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In-beam spectroscopy of low-lying energy levels at extreme isospin at the RIBF

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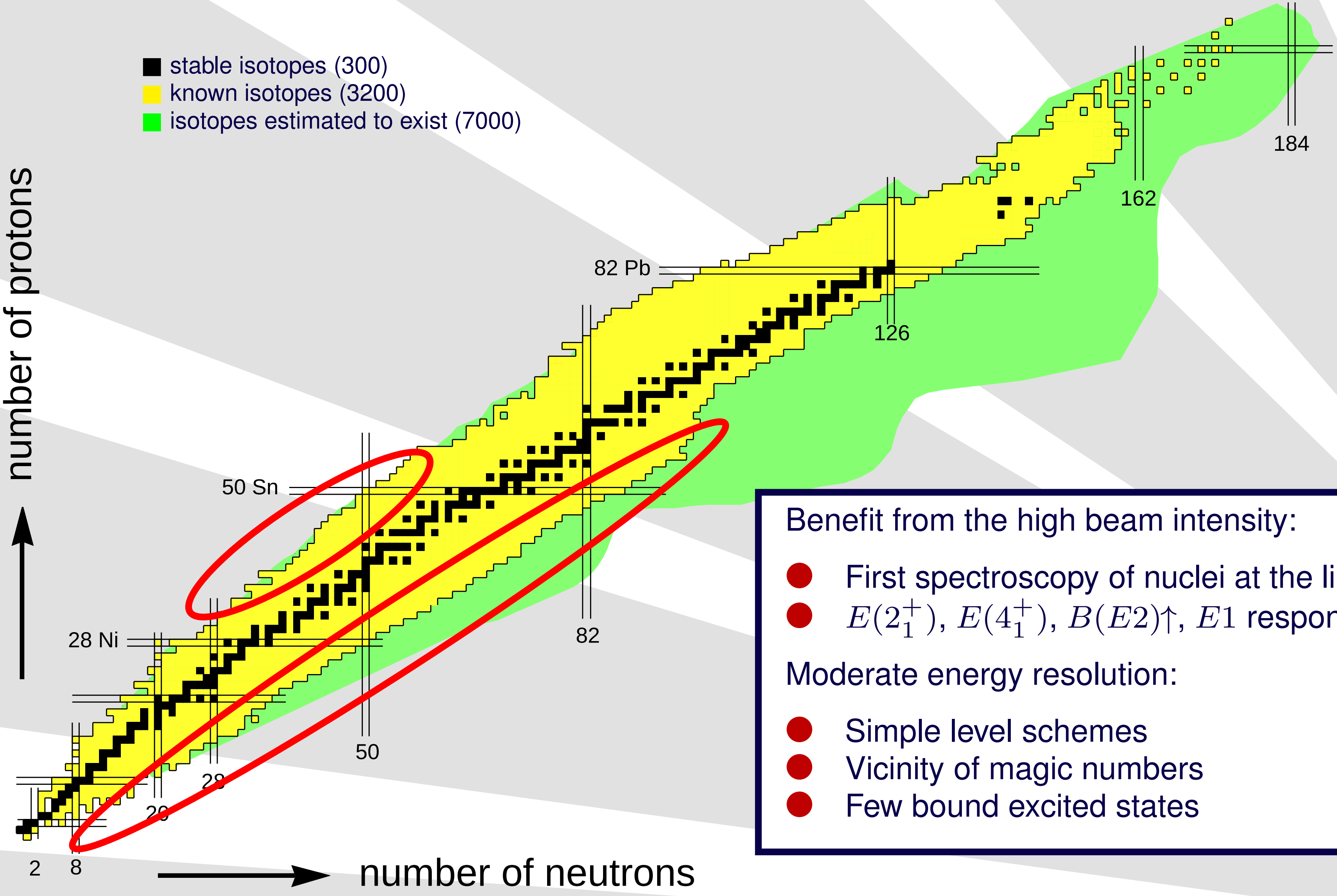
Setup and Overview

Regions of Interest



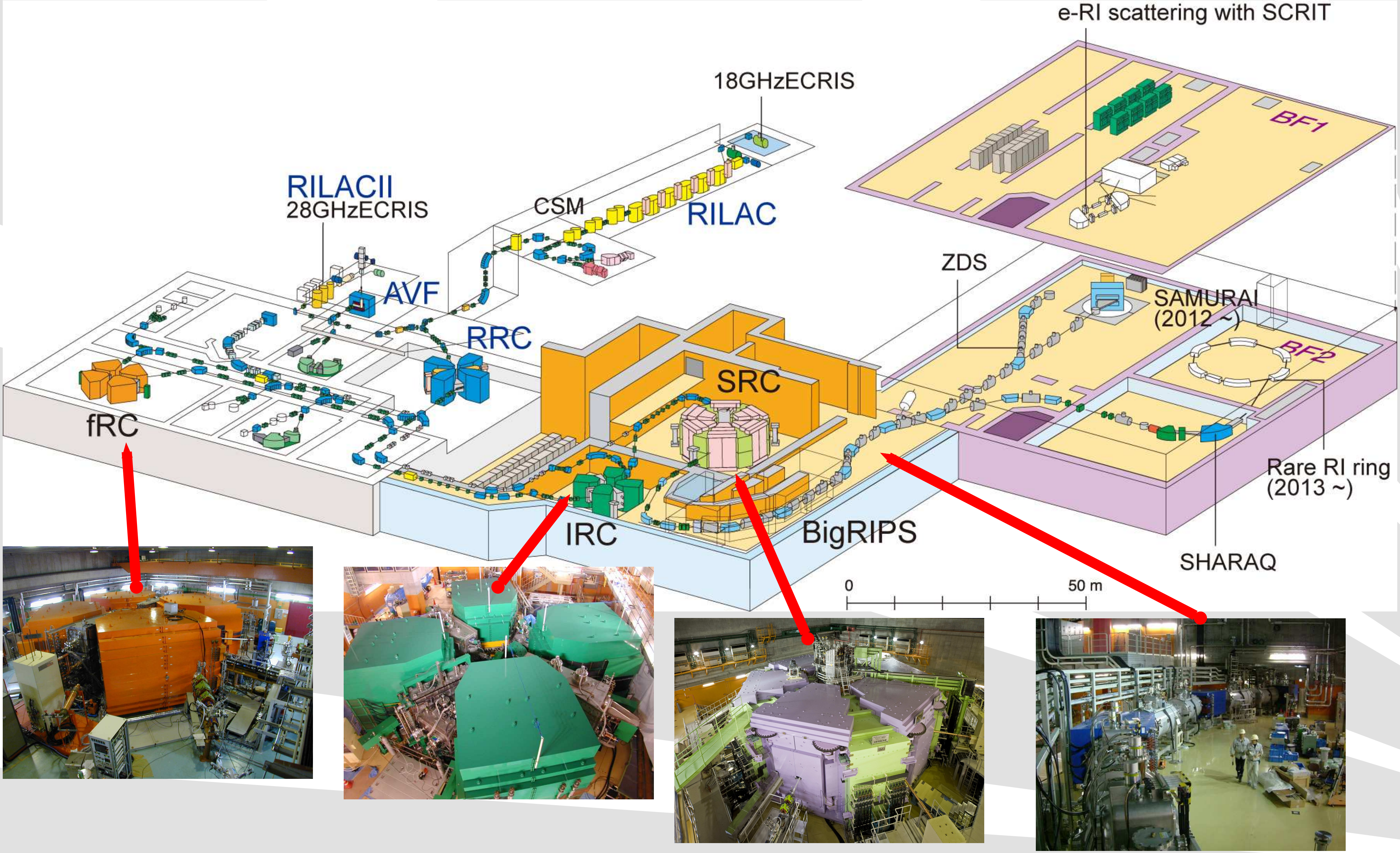
Benefit from the high beam intensity:

- First spectroscopy of nuclei at the limit
- $E(2_1^+)$, $E(4_1^+)$, $B(E2)\uparrow$, $E1$ response

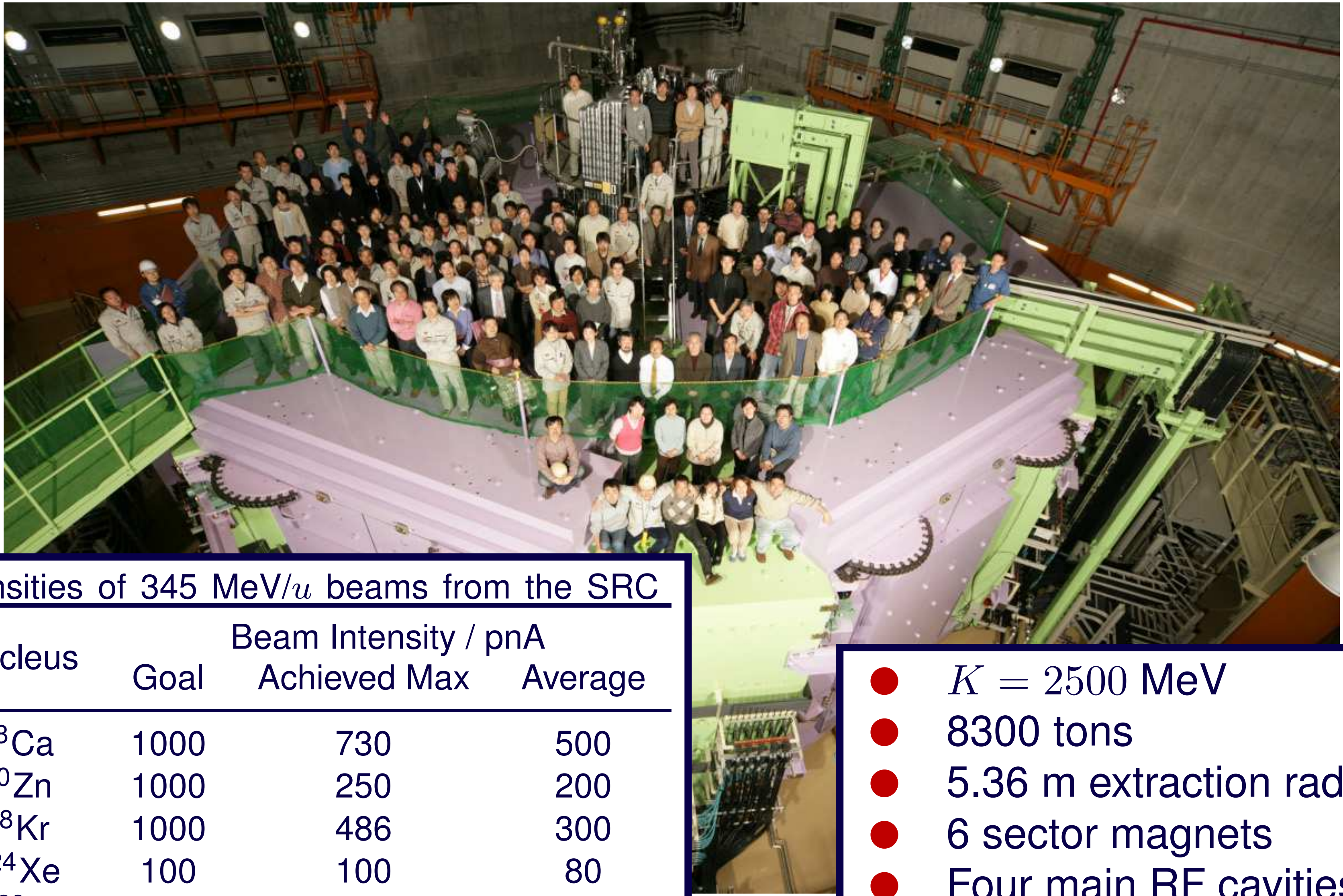
Moderate energy resolution:

- Simple level schemes
- Vicinity of magic numbers
- Few bound excited states

RIBF Overview



Superconducting Ring Cyclotron (SRC)

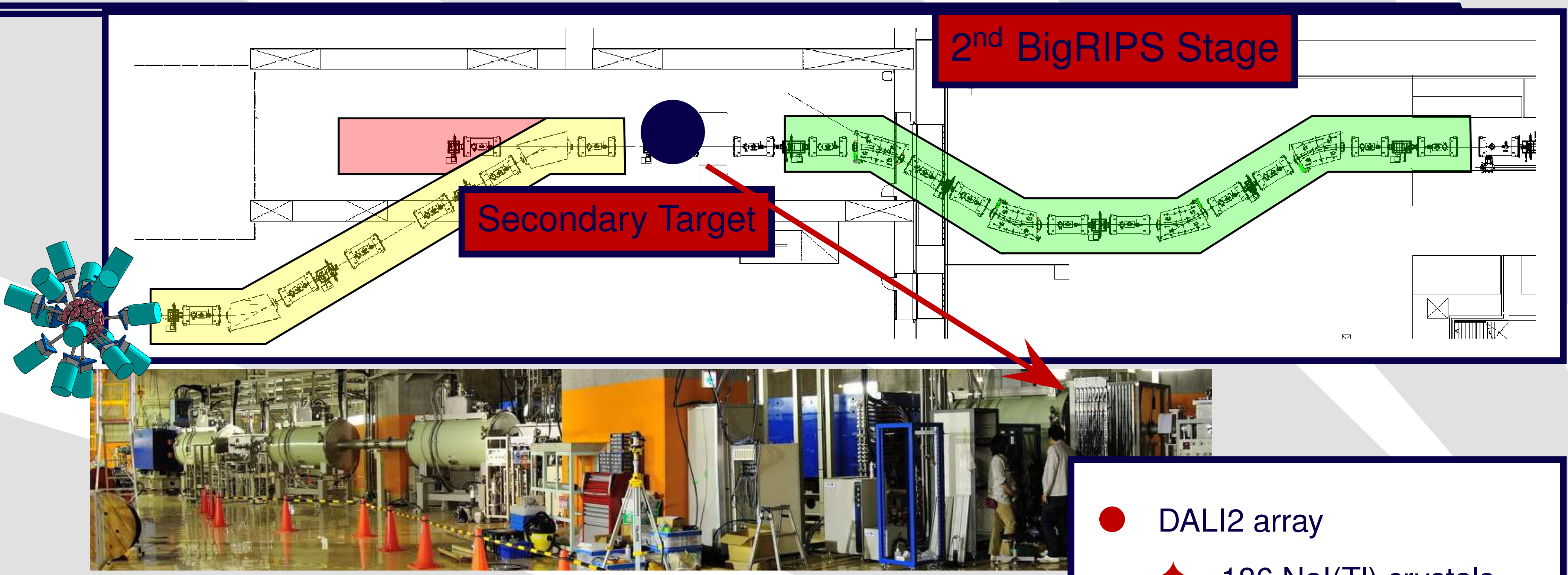


Intensities of 345 MeV/u beams from the SRC

Nucleus	Beam Intensity / pnA		
	Goal	Achieved Max	Average
^{48}Ca	1000	730	500
^{70}Zn	1000	250	200
^{78}Kr	1000	486	300
^{124}Xe	100	100	80
^{238}U	100	58	40

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

ZeroDegree Spectrometer



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

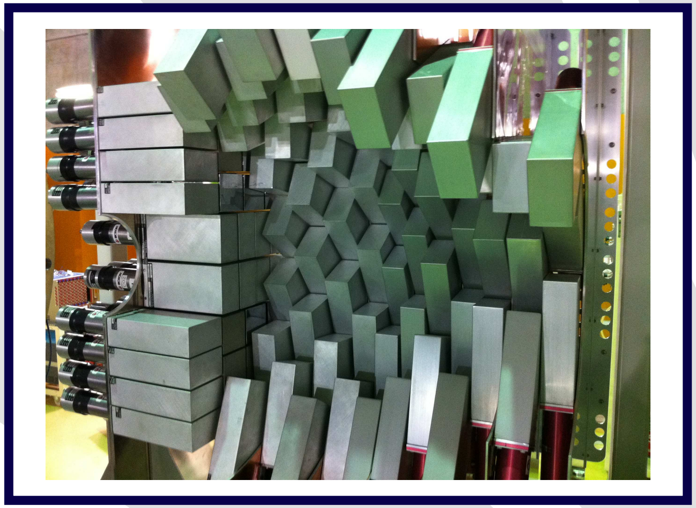
0° Spectrometer ZeroDegree

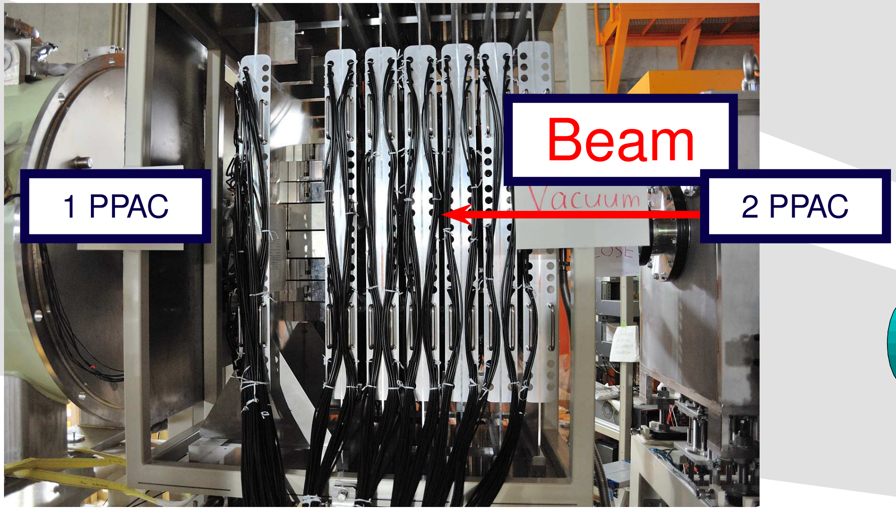
- **Particle ID** after secondary target
- Fragment momentum distribution
- Various modes of operation

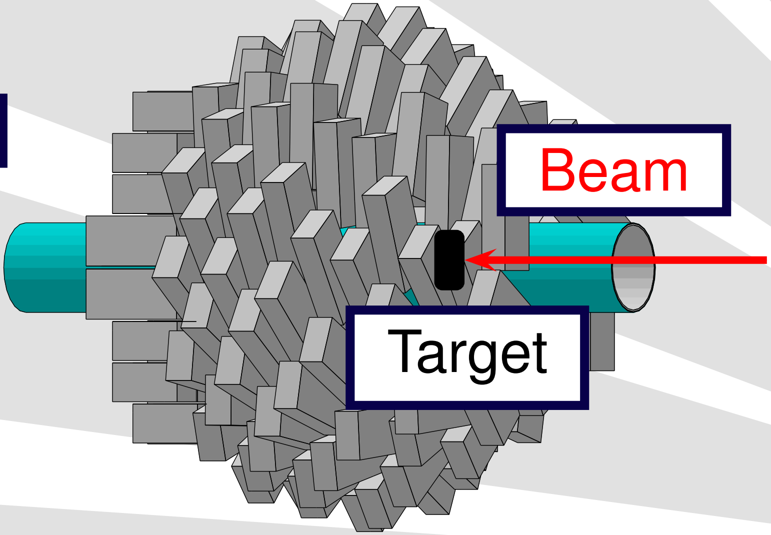
mode	$p/\Delta p$	Δp	Ang. Accep.
Large Accep.	**1240**	**$\pm 3\%$**	**± 45 mrad(H) ± 30 mrad(V)**
High res.(achrom)	2120	$\pm 3\%$	± 20 mrad(H) ± 30 mrad(V)
Dispersive	4130	$\pm 2\%$	± 20 mrad(H) ± 30 mrad(V)

DALI2 (2010–2016)

- 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







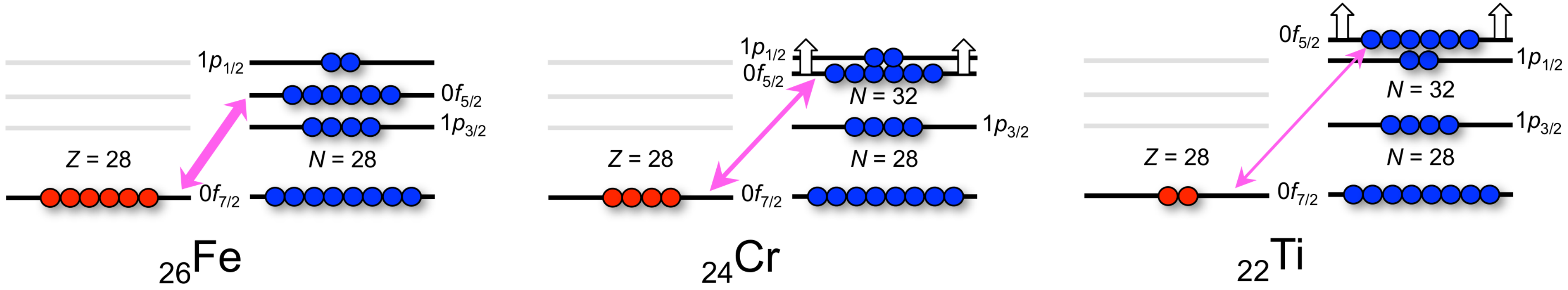
S. Takeuchi *et al.*, NIMA 763, 596 (2014).

Evolution in fp Shell for Neutron-Rich Nuclei

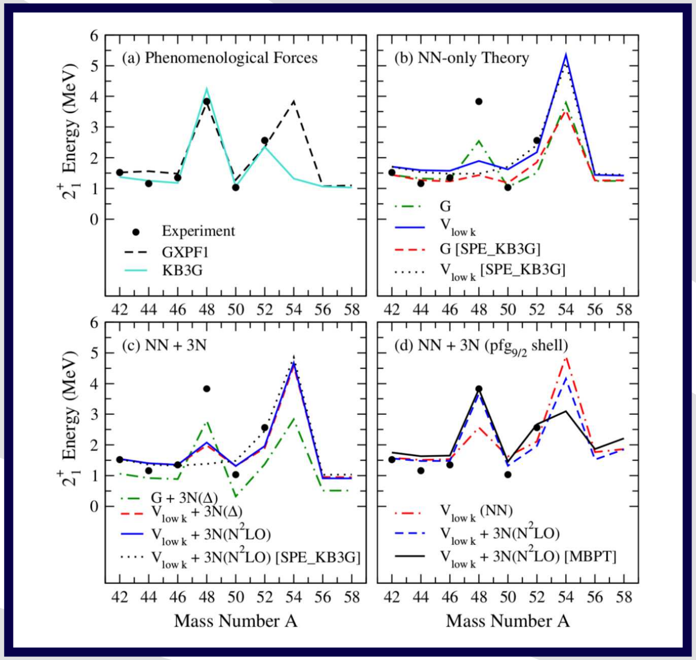
- Neutron-rich *fp* shell (bounded by $Z = 20 – 28$ and $N = 28 – 40$)
- Attractive interaction between $\pi 1f_{7/2}$ and $\nu 1f_{5/2}$ orbitals is important [1]; responsible for some features of nuclear shell evolution in this mass region

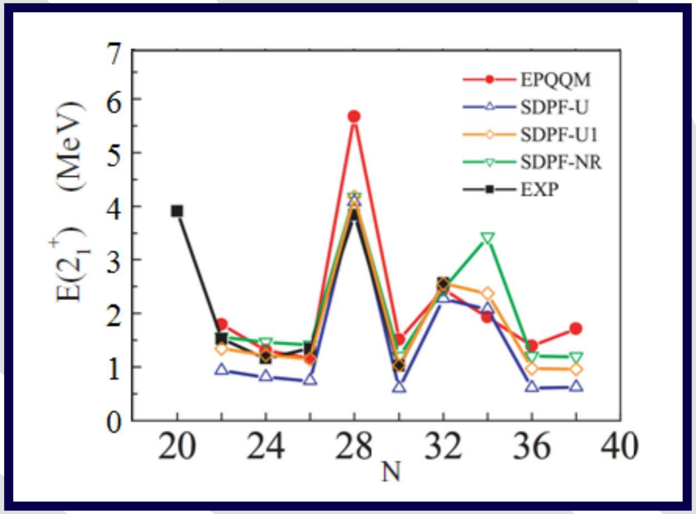
[1] T. Otsuka *et al.*, Phys. Rev. Lett. **95** (2005) 232502

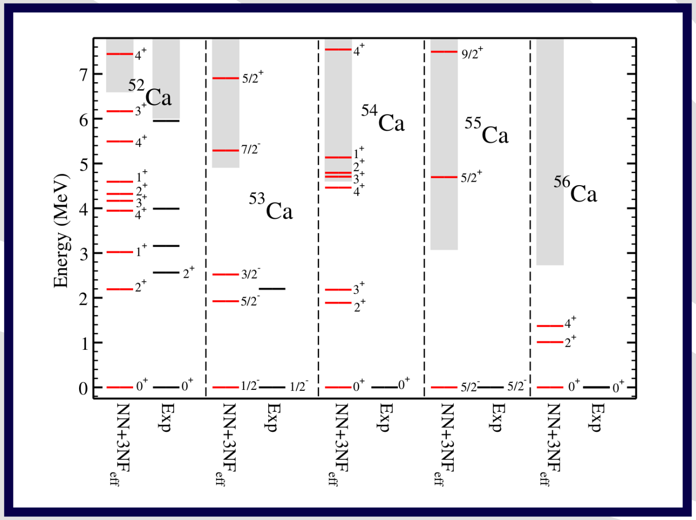
- As protons are removed from the $\pi f_{7/2}$ orbital (i.e., from $_{28}$Ni to $_{20}$Ca) the strength of the π-ν interaction weakens, causing the $\nu f_{5/2}$ orbital to shift up in energy relative to $\nu p_{1/2}$ and $\nu p_{3/2}$



$E(2_1^+)$ *Predictions for Calcium Isotopes*



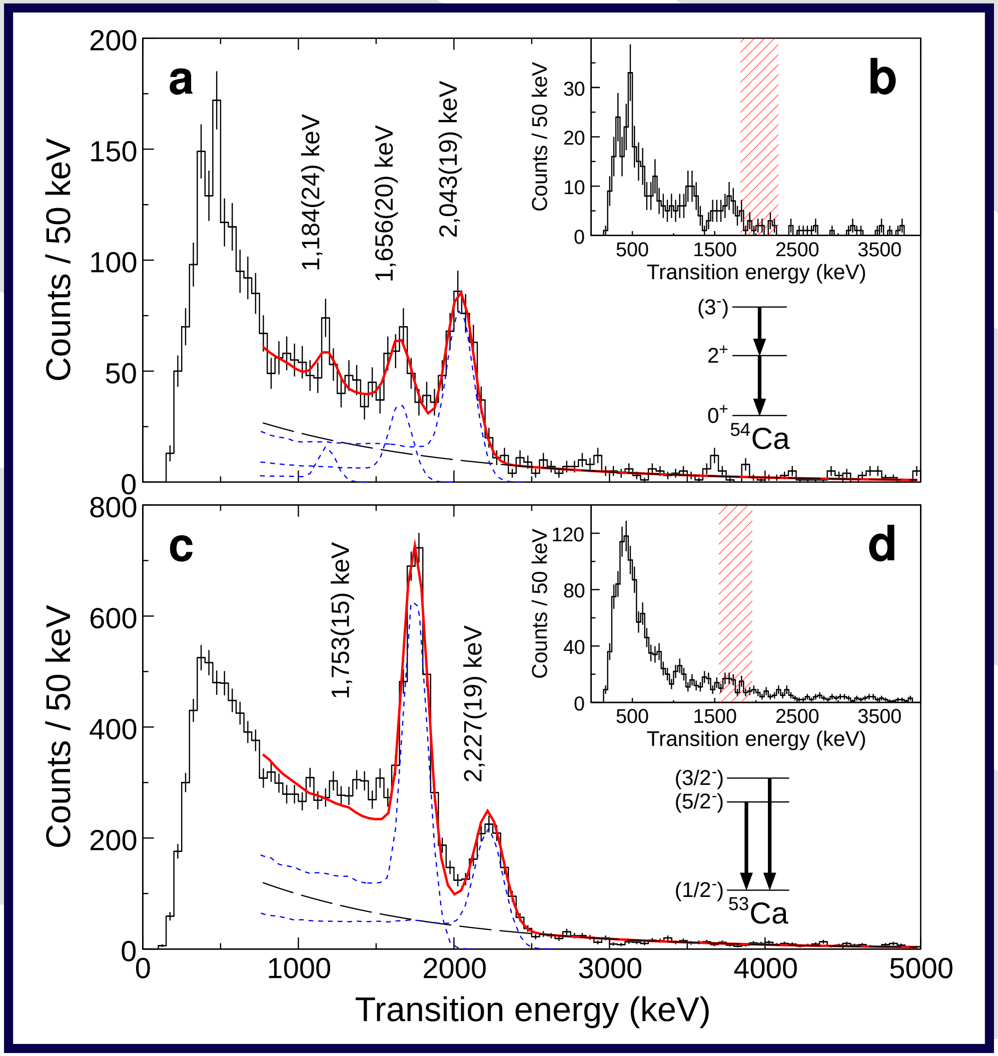




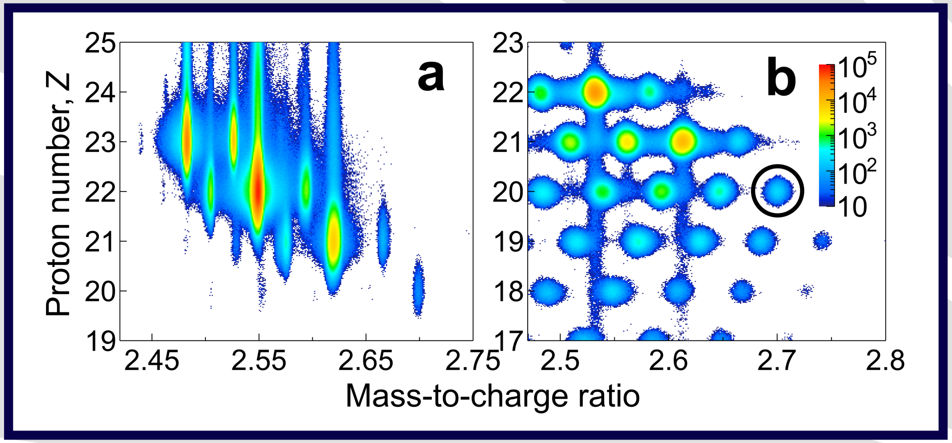
Large variation for $E(2_1^+)$ predictions in ^{54,56}Ca

J. D. Holt *et al.*, Journal of Physics G 39, 085111 (2012).
K. Kaneko *et al.*, Phys. Rev. C 83, 014320 (2011).
G. Hagen *et al.*, Phys. Rev. Lett. 109, 032502 (2012).

In-Beam γ-Ray Spectra of ^{53,54}Ca

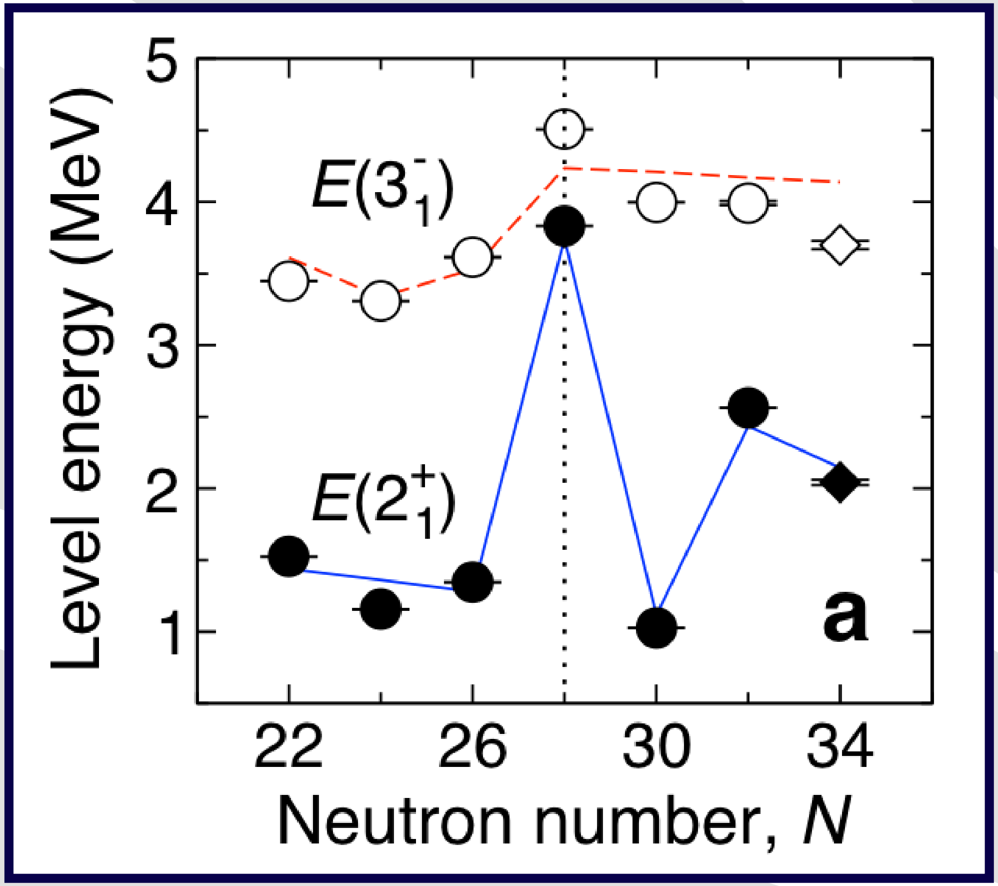


- ^{70}Zn, 60 pnA primary beam
- Be(^{55}Sc,^{54}Ca*), Be(^{56}Ti,^{54}Ca*)
- F8 target: ^{9}Be, 1.85 g/cm^2
- 124 pps/pnA ^{56}Ti
- 12 pps/pnA ^{55}Sc
- **40 hours data taking**
- $E(2_1^+)$ at 2043(19) keV in ^{54}Ca



^{53}Ca: 2220(1) keV level observed, F. Perrot *et al.*, PRC **74**, 014313 (2006).
D. Steppenbeck, S. Takeuchi *et al.*, Nature 502, 207 (2013).

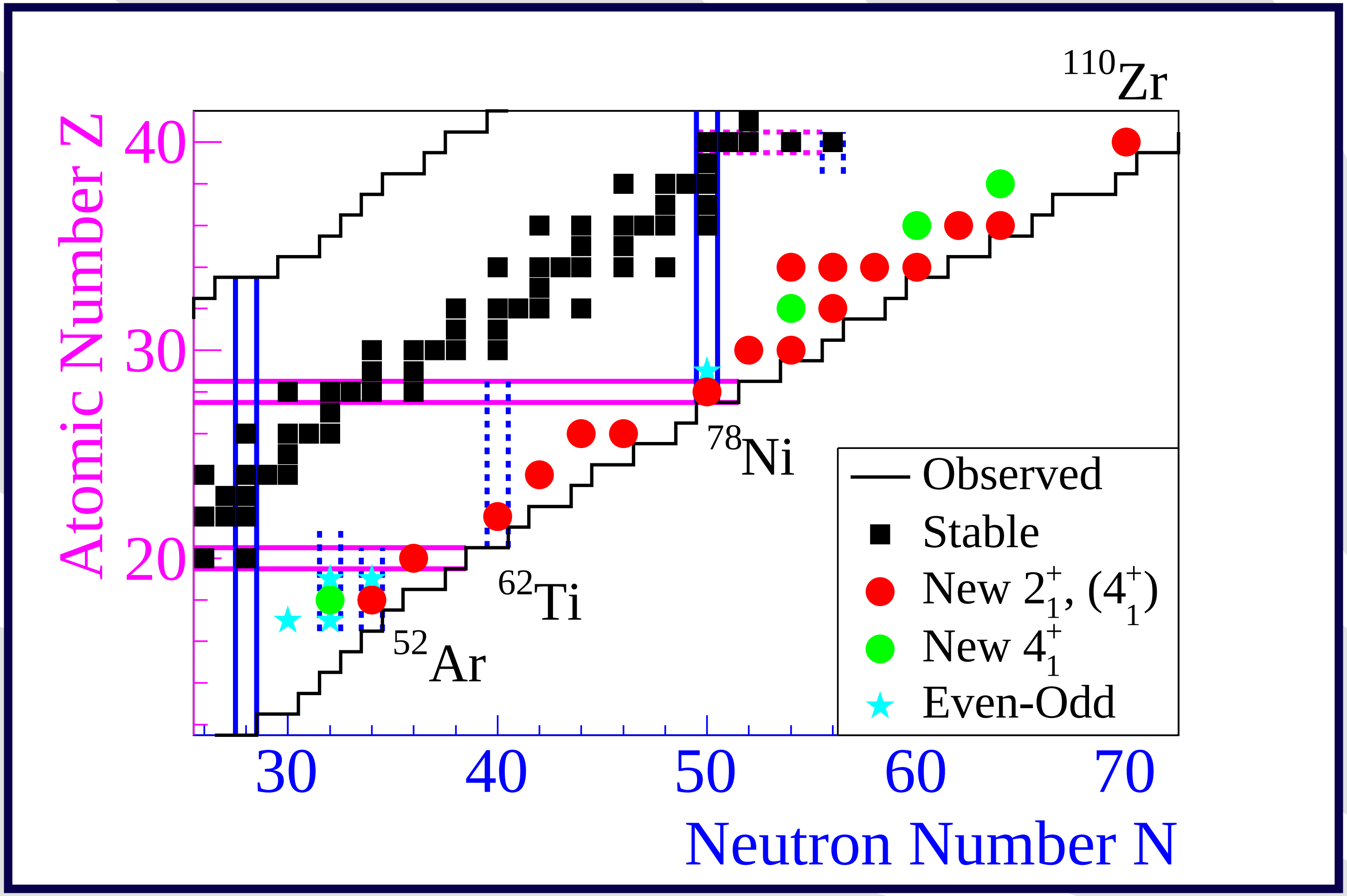
Shell Model Calculations for ^{54}Ca



- Shell-model calculations based on a modified GXPF1B effective interaction (fp model space) and cross-shell excitations within the $sd - fp - sdg$ model space
- Concluded that the magnitude of the $N = 34$ subshell closure ($\nu f_{5/2} - \nu p_{1/2}$) is similar to the $N = 32$ subshell closure in ^{52}Ca ($\nu p_{1/2} - \nu p_{3/2}$)

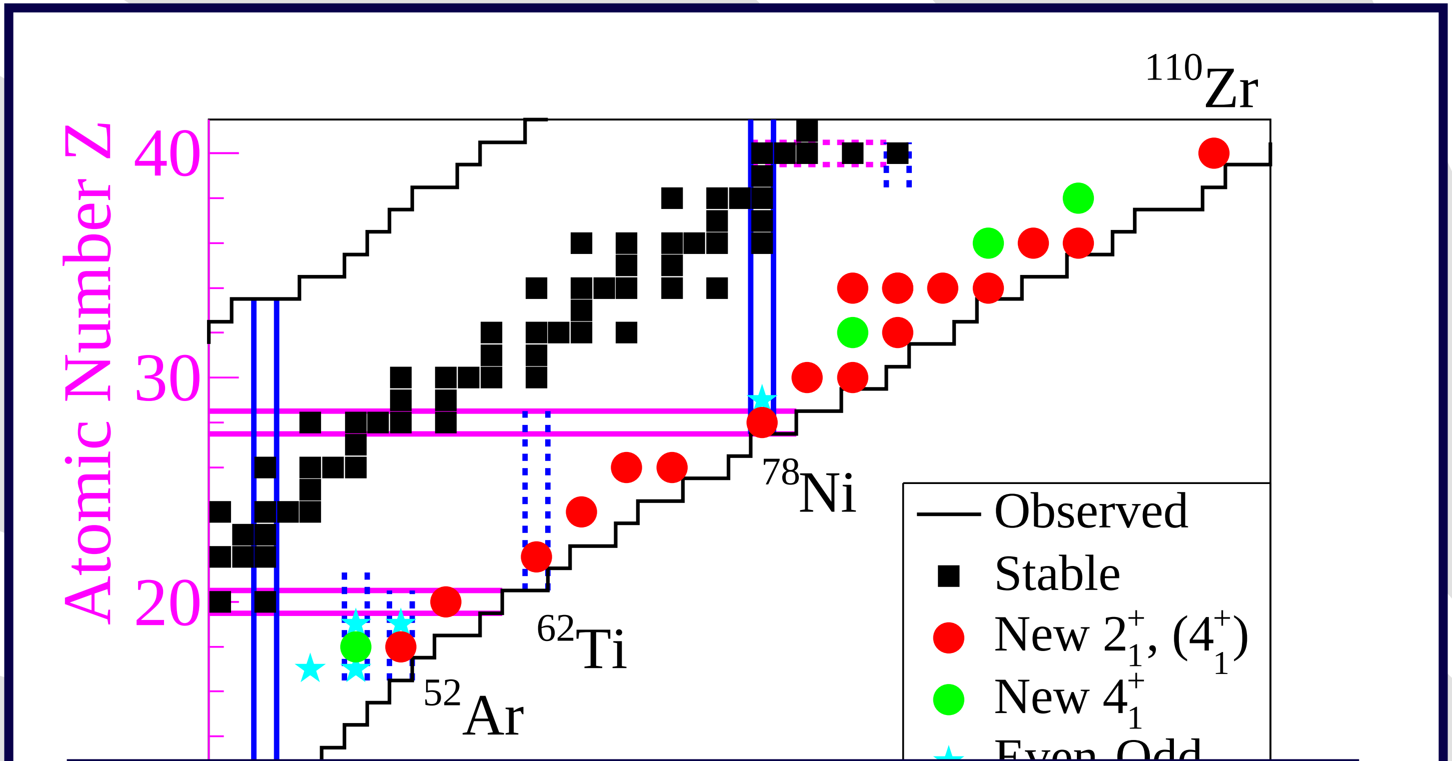
SEASTAR

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



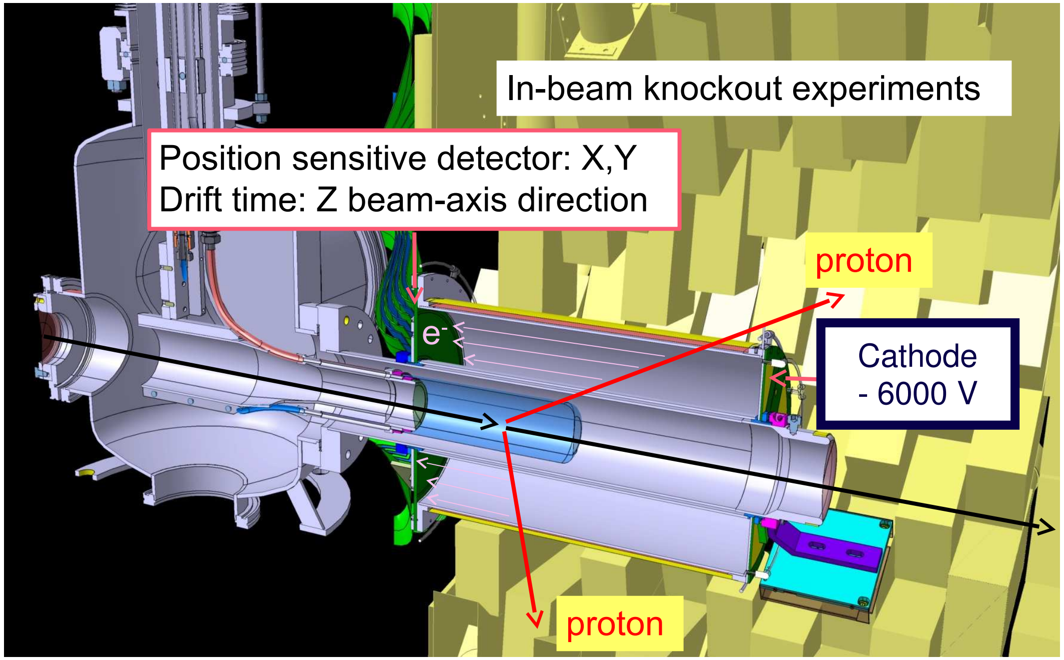
- 10–30 pnA ^{238}U, 250 pnA ^{70}Zn primary beams
- 3 campaigns in 2014 (ZDS), 2015 (ZDS), 2017 (SAMURAI)
- 10 + 9 + 8 = 27 days of beam time
- Proposal NP1312-RIBF118 (Spokespersons: PD, A. Obertelli)
- 6 days for ^{78}Ni

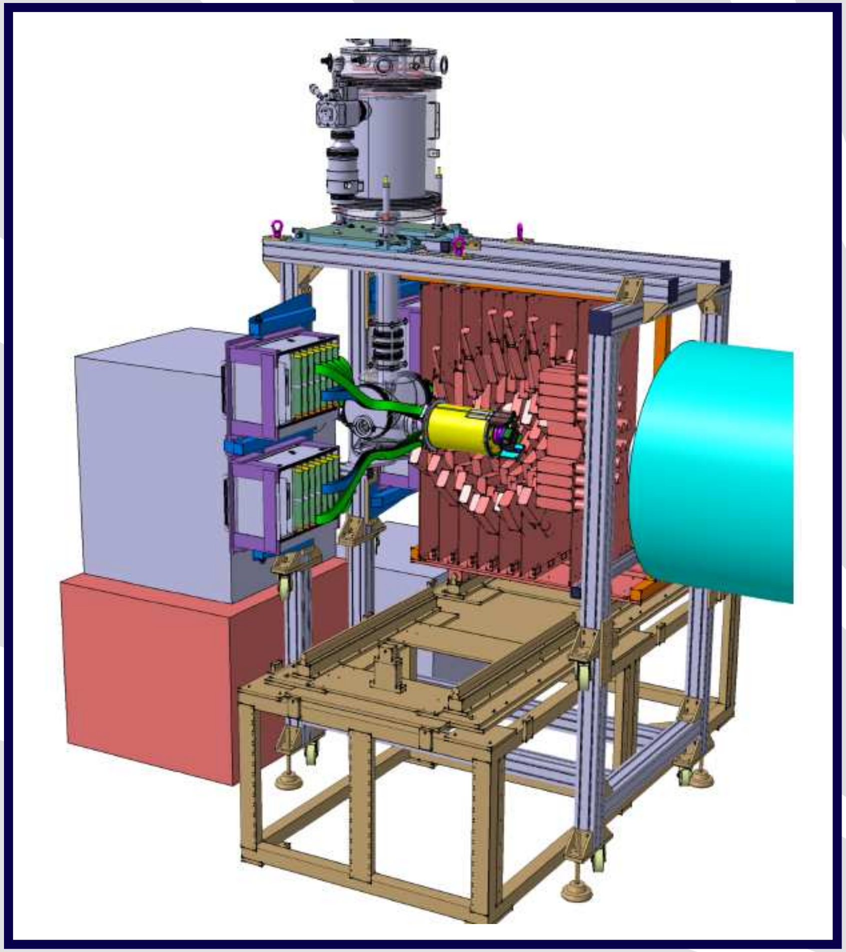
Shell Evolution And Search for Two-plus energies At the RIBF (SEASTAR)



- 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





Mag**I**c **N**umbers **O**ff **S**tability

`http://minos.cea.fr`

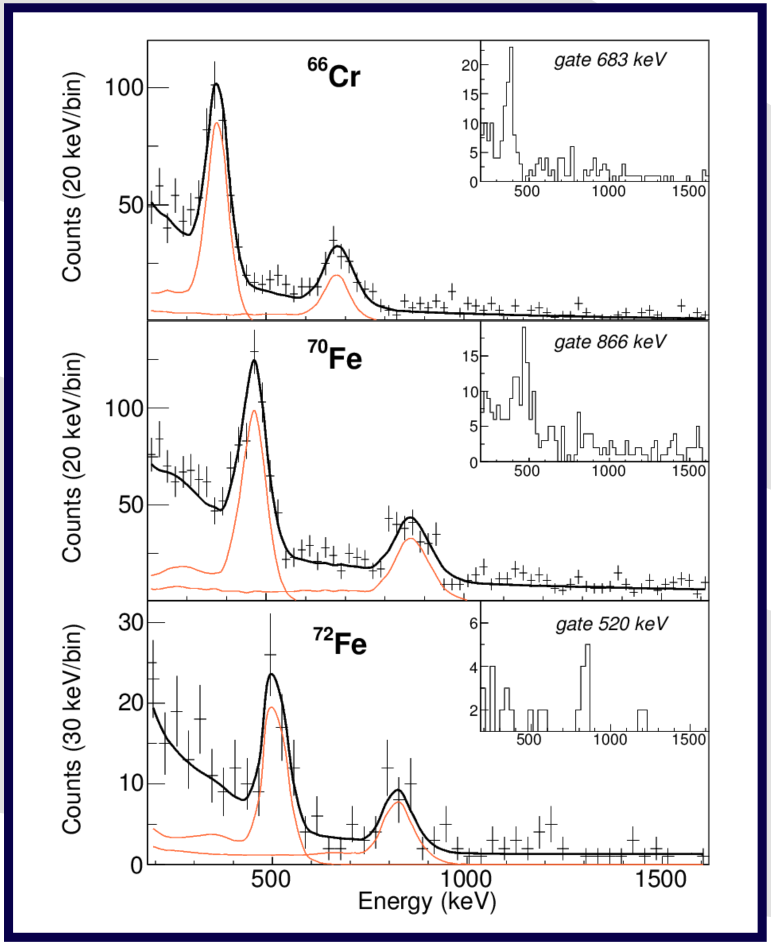
- Up to 1 g/cm^2 liquid hydrogen target
- Position sensitive TPC
  - Driftime → Z-beam axis
  - Vertex position reconstruction
  - Achieved ≈5 mm (FWHM)

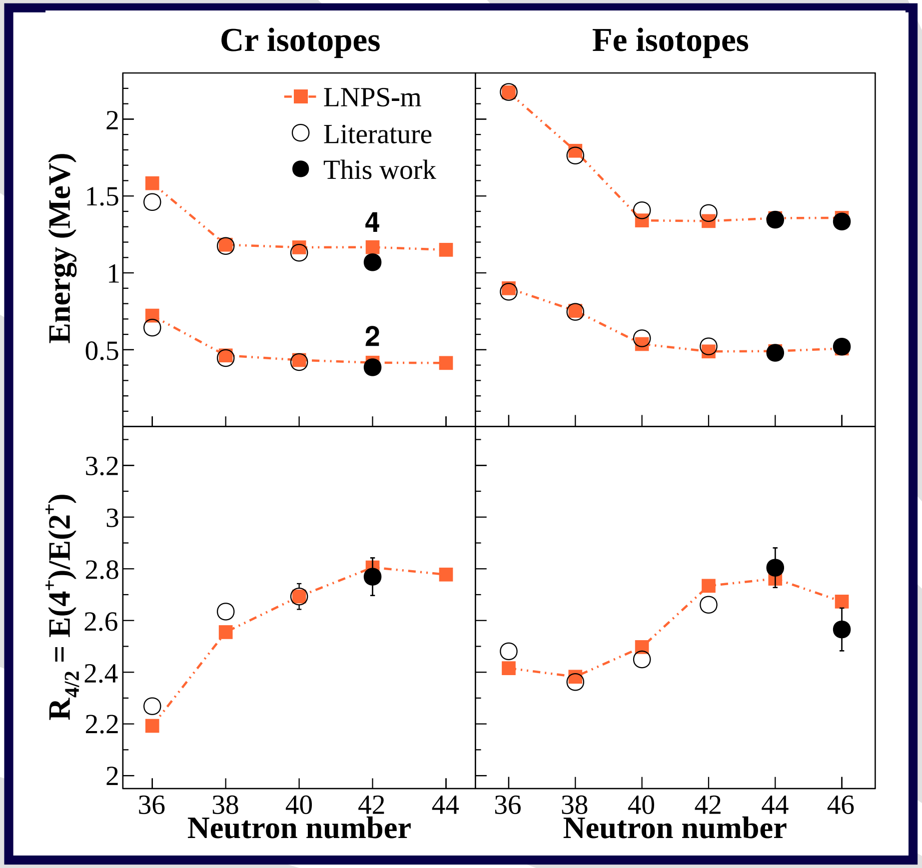
A. Obertelli *et al.*, Eur. Phys. J. A 50, 8 (2014).

First Campaign:

^{66}Cr, ^{70,72}Fe, ^{78}Ni

Maximum of Collectivity Beyond $N = 40$

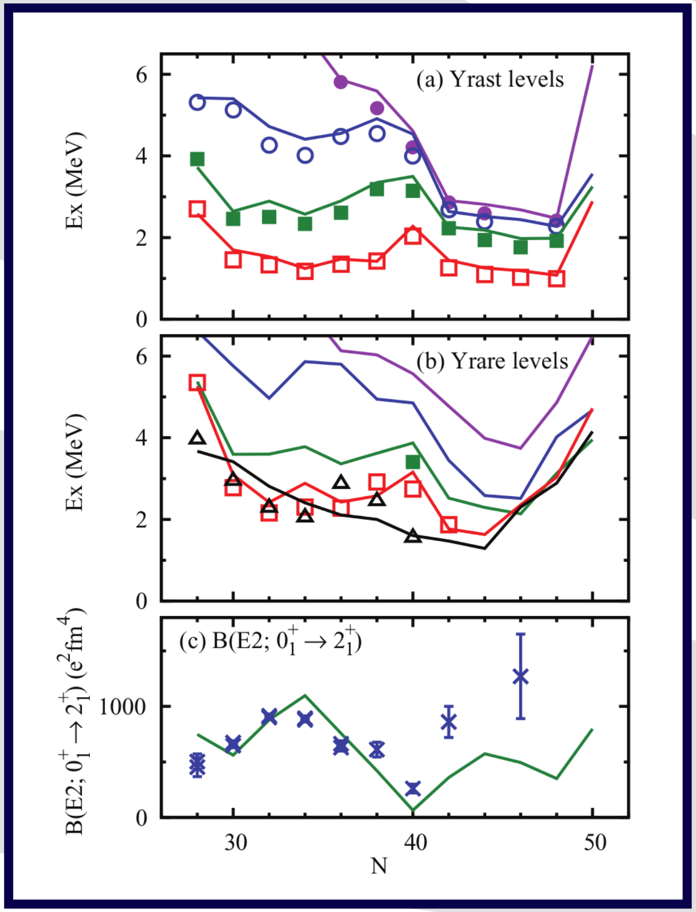




- Collaboration with F. Nowacki, IPHC, $fp - fpg_9d_5$ valence space
  - additional $gd - gd$ monopole strength
- Extension of $N = 40$ “Island of Inversion” towards $N = 50$

C. Santamaria, C. Louchart *et al.*, Phys. Rev. Lett. 115, 192501 (2015).

At and Beyond ^{78}Ni: Are $Z = 28$ and $Z = 50$ Shell Closures?



Y. Tsunoda *et al.*, Phys. Rev. C 89, 031301(R) (2014).

- A3DA: ^{40}Ca core, pf, $0g_{9/2}1d_{5/2}$ orbits for π and ν

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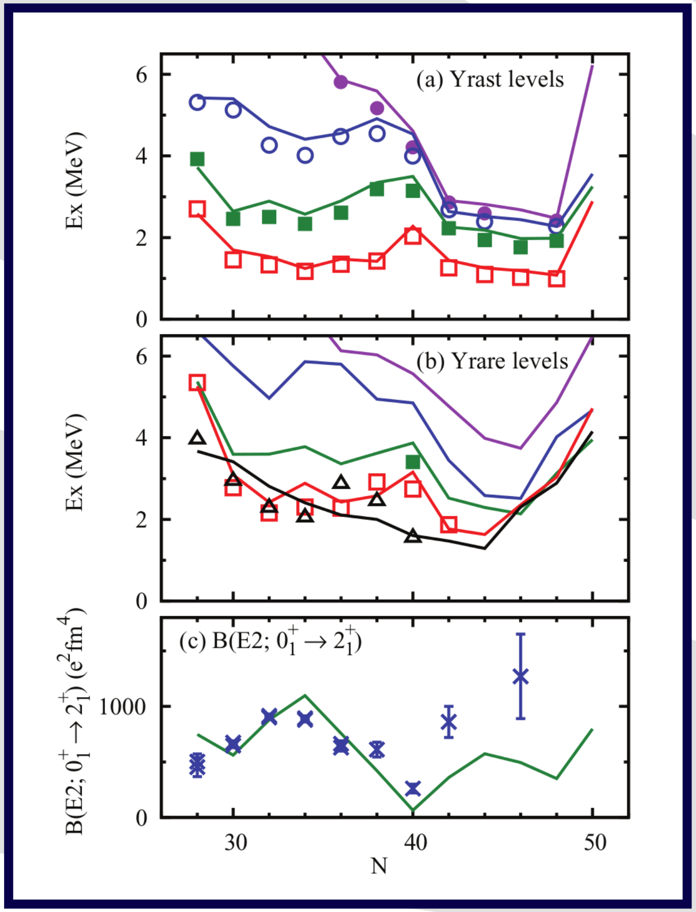

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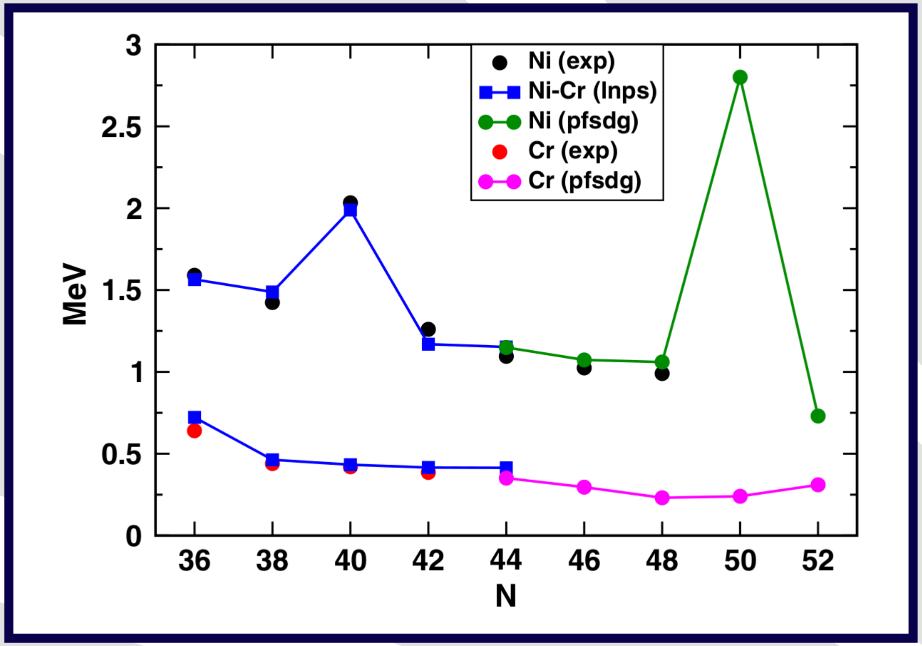

F. Nowacki *et al.*, Phys. Rev. Lett. 117, 272501 (2016).

- LNPS: ^{48}Ca core, πpf and $\nu 1p0f_{5/2}0g_{9/2}1d_{5/2}$ orbits
- PFSDG-U: ^{60}Ca core, πpf and νgds shells

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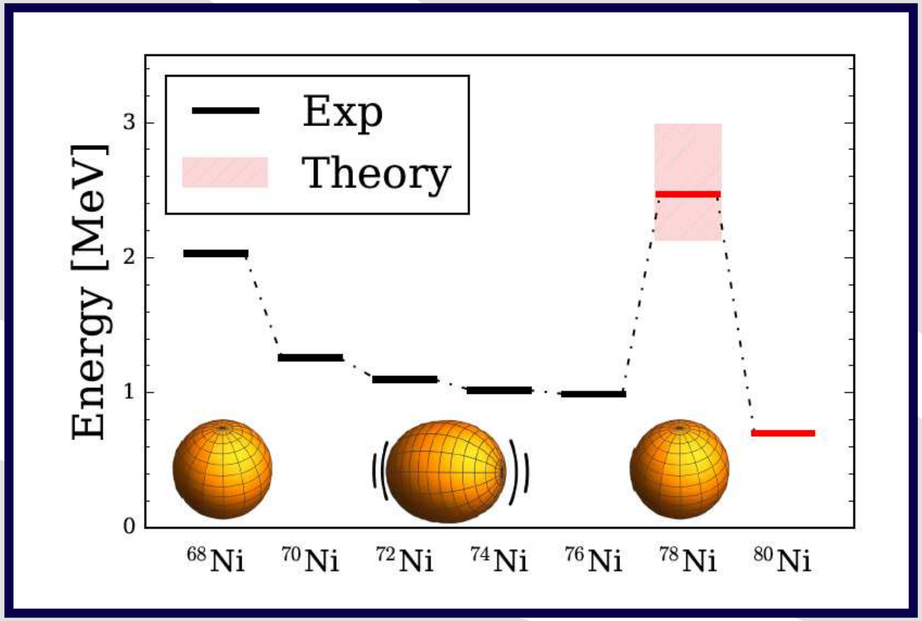
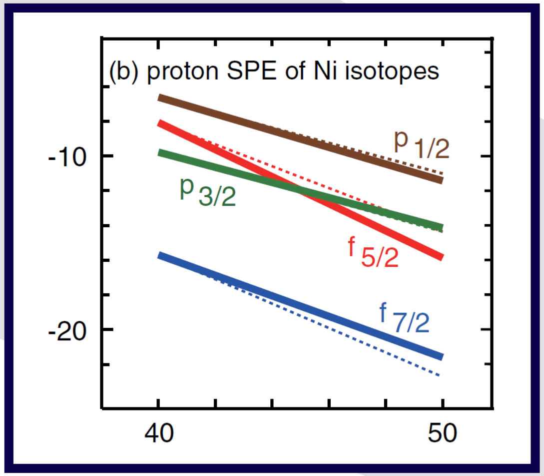


G. Hagen *et al.*, Phys. Rev. Lett. 117, 172501 (2016).

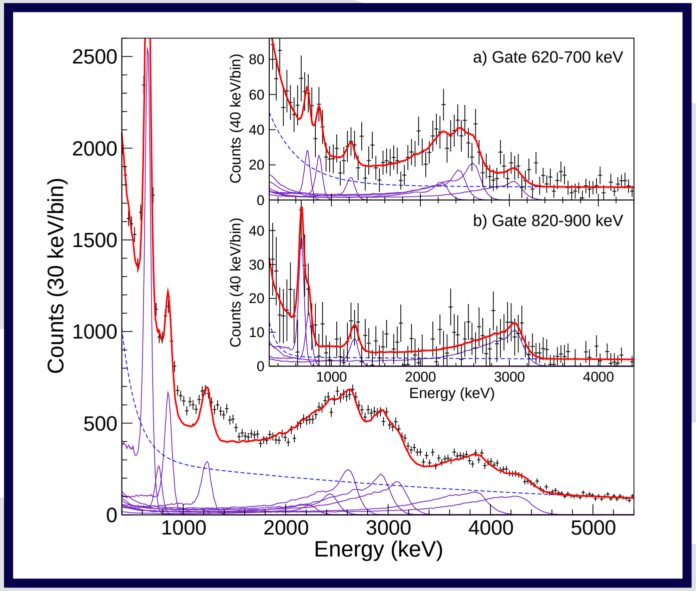
- Coupled Cluster, 2N+3N forces

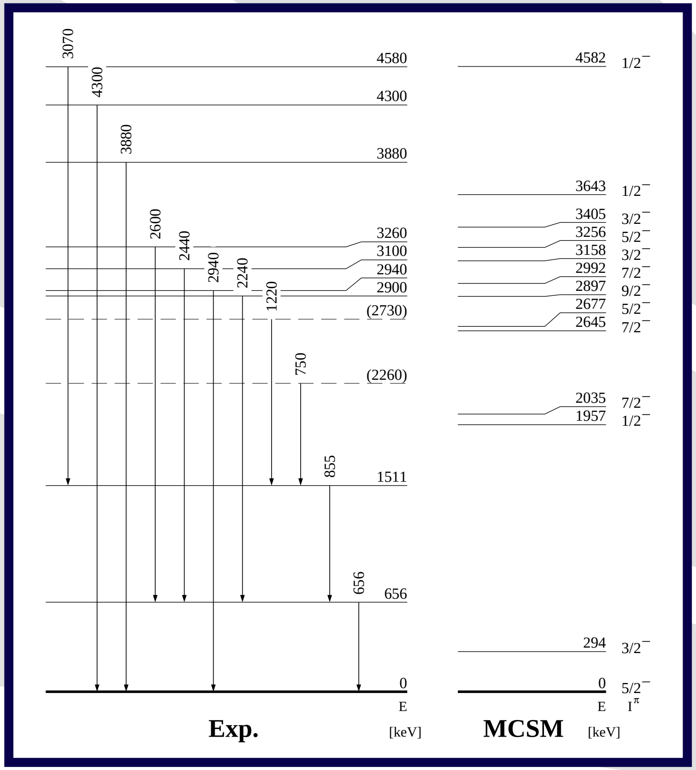
Spectroscopy of ^{79}Cu



T. Otsuka *et al.*, Phys. Rev. Lett. 104, 012501 (2010).

- No significant $f_{7/2}$ knockout feeding to states below 2.2 MeV
- Mulitplet of states between 2.7 and 3.3 MeV: 78Ni 2^+ coupled to proton in $f_{5/2}$ or $p_{3/2}$
- Consistent with (shell model):
  - Sizeable $Z = 28$ shell gap
  - ^{80}Zn(gs) = two protons + ^{78}Ni core





L. Olivier, S. Franchoo *et al.*, Phys. Rev. Lett., accepted.

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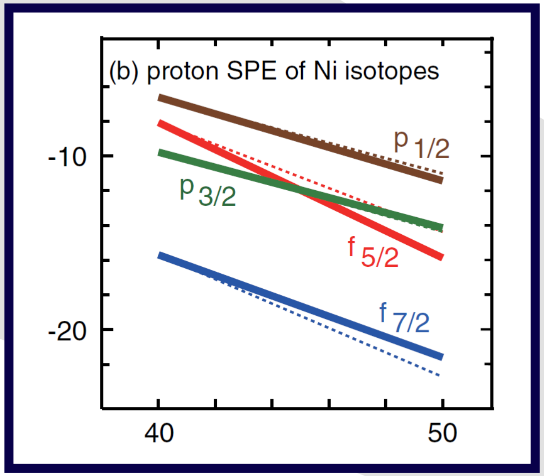

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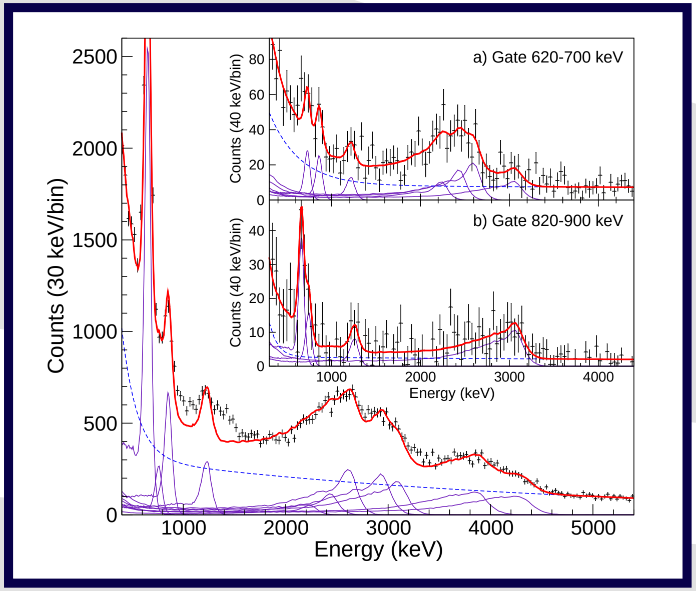
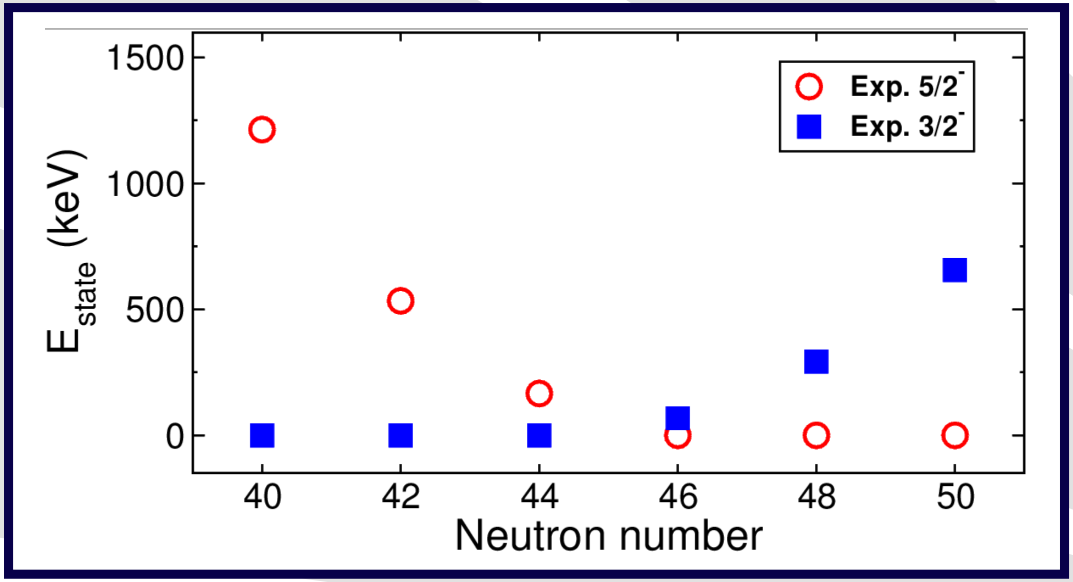


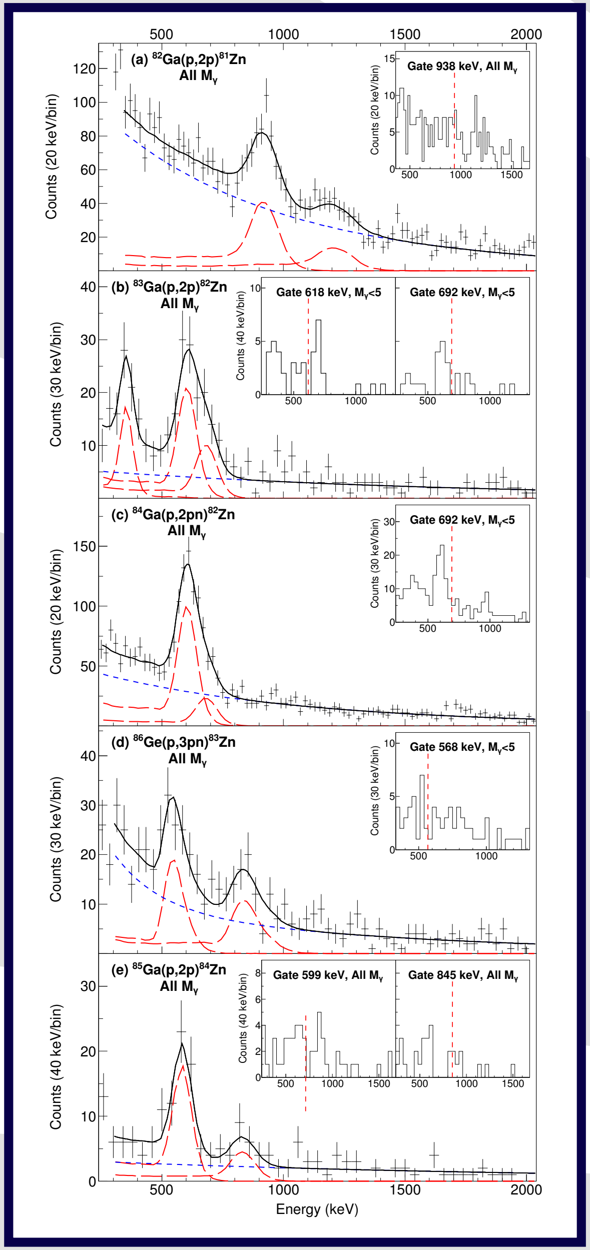


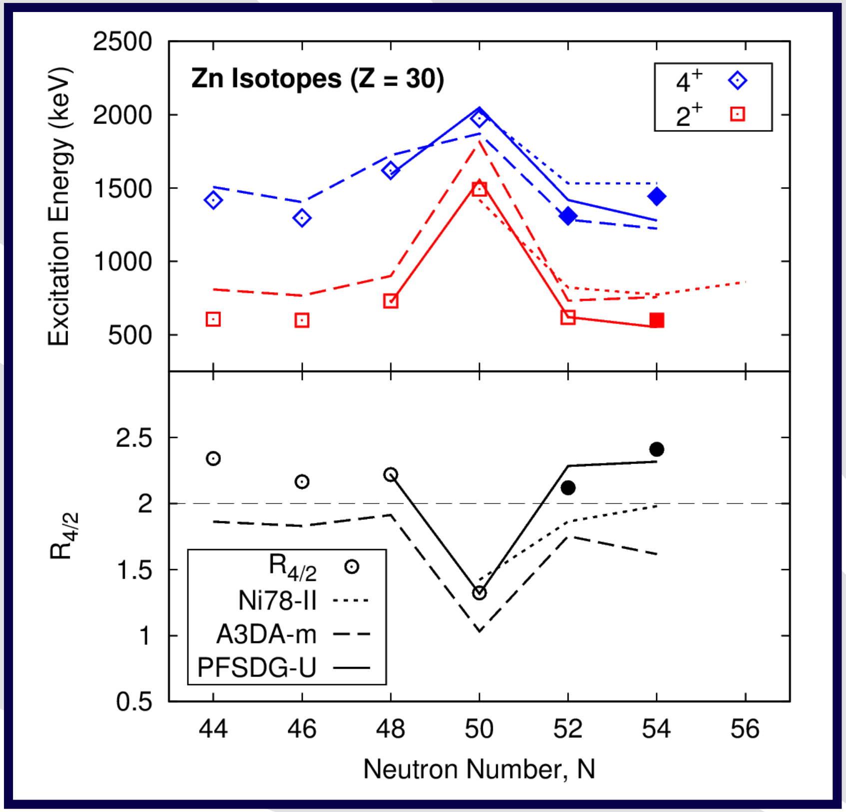
L. Olivier, S. Franchoo *et al.*, Phys. Rev. Lett., accepted.

Second Campaign:

^{82,84}Zn, ^{88}Ge, ^{88,90,92,94}Se,
^{98,100}Kr, ^{110}Zr, ^{112}Mo

Shell Structure Beyond $N = 50$: Spectroscopy of $^{81–84}$Zn

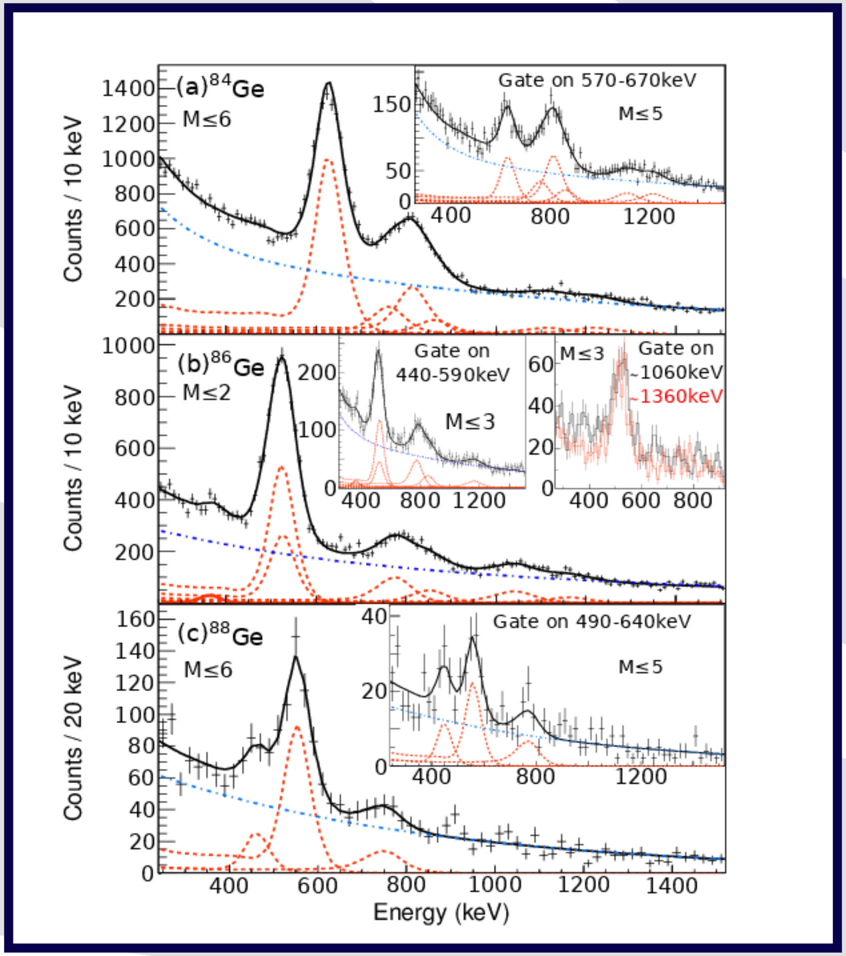


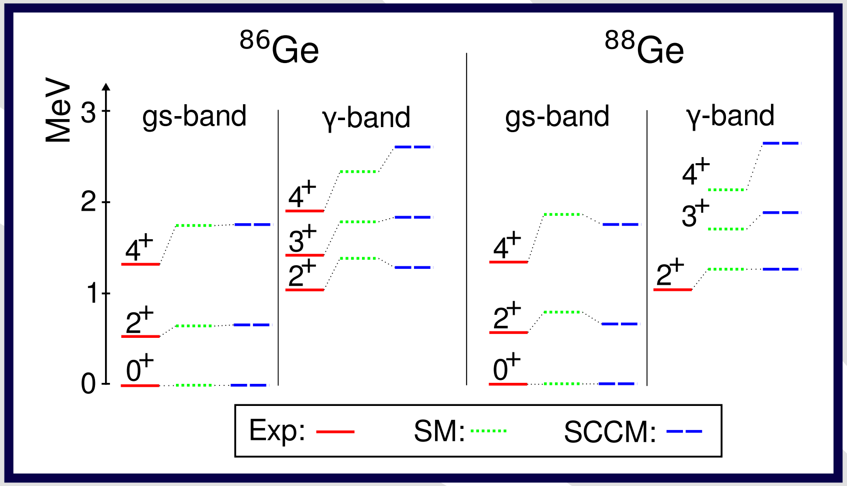


- New states observed in ^{81,82,83,84}Zn
- Interpreted within the shell-model framework
  - Ni78-II: ^{78}Ni core, $Z = 28 - 50$, $N = 50 - 82$ orbits
  - MCSM: ^{40}Ca core, pf shell + $g_{9/2}d_{5/2}$ orbits
  - PFSDG-U: ^{60}Ca core, πpf and νgds shells
  - Breaking of the $Z = 28$ and $N = 50$ improve agreement with data

C. Shand *et al.*, Phys. Lett. B 773, 492 (2017).

Triaxiality in Neutron Rich Ge Isotopes

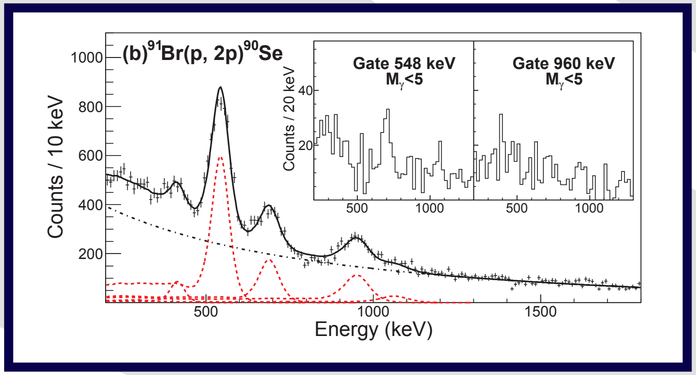


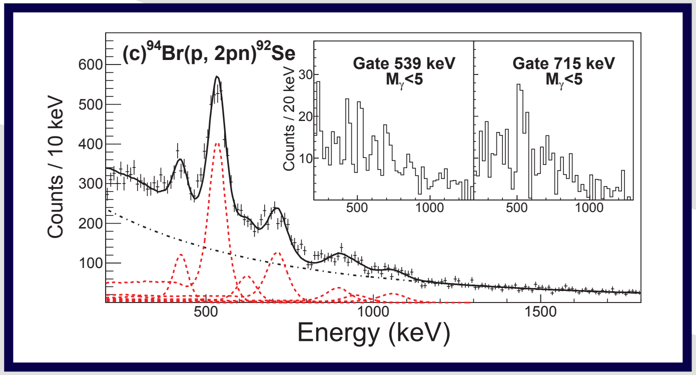


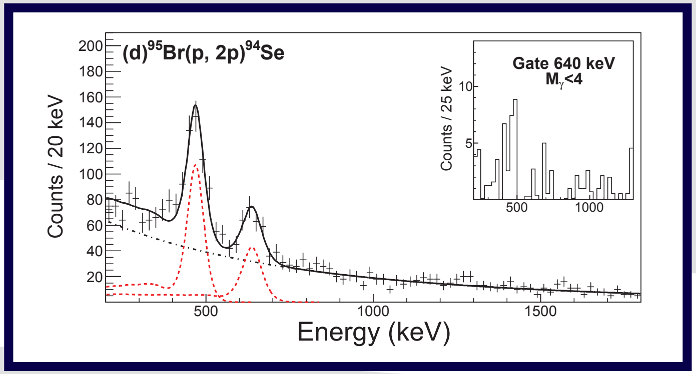
- Spin assignment agrees with prediction from theory K. Sieja *et al*.., Phys. Rev. C 88, 034327 (2013).
  - SM (K. Sieja): ^{78}Ni core, πr3g - νr4h interaction
  - SCCM (T.R. Rodriguez): Symmetry Conserving Configuration mixing
- Energies overestimated systematically
- Similar relative energy distances predicted in the γ-band

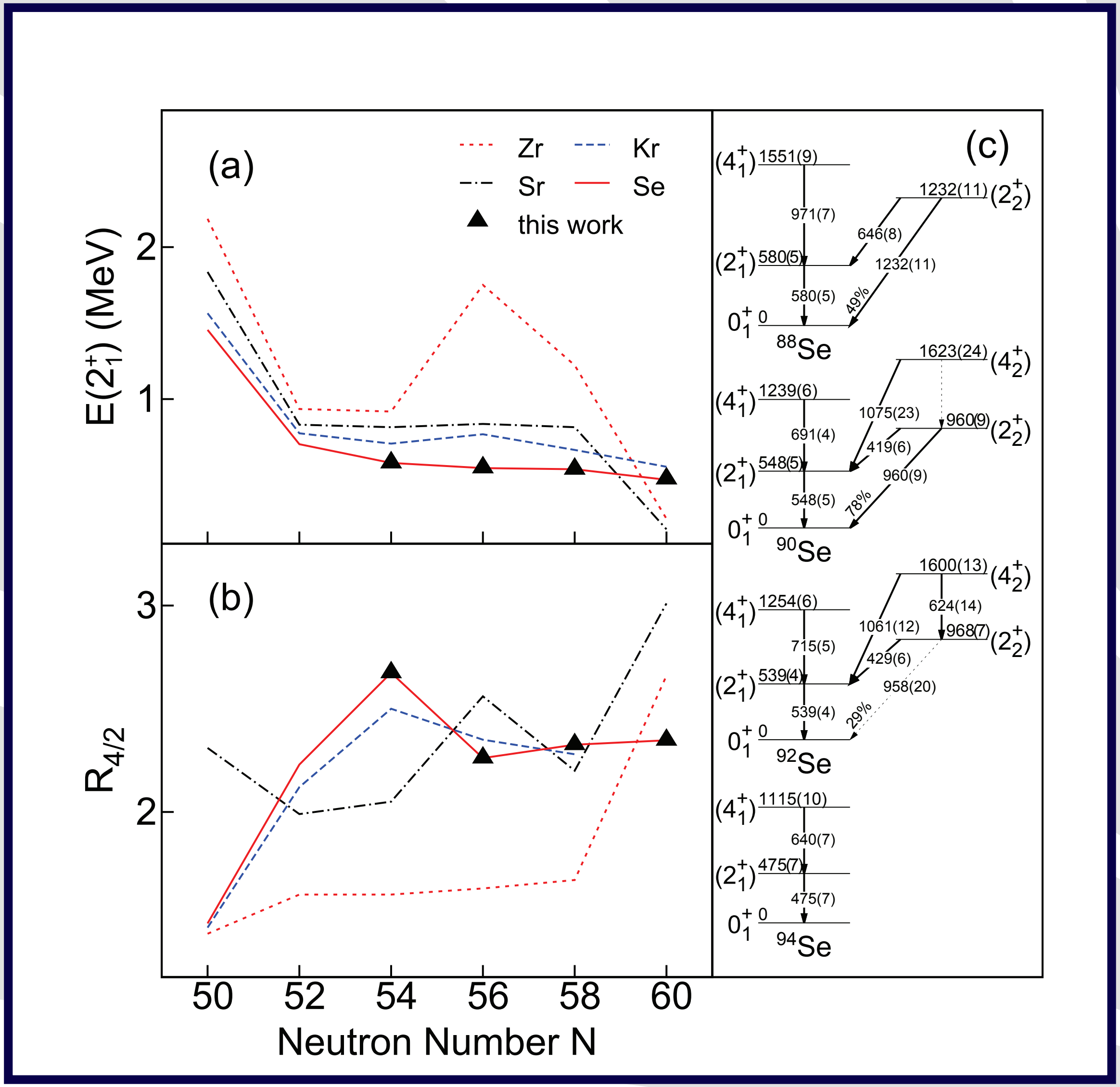
M. Lettmann *et al.*, Phys. Rev. C 96, 011301(R) (2017).

Shape Evolution in Neutron-Rich Se Isotopes



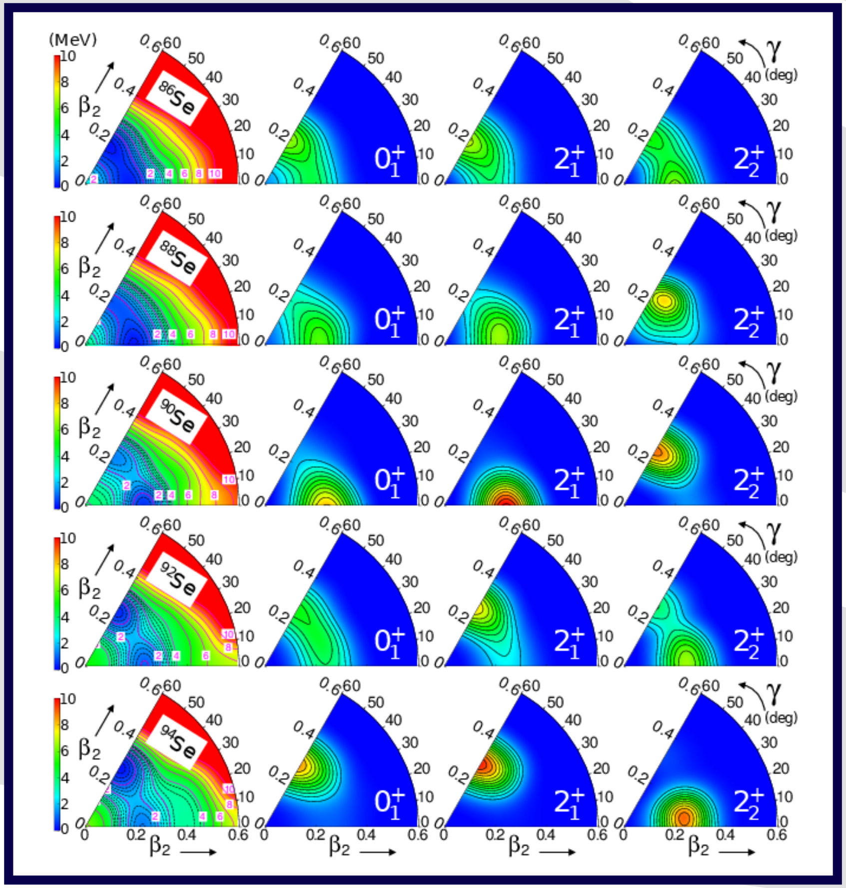


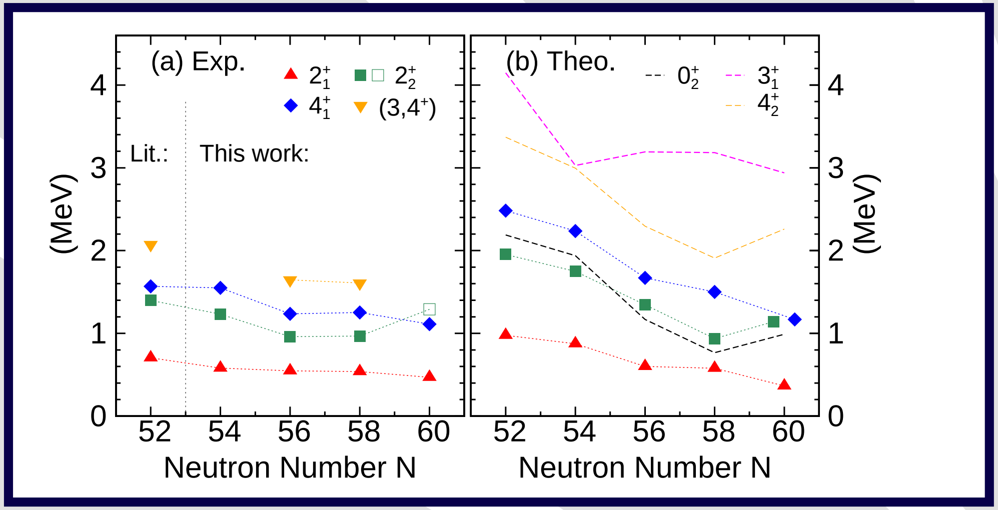




S. Chen *et al.*, Phys. Rev. C 95, 041302(R) (2017).

Shape Evolution in Neutron-Rich Se Isotopes

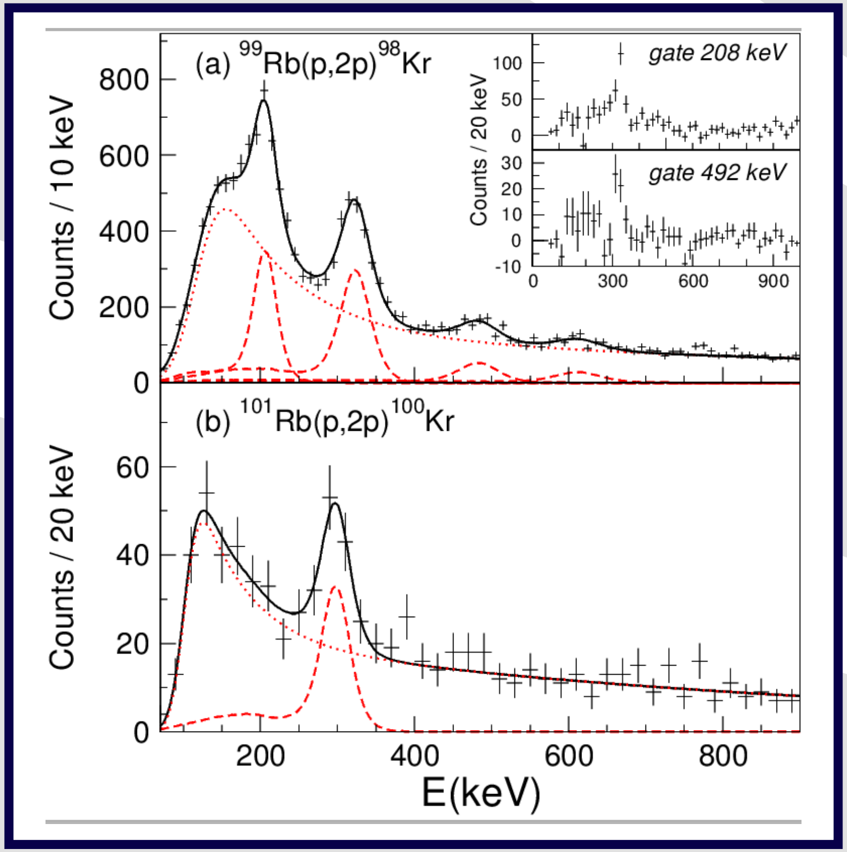


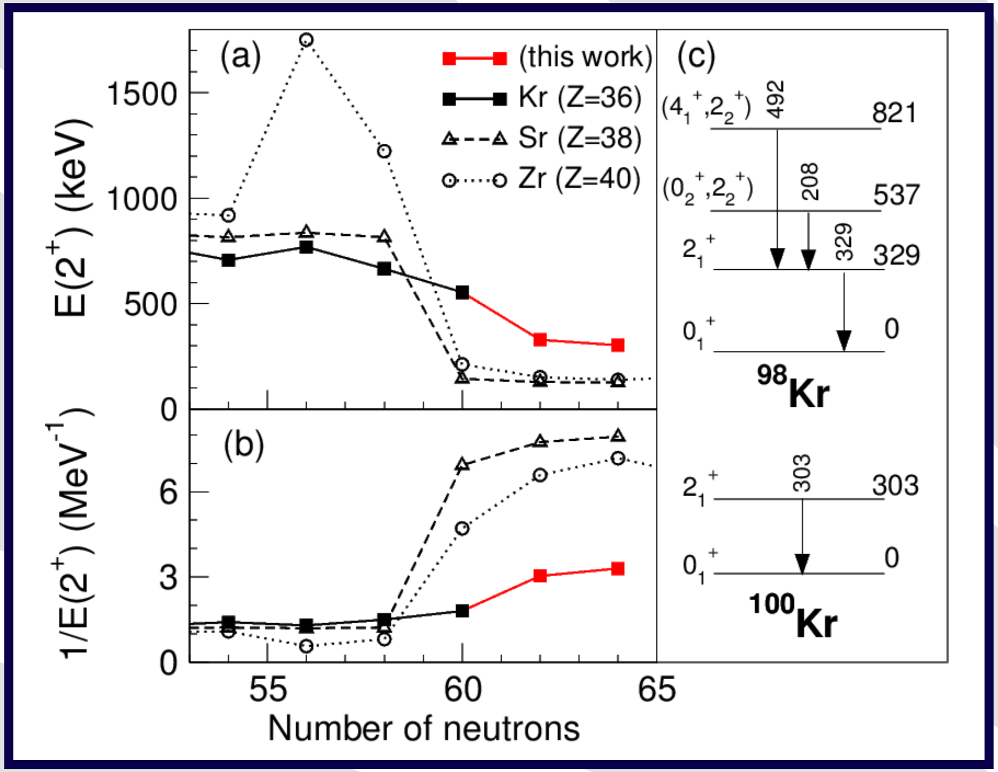


- Gogny D1S effective interaction
- Full GCM for all quadrupole degrees of freedom
- Prediction for shape coexistence
- AND prolate to oblate shape transition at $N = 58 - 60$
- T.R. Rodriguez, Madrid, Spain
- Good agreement between expt and theory for 2_1^+, 2_2^+, 4_1^+, 4_2^+

S. Chen *et al.*, Phys. Rev. C 95, 041302(R) (2017).

Shape Evolution in Neutron-rich Kr Isotopes

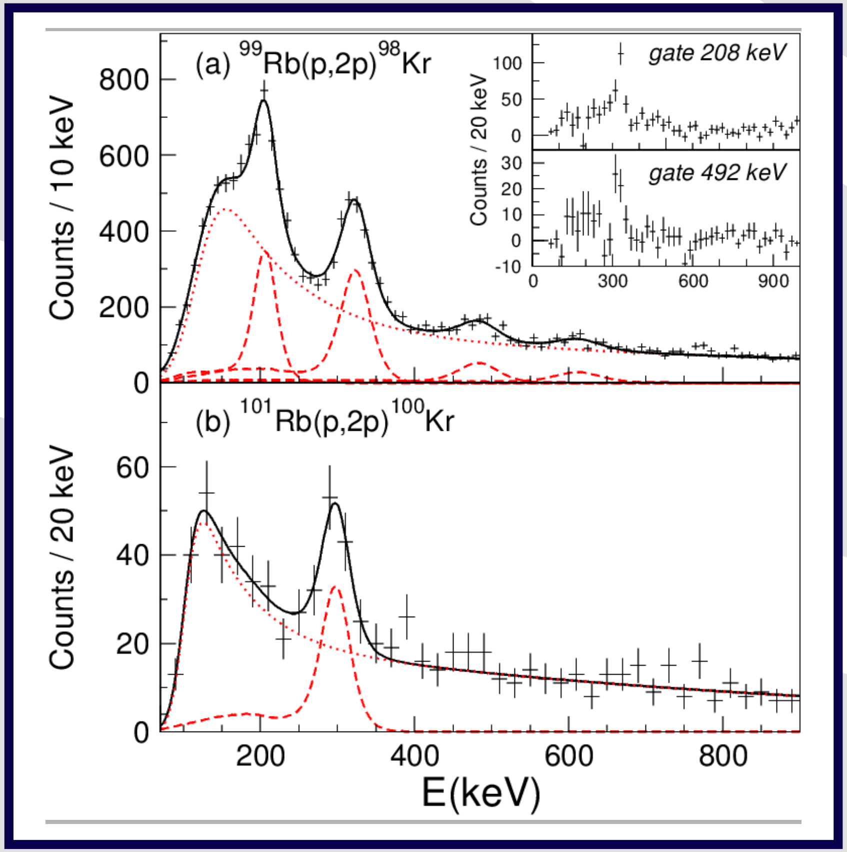


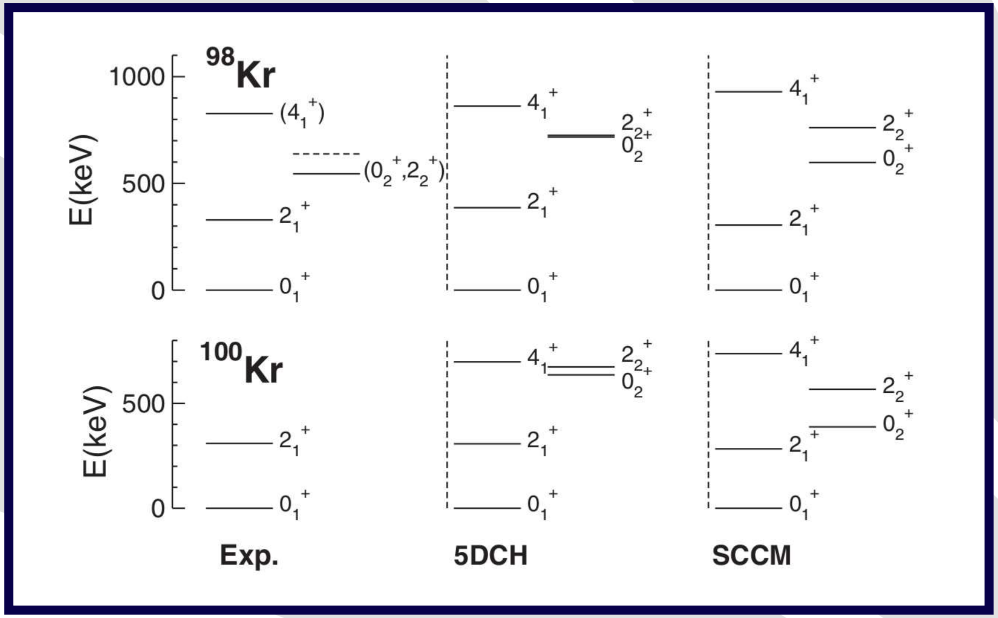


- Smoother onset of collectivity than in Zr, Sr
- Shape transition predicted beyond N=60: ground state from prolate to oblate
- Low-lying 2_2^+ state in agreement with shape competition at low energy

F. Flavigny *et al.*, PRL 115, 242501 (2017).

Shape Evolution in Neutron-rich Kr Isotopes





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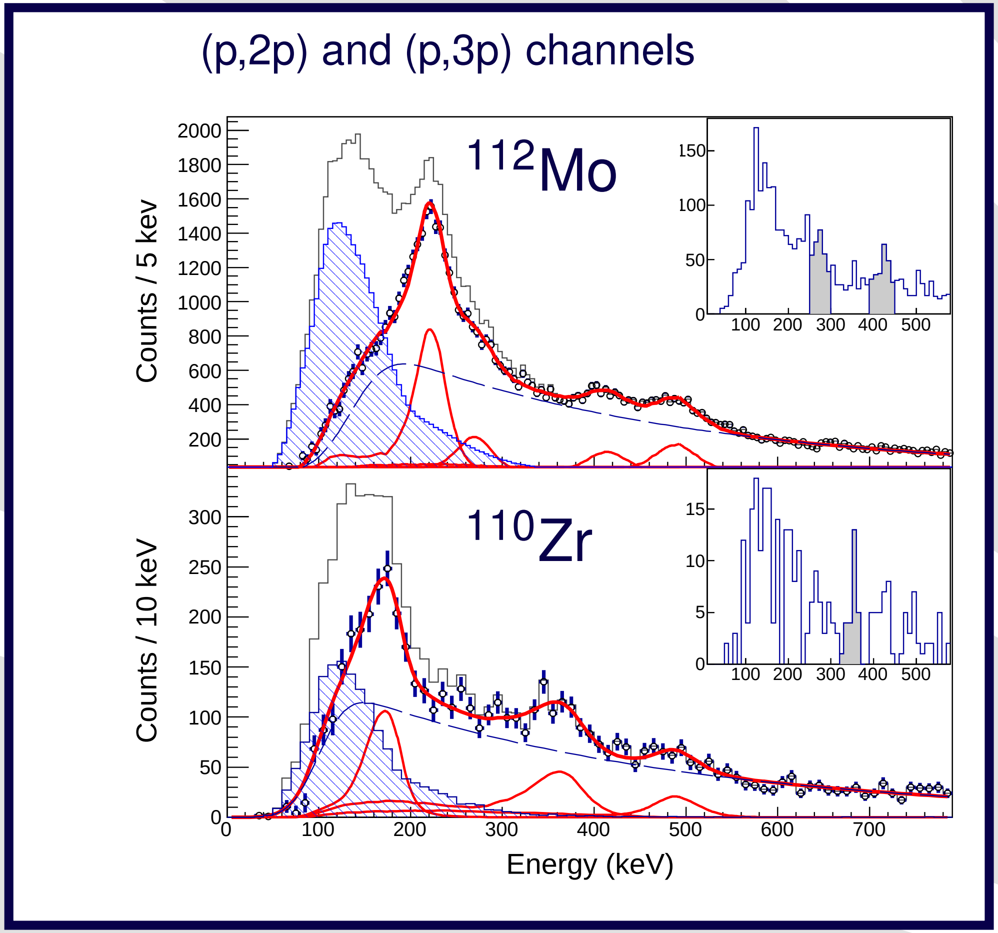
F. Flavigny *et al.*, PRL 115, 242501 (2017).

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

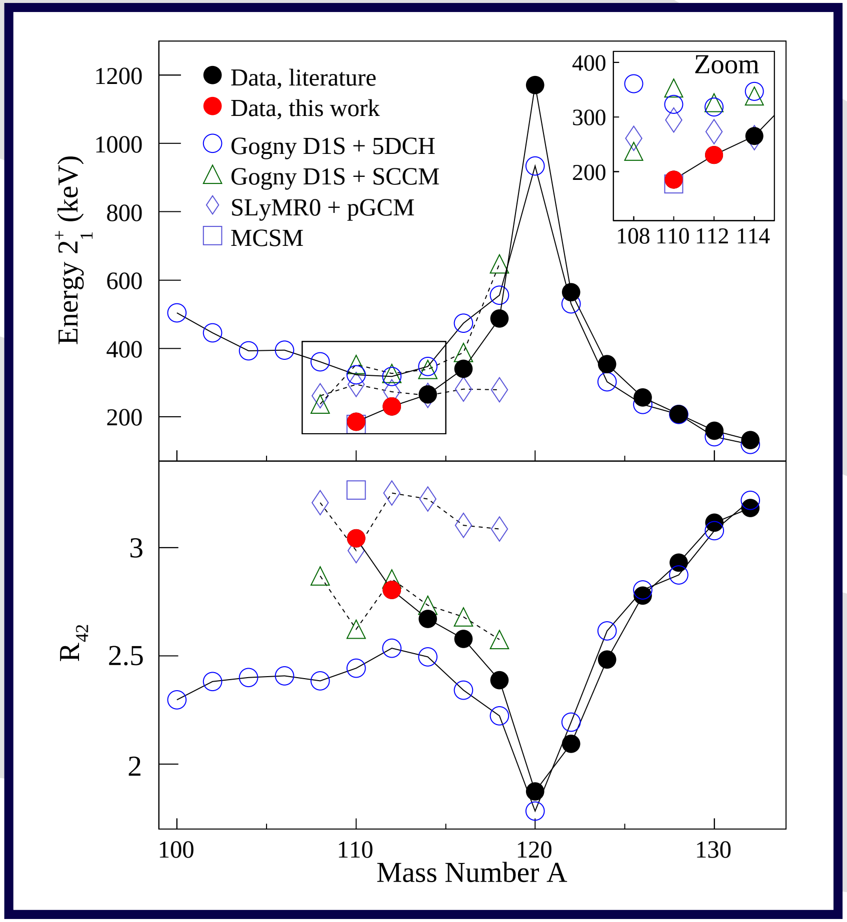
First Spectroscopy of ^{110}Zr



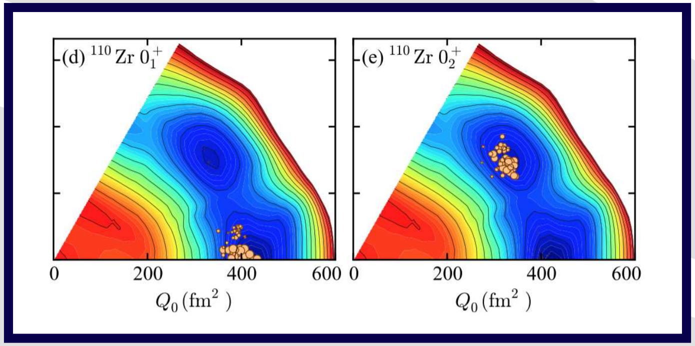
- DALI2 thresholds < 100 keV
- Subtraction of Bremsstrahlung components from elastic events (with absolute normalisation)
- Benchmark on ^{108}Zr and in agreement with ^{112}Mo β-decay from EURICA
- Lifetime effects taken into account

N. Paul *et al.*, Phys. Rev. Lett 118, 032501 (2017).

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
- ^{110}Zr well deformed, prolate nucleus

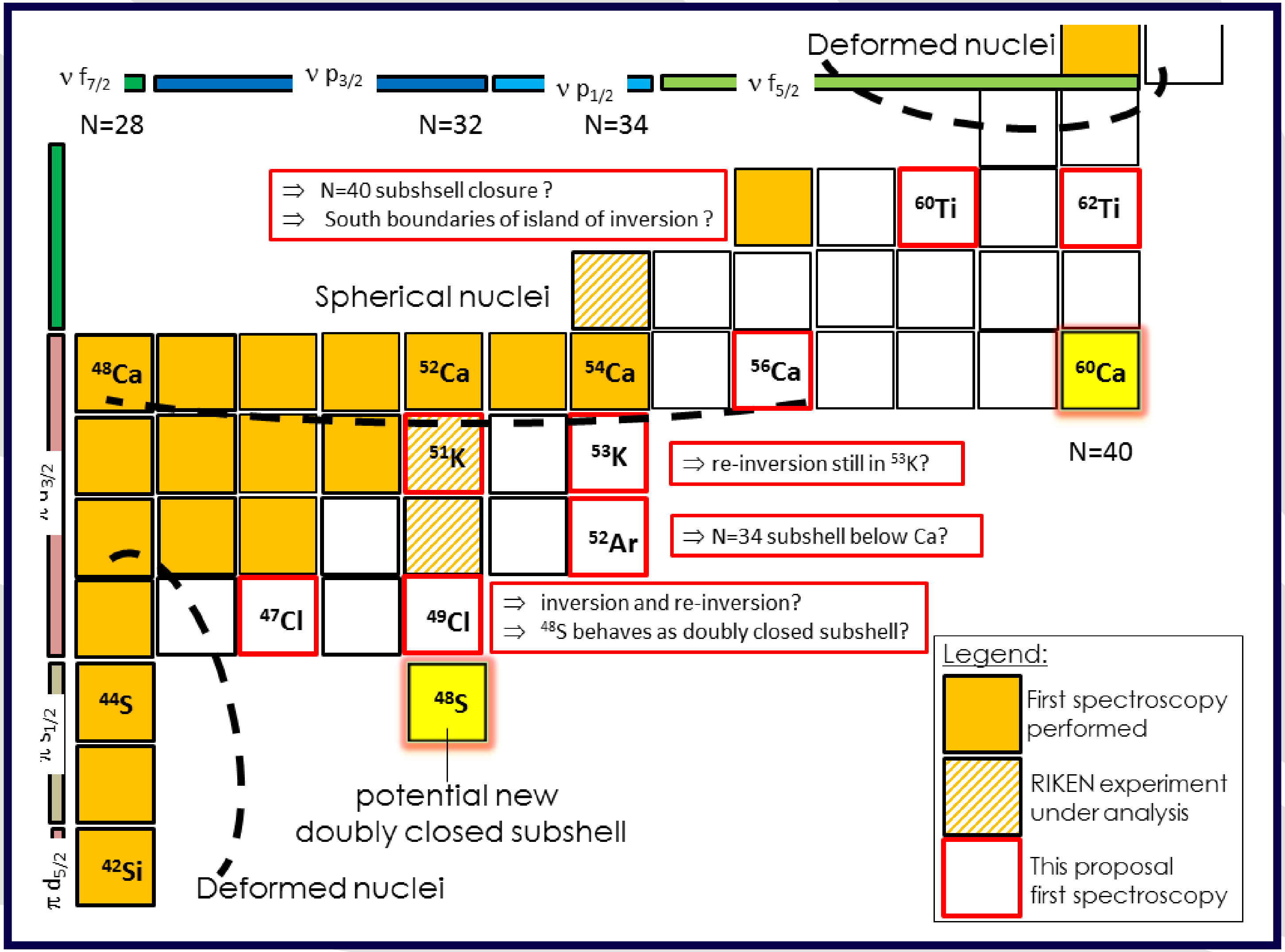


T. Togashi *et al.*, Phys. Rev. Lett. 117, 172502 (2016).

Third Campaign:

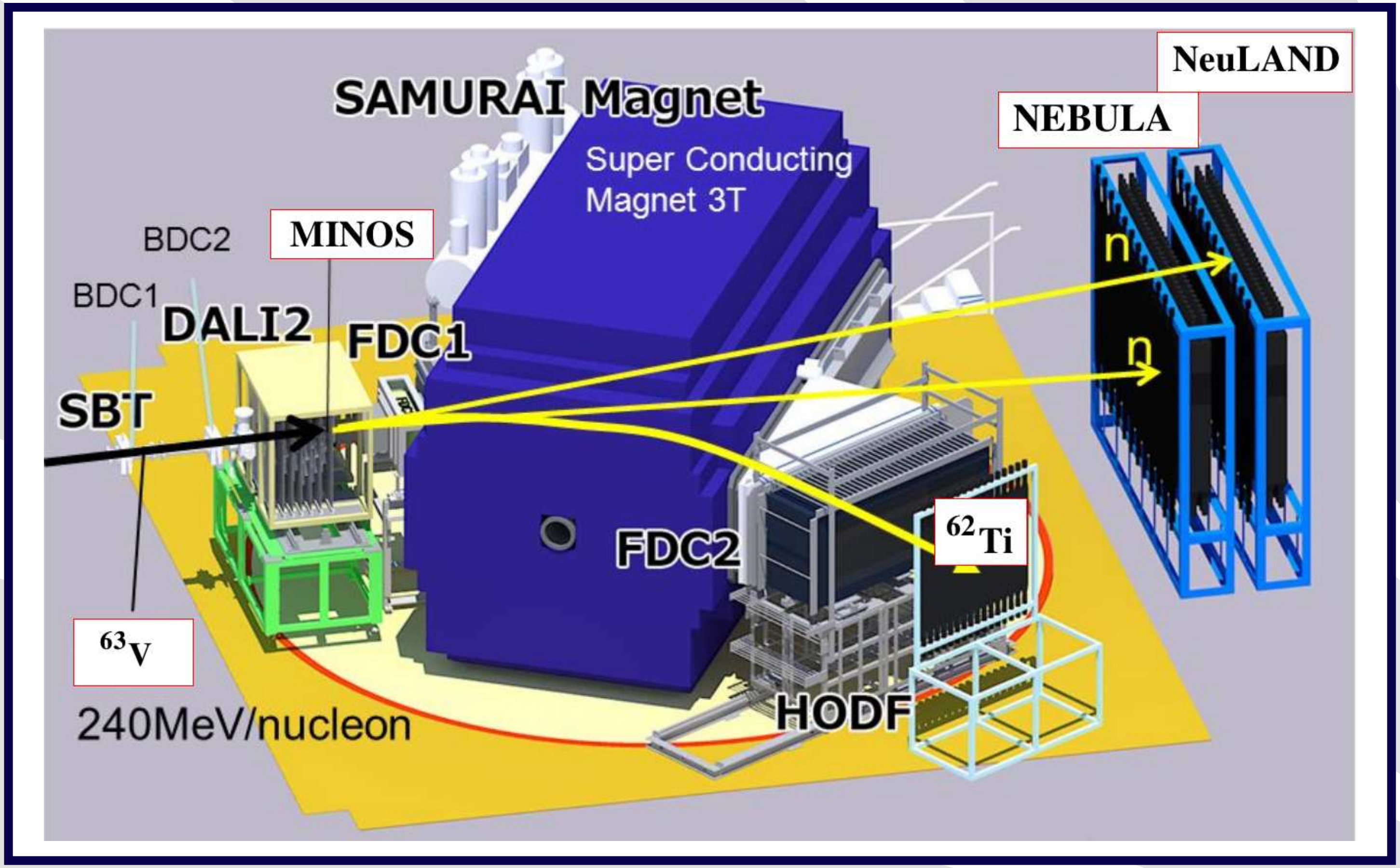
^{52}Ar, ^{56}Ca, ^{62}Ti

Physics Case of 3rd SEASTAR Campaign



- At SAMURAI, 8 days, 250 pnA ^{70}Zn primary beam intensity needed
- First spectroscopy of ^{52}Ar, ^{56}Ca, and ^{62}Ti

SEASTAR at SAMURAI



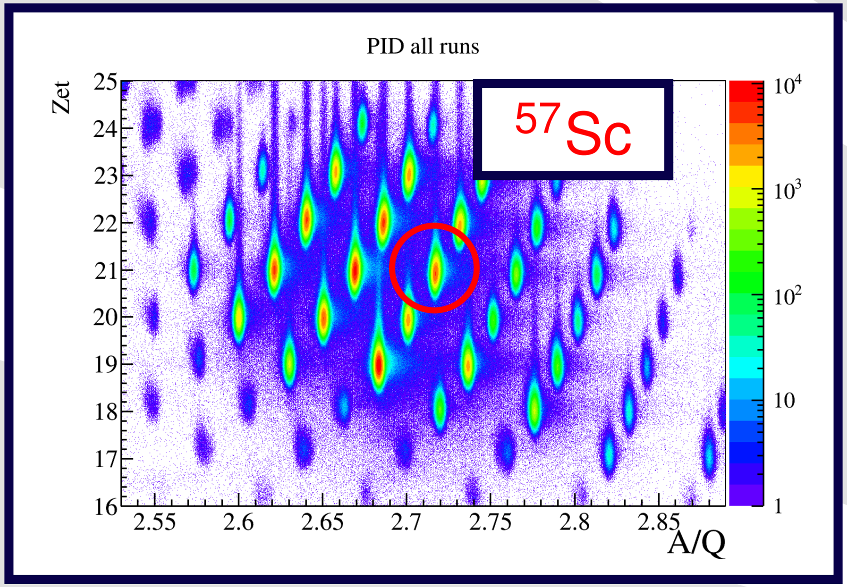
- Outgoing particle ID
- Large acceptance
  - Simultaneous measurement of ^{52}Ar, ^{56}Ca, and ^{62}Ti

SEASTAR at SAMURAI Setup

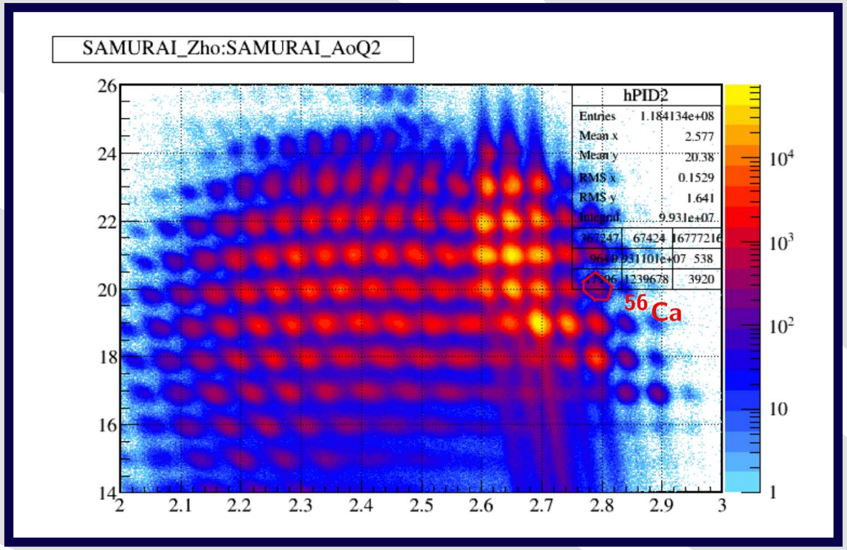
- 150 mm target
- DALI2$^+$
  - 226 NaI(Tl) detectors, 20 % more efficiency
- New MINOS TPC

SEASTAR at SAMURAI Particle Identification

BigRIPS



SAMURAI



- ^{70}Zn primary beam, 345 MeV/u, 250 pnA
- Secondary beam at 240 MeV/nucleon
- **ONE unique setting**
- Total beam intensity: 200 pps; ^{53}K: 0.8 pps, ^{57}Sc: 13 pps, ^{63}V: 3 pps

Summary and Outlook

Summary

- RIBF measured all bound $E(2_1^+)$ of n-rich nuclei presently accessible up to ^{132}Sn region and beyond
- SEASTAR Project at the RIBF is a major contributor
  - Combination of LH$_2$ target up to 15 cm with DALI2
  - 27 days of beam time
    - 4 days for BigRIPS tuning
    - 23 days of ZDS/SAMURAI tuning and data collection
  - 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
- Further measurements would require:
  - Major upgrade in beam intensity ($\times 10$ beam intensity)
  - Major detector upgrade ($> \times 5$ resolving power)
- Many exciting results published, a lot more to come
  - Stay tuned for ^{78}Ni and others

SEASTAR Collaboration

SEASTAR:

N. Alamanos, T. Aumann, G. de Angelis, N. Aoi, H. Baba, C. Barbieri, C. Bertulani, C. Bernards, A. Blazhev, S. Boissinot, F. Browne, A. Bruce, B. Cakirli, B. Cederwall, S. Chen, N. Cooper, A. Corsi, M. L. Cortés, L.X. Chung, F. Delaunay, B. Ding, Z. Dombradi, P. Doornenbal, T. Duguet, F. Flavigny, S. Franchoo, R. Gerst, J. Gibelin, A. Gillibert, S. Go, M. Gorska, A. Gottardo, S. Grevy, J.D. Holt, E. Ideguchi, T. Isobe, A. Jungclaus, N. Kobayashi, T. Kobayashi, T. Koiwai, Y. Kondo, W. Korten, T. Kroell, Y. Kubota, I. Kuti, V. Lapoux, S. LeBlond, M. Lettmann, J. Lee, S. Lenzi, B.D. Lin, H. Liu, Z. Liu, G. Lorusso, C. Louchart, R. Lozeva, F.M. Marques, I. Matea, K. Matsui, Y. Matsuda, M. Matsushita, J. Menendez, D. Mengoni, S. Michimasa, T. Miyazaki, S. Momiyama, P. Morfouace, K. Moschner, T. Motobayashi, T. Nakamura, D. Napoli, F. Naqvi, M. Niikura, M. Nishimura, S. Nishimura, C. Nita, F. Nowacki, A. Obertelli, L. Olivier, N. Orr, S. Ota, H. Otsu, T. Otsuka, N. Paul, N. Pietralla, Zs. Podolyak, E.C. Pollacco, G. Potel, G. Randisi, F. Recchia, T.R. Rodriguez, E. Sahin, H. Sakurai, C. Santamaria, M. Sasano, H. Sato, A. Schwenk, C. Shand, Y. Shiga, Y. Shimizu, S. Shimoura, J. Simonis, P.A. Soederstroem, D. Sohler, V. Soma, I. Stefan, D. Steppenbeck, T. Sumikama, Y. Sun, D. Suzuki, H. Suzuki, S. Takeuchi, J. Tanaka, M. Tanaka, R. Taniuchi, K.N. Tuan, T. Uesaka, Y. Utsuno, J. Valiente Dobon, Zs. Vajta, D. Verney, H. Wang, V. Werner, K. Wimmer, Zh. Xu, R. Yokoyama, and K. Yoneda

Thank You!

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