
RIKEN
NISHINA
CENTER

Recent Results of In-Beam Gamma-Ray Spectroscopy at the RIBF

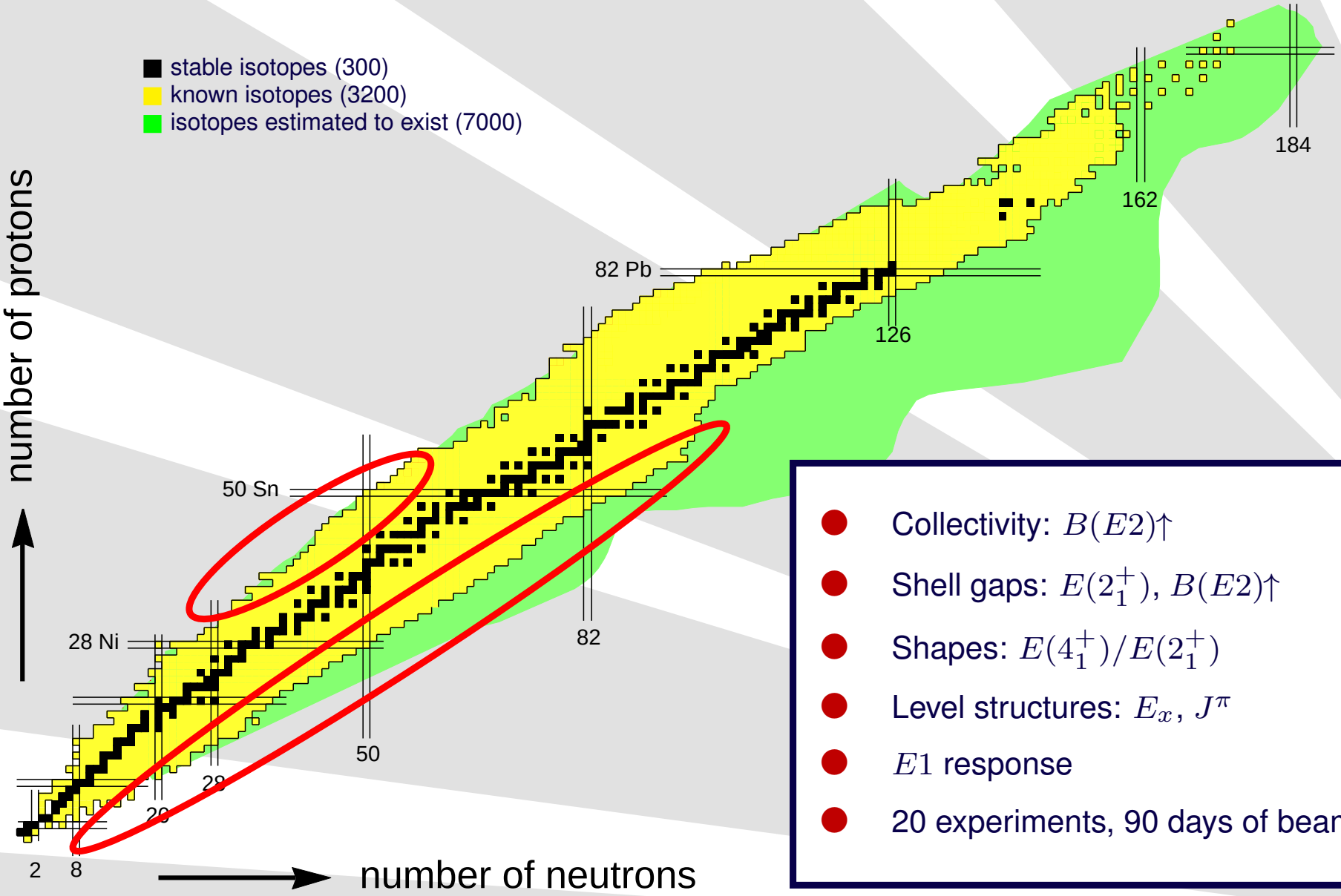
P. Doornenbal, for the SUNFLOWER Collaboration
ピーター　ドルネンバル

Outline

- Physics case
- Setup
- Selected results
  - The “Island of Inversion”
  - SEASTAR
    - Neutron-rich Cr, Fe isotopes
    - Kr isotopes beyond $N = 60$
    - $N = 70$ isotones
- Conclusions and perspectives

Physics Case

Regions of Interest



- Collectivity: $B(E2)\uparrow$
- Shell gaps: $E(2_1^+)$, $B(E2)\uparrow$
- Shapes: $E(4_1^+)/E(2_1^+)$
- Level structures: E_x, J^π
- $E1$ response
- 20 experiments, 90 days of beam

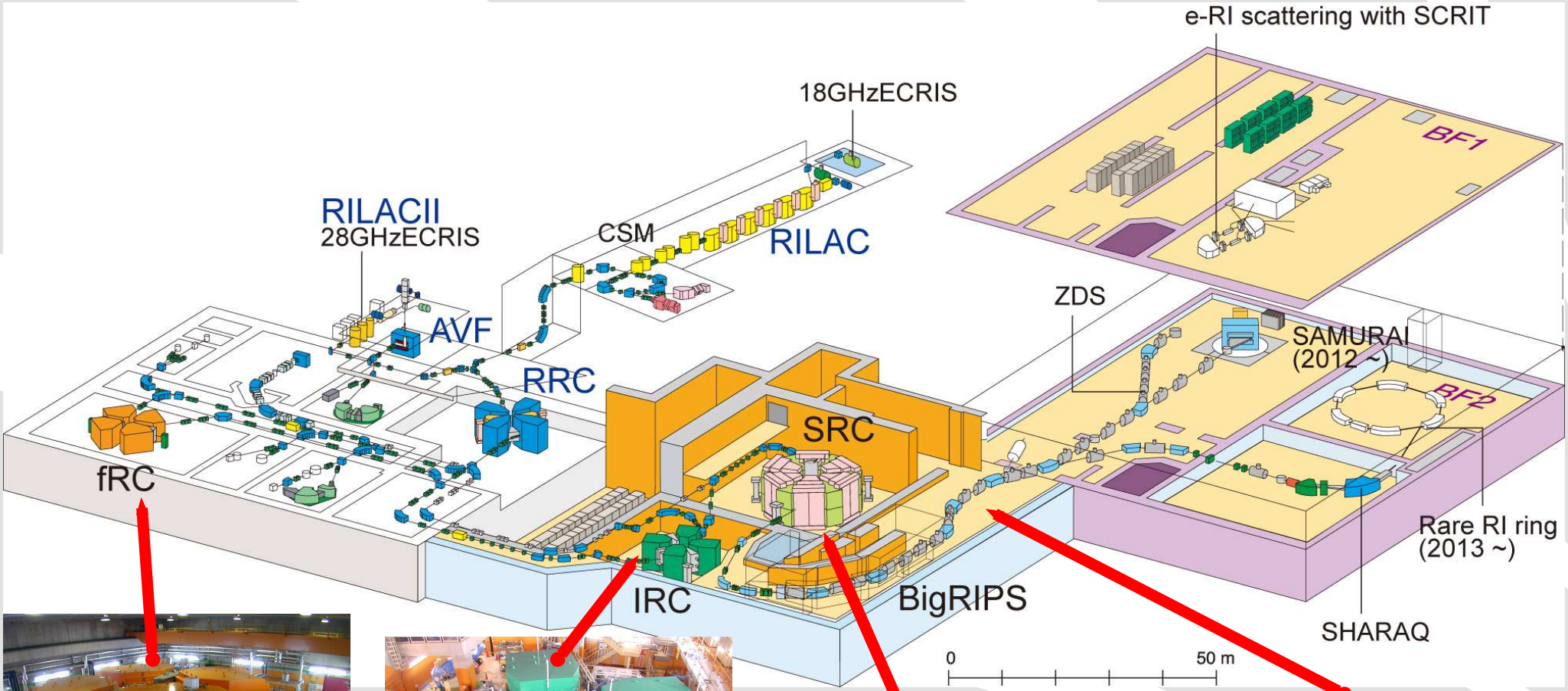
Regions of Interest

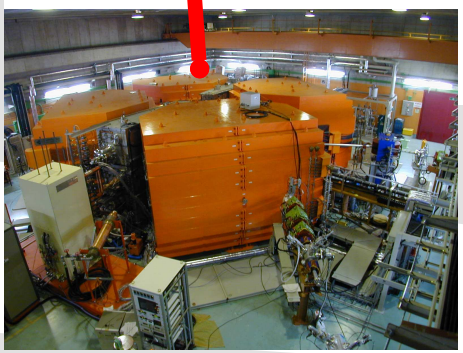
Other in-beam gamma talks during INPC 2016:

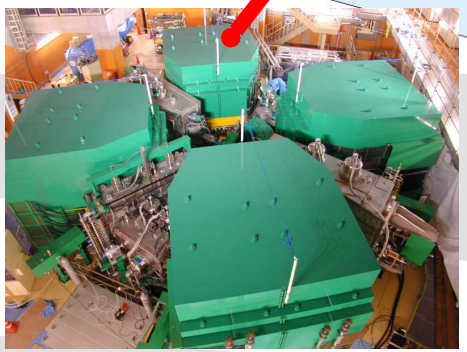
- Mo: K. Wimmer,
  Shape Coexistence at $N = Z$: Spectroscopy of the $T_z = -1$ nucleus ^{70}Kr
- Mo: S. Chen
  In-beam γ-ray spectroscopy of ^{88,90,92,94}Se
- Tu: R. Taniuchi,
  First Spectroscopy of the doubly-magic ^{78}Ni knockout reaction
- Tu: V. Werner
  Gamma-ray spectroscopy into the neutron-rich $A \approx 90$ region
- Tu: M.L. Cortes
  Inelastic scattering of Ni and Zn isotopes off a proton target
- Th: D. Steppenbeck
  Low-lying structures of exotic Sc isotopes an the evolution of the $N = 34$ subshell closure

Experimental Setup

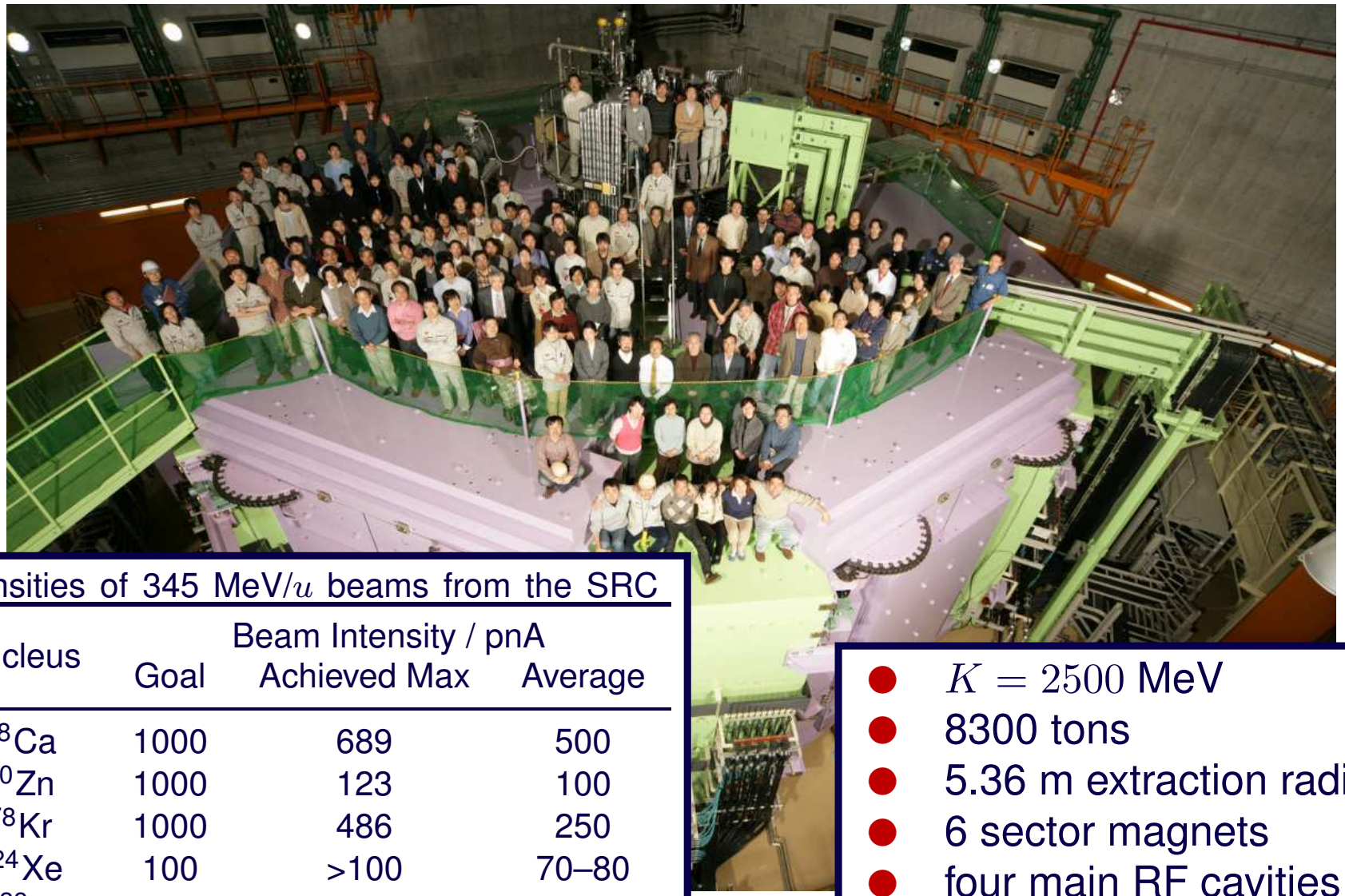
RIBF Overview







Superconducting Ring Cyclotron (SRC)

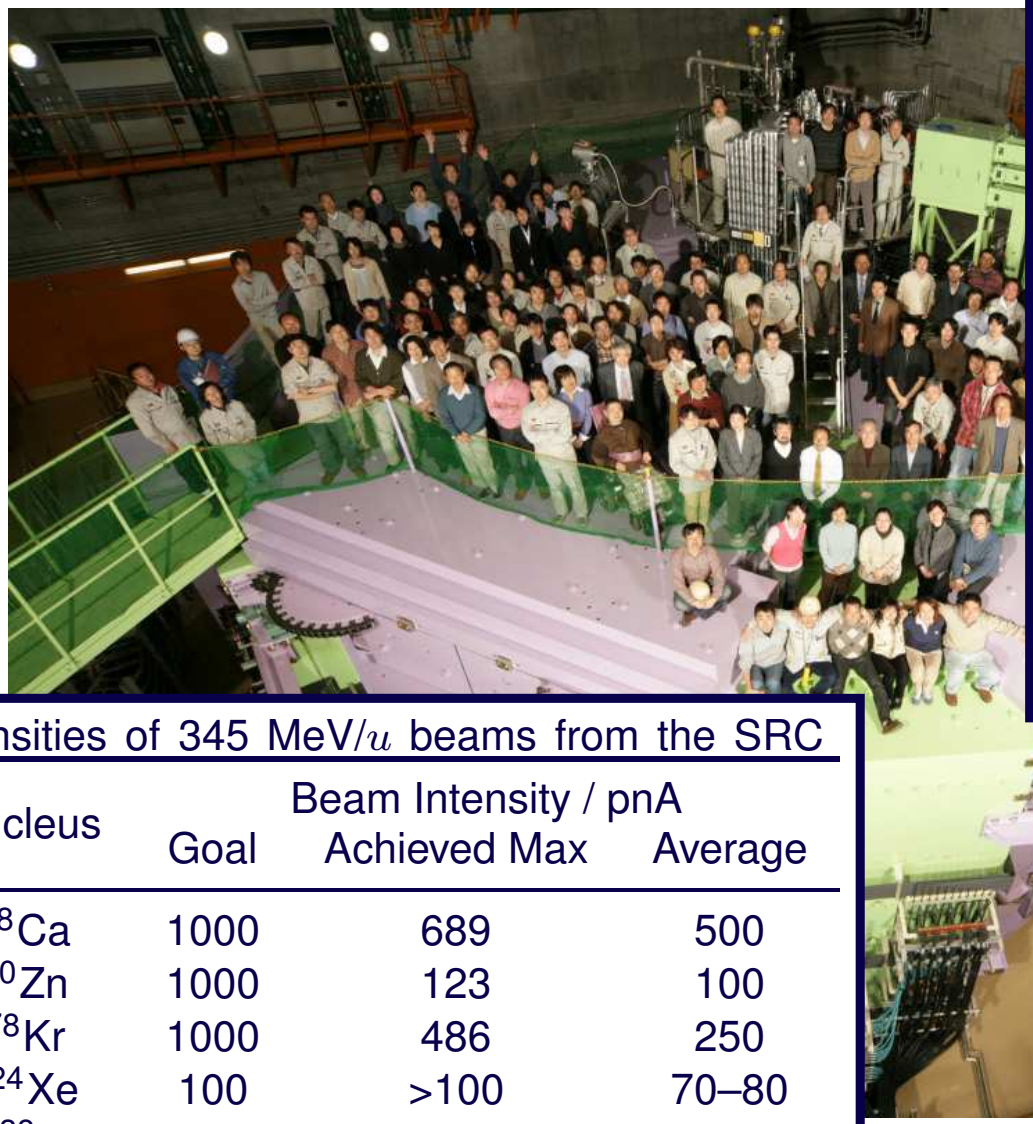


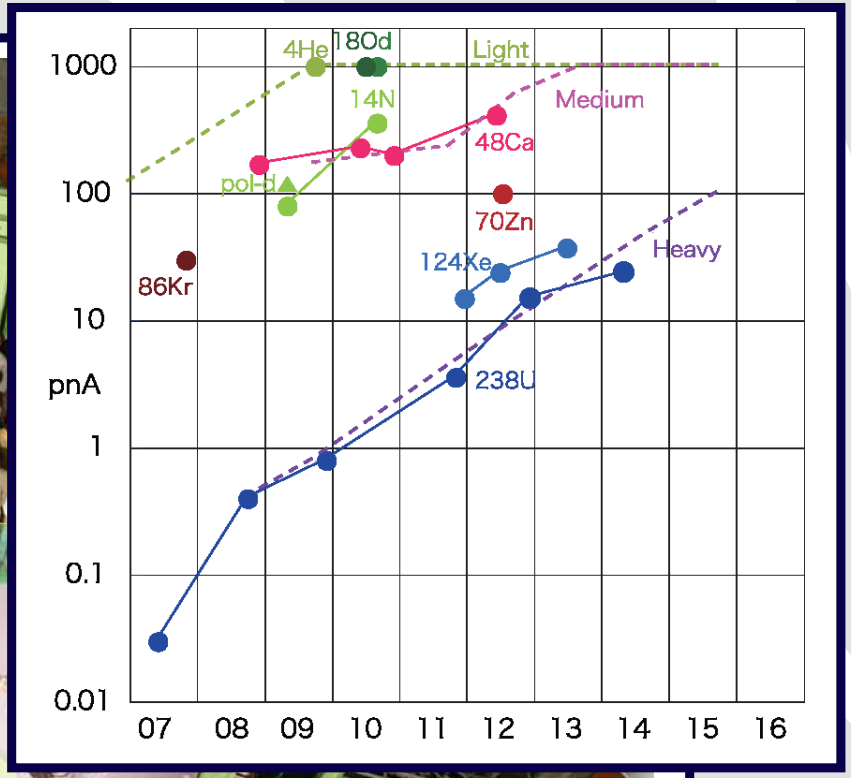
Intensities of 345 MeV/u beams from the SRC

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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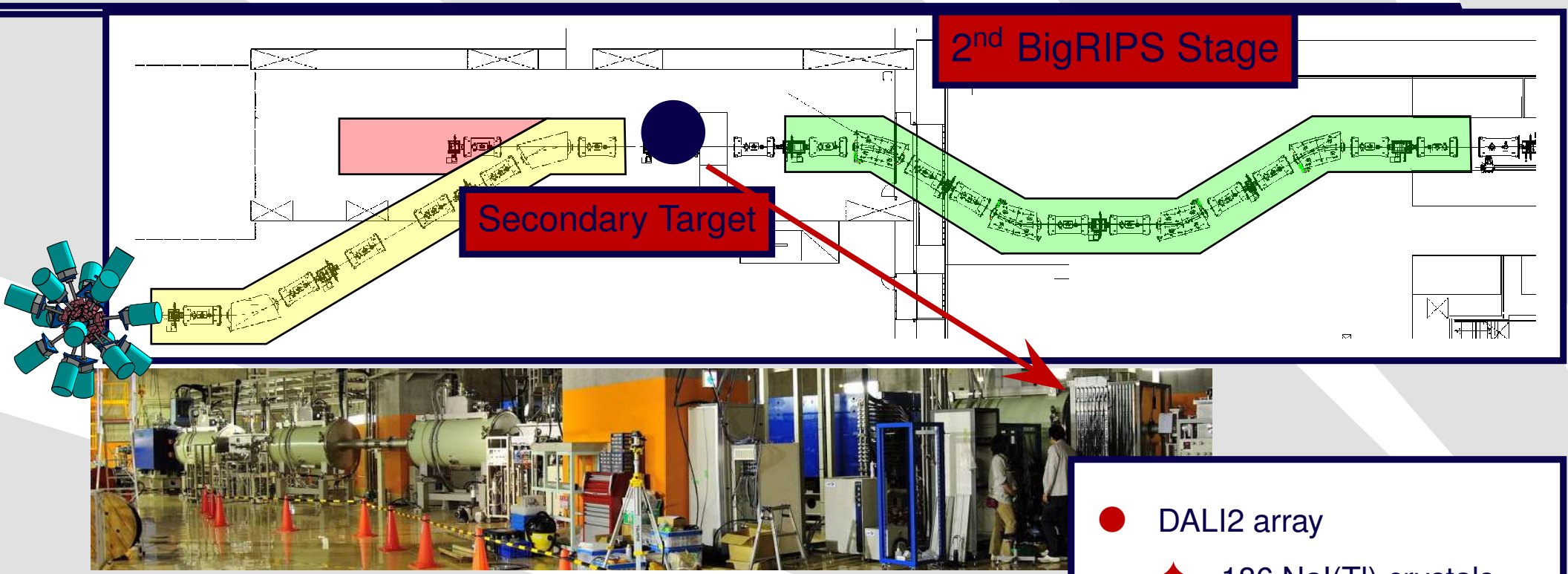
ZeroDegree Spectrometer



0° Spectrometer ZeroDegree

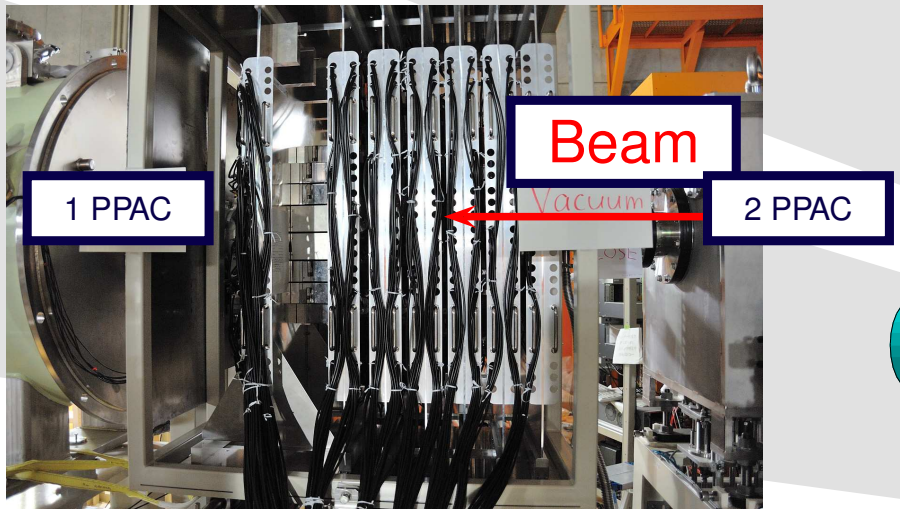
- **Particle ID** after secondary target
- Fragment momentum distribution
- Various modes of operation

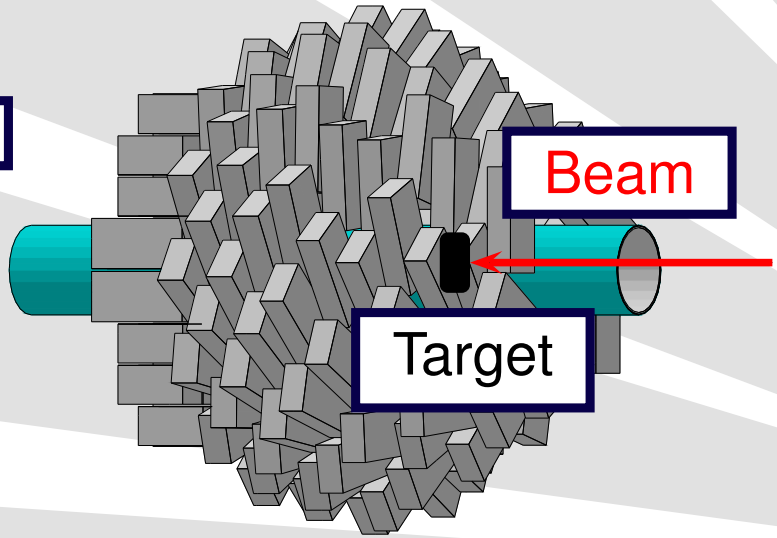
mode	$p/\Delta p$	Δp	Ang. Accep.
Large Accep.	**1240**	± 3**%**	± 45 **mrad(H)** ± 30 **mrad(V)**
High res.(achrom)	2120	± 3%	± 20 mrad(H) ± 30 mrad(V)
Dispersive	4130	± 2%	± 20 mrad(H) ± 30 mrad(V)

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

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

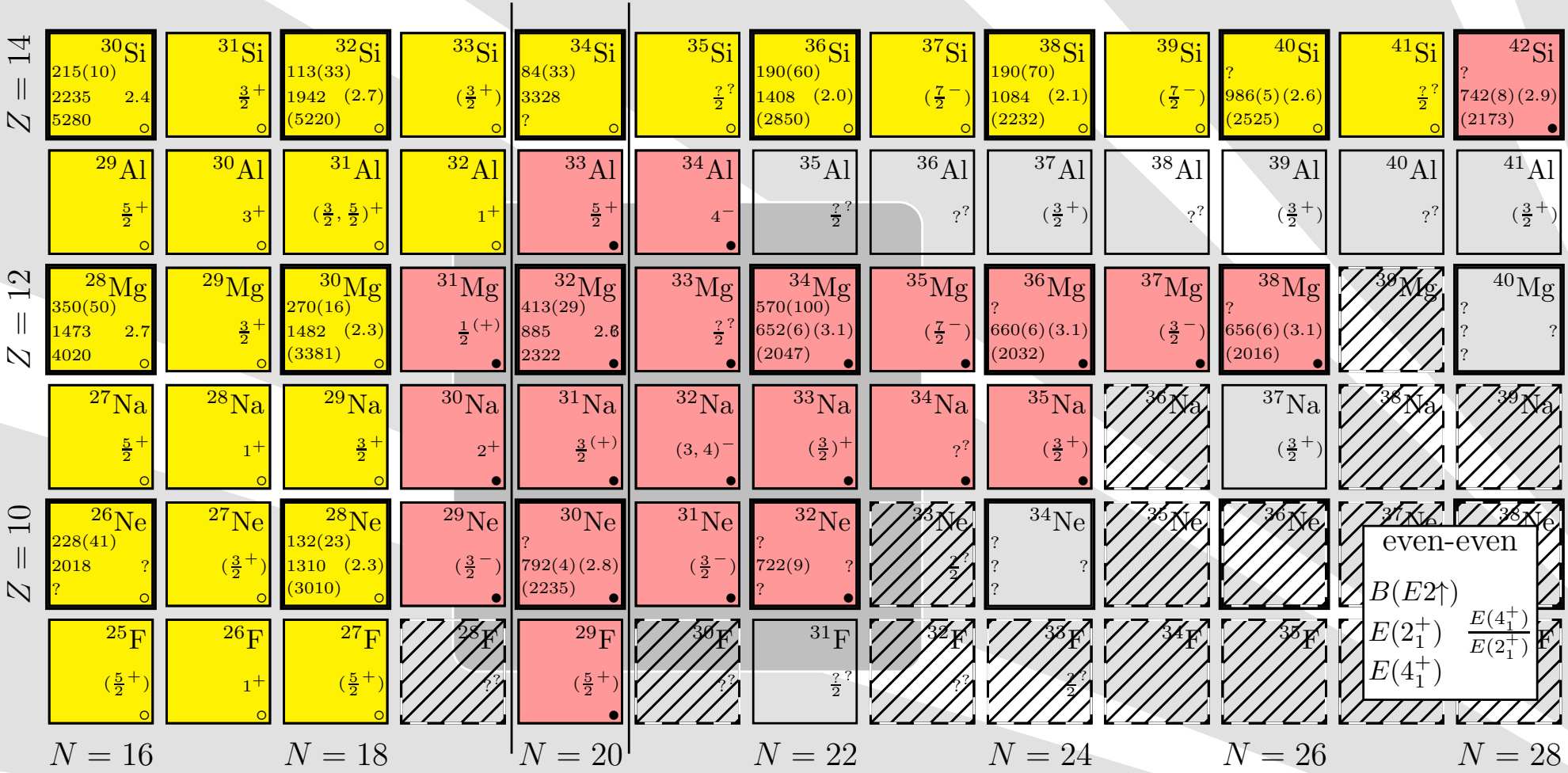




S. Takeuchi *et al.*, NIMA 763, 596 (2014).

Results on "Island of Inversion"

Overview of Deformed Nuclei Around "Island of Inversion"



- Original boundaries: E. K. Warburton *et al.*, Phys. Rev. C **41**, 1147 (1990).
- $N = 20, 28$ shell erosions merge to "Big Island of Deformation" E. Caurier *et al.*, PRC **90**, 014302 (2014).

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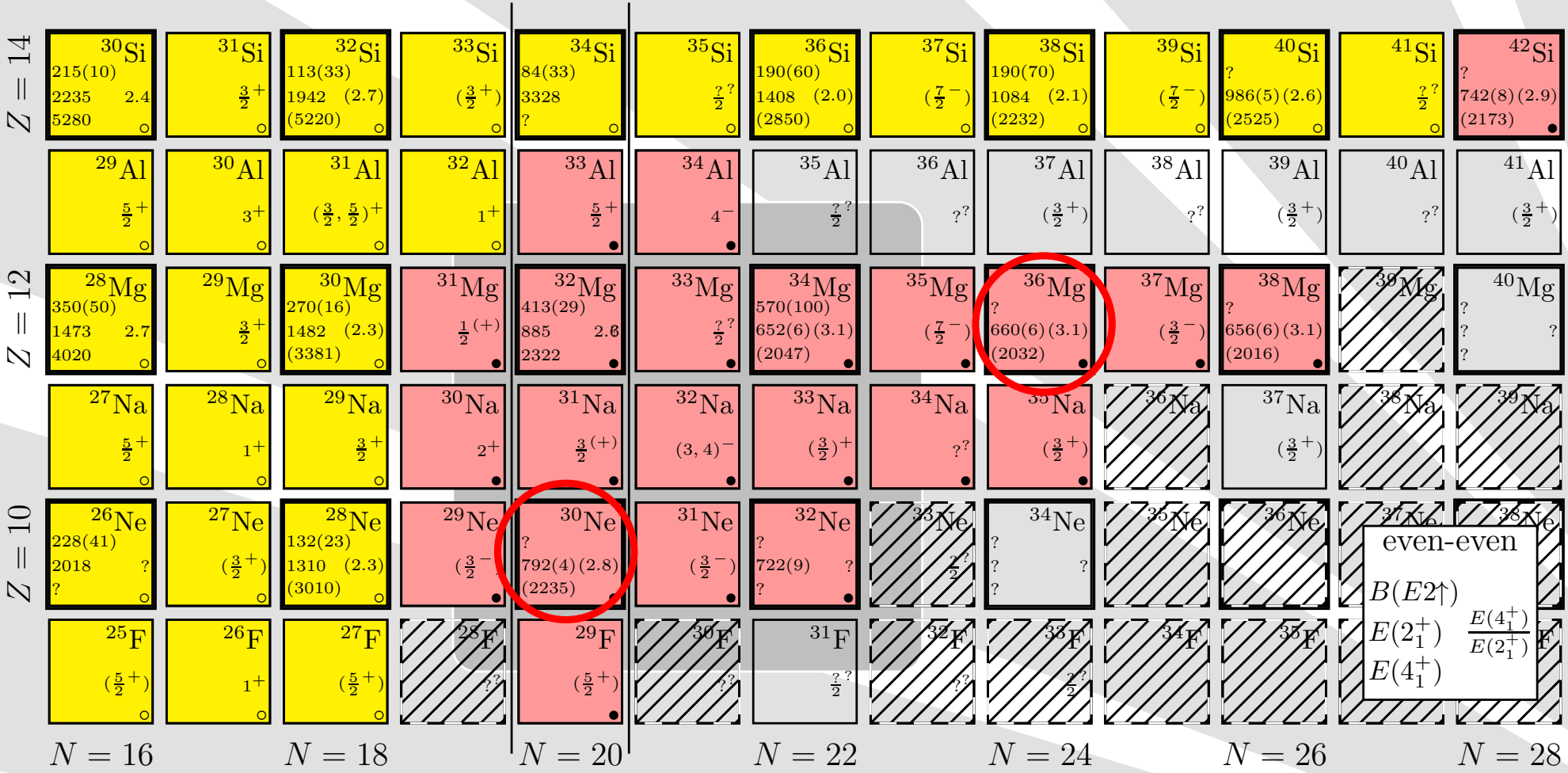

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- Quantify deformation of ^{30}Ne and ^{36}Mg $\rightarrow B(E2)\uparrow$ measurements

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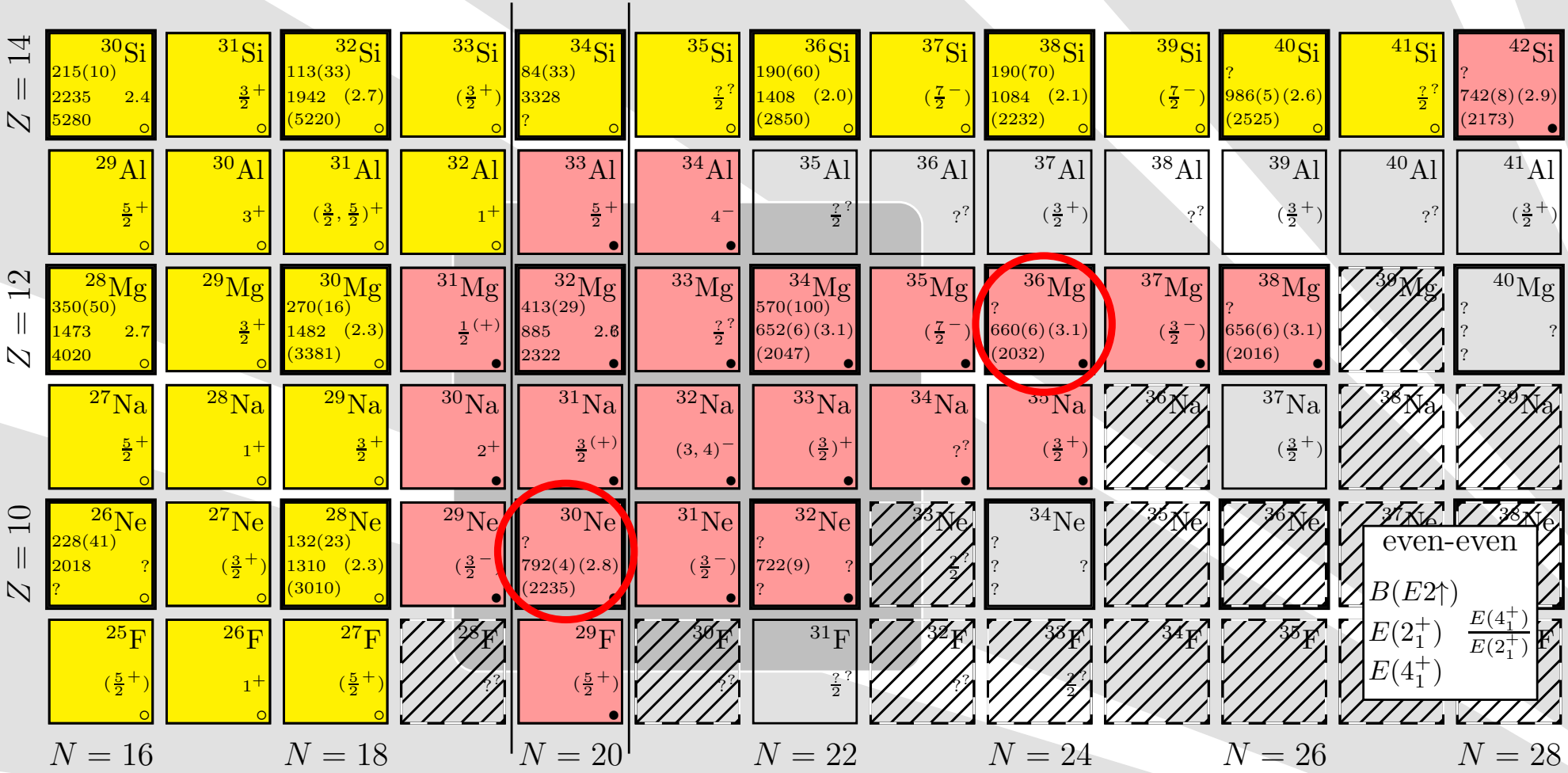

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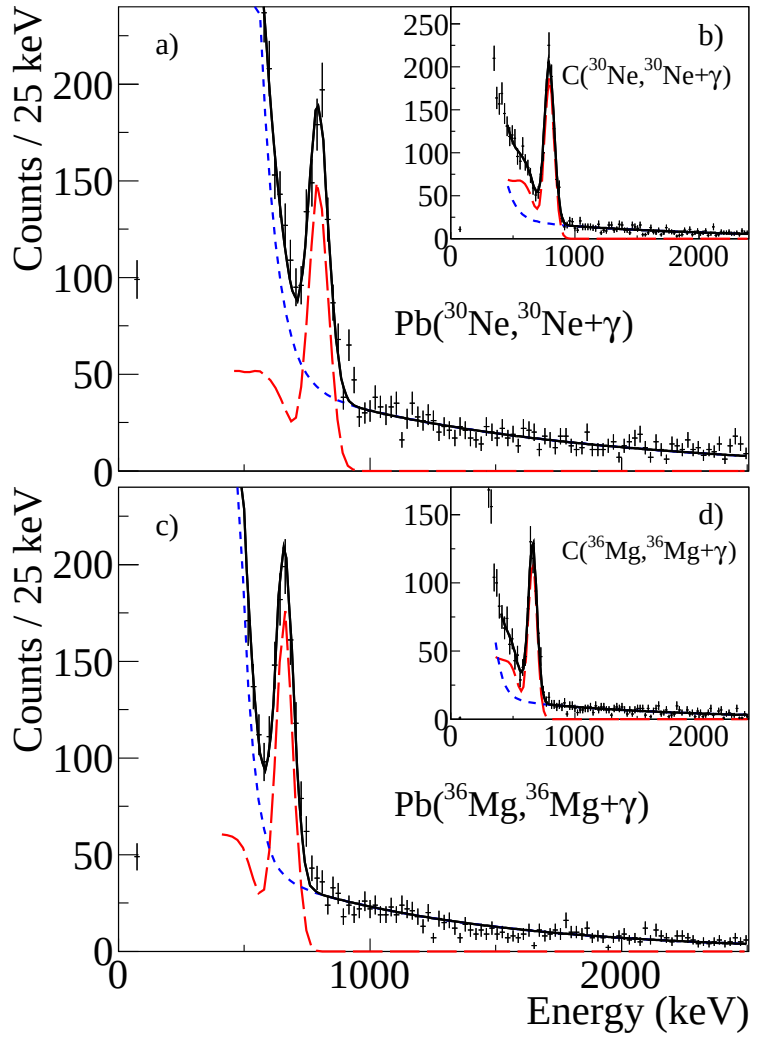
- Quantify deformation of ^{30}Ne and ^{36}Mg $\rightarrow B(E2)\uparrow$ measurements
- Investigation of intruder components in g.s. of ^{30}Ne

Scattering of ^{30}Ne and ^{36}Mg

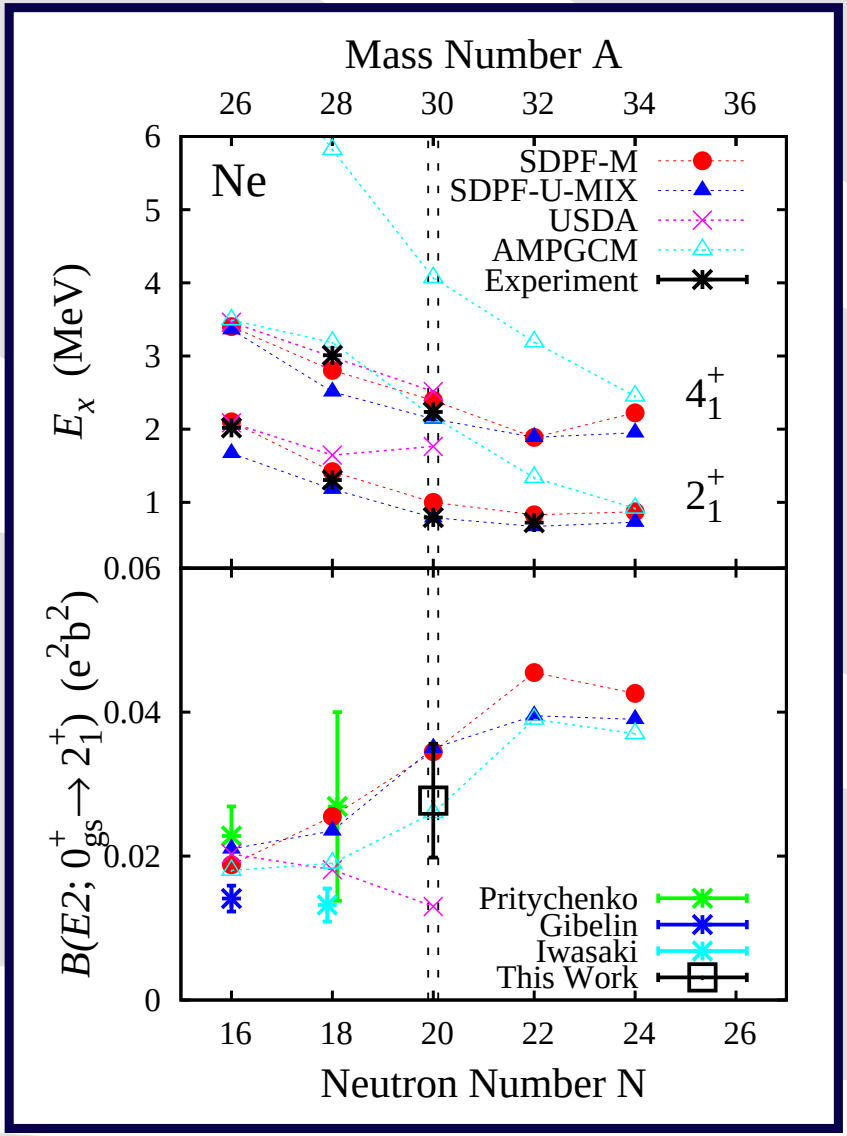
- ^{48}Ca primary beam, 70 pnA
- 2.54 g/cm^2 C, 3.37 g/cm^2 Pb
- $\approx$ 220 MeV/u at target-center
- 28 hours measuring time

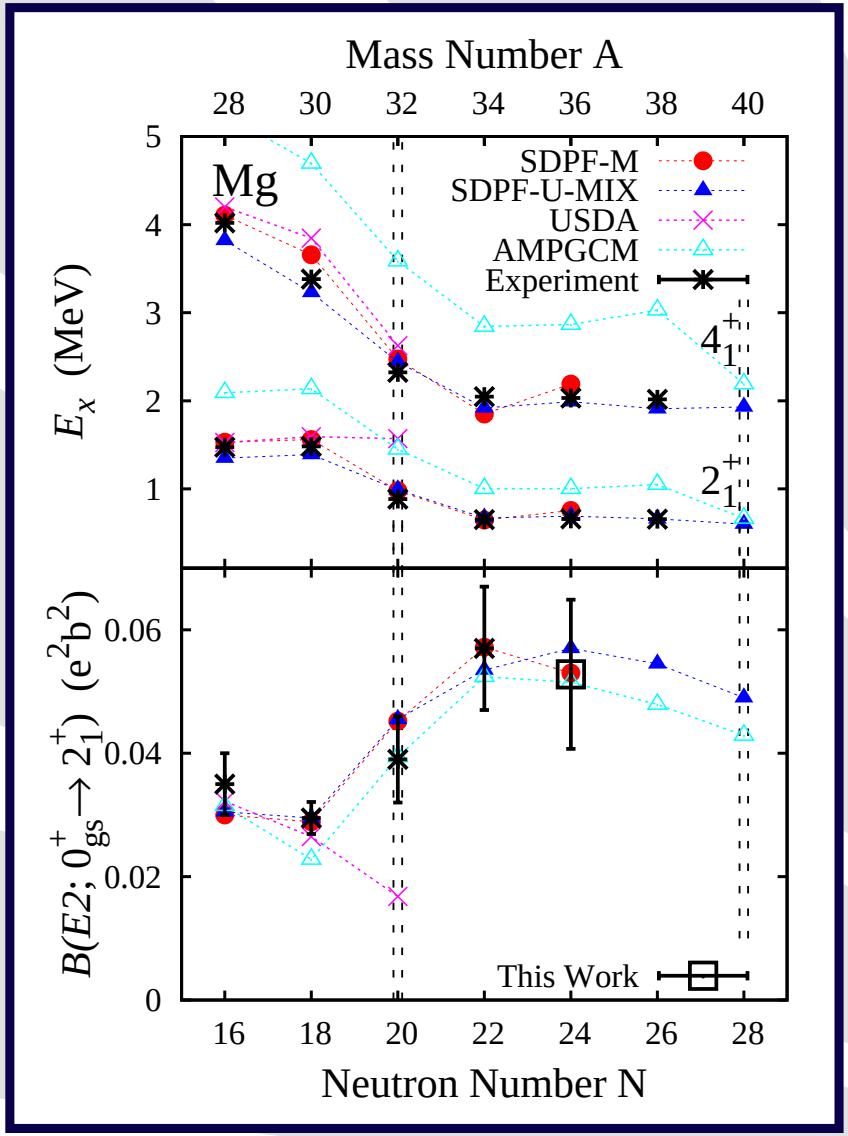
Proj.	Tar.	$E(2_1^+)$	$\sigma(2_1^+)$/mb	δ/fm	β
^{30}Ne[1]	C	799(5)	14(1)	1.98(7)	0.53(2)
	Pb	801(6)	56(5)	1.86(19)	0.50(5)
^{36}Mg[1]	C	666(5)	15(1)	1.94(7)	0.49(2)
	Pb	665(5)	72(7)	2.02(16)	0.51(4)
^{30}Ne[2]	H	800(7)	37(4)	1.59(8)	0.45(2)
^{36}Mg[2]	H	656(13)	47(8)	1.90(16)	0.50(5)



[1] PD, HS *et al.*, PRC 93, 044306 (2016).
[2] S. Michimasa *et al.*, PRC 89, 054307 (2014).

Scattering of ^{30}Ne and ^{36}Mg



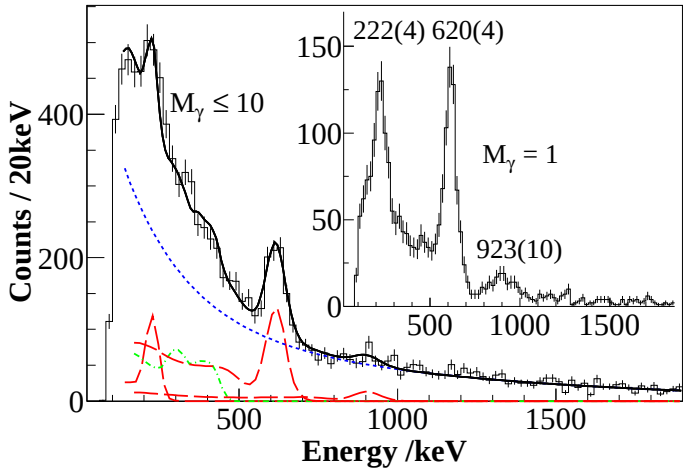


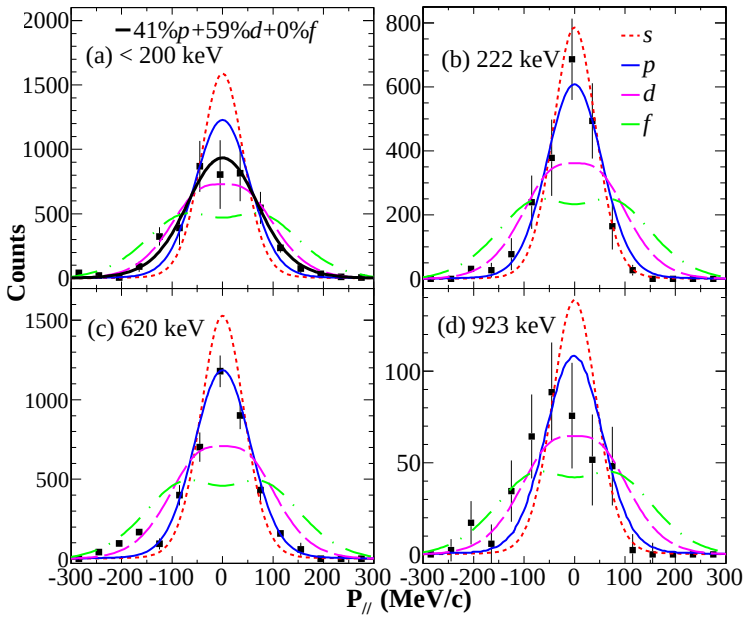
B.V. Pritychenko *et al.*, PLB 461, 322 (1999).
J. Gibelin *et al.*, PRC 75, 057306 (2007).
H. Iwasaki *et al.*, PLB 620, 118 (2005).

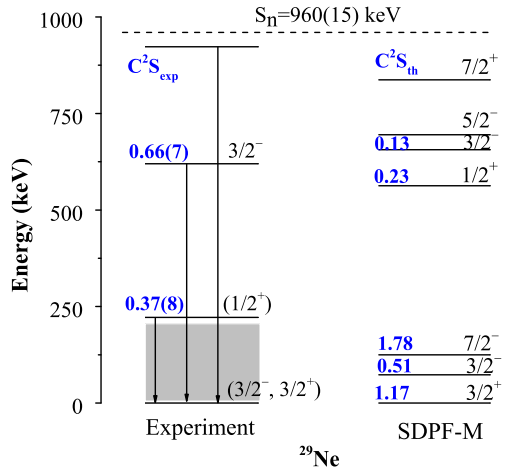
SDPF-P: Y. Utsuno *et al.*, PRC 60, 054315 (1999).
SDPF-U-MIX: E. Caurier *et al.*, PRC 90, 014302 (2014).
USDA: B.A. Brown and W.A. Richter, Phys. Rev. C 74, 433 (2006).
AMPGCM: R. Rodriguez-Guzman *et al.* Phys. Lett. B 474, 15 (2000).

Partial Cross-Sections and Momentum Distributions in $^{12}C(^{30}Ne,^{29}Ne+\gamma)X$

- 2.54 g/cm^2 C
- $\approx$ 228 MeV/u at target-center
- 3.5 hours measuring time
- Results:
  - No f-wave contribution
  - Low $7/2^-$ SDPF-M state is unbound
  - $7/2^-$ state in ^{27}Ne unbound, 1.5 MeV higher than in SDPF-M



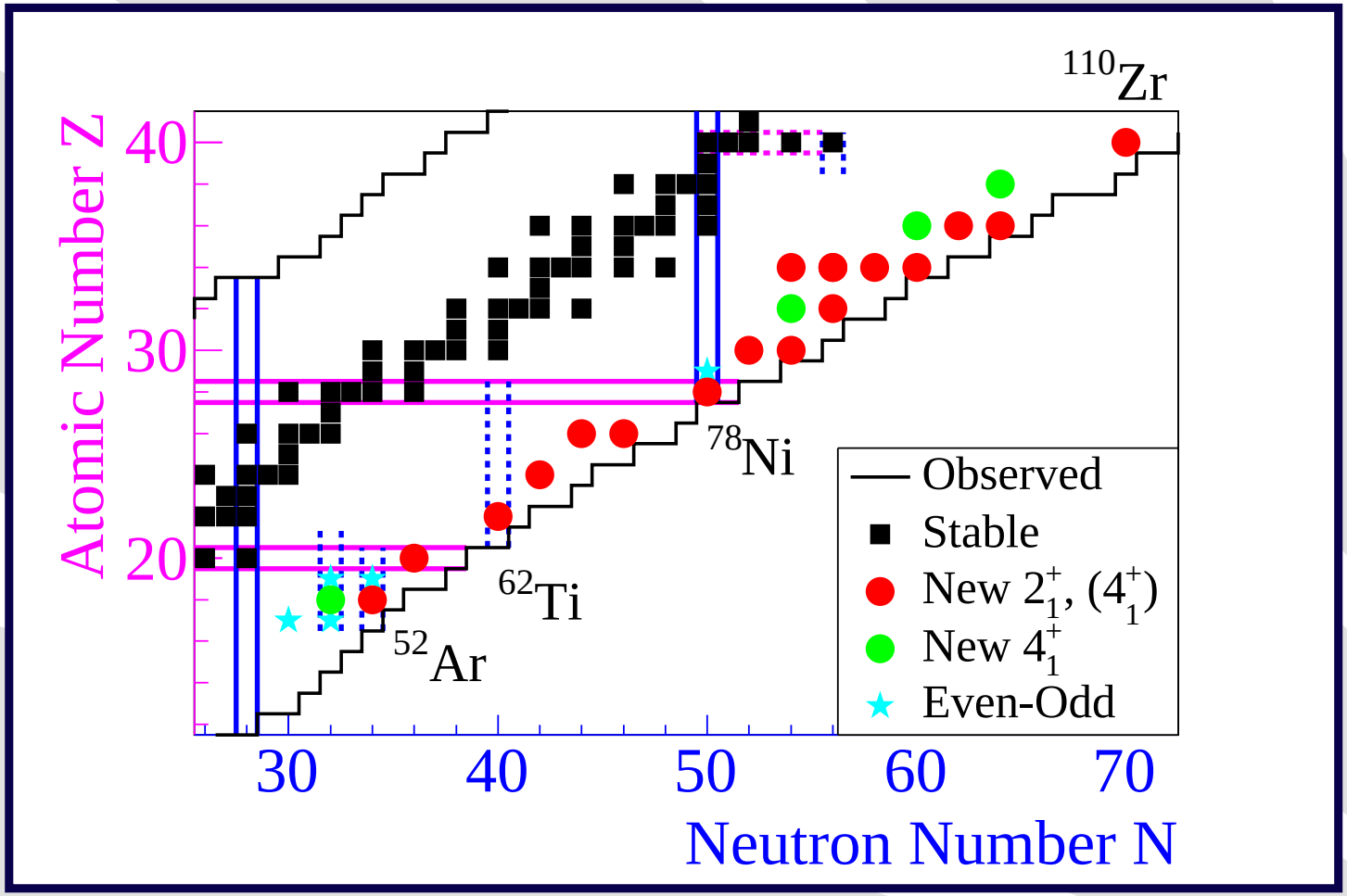




H. Liu, J. Lee *et al.*, submitted
Calculations by Y. Utsuno and J. Tostevin

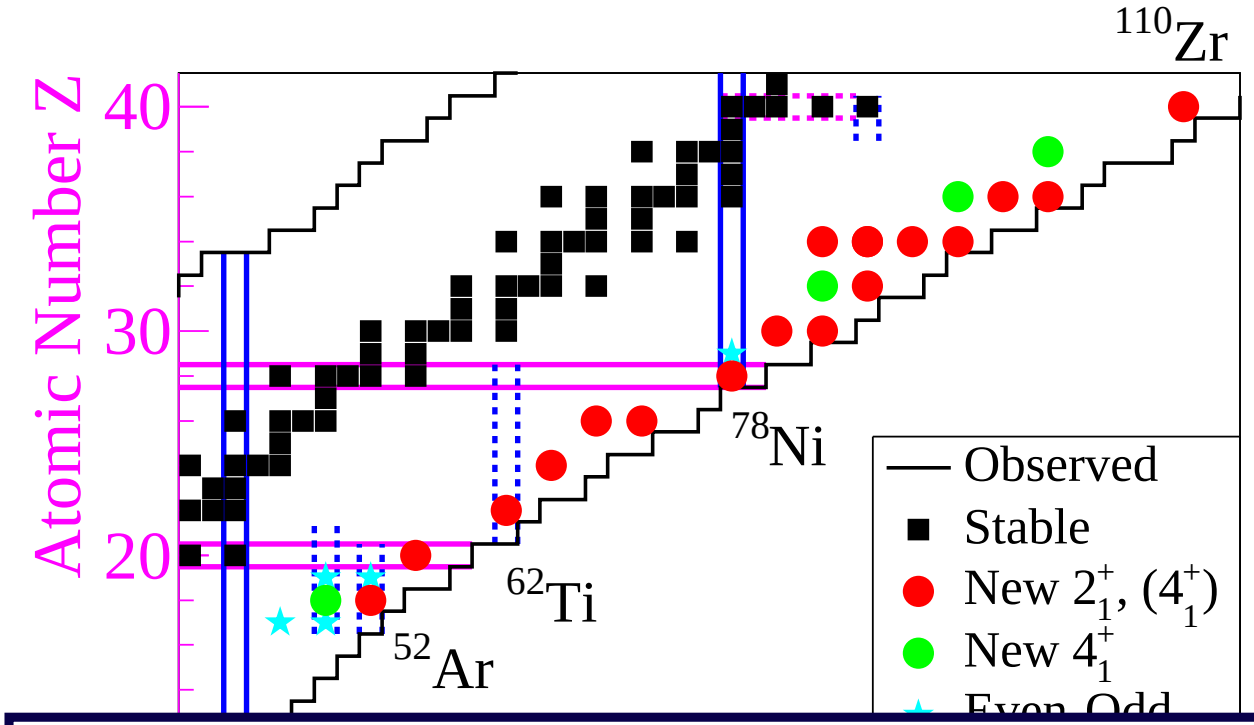
SEASTAR

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



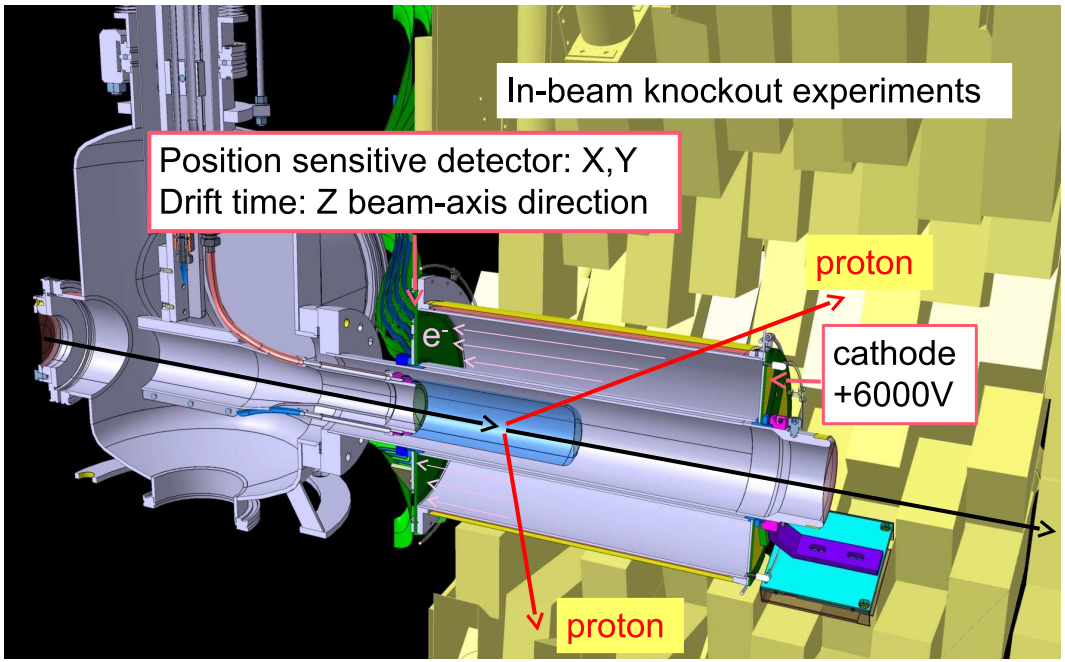
- 10 pnA ^{238}U, 75 pnA ^{70}Zn primary beams
- 24 days for data runs, 32.5 days including BigRIPS/ZD tuning
- DALI2+MINOS+ZDS+(EURICA) or DALI2+MINOS+SAMURAI
- Proposal NP1312-RIBF118 (Spokespersons: PD, A. Obertelli)
- 6 days for ^{78}Ni

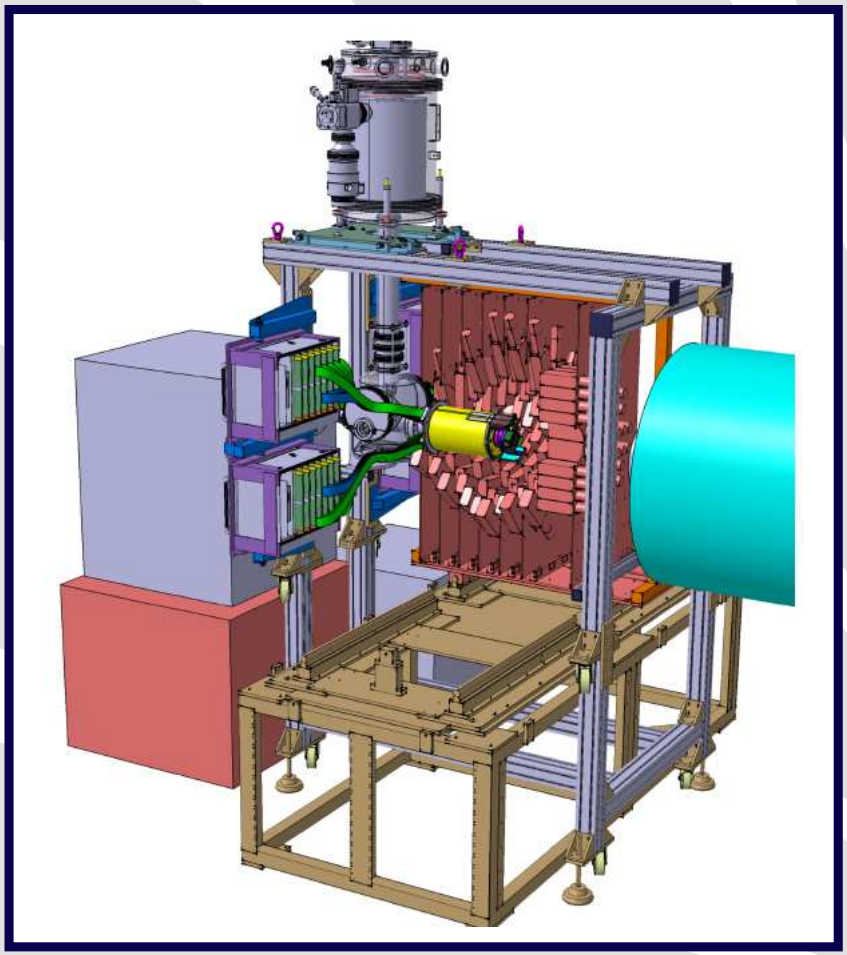
Shell Evolution And Search for Two-plus energies At the RIBF (SEASTAR)



- 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





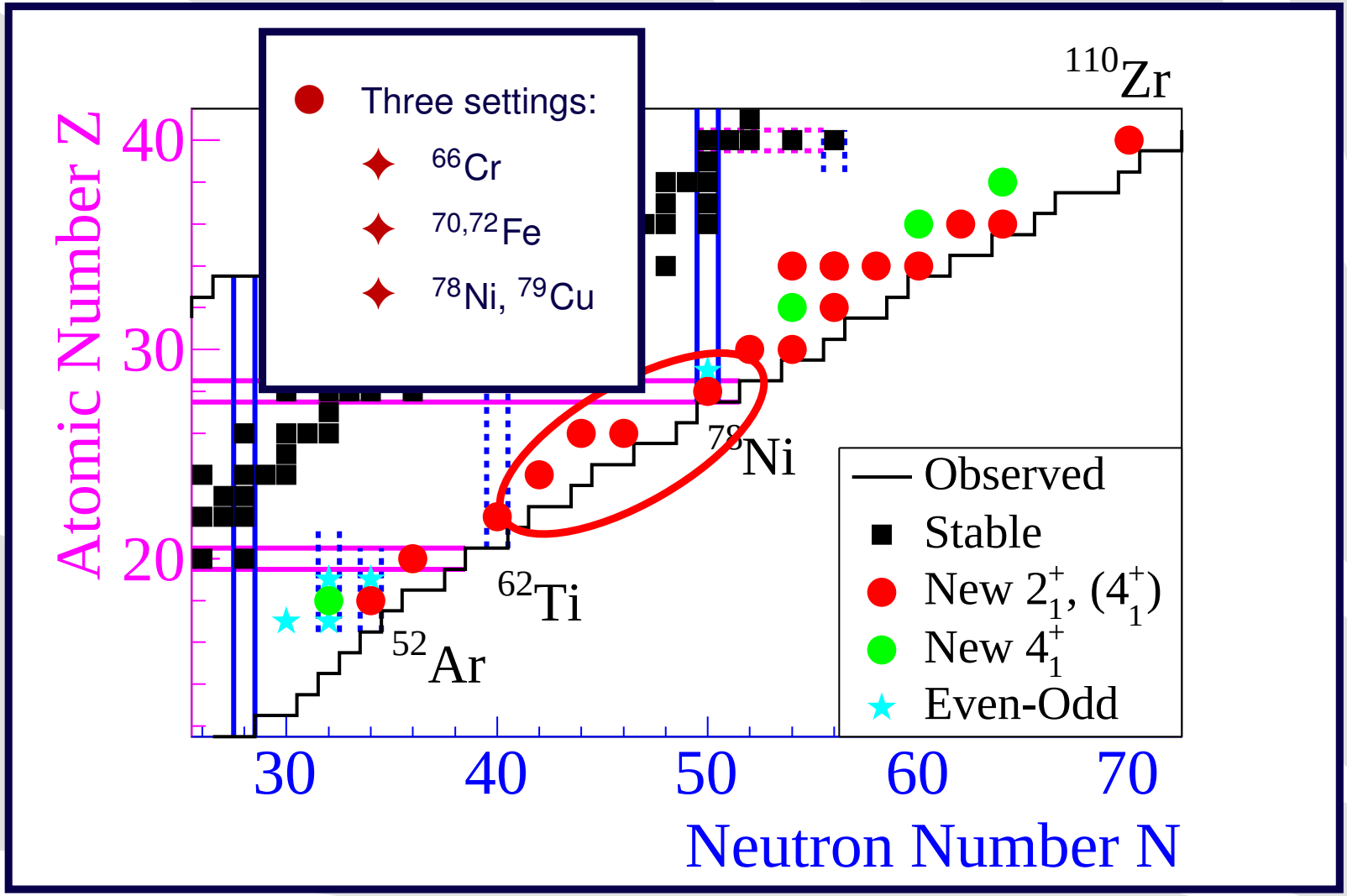
MagIc Numbers Off Stability

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)

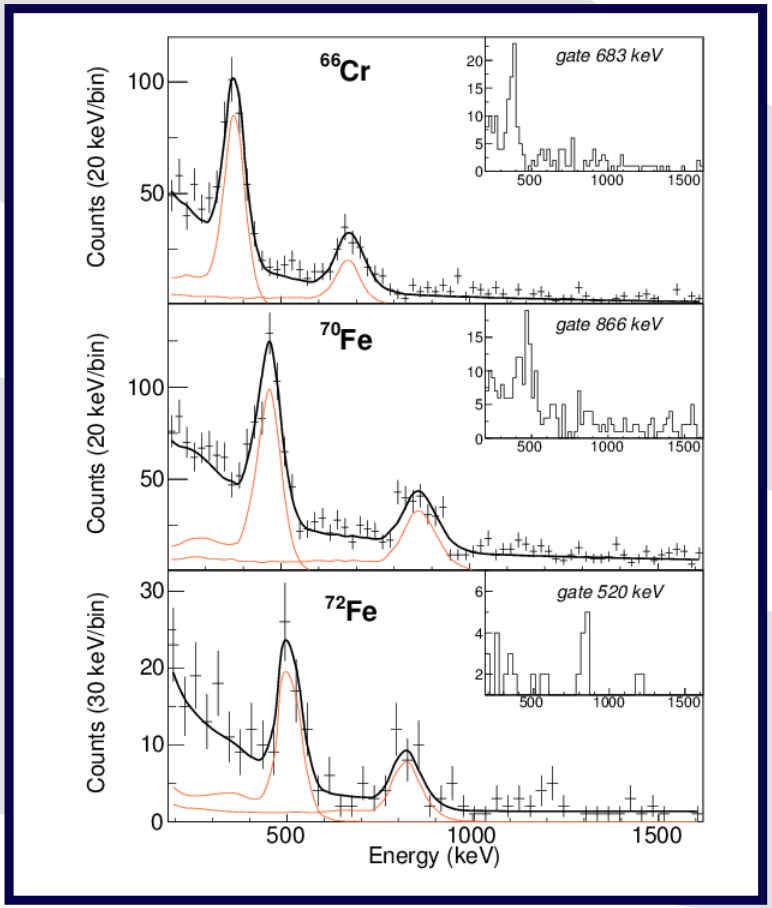
A. Obertelli *et al.*, Eur. Phys. J. A 50, 8 (2014).

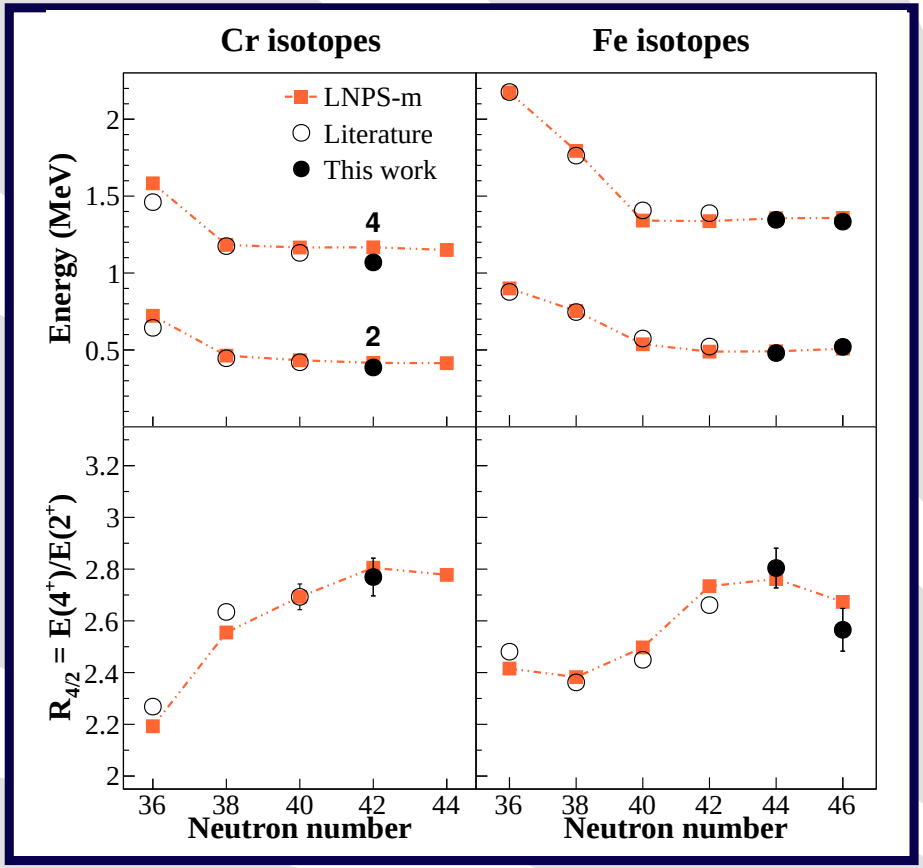
Nuclei of Interest for First SEASTAR Campaign, May 2014



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

Maximum of Collectivity Beyond $N = 40$

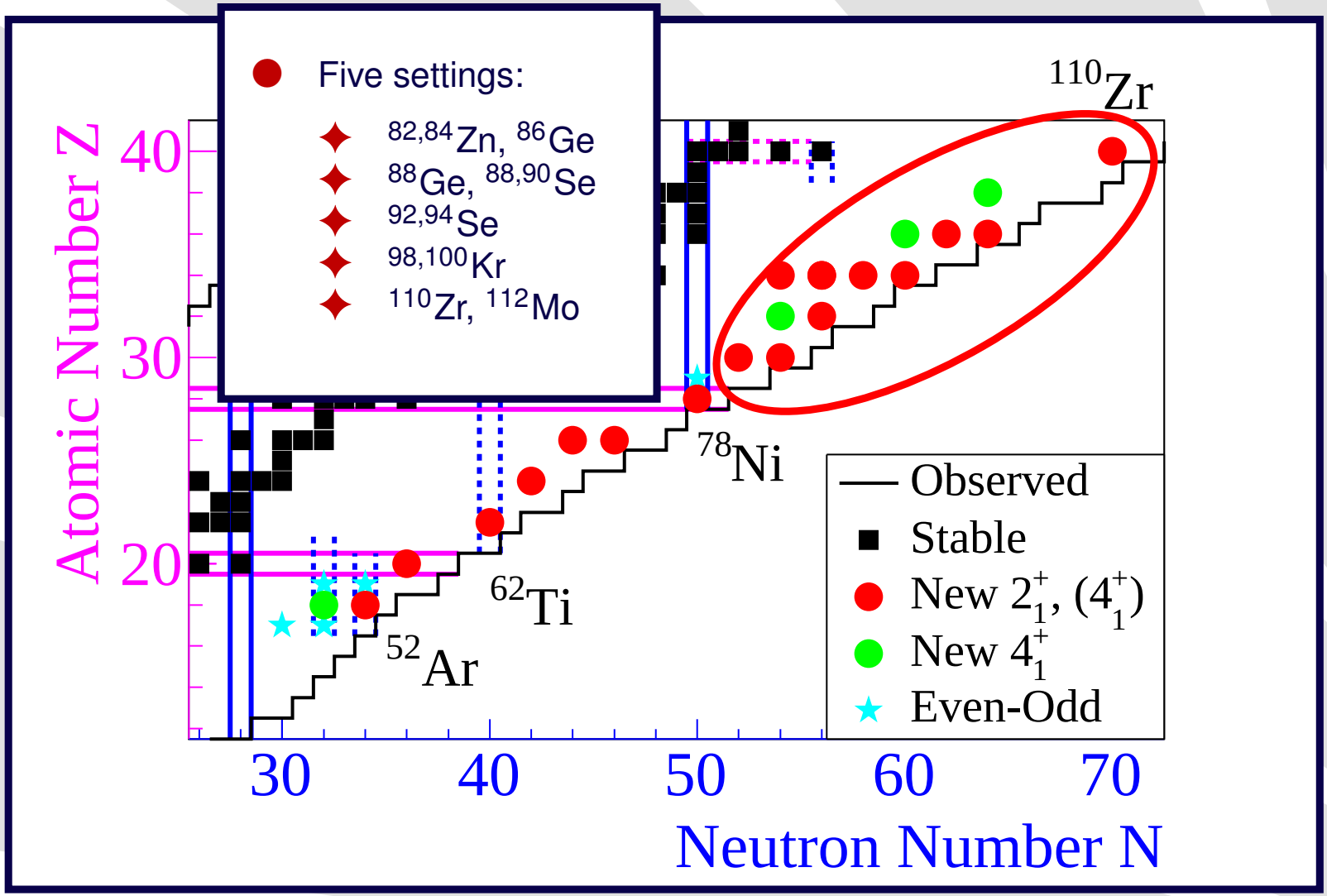




- Collaboration with F. Nowacki, IPHC, $fp - fpg_9d_5$ valence space
  - additional $gd - gd$ monopole strength
- Extension of $N = 40$ "Island of Inversion" towards $N = 50$

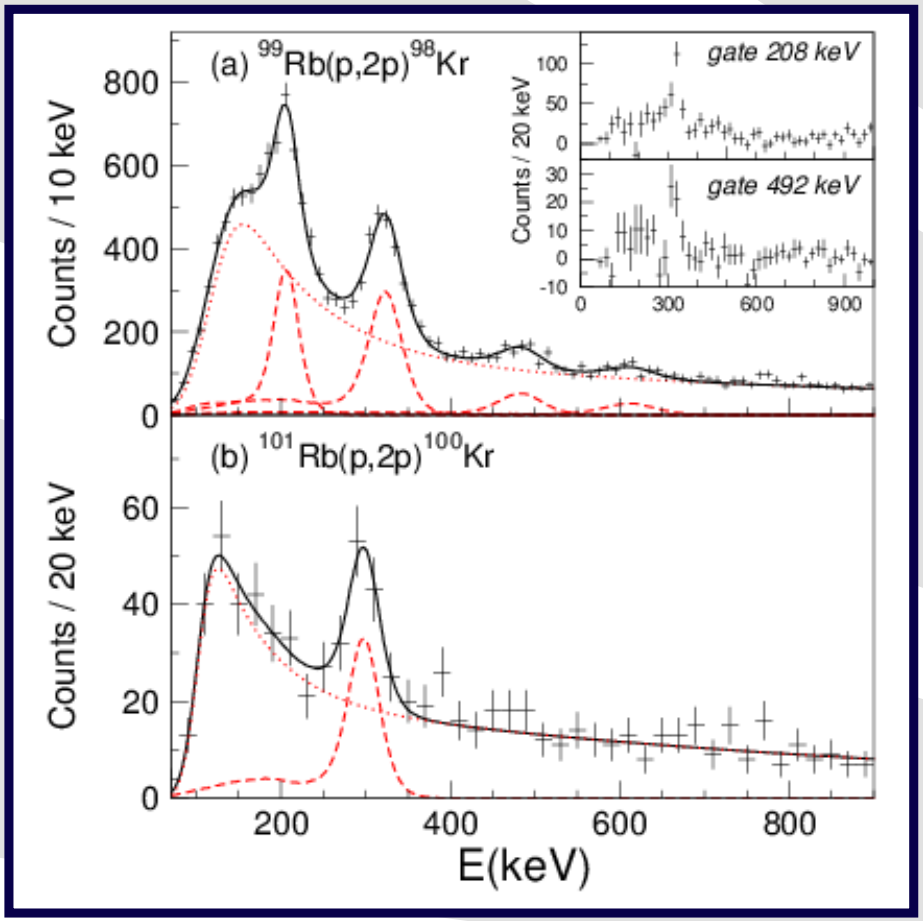
C. Santamaria, C. Louchart *et al.*, PRL 115, 192501 (2015).

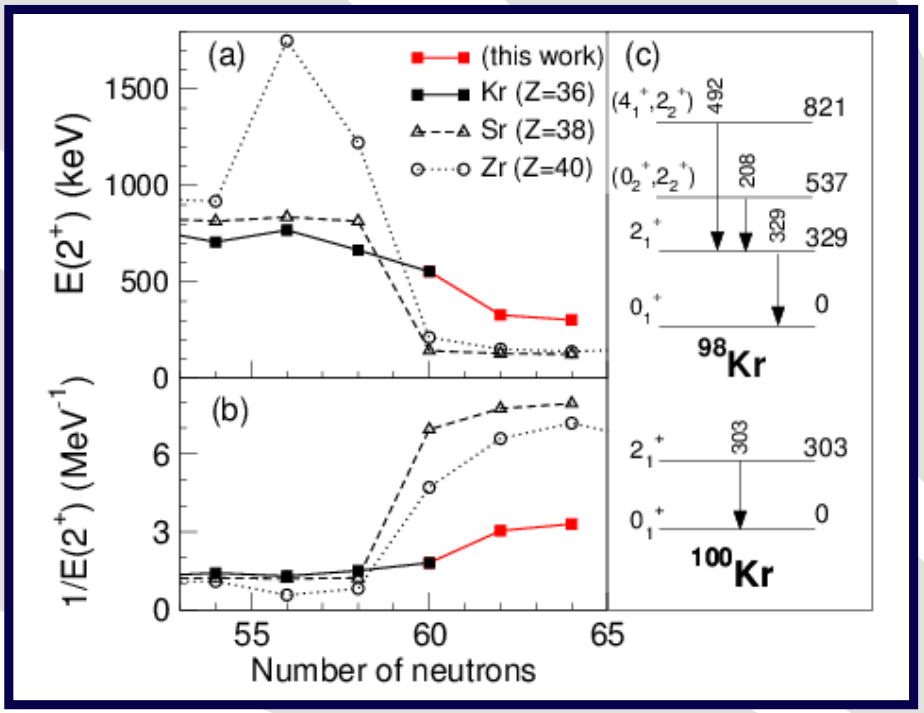
Nuclei of Interest for Second SEASTAR Campaign, May 2015



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

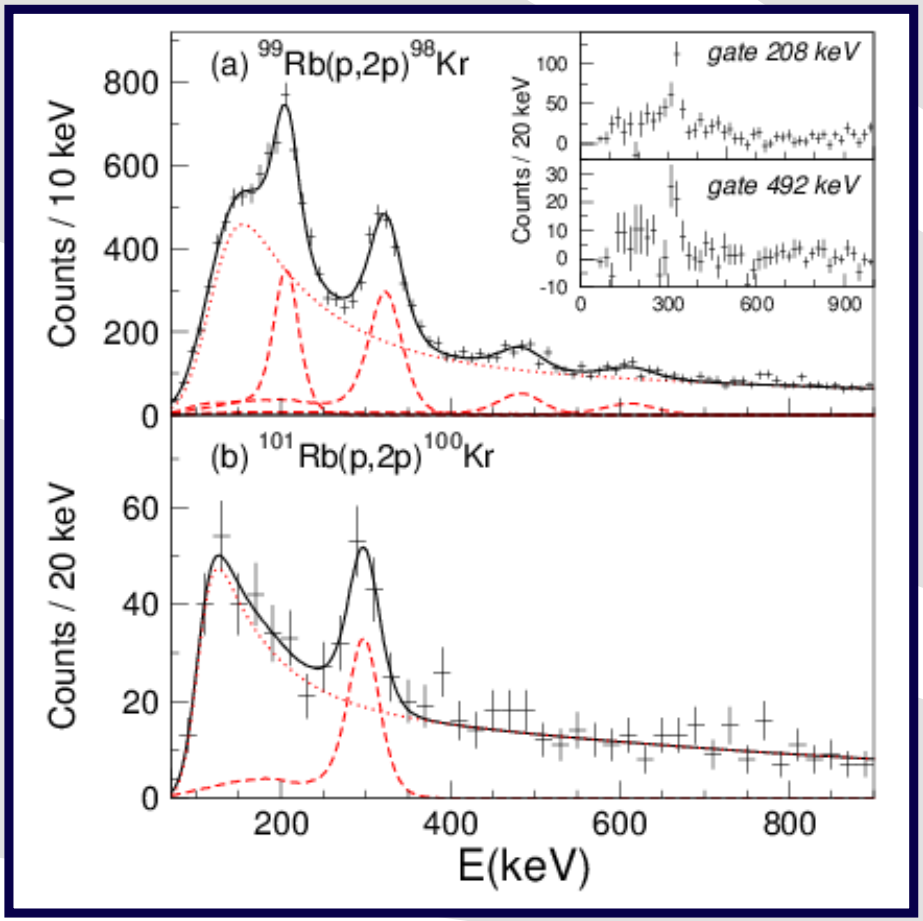
Neutron-rich Kr Isotopes

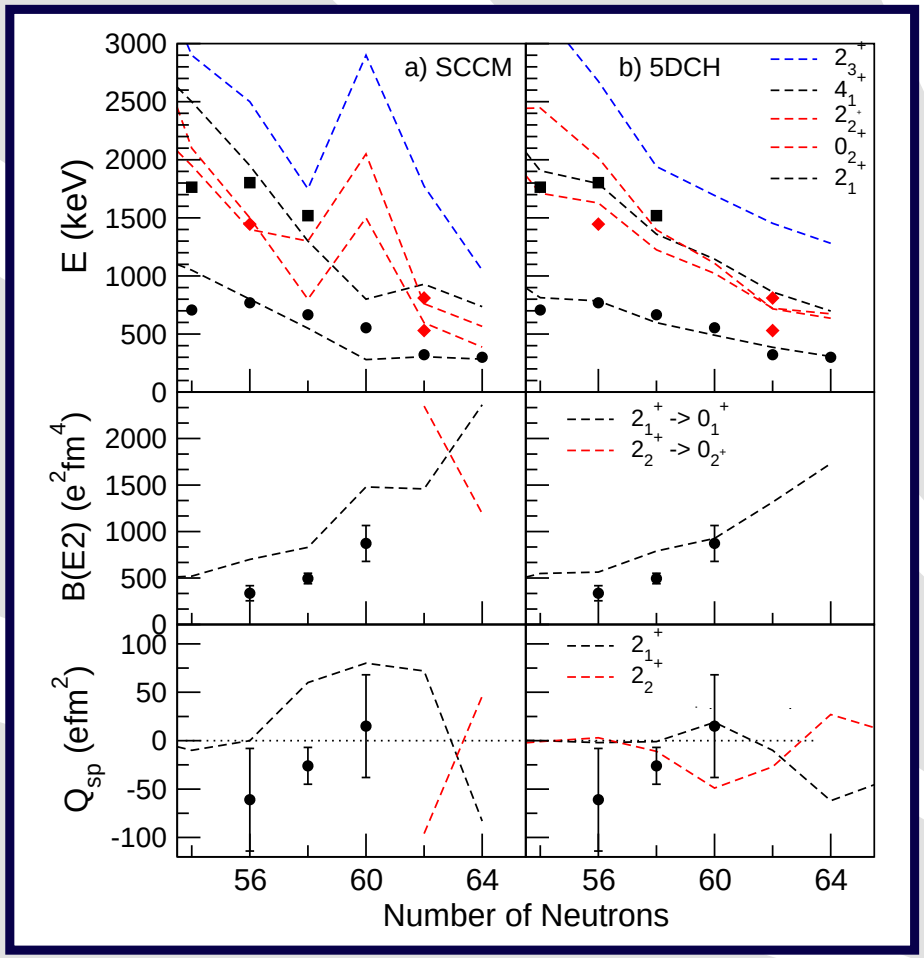




Analysis by F. Flavigny, IPN Orsay

Neutron-rich Kr Isotopes

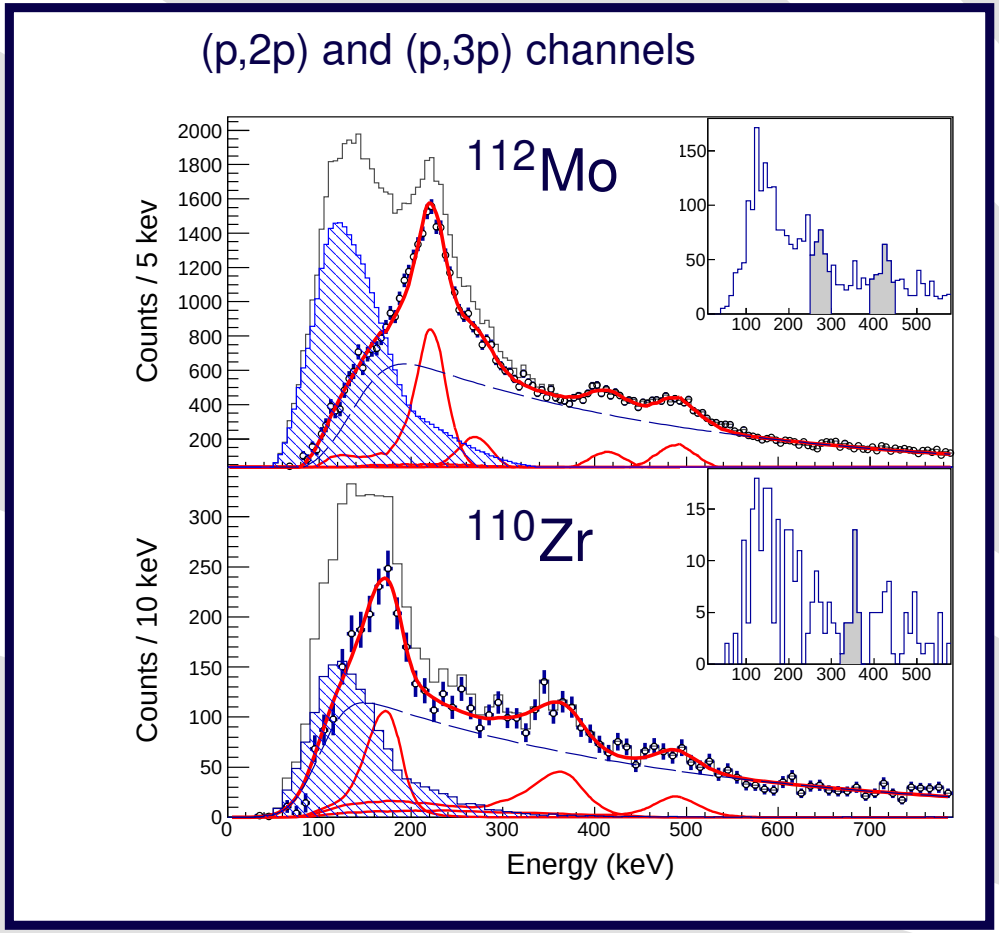




Analysis by F. Flavigny, IPN Orsay

SCCM: T.R. Rodriguez PRC 90, 034306 (2014).
5DCH: J.-P. Delaroch *et al.*, PRC 81, 014303 (2010).

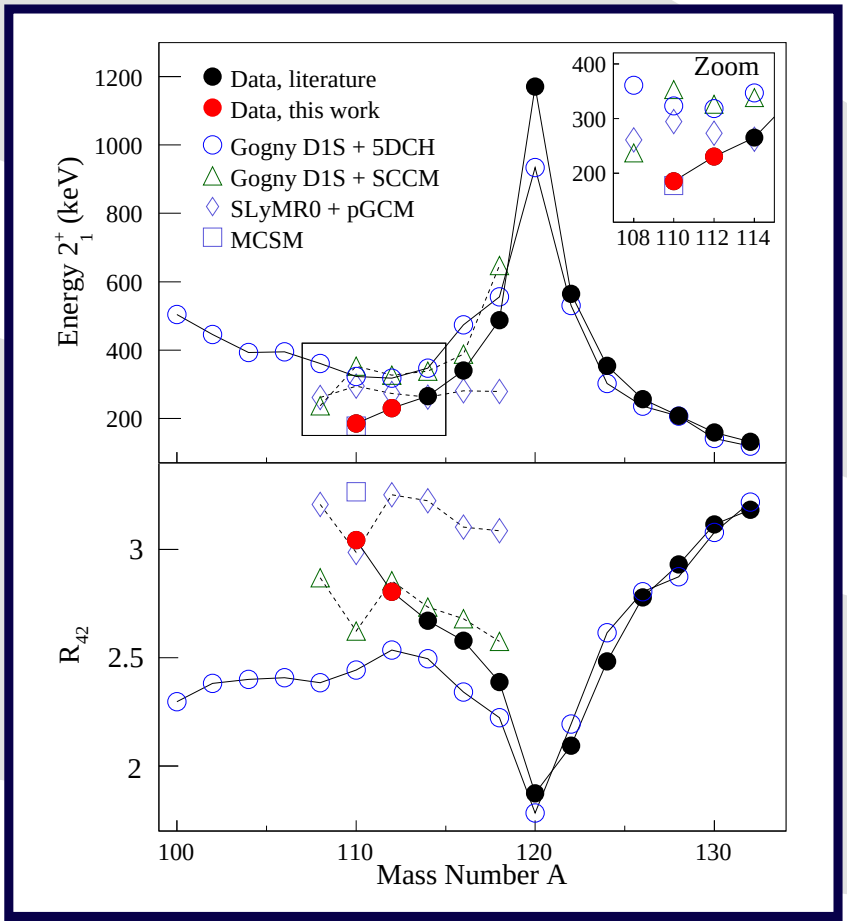
First Spectroscopy of ^{110}Zr



- 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

Analysis by N. Paul, CEA Saclay

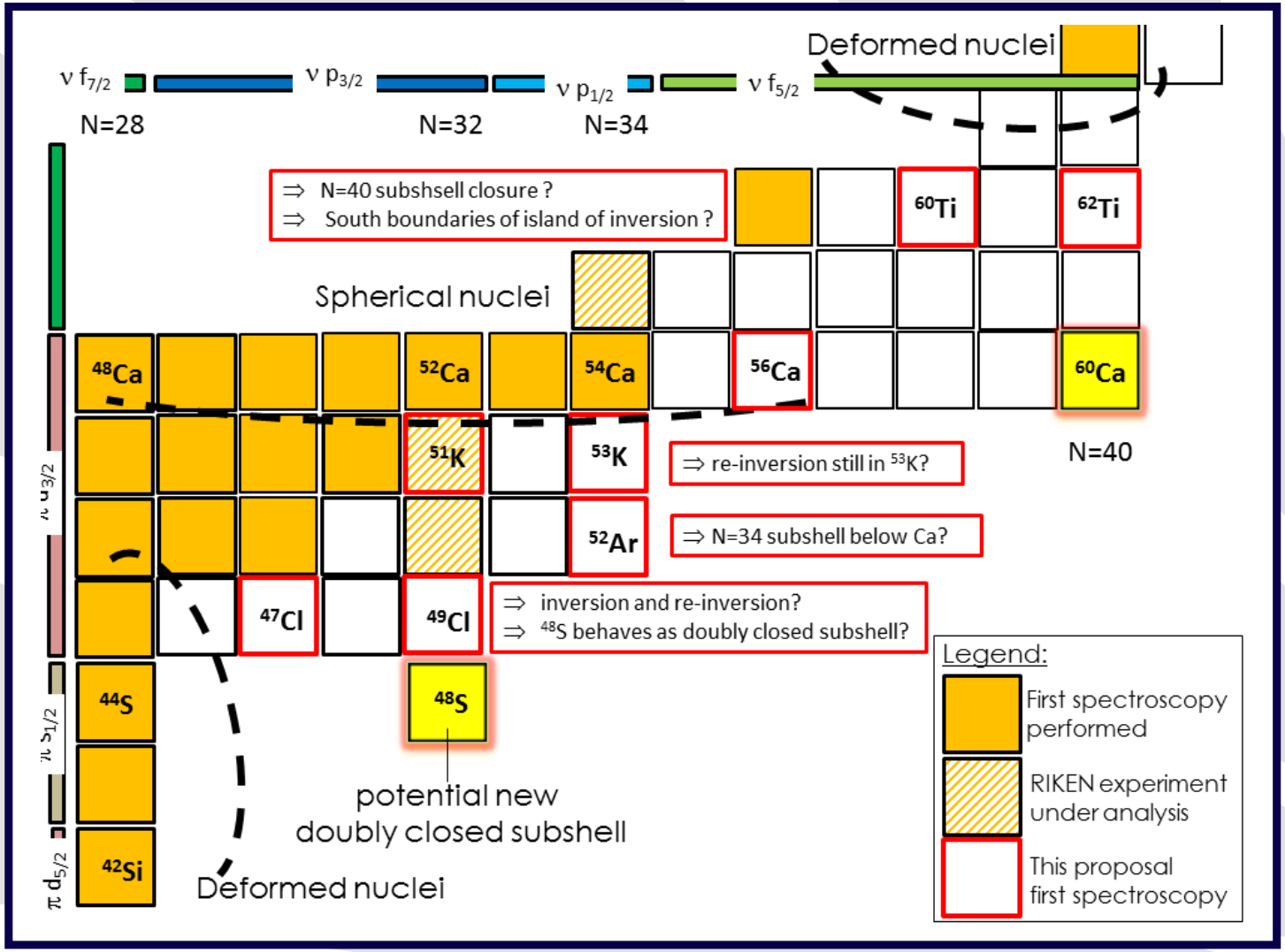
Extreme Deformation at $N = 70$ in ^{112}Mo and ^{110}Zr



- Data show increase of deformation along $N = 70$
- Comparison to beyond mean field approaches:
  - Gogny D1S, Bohr Hamiltonian (5DCH)
  - Gogny D1S, full GCM
  - SlyMR0, full GCM
- Good agreement for ^{110}Zr with MCSM
- No stabilizing $N = 70$ subshell

Summary and Outlook

Physics Case of 3rd SEASTAR Campaign



- At SAMURAI, 8 days, 300 pnA ^{70}Zn primary beam intensity needed
- First spectroscopy of ^{52}Ar, ^{56}Ca, and ^{62}Ti

Summary

- In-beam spectroscopy at RIBF efficient to study evolution at maximum isospin
  - Basic nuclear properties 2_1^+, 4_1^+, $B(E2)\uparrow$
  - Spin-assignments from momentum distribution
  - Can measure absolute $B(E2)\uparrow$ with 15–20 % accuracy at 200 MeV/u
- Large deformation of $\beta \approx 0.5$ in all n-rich Ne and Mg isotopes
- 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

RIBF32 Collaboration (Dec. 2010 Campaign)

N. Aoi[1], H. Baba[1], H. Crawford[2], P. Doornenbal[1], C.R. Hoffman[3], R. Hughes[4], E. Ideguchi[5], N. Kobayashi[6], Y. Kondo[6], J. Lee[1], K. Li[1,7], M. Matsushita[1,8], S. Michimasa[5], T. Motobayashi[1], H. Sakurai[1], **H. Scheit[1,7]**, D. Steppenbeck[1], M. Takechi[1], **S. Takeuchi[1]**, Y. Togano[1], H. Wang[1,7], R. Winkler[9], and K. Yoneda[1]

[1]RIKEN, [2]LBNL, [3]ANL, [4]Univ. Richmond, [5]CNS, [6]TITEC, [7]Univ. Peking, [8]Rikkyo Univ., [9]NSCL

SEASTAR Collaboration

SEASTAR:

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Thank You!

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