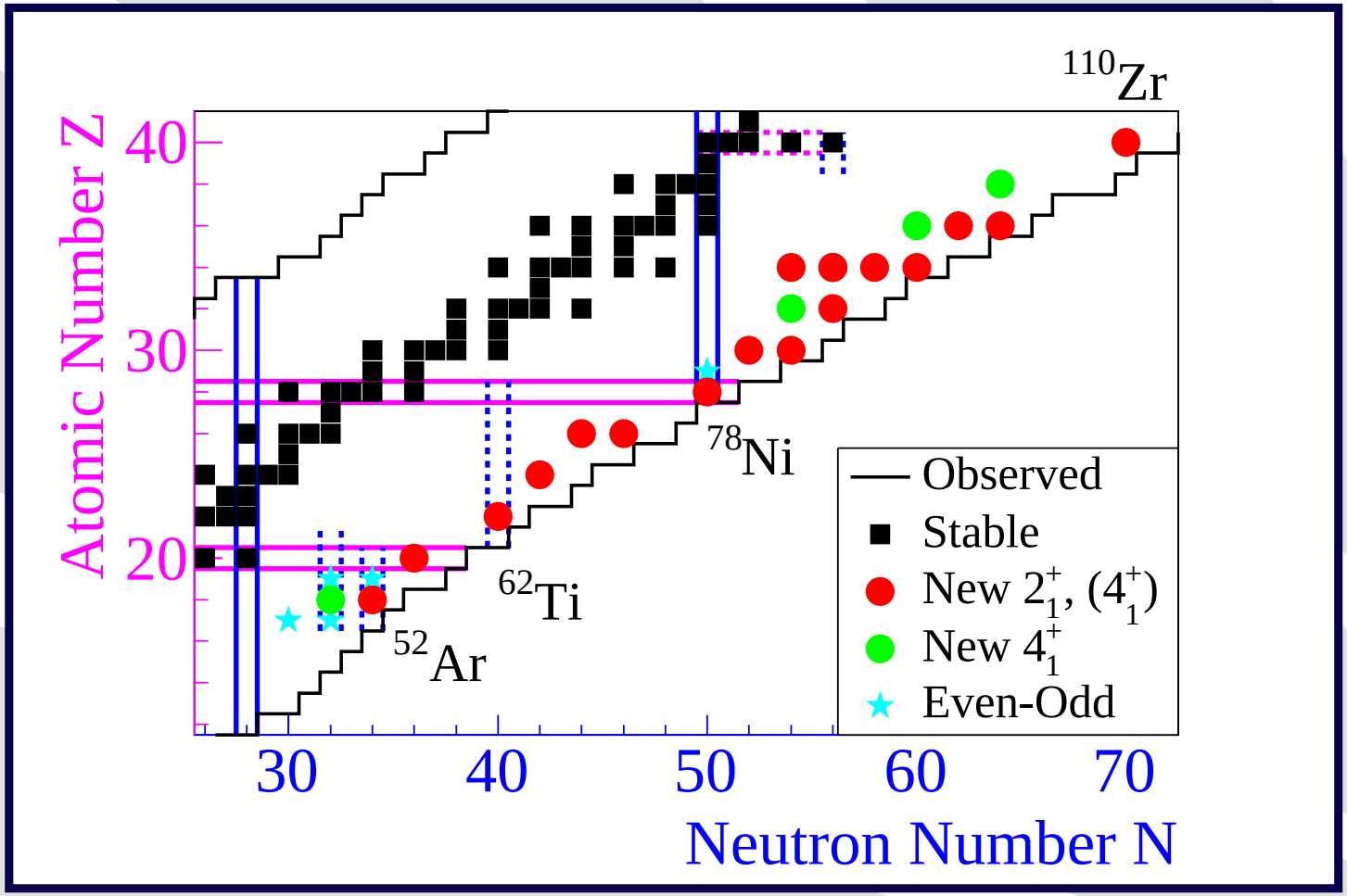


- First 2^+ and 4^+ states populated by β decay of ^{104,106}Y
- Clear exponential tail for the 2^+ state and a prompt 4^+ state
- Extraction of life-time shows deformation maximum for ^{104}Zr

F. Browne *et al.*, Phys. Lett. B 750, 448 (2015)

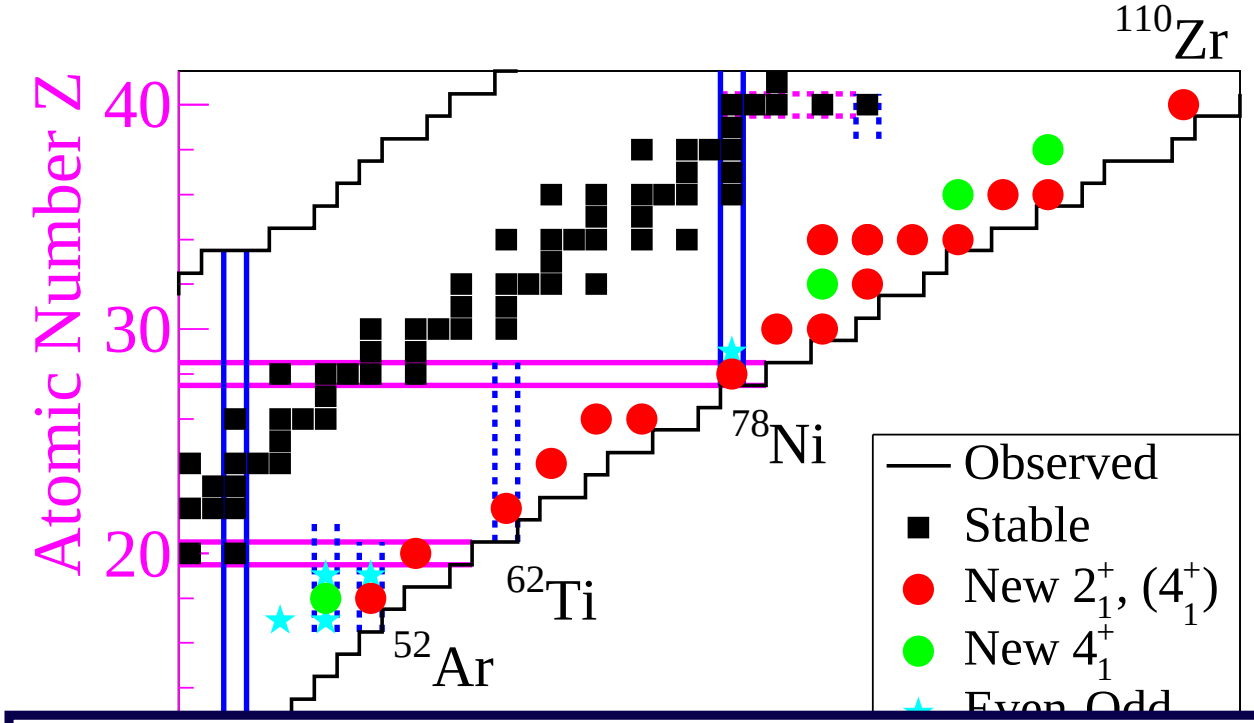
Selected DALI2 Results with SEASTAR

Shell Evolution And Search for Two-plus energies At the RIBF (SEASTAR)



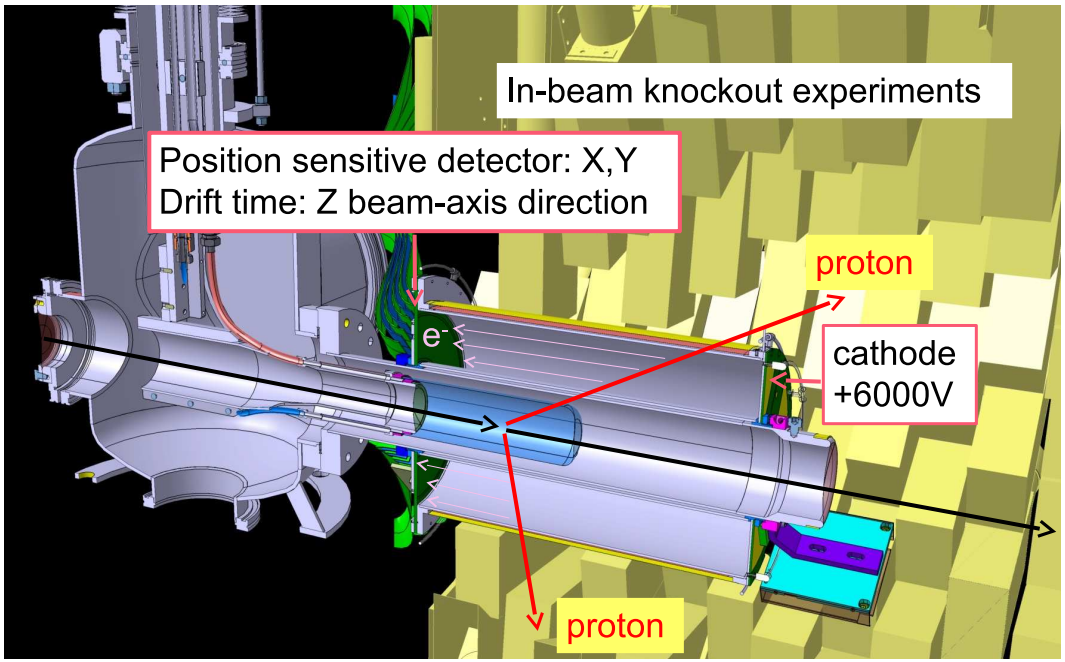
- 10 pnA ^{238}U, 75 pnA ^{70}Zn primary beams
- 24 days for data runs, 32.5 days including BigRIPS/ZD tuning
- DALI2+MINOS+ZDS+(EURICA) or DALI2+MINOS+SAMURAI
- Proposal NP1312-RIBF118 (Spokespersons: PD, A. Obertelli)
- 6 days for ^{78}Ni

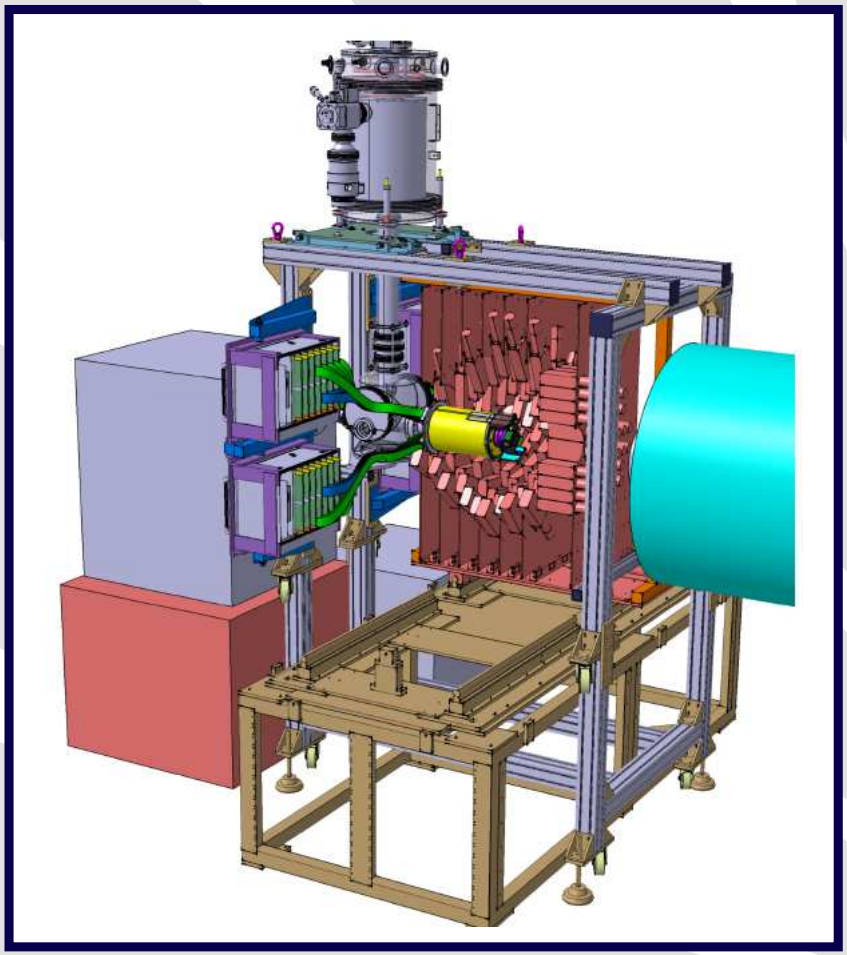
Shell Evolution And Search for Two-plus energies At the RIBF (SEASTAR)



- Neutron sub-shell at $N = 34$ below ^{54}Ca (^{52}Ar)
- Correlations in Ca isotopes beyond ^{54}Ca (^{56}Ca)
- Low-Z shore of the $N = 40$ "Island of Inversion" (^{60,62}Ti)
- Collectivity evolution beyond $N = 40$ (^{66}Cr, ^{72}Fe)
- Anticipated new doubly-magic nucleus ^{78}Ni
- Orbital migration beyond $N = 50$ ($^{82\text{-}84}$Zn, ^{86,88}Ge, ^{90,92}Se)
- Rise in collectivity at $N \geqslant 60$ (^{94}Se, ^{98,100}Kr)
- Evidence for a $N = 70$ sub-shell effect (^{110}Zr)

MINOS: Coupling of a Liquid Hydrogen Target with a TPC





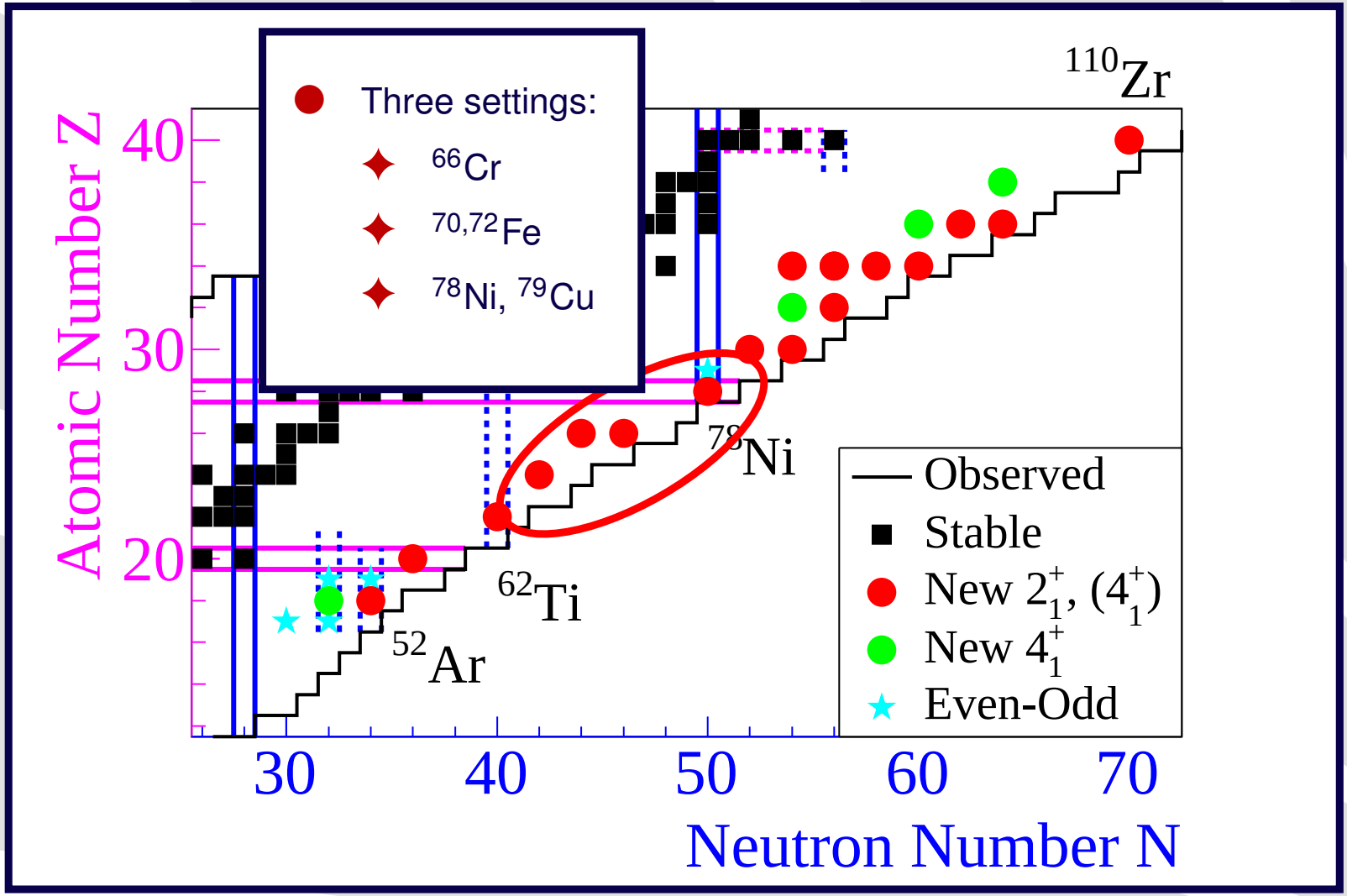
MagIc Numbers Off Stability

`http://minos.cea.fr`

- Up to 1 g/cm^2 liquid hydrogen target
- Position sensitive TPC
  - Driftime $\rightarrow$ Z-beam axis
  - Vertex position reconstruction
  - Achieved $\approx$5 mm (FWHM)

A. Obertelli *et al.*, Eur. Phys. J. A 50, 8 (2014).

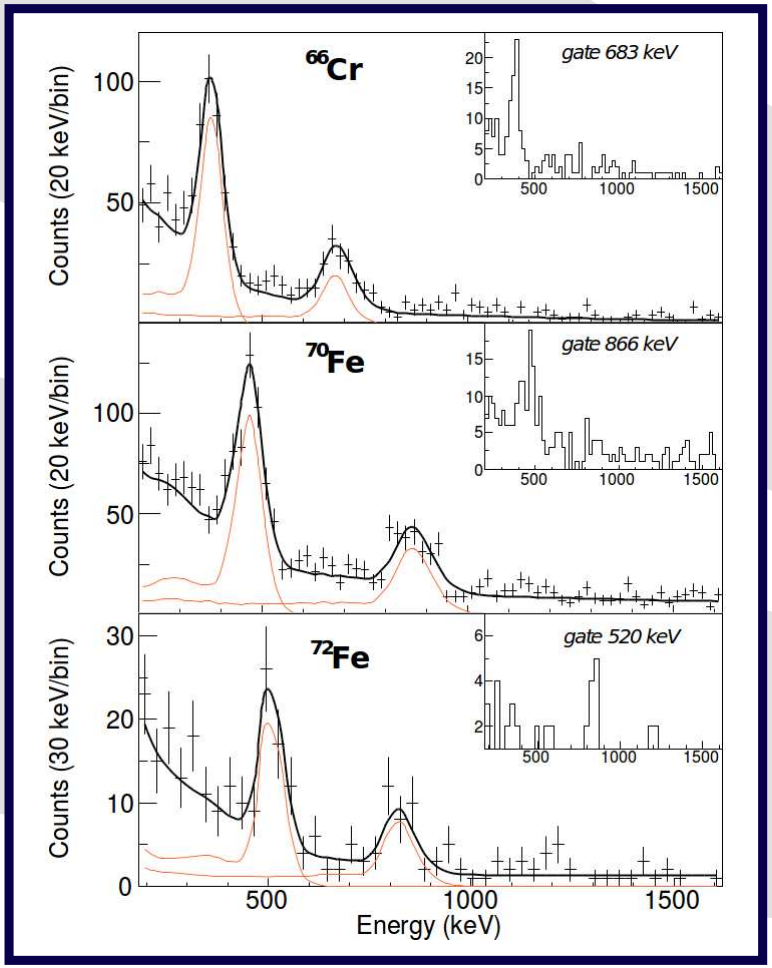
Nuclei of Interest for First SEASTAR Campaign, May 2014

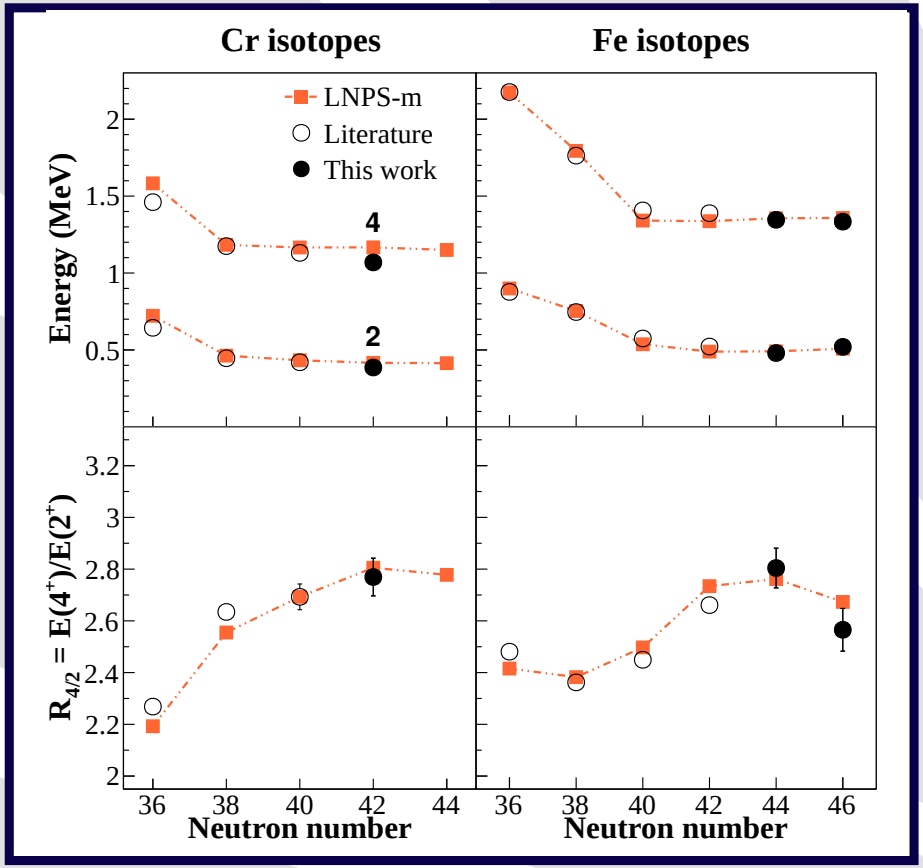


- 10 days of beam time
- ^{238}U primary beam, **average intensity 13–15 pnA!**
- Secondary beams at 240 MeV/u, 100-mm target, $\delta\beta = 20\%$

SEASTAR Collaboration, May 2014

Maximum of Collectivity Beyond $N = 40$

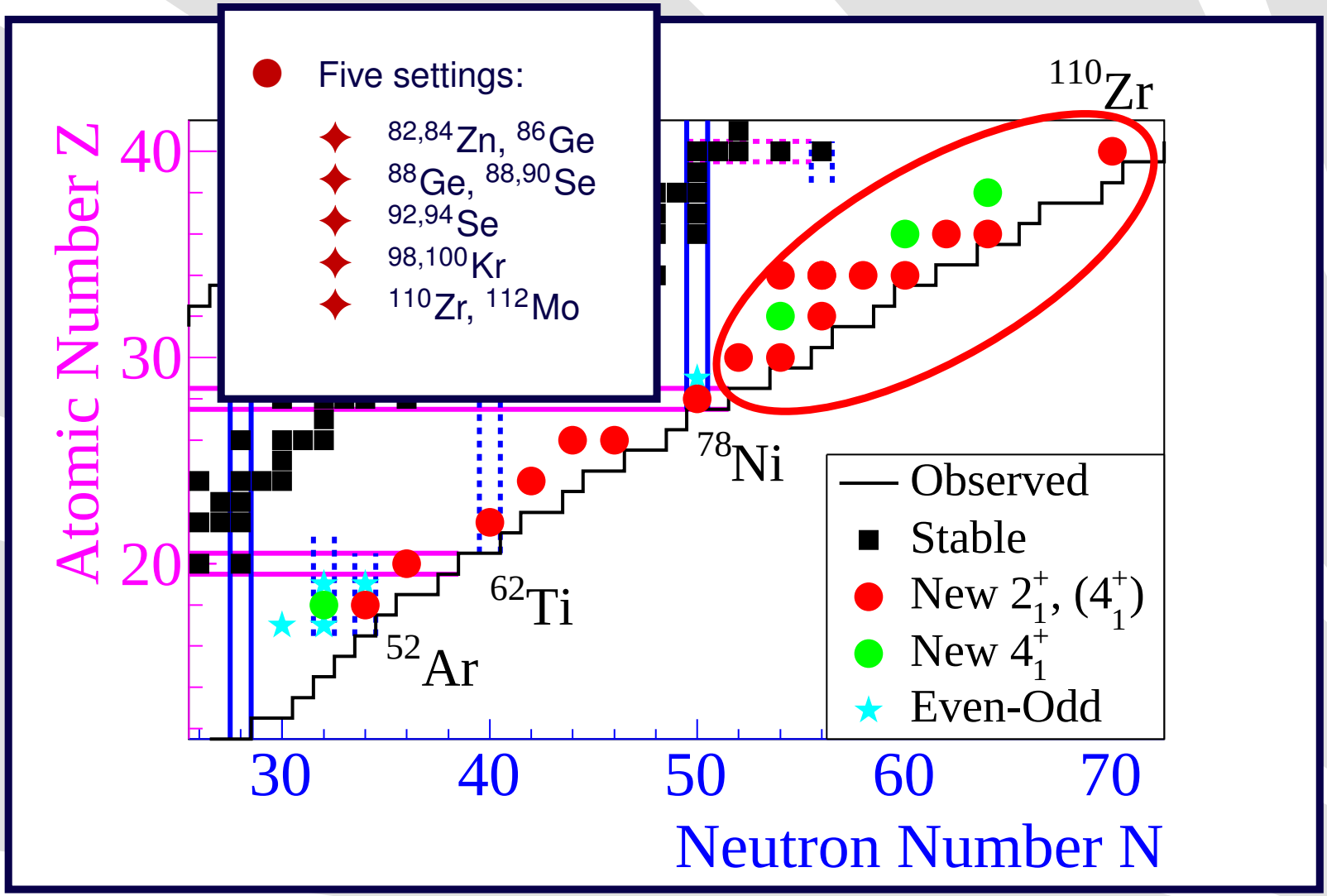




- Collaboration with F. Nowacki, IPHC, $fp - fpg_9d_5$ valence space
  - additional $gd - gd$ monopole strength
- Extension of $N = 40$ "Island of Inversion" towards $N = 50$

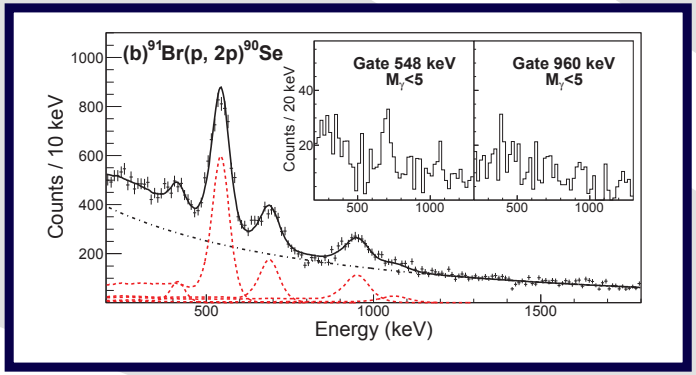
C. Santamaria, C. Louchart *et al.*, PRL 115, 192501 (2015).

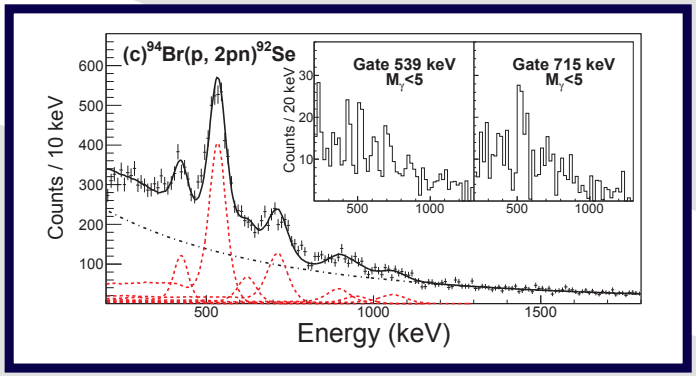
Nuclei of Interest for Second SEASTAR Campaign, May 2015

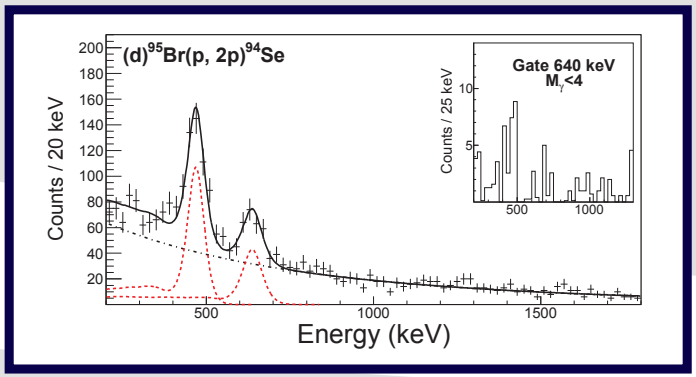


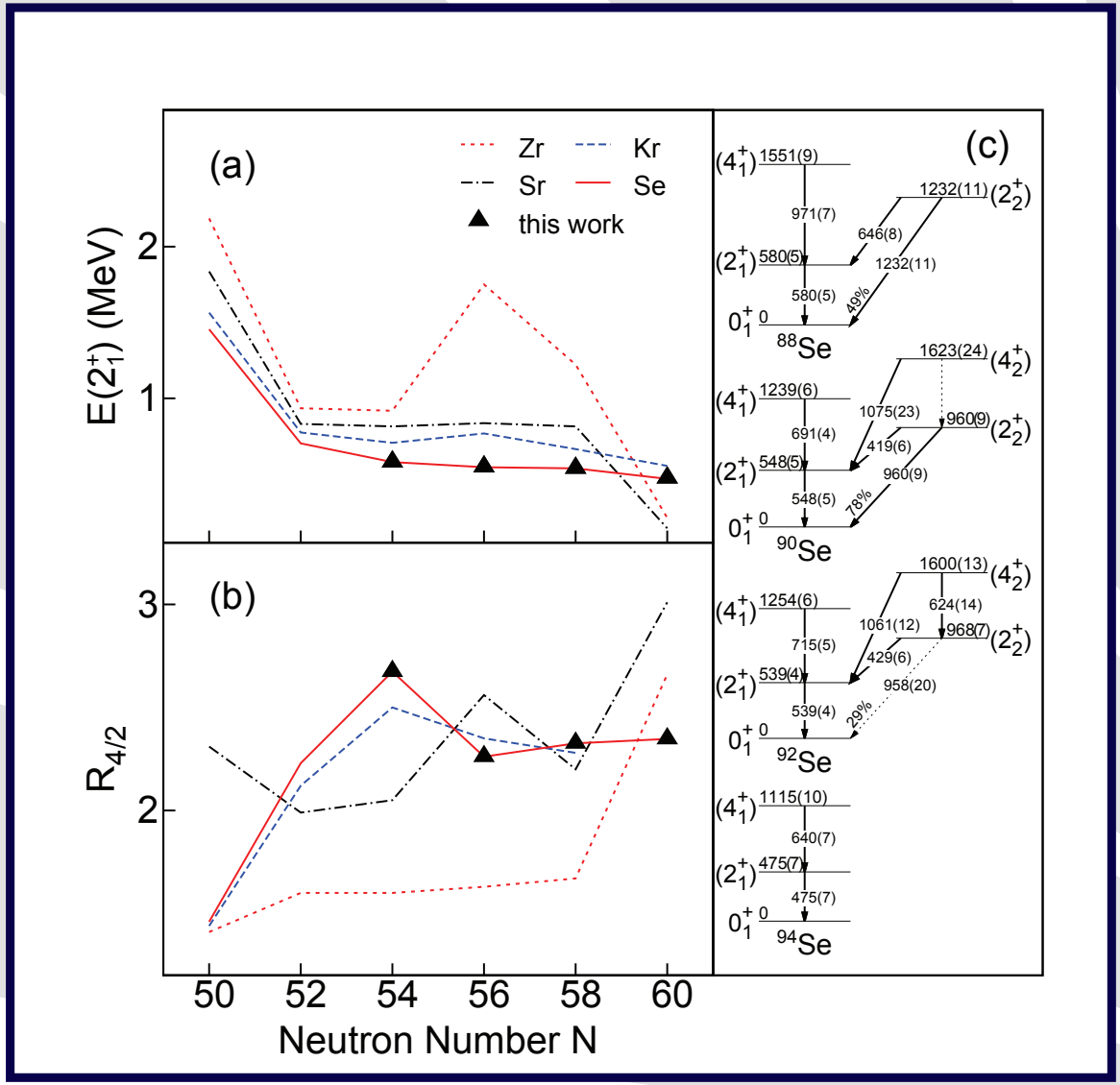
- 9 days of beam time
- ^{238}U primary beam, **average intensity 30 pnA!**
- Secondary beams at 260 MeV/u, 100-mm target, $\delta\beta = 20\%$

Neutron-rich Se Isotopes



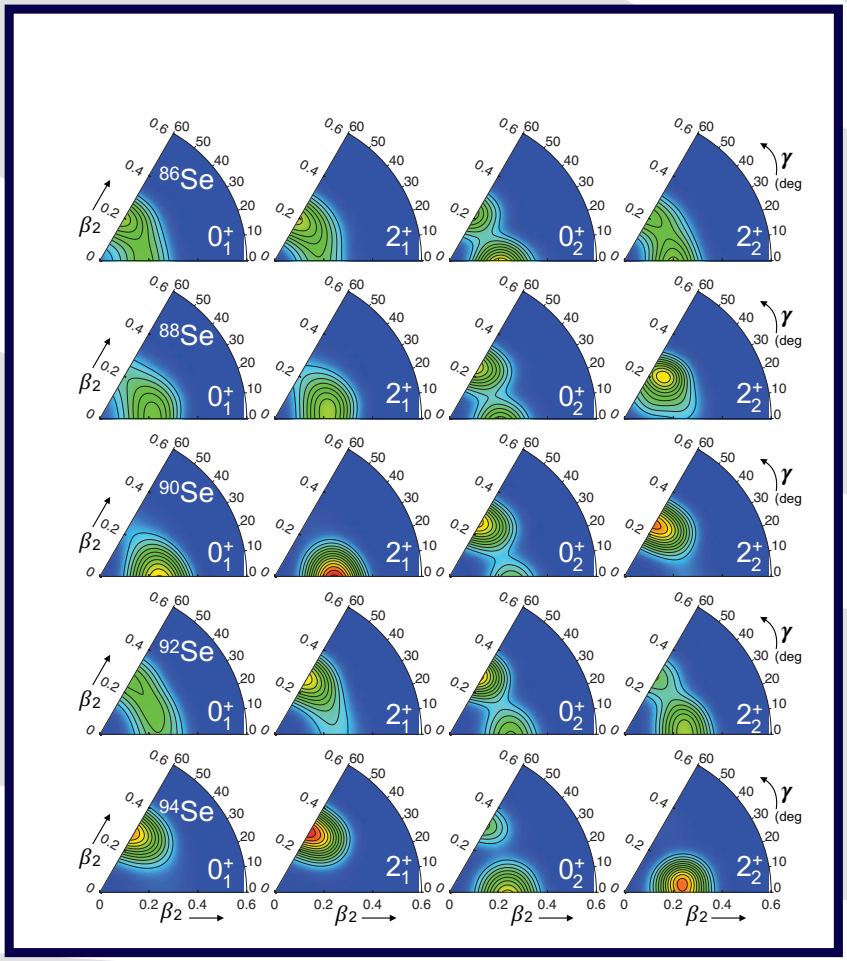


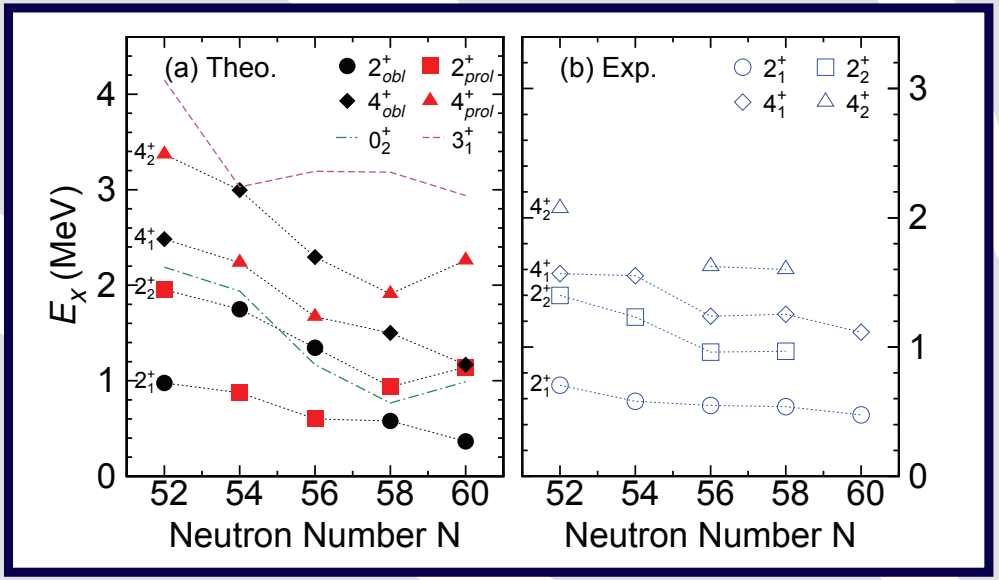




DALI2 analysis by S. Chen, RIKEN; EURICA ^{92,94}Se isomers by C. Lizarazo, TU Darmstadt

Neutron-rich Se Isotopes

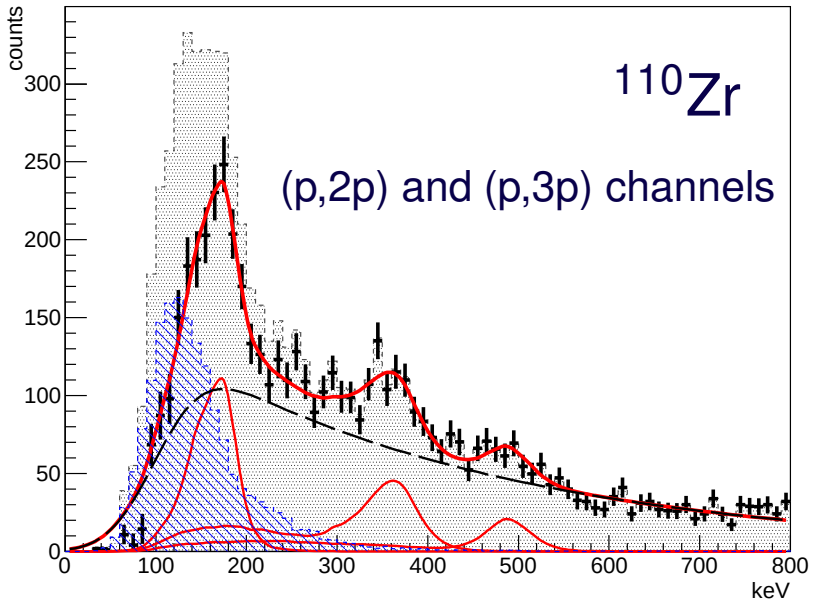


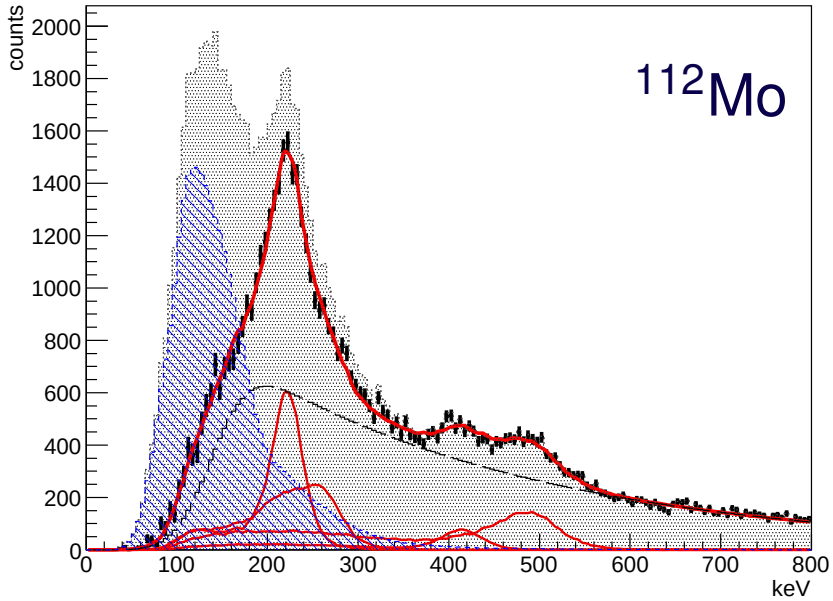


- Gogny D1S effective interaction
- Full GCM for all quadrupole degrees of freedom
- Prediction for shape coexistence
- AND prolate to oblate shape transition at N=58-60
- T.R. Rodriguez, Madrid, Spain
- Good agreement between expt and theory for 2_1^+, 2_2^+, 4_1^+, 4_2^+

DALI2 analysis by S. Chen, RIKEN; EURICA ^{92,94}Se isomers by C. Lizarazo, TU Darmstadt

First Spectroscopy of ^{110}Zr

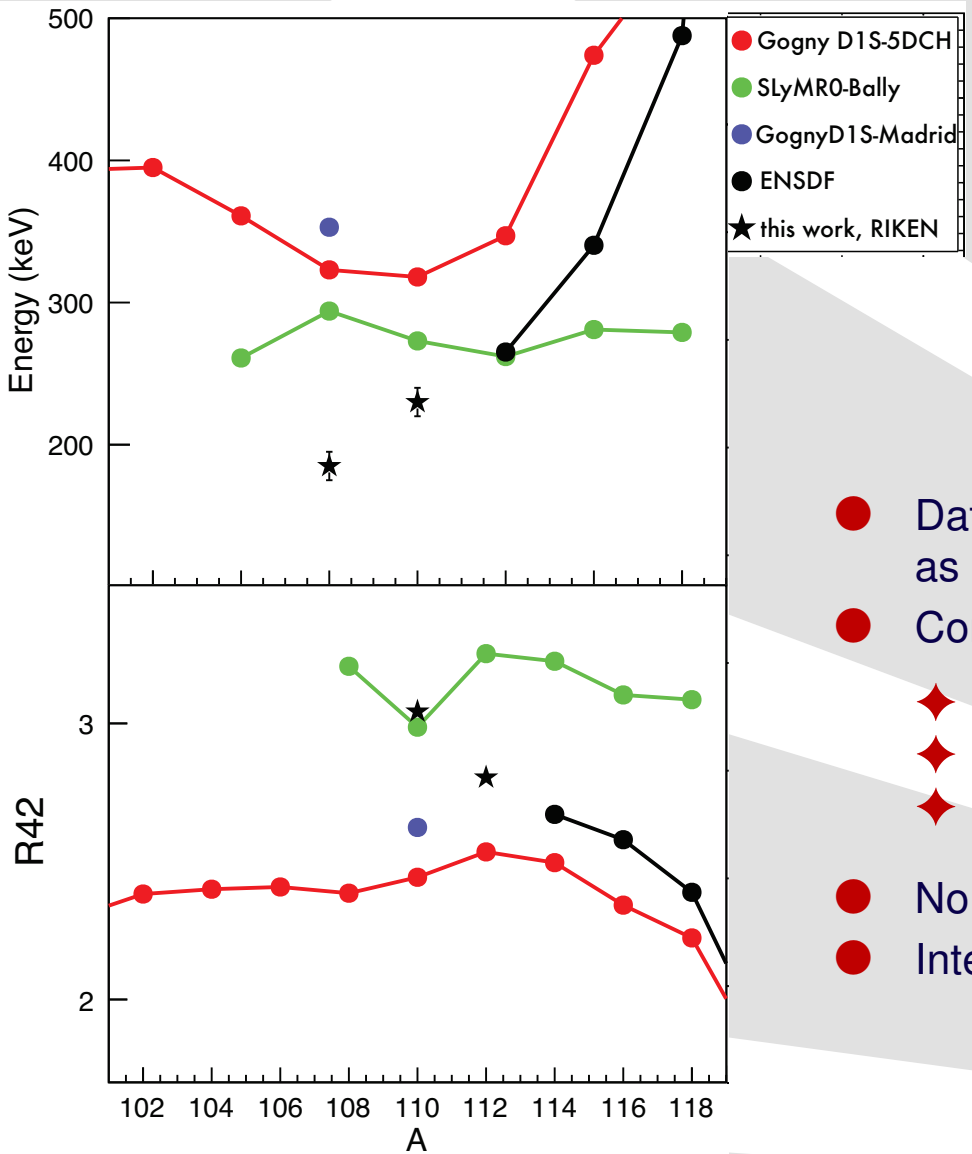




- DALI2 thresholds < 100 keV
- Subtraction of Bremsstrahlung components from elastic events (with absolute normalisation)
- Benchmark on ^{108}Zr and in agreement with ^{112}Mo β-decay from EURICA
- Lifetime effects taken into account

DALI2 analysis by N. Paul, CEA Saclay

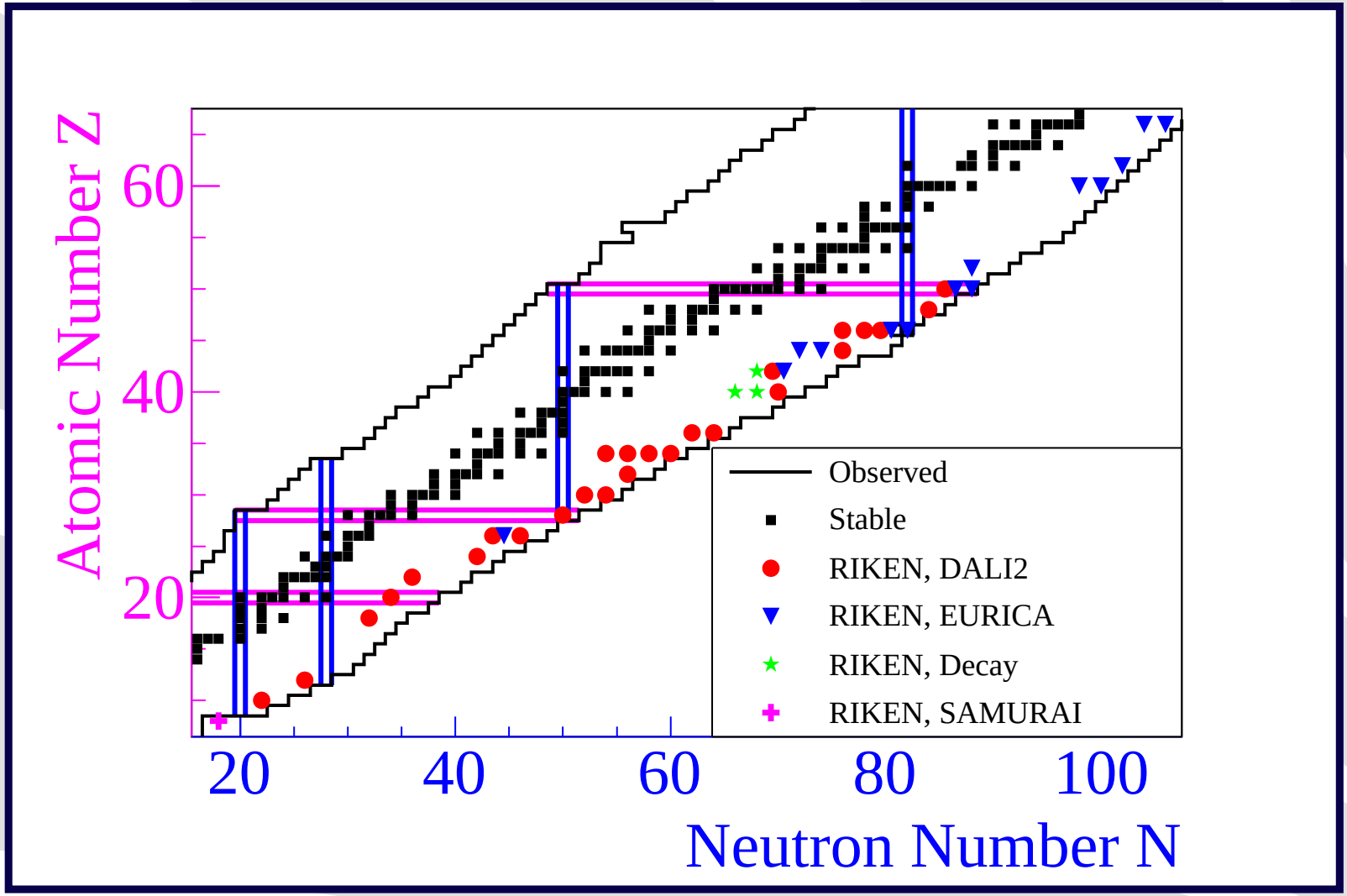
Extreme deformation at $N = 70$ in ^{112}Mo and ^{110}Zr



- Data show an unpredicted increase of deformation as one goes more neutron rich
- Comparison to beyond mean field approaches:
  - Gogny D1S, Bohr Hamiltonian (5DCH)
  - Gogny D1S, full GCM
  - SlyMR0, full GCM
- No stabilizing $N = 70$ subshell
- Interpretation still in progress

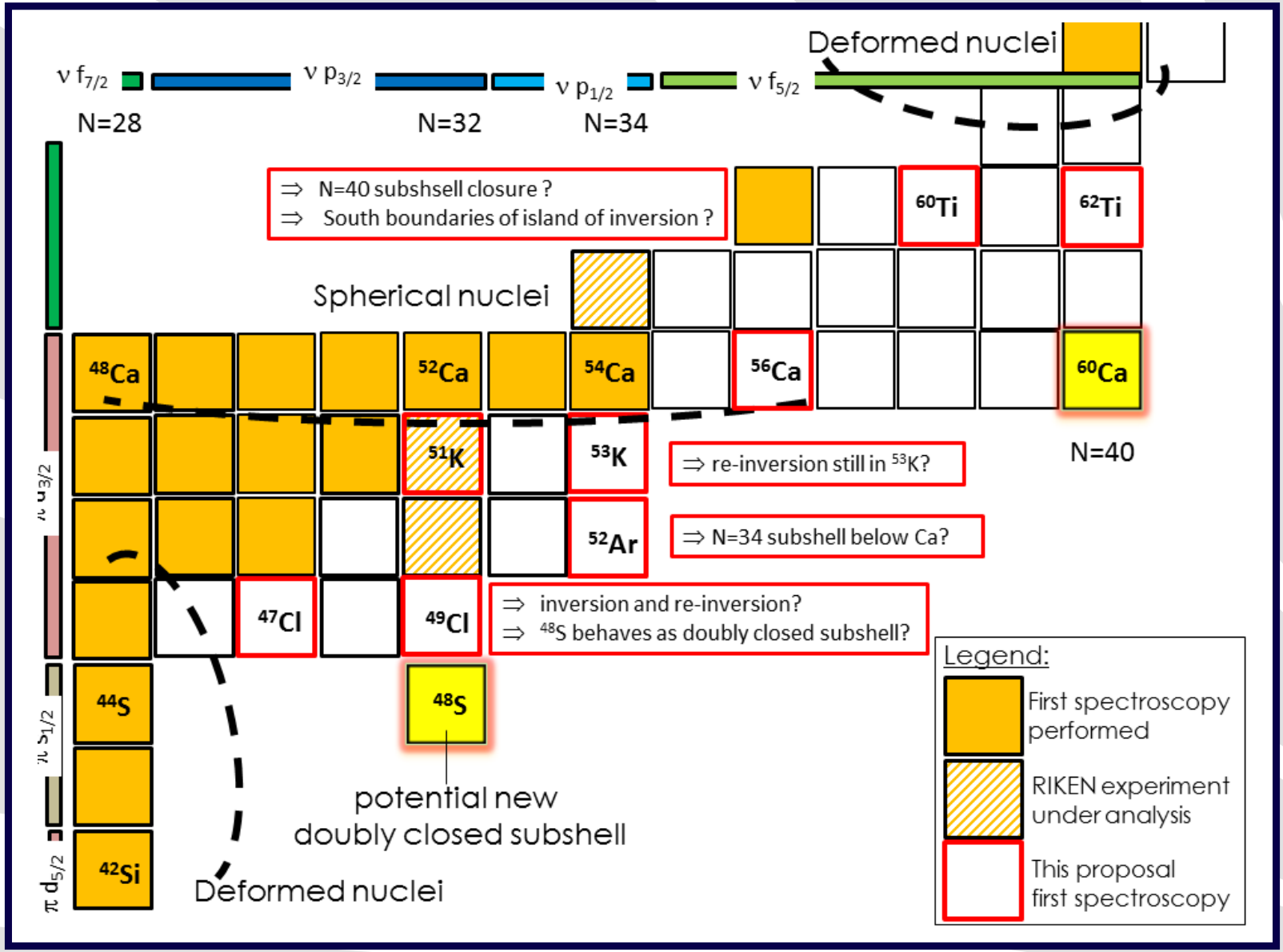
Summary and Outlook

Observed Neutron-Rich $E(2_1^+)$ at RIBF Since 2009

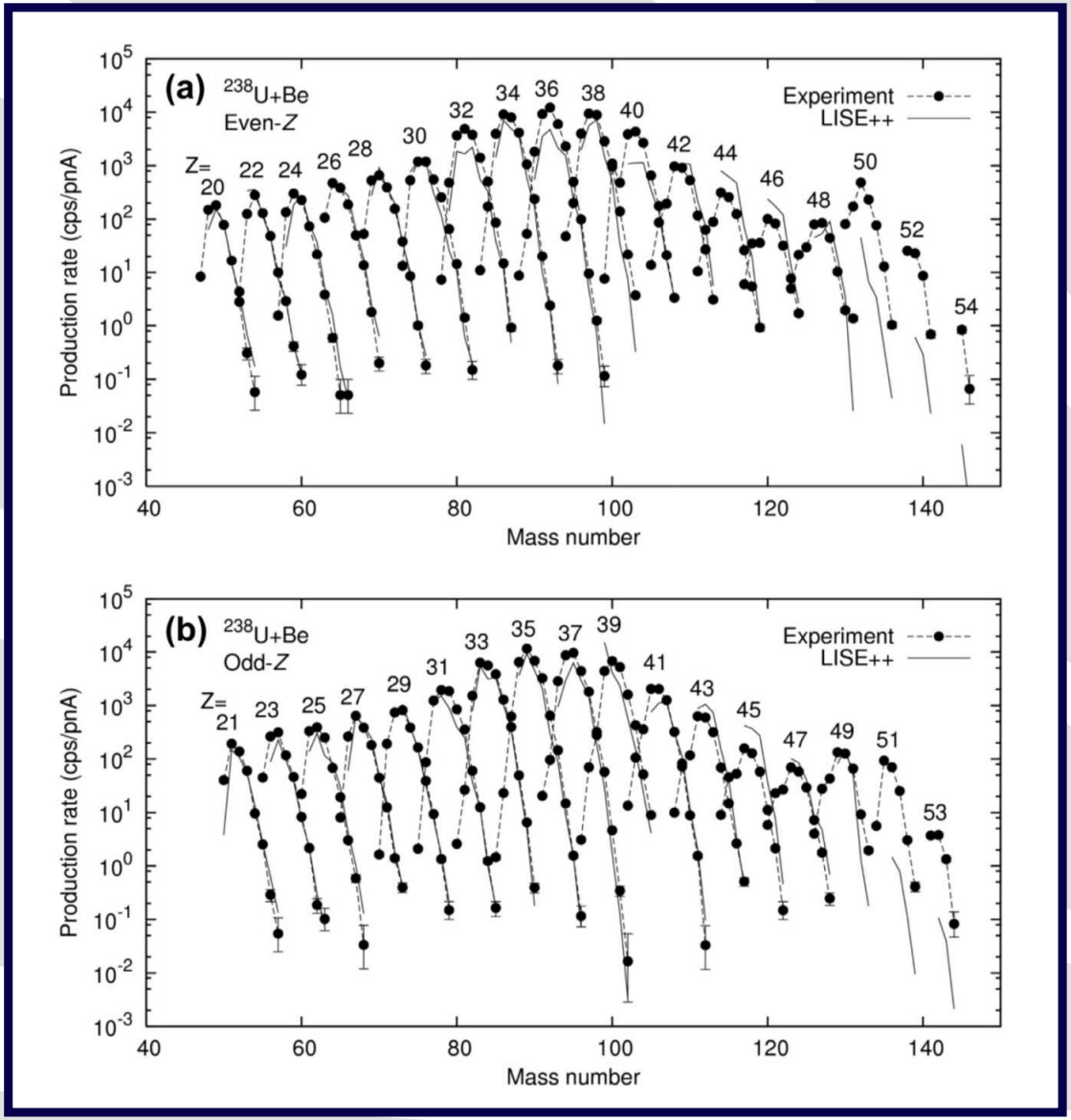


- 41 new $E(2_1^+)$ observed since 2009 at RIBF

Physics Case of 3rd SEASTAR Campaign



Production Cross-Sections



H. Suzuki *et al.*, NIMB 317, 756 (2013).

Summary

- EURICA physics program very successful
  - Experimental program completed
  - 107 days of beam time used since 2012
  - ≈25 publications so far
  - Cluster detectors go back to GSI this year
- SUNFLOWER experiments with DALI2
  - 87 days of beam time used since 2010
    - 25 days of backlog
  - ≈25 publications so far
- SEASTAR Project at the RIBF
  - Combination of LH_2 target up to 15 cm with DALI2
  - First spectroscopy of:
    - May 2014: ^{66}Cr, ^{70,72}Fe, ^{78}Ni
    - May 2015: ^{84}Zn, ^{88}Ge, ^{88,90,92,94}Se, ^{98,100}Kr, ^{110}Zr, ^{112}Mo
    - Spring 2017: ^{52}Ar, ^{56}Ca, ^{62}Ti
- In-beam spectroscopy of ^{100}Sn now within reach

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SEASTAR Collaboration

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Thank You!

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