RIKEN NiSHiNA CENTER

In-beam γ-ray spectroscopy with fast RI beams at RIKEN

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Outline

Overview

^{78}Ni

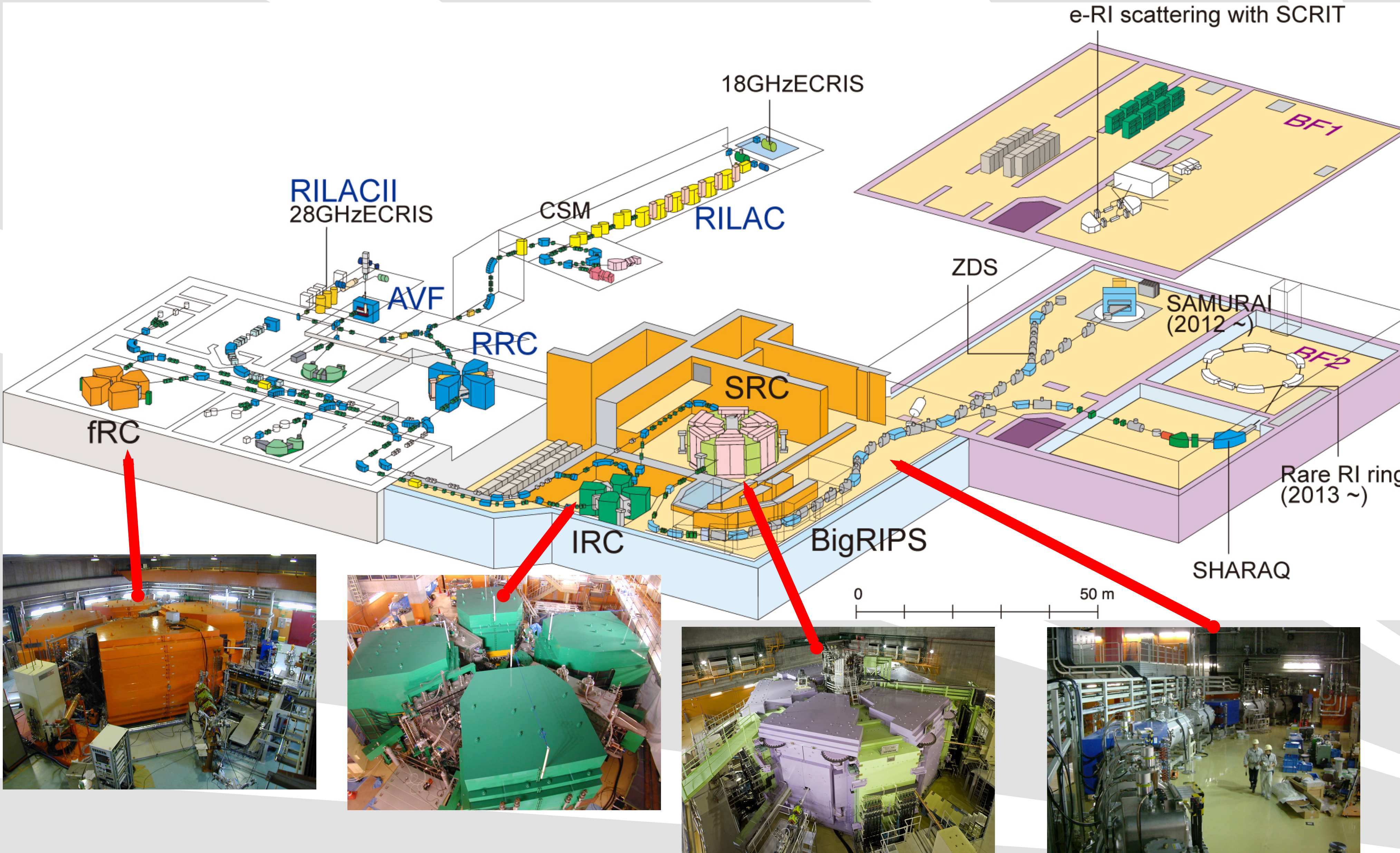
Neutron-Rich Ca Isotopes

Summary and Outlook

- Setup
  - DALI2
  - MINOS
  - ZeroDegree
  - SAMURAI
- Selected Results
  - First spectroscopy of ^{78}Ni
  - Structure around neutron-rich Ca isotopes
    - The N = 32,34,40 magic numbers
- Summary and conclusions

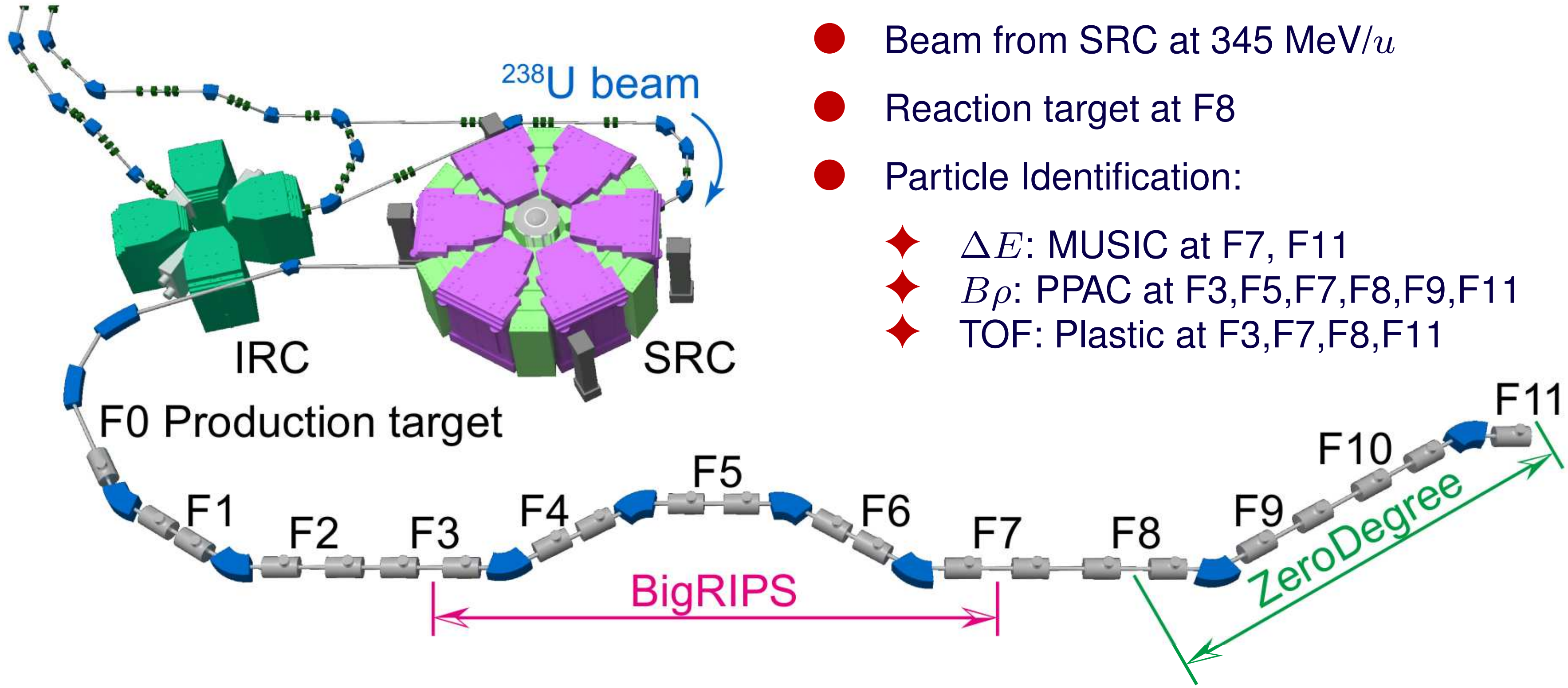
Overview and Setup

RIBF Overview



BigRIPS and ZeroDegree

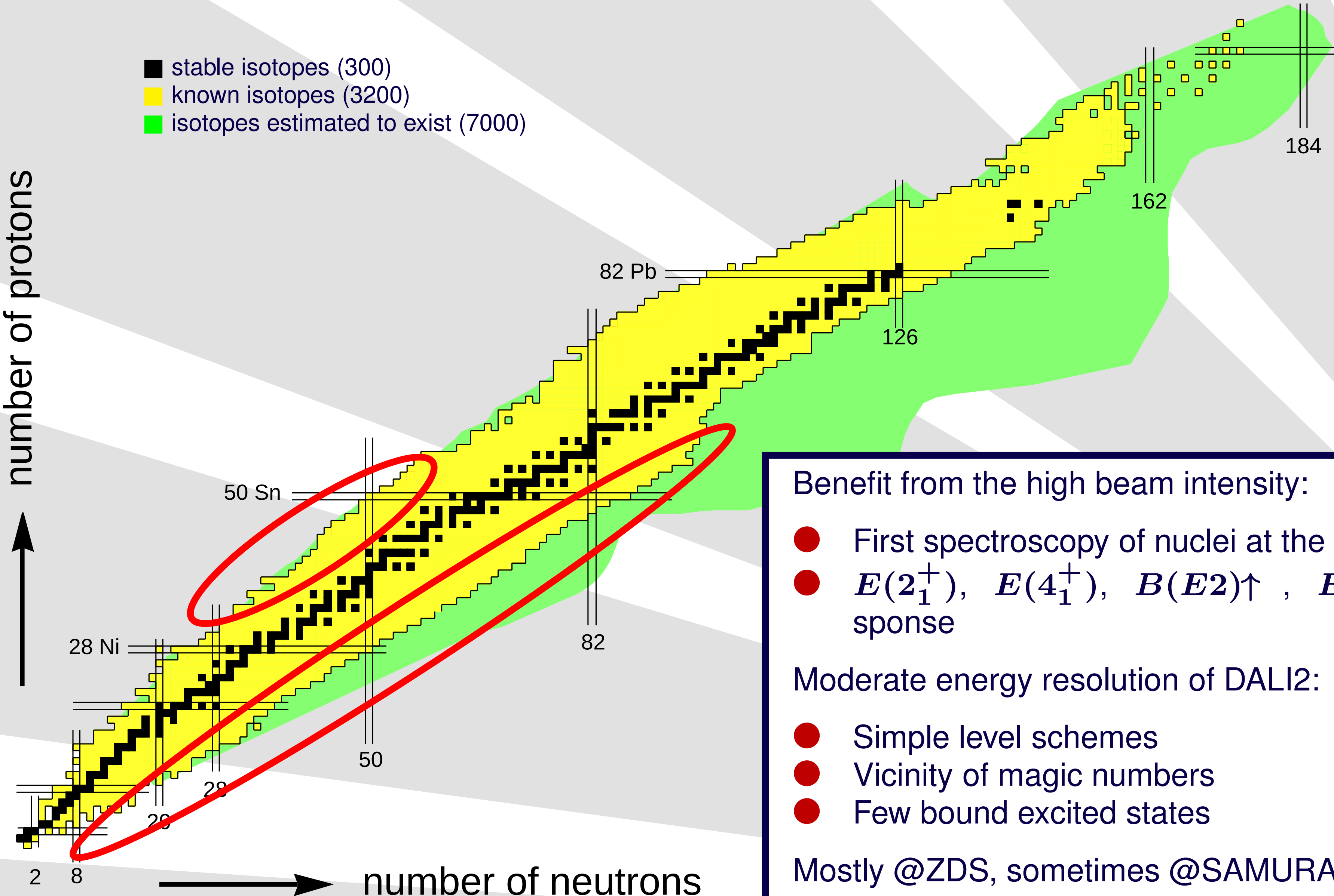
- BigRIPS, standard mode
  - Two-stage separator
  - ± 40 mrad (H) ± 50 mrad (V)
  - 6% momentum acceptance
- ZeroDegree, large acceptance achromatic
  - ± 40 mrad (H) ± 25 mrad (V)
  - 6% momentum acceptance



- Beam from SRC at 345 MeV/u
- Reaction target at F8
- Particle Identification:
  - ΔE: MUSIC at F7, F11
  - $B\rho$: PPAC at F3,F5,F7,F8,F9,F11
  - TOF: Plastic at F3,F7,F8,F11

IRC/SRC: Y. Yano, Nucl. Instr. Meth. B, 1009 (2007).
BR/ZD: T. Kubo *et al.*, Prog. Theor. Exp. Phys. 03C003 (2012).

Regions of Interest



Benefit from the high beam intensity:

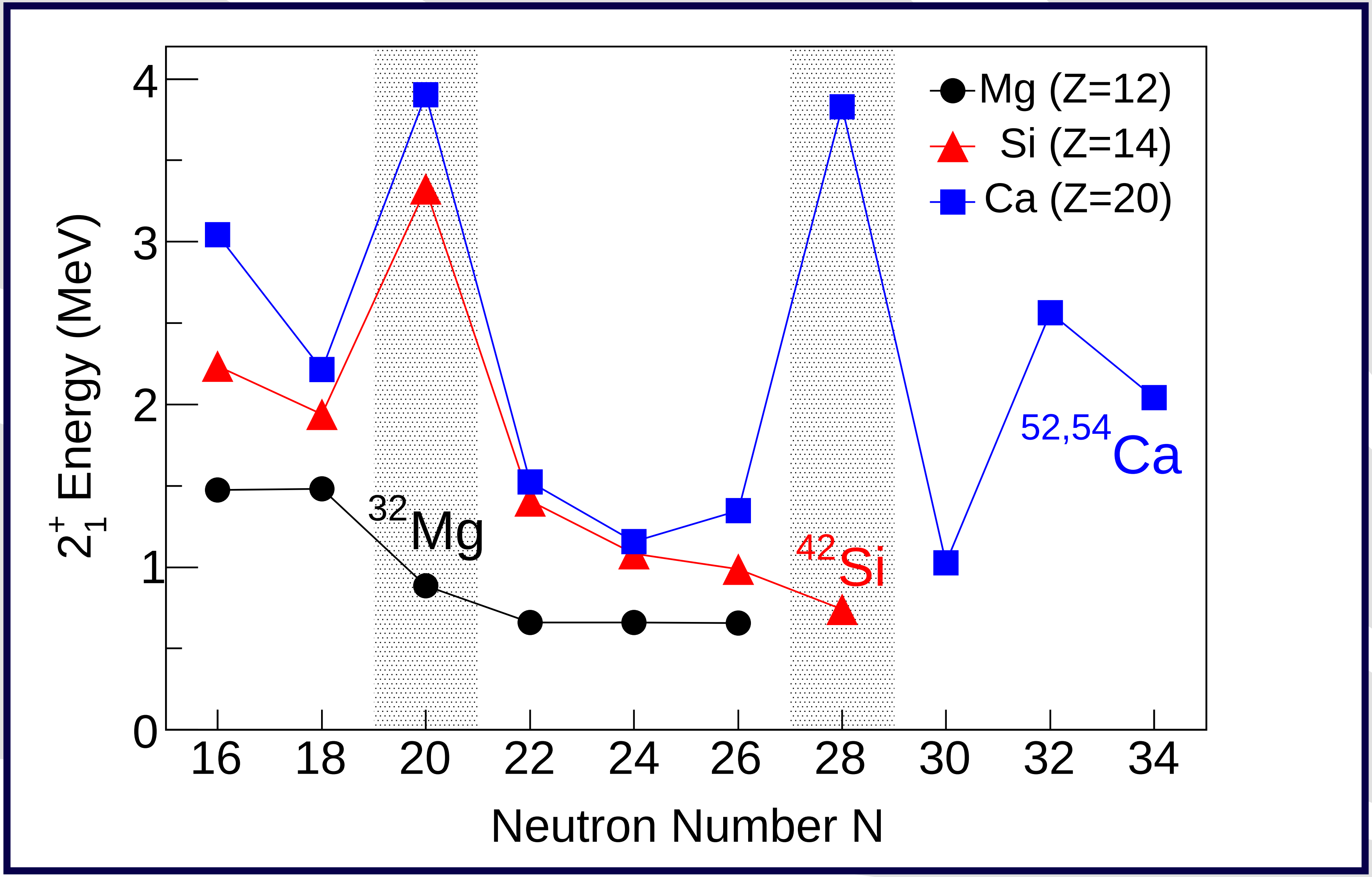
- First spectroscopy of nuclei at the limit
- $E(2_1^+)$, $E(4_1^+)$, $B(E2)\uparrow$, $E1$ response

Moderate energy resolution of DALI2:

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

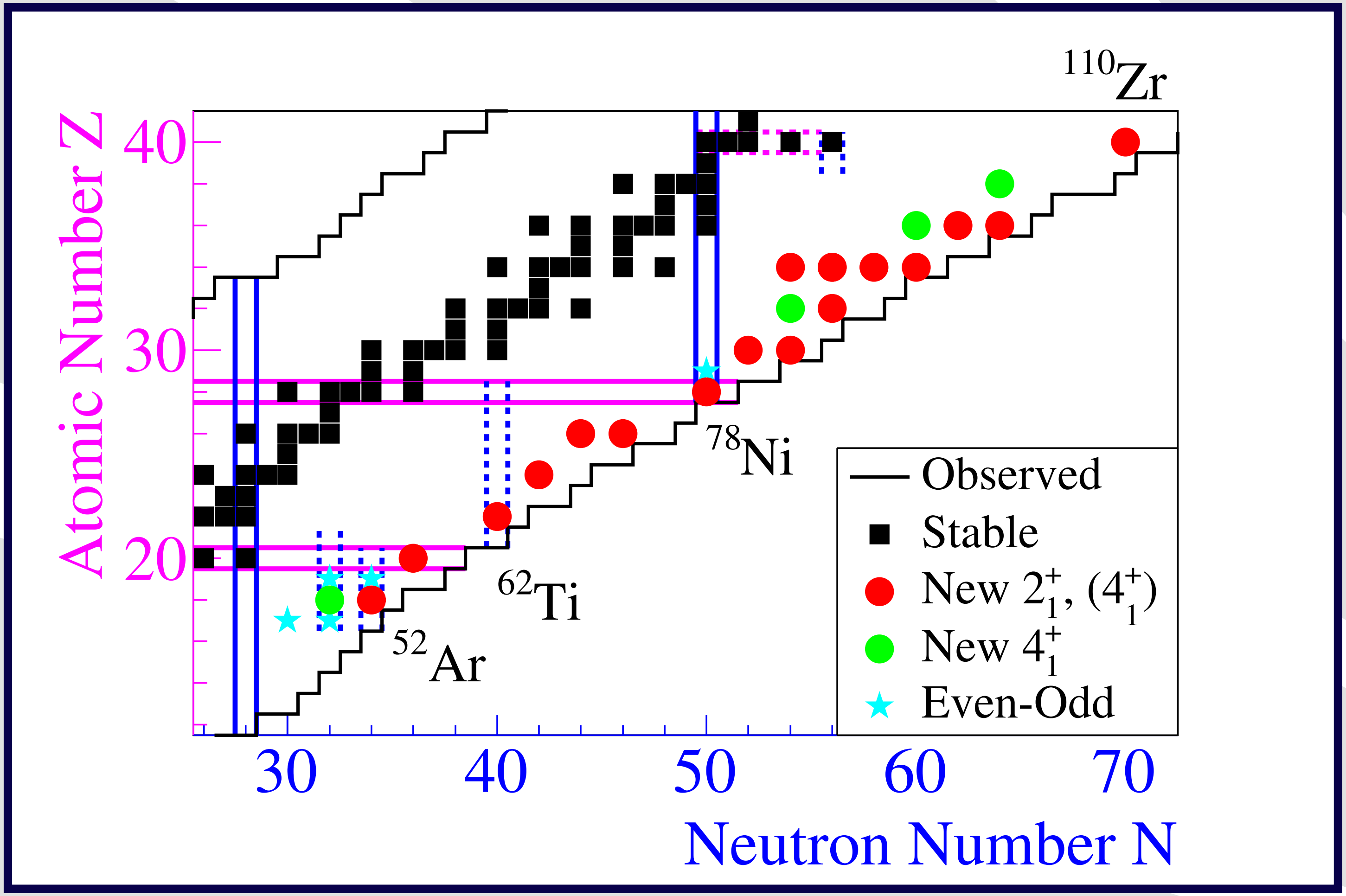
Mostly @ZDS, sometimes @SAMURAI

$E(2_1^+)$-Systematics
A First Indicator for "Magicity"



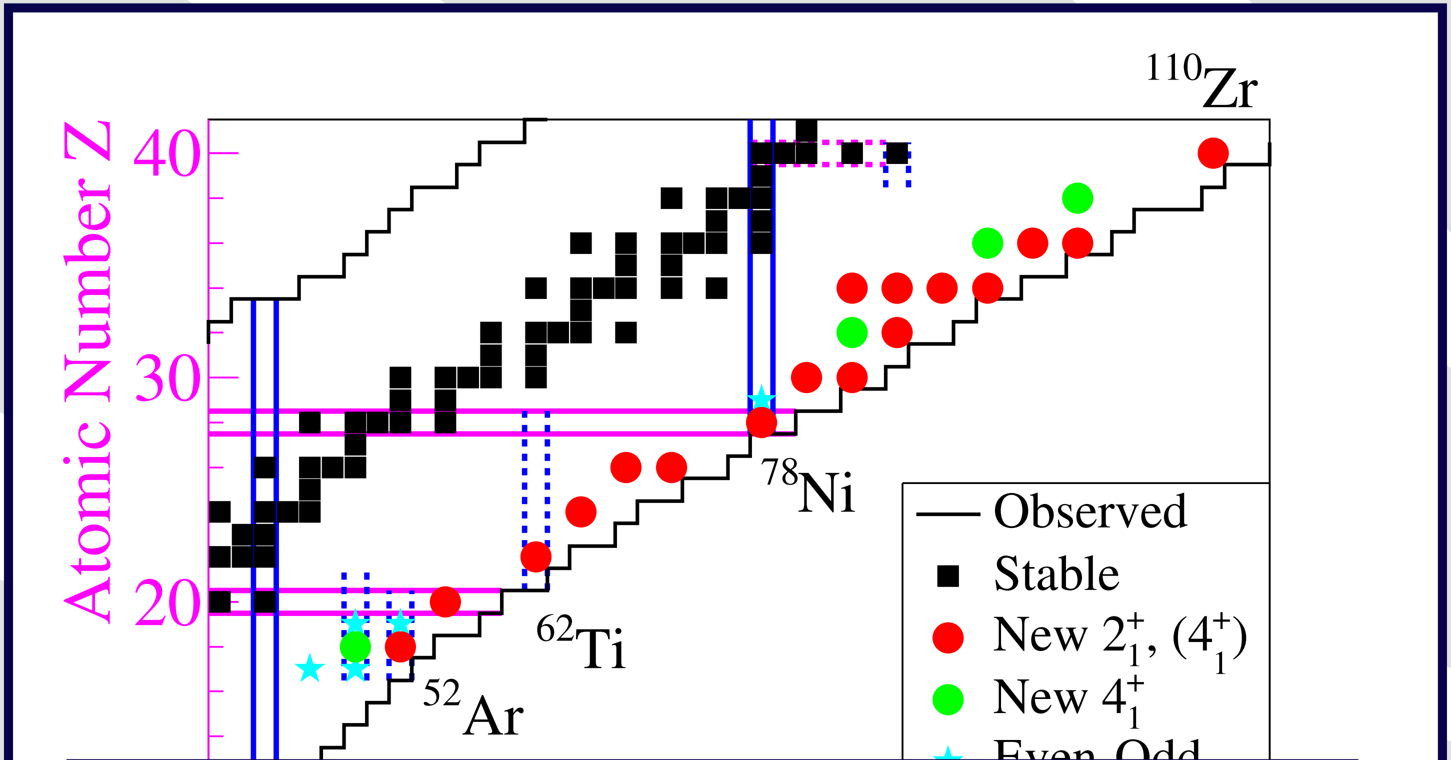
^{32}Mg: C. Détraz *et al.*, PRC 19, 164 (1979).
^{42}Si: B. Bastin *et al.*, PRL 99, 022503 (2007).
^{52}Ca: A. Huck *et al.*, PRC 31, 226 (1985).
^{54}Ca: D. Steppenbeck *et al.*, Nature, 207 (2013).

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

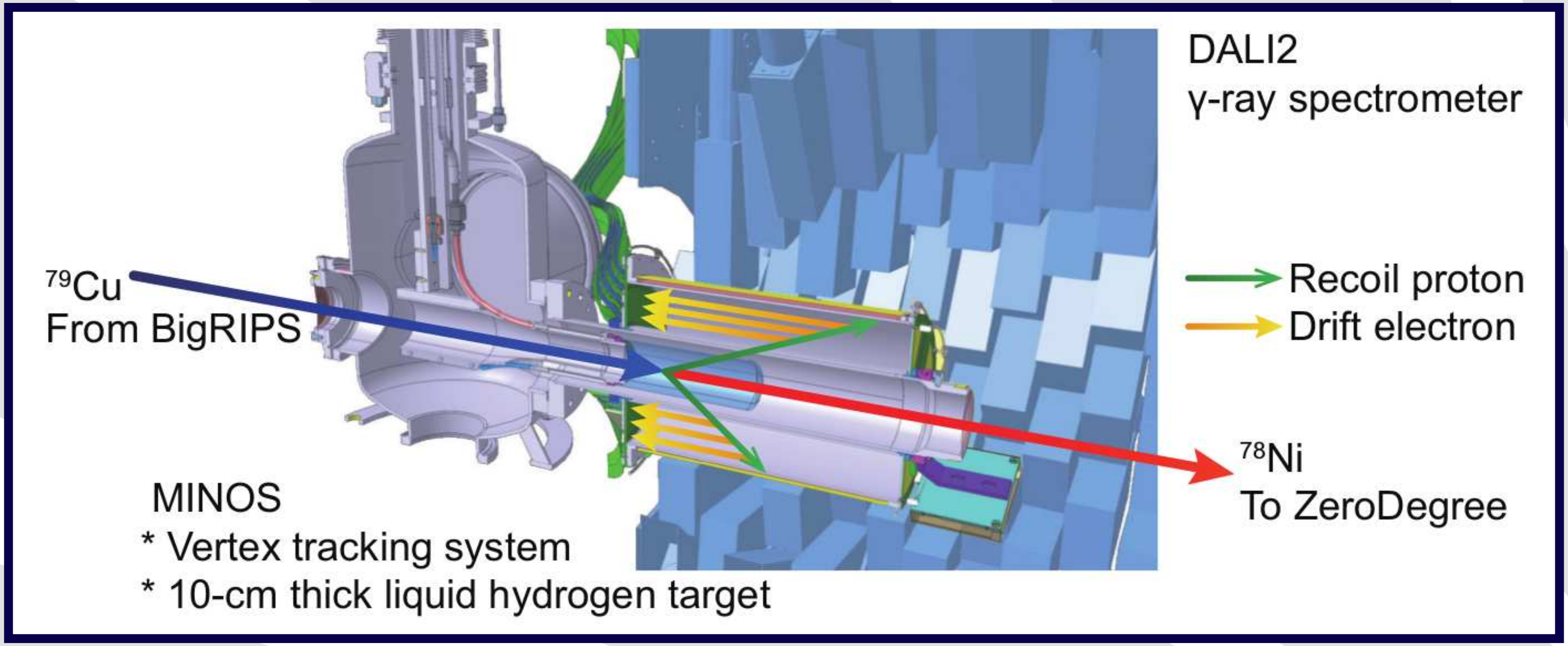
Shell Evolution And Search for Two-plus energies At the RIBF (SEASTAR)



- 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)

Secondary Reaction Target and γ-Ray Spectrometer

Overview
❖ RIBF Overview
❖ BR and ZD
❖ Regions of Interest
❖ $E(2_1^+)$-Systematics
❖ New $E(2_1^+)$
❖ SETUP
^{78}Ni
Neutron-Rich Ca Isotopes
Summary and Outlook

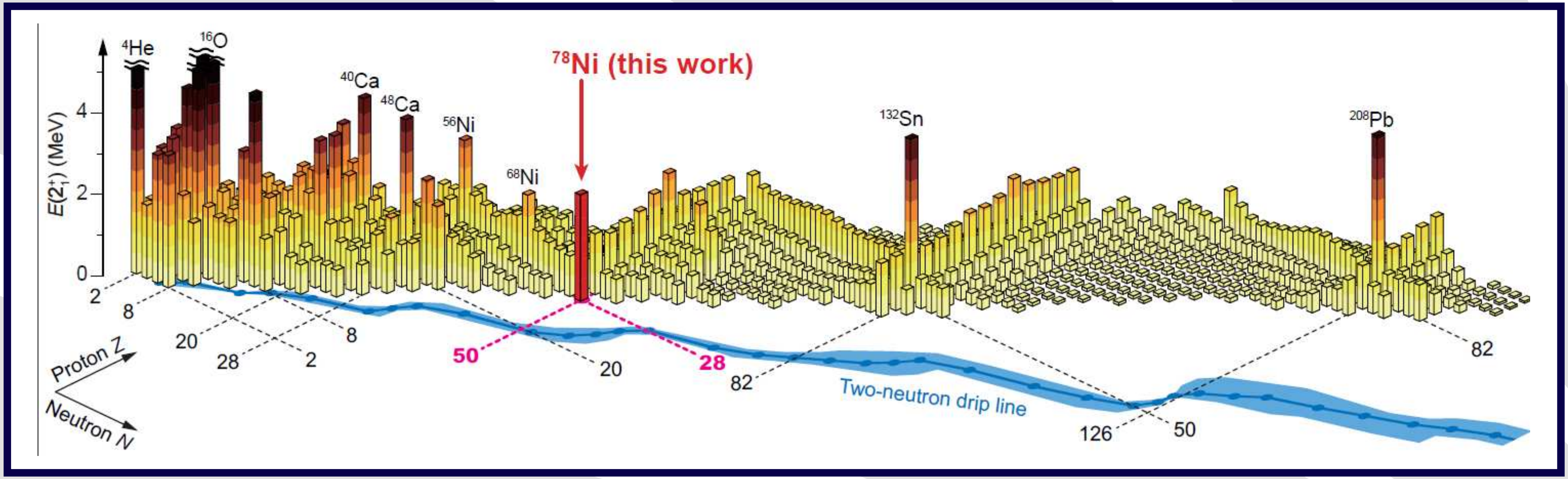


- MINOS
  - Up to 1 g/cm^2 liquid hydrogen target
  - Position sensitive TPC, Vertex position reconstruction with ≈5 mm (FWHM)
- DALI2
  - 186 (226) NaI(Tl) detectors, large solid angle coverage
  - 7 % intrinsic resolution at 1 MeV, 10(11) % at 100(250) MeV/u
  - 20 % efficiency w/o add-back

A. Obertelli *et al.*, EPJA 50, 8 (2014), S. Takeuchi *et al.*, NIMA 763, 596 (2014).

First Spectroscopy of ^{78}Ni

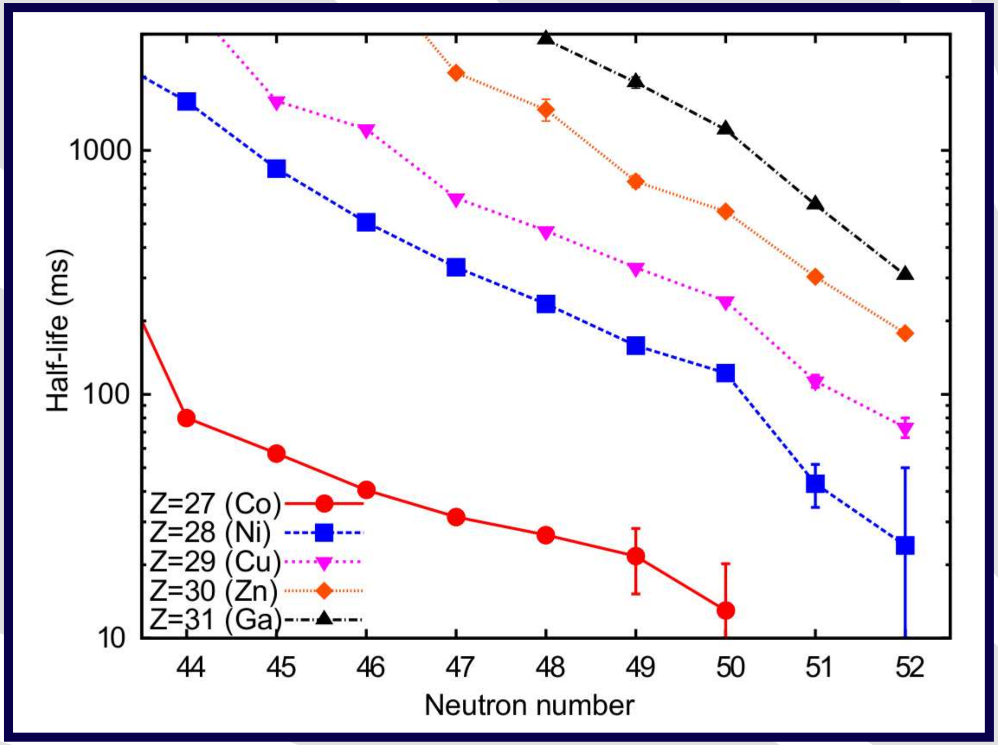
Global $E(2_1^+)$ Systematics



- ^{78}Ni is only doubly magic neutron rich isotope within two-neutron drip line with unknown $\boldsymbol{E(2_1^+)}$
- Evaluation of the drip line:
  J. Erler *et al.*, Nature 486, 509-512 (2012).

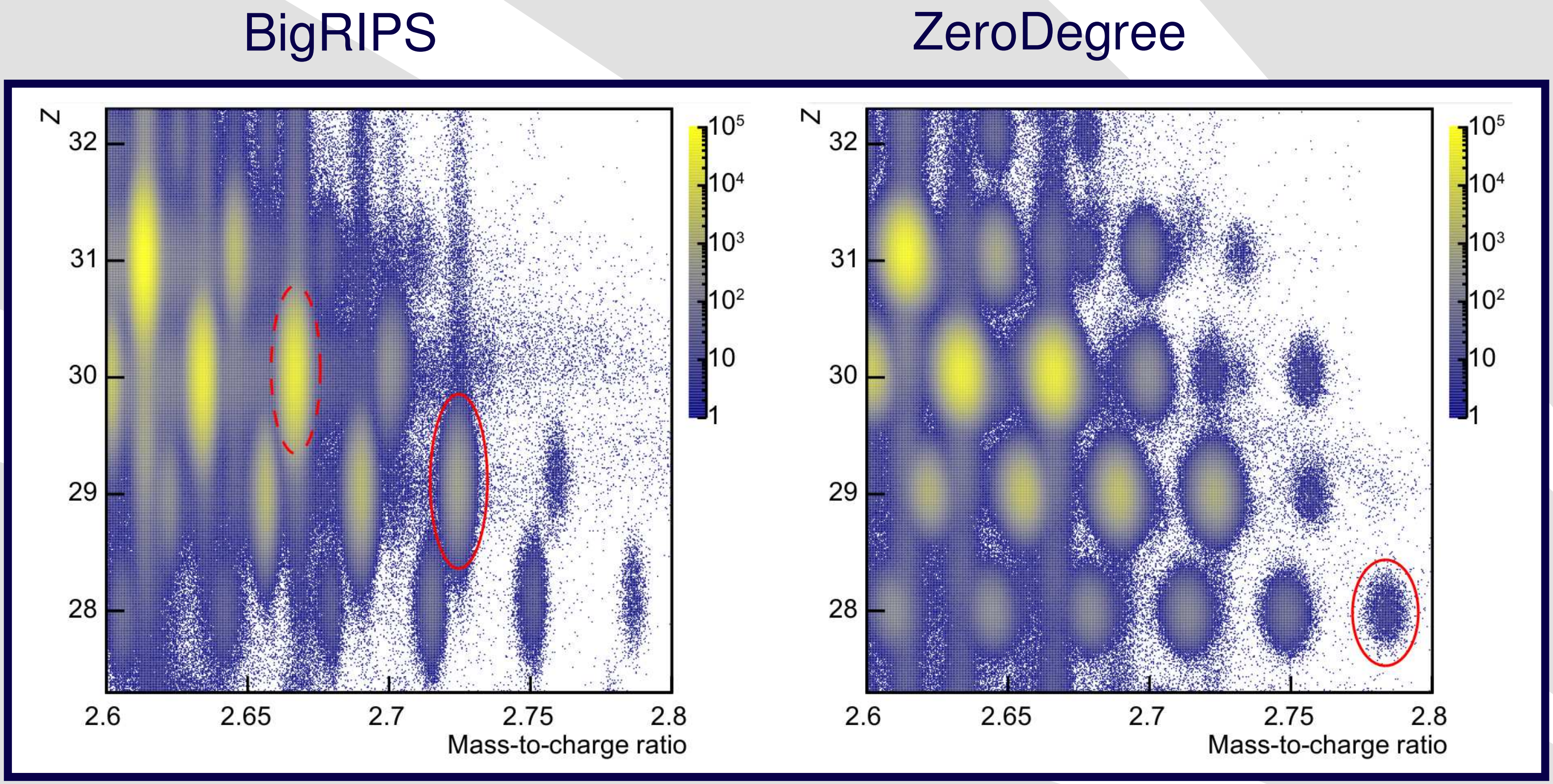
Experimental Studies on ^{78}Ni

- First production at GSI:
  3 counts in 5.5 days
- First β decay $T_{1/2}$ at NSCL:
  11 counts in 4.3 days
- $T_{1/2}$ studay at RIBF:
  4000 counts in 7.5 days



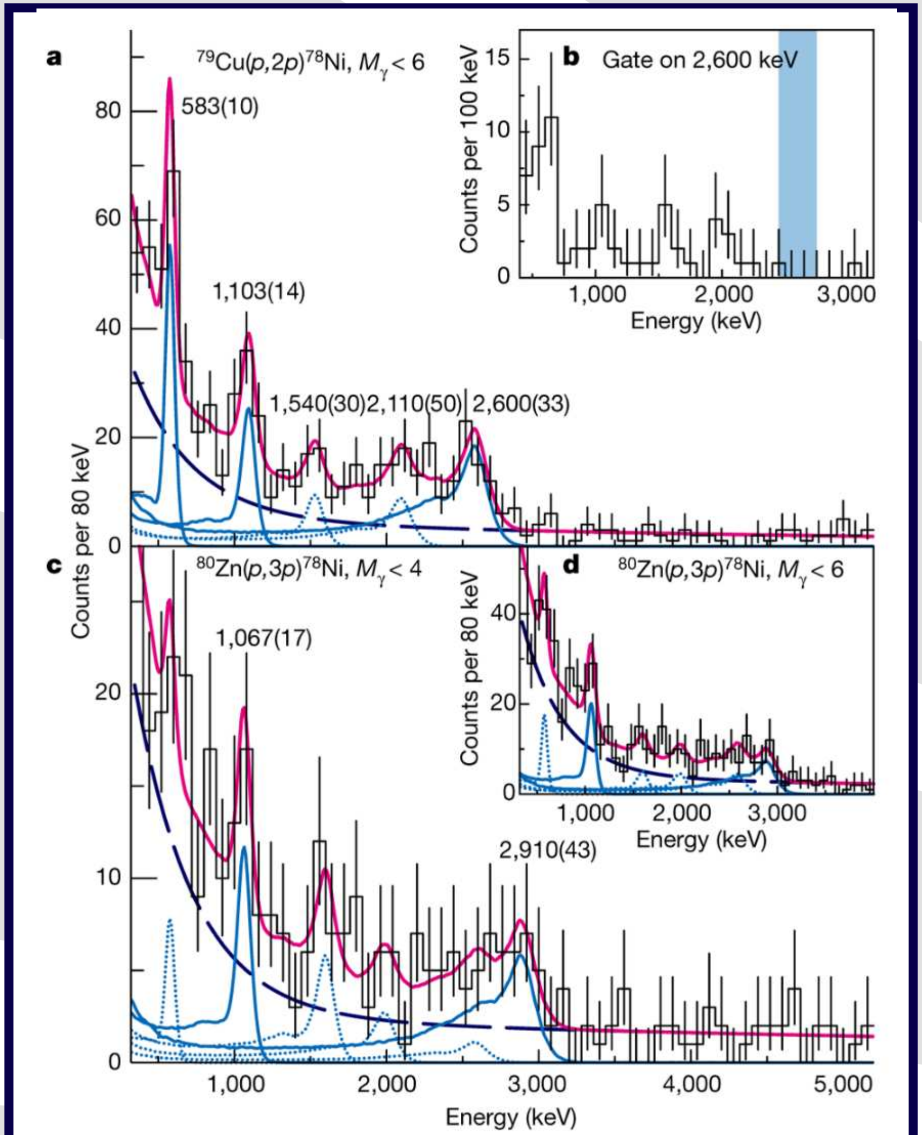
Ch. Engelmann *et al.*, Z. Phys. A 352, 351-352 (1995).
P.T. Hosmer *et al.*, Phys. Rev. Lett. 94, 112501 (2005).
Z.Y. Xu *et al.*, Phys. Rev. Lett. 113, 032505 (2014).

Particle Identification



- ^{238}U primary beam at 345 MeV/u, 13 pnA, 6 days
- 5.2 pps ^{79}Cu, 290 pps ^{80}Zn
- ^{79}Cu(p,2p)^{78}Ni: 937 events
- ^{80}Cu(p,3p)^{78}Ni: 815 events

^{79}Cu(p,2p)^{78}Ni and ^{80}Zn(p,3p)^{78}Ni



R. Taniuchi, C. Santamaria *et al.*, Nature 569, 53 (2019).

^{79}Cu(p,2p)^{78}Ni

E_γ (keV)	I_{rel} %	S.L.
583(10)	49(11)	5.7
1103(14)	49(12)	4.3
1540(25)	28(11)	2.9
2110(48)	33(13)	2.9
2600(33)	**100(15)**	**7.6**

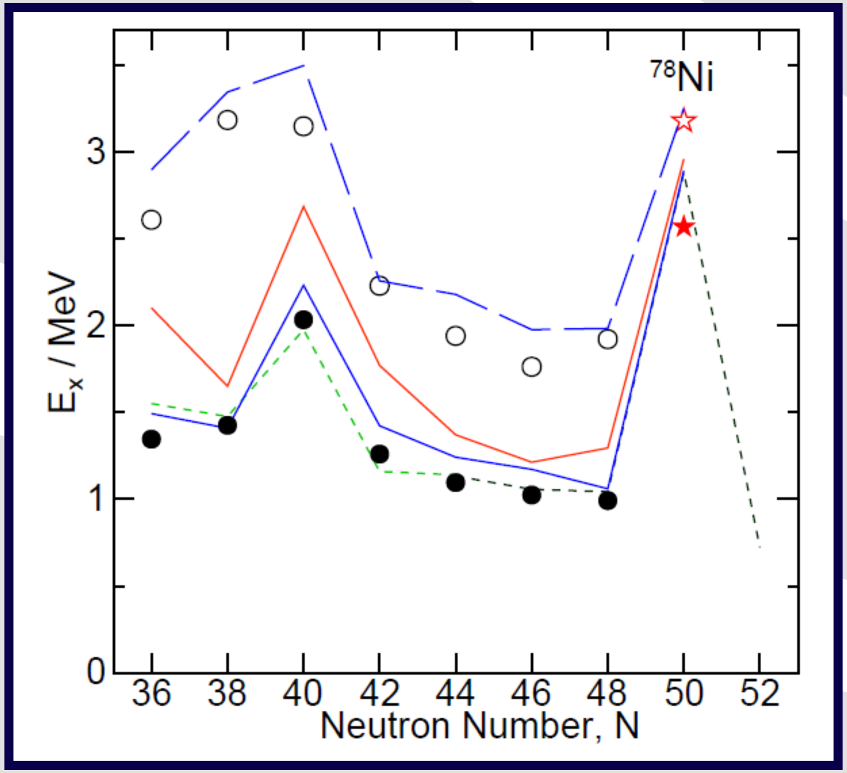
- 937 events, $\sigma_{\rm incl}$ = 1.7(4) mbarn
- $E(2_1^+)$ at 2.60(3) MeV
- Tentative $4_1^+ \rightarrow 2_1^+$ at 583(10) keV

^{80}Zn(p,3p)^{78}Ni

E_γ (keV)	I_{rel} %	S.L.
2710(200)	49(30)	1.5
2910(43)	100(29)	3.9

- 815 events, $\sigma_{\rm incl}$ = 16(6) μbarn
- New transition at 2.91(4) MeV
- $E(2_1^+)$ Not observed!

Doubly Magic Structure of ^{78}Ni



● Literature 2^+ ○ Literature 4^+
★ This work 2^+ ☆ This work 4^+

— A3DA-m solid: 2^+, dashed 4^+
Monte Carlo shell model (Tokyo)
pf-$g_{9/2}$-$d_{5/2}$ orbitals for both proton and neutron
Y. Tsunoda *et al.*, Phys. Rev. C **89**, 031301(R) (2014)

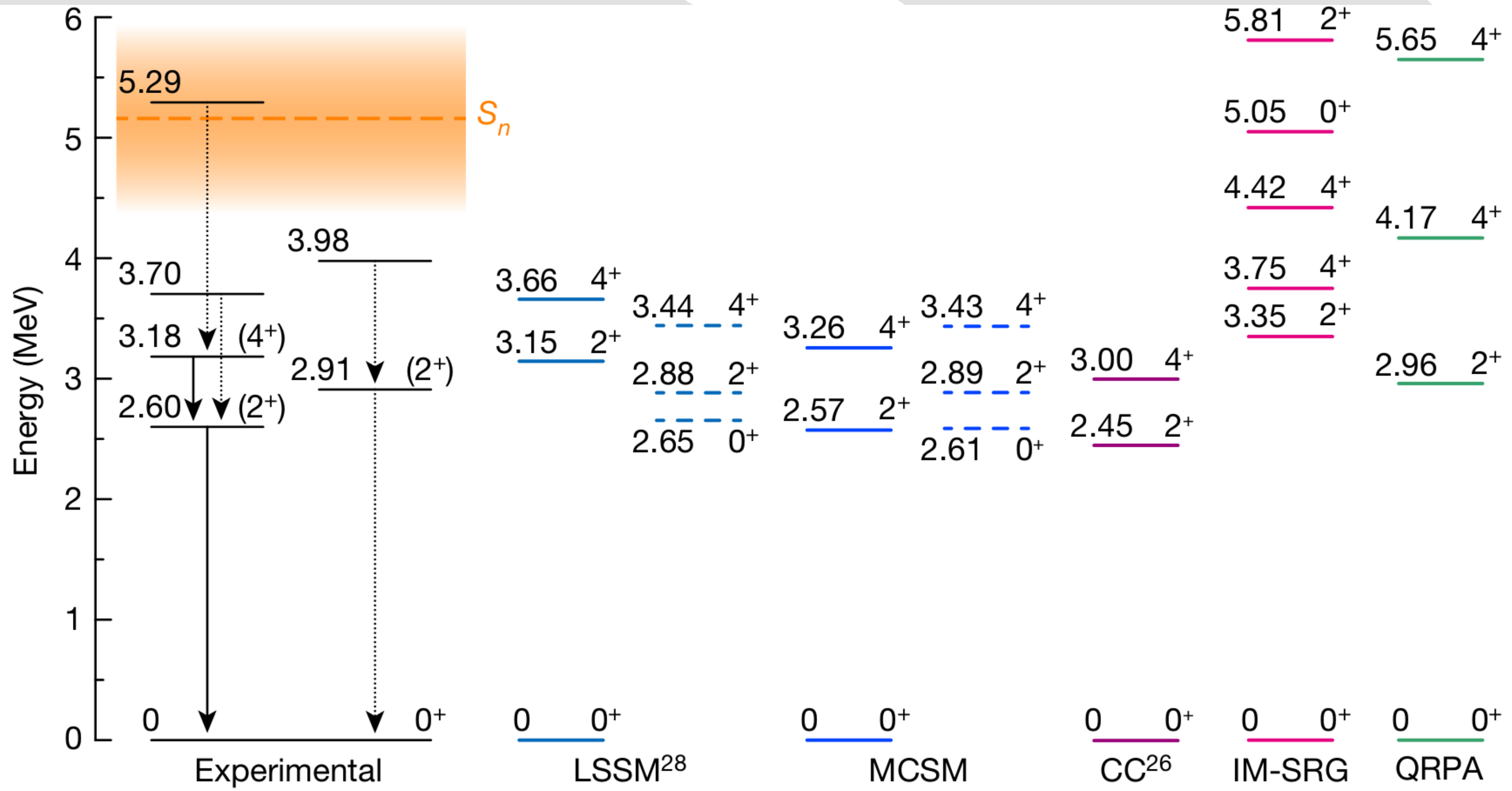
--- LNPS
Large scale shell model (Strasbourg)
pf (proton) and $f_{5/2}$-$p_{1/2,3/2}$-$d_{5/2}$ orbitals (neutron)
S. Lenzi *et al.*, Phys. Rev. C **82**, 054301 (2010)

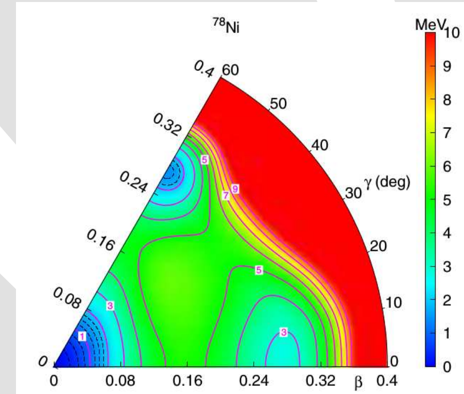
--- PFSDG-U
Large scale shell model (Strasbourg)
pf (proton) and *sdg* (neutron)
F. Nowacki *et al.*, Phys. Rev. Lett. **117**, 272501 (2016)

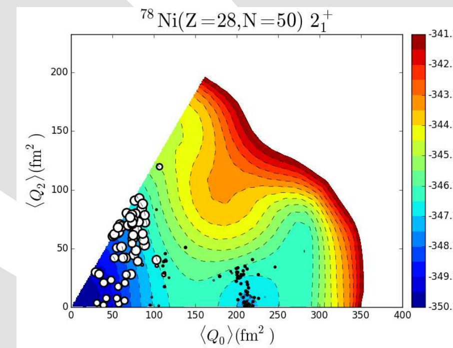
— QRPA
Beyond mean-field calculation (S. Péru)
based on finite-range Gogny interaction
S. Péru and M. Martini, EPJA **50**, 88 (2014)

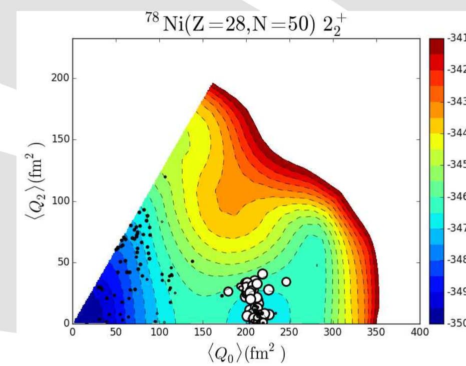
- EOM-CCSD(T) with “1.8/2.0 (EM)”: 2.5 MeV
  G. Hagen *et al.*, PRL 117, 172501 (2016).
- IM-SRG with “1.8/2.0 (EM)”: 3.35 MeV
  J.D. Holt, J. Menendez *et al.*

Level Scheme of ^{78}Ni



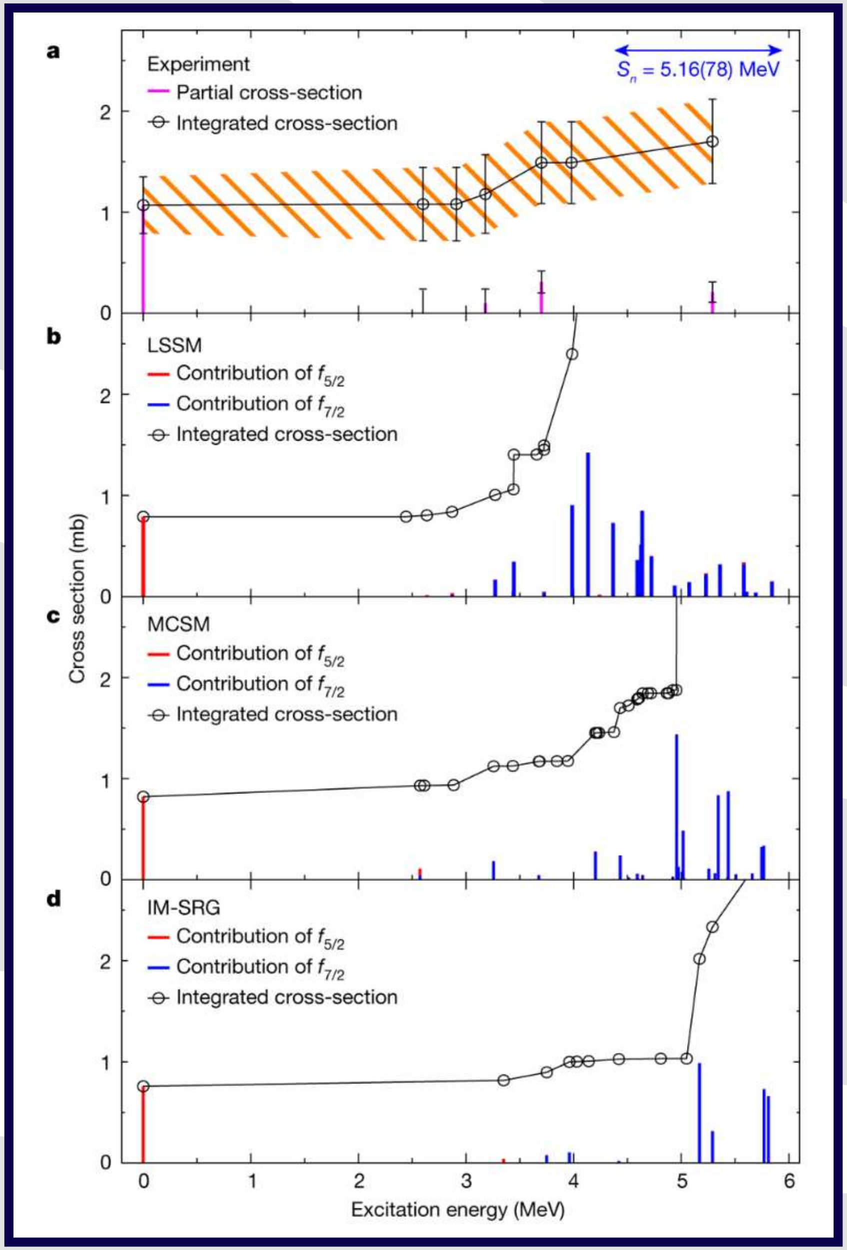






MCSM: Y. Tsunoda *et al.*, extension to full pf and sdg shells for π and ν
S_n: AME2016, M. Wang *et al.*, CPC 41, 1 (2017).

Low (p,2p) Cross Section of ^{78}Ni



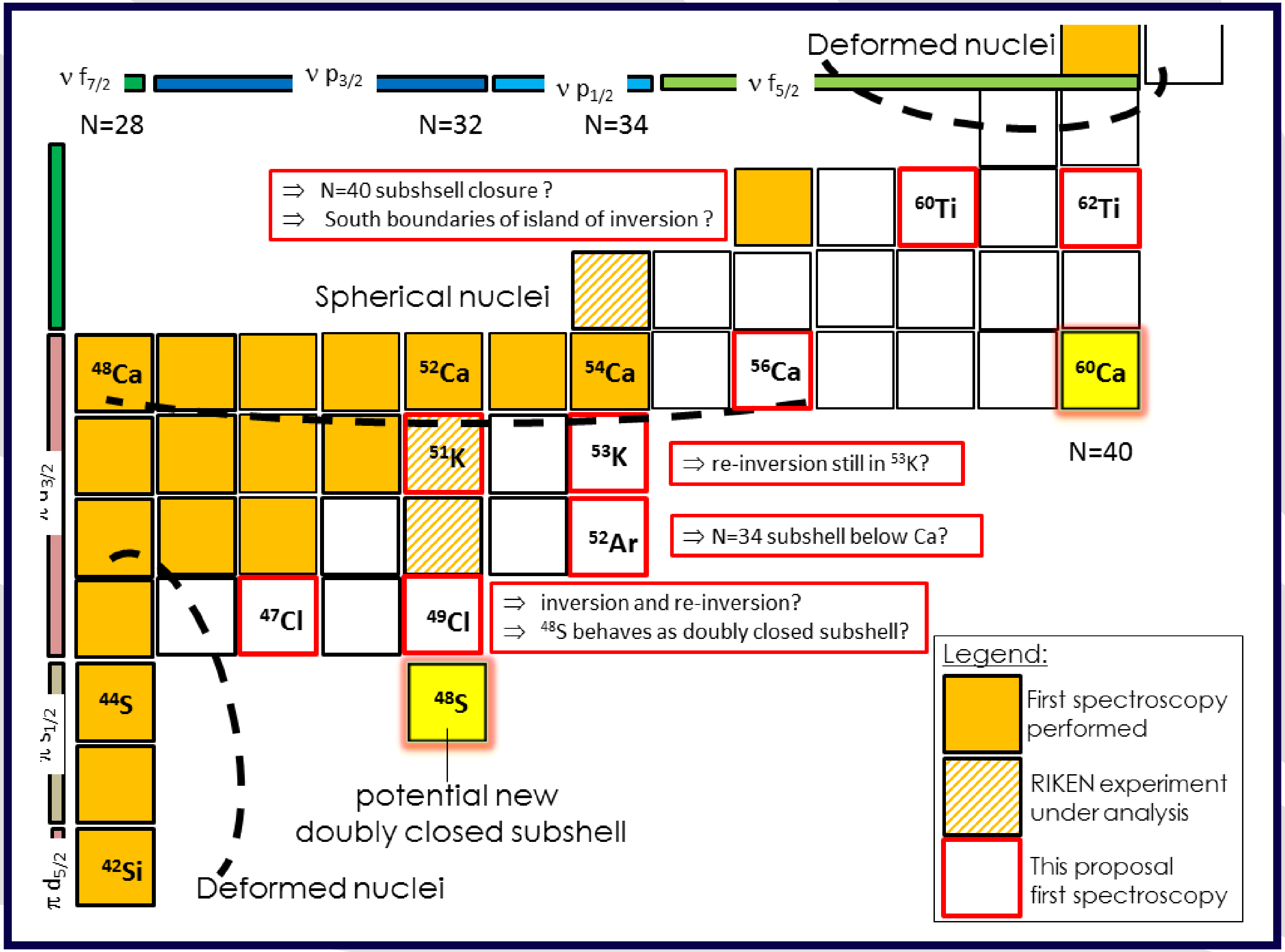
Final Nucleus	σ_{incl} (mbarn)
^{78}Ni	1.7(4)
^{79}Cu	8.0(3)
^{80}Zn	5.2(3)
^{81}Ga	7.5(9)

- Inclusive cross sections 4 times smaller than heavier isotones
- Distorted-wave impulse approximation (DWIA) T. Wakasa *et al.*, PPNP 96, 31-87 (2017).
- Most of the strength goes beyond S_n

Structure Around Neutron-Rich Calcium Isotopes

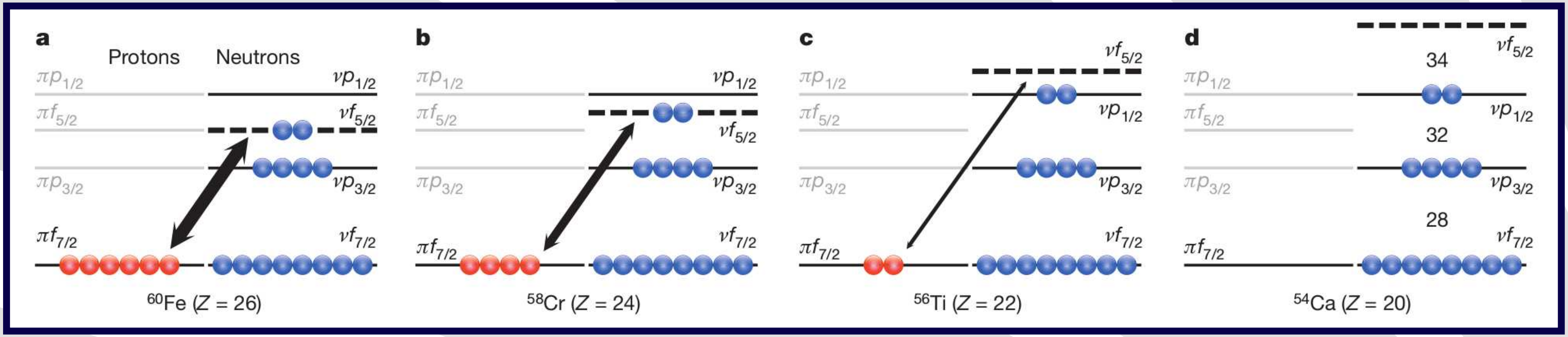
Physics Case of 3rd SEASTAR Campaign

Overview
78Ni
Neutron-Rich Ca Isotopes
❖ 3rd SEASTAR Campaign
❖ Shell Evolution
❖ Shell Closures
❖ SAMURAI
❖ Campaign3 PID
❖ 53Ca
❖ 52Ar
❖ $E(2_1^+)$ Systematics
Summary and Outlook



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

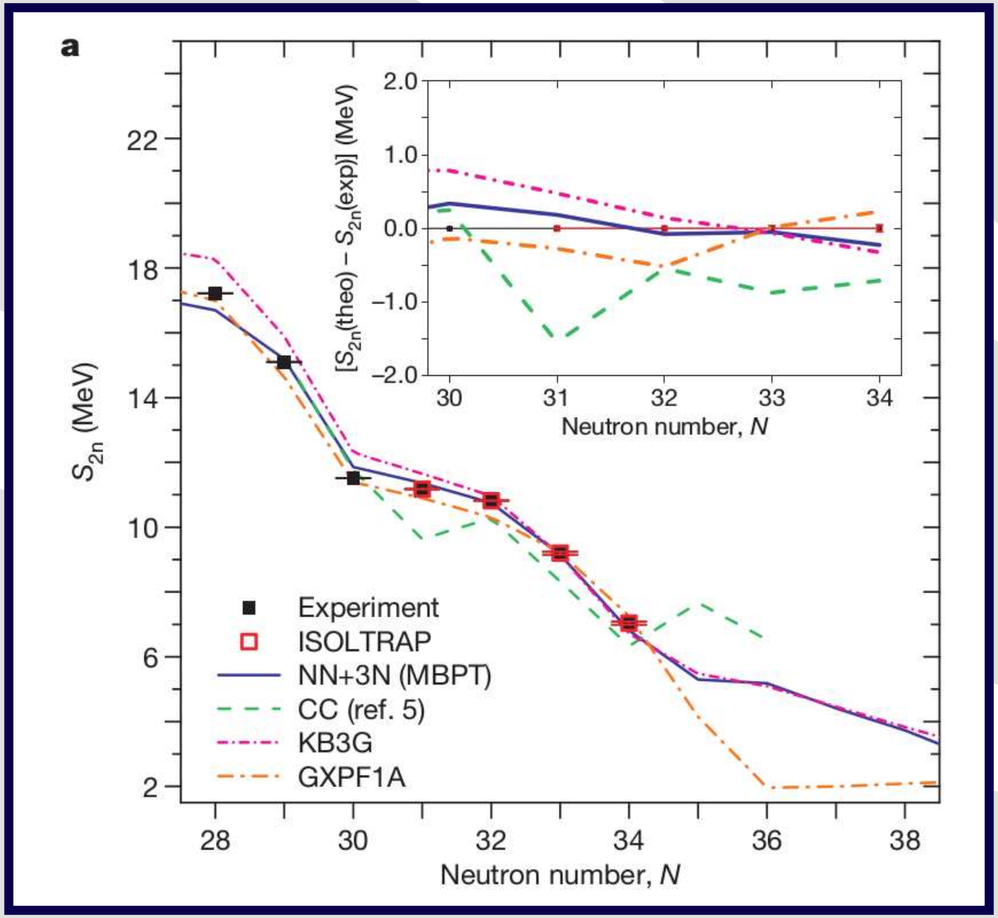
Shell Evolution at $N = 34$

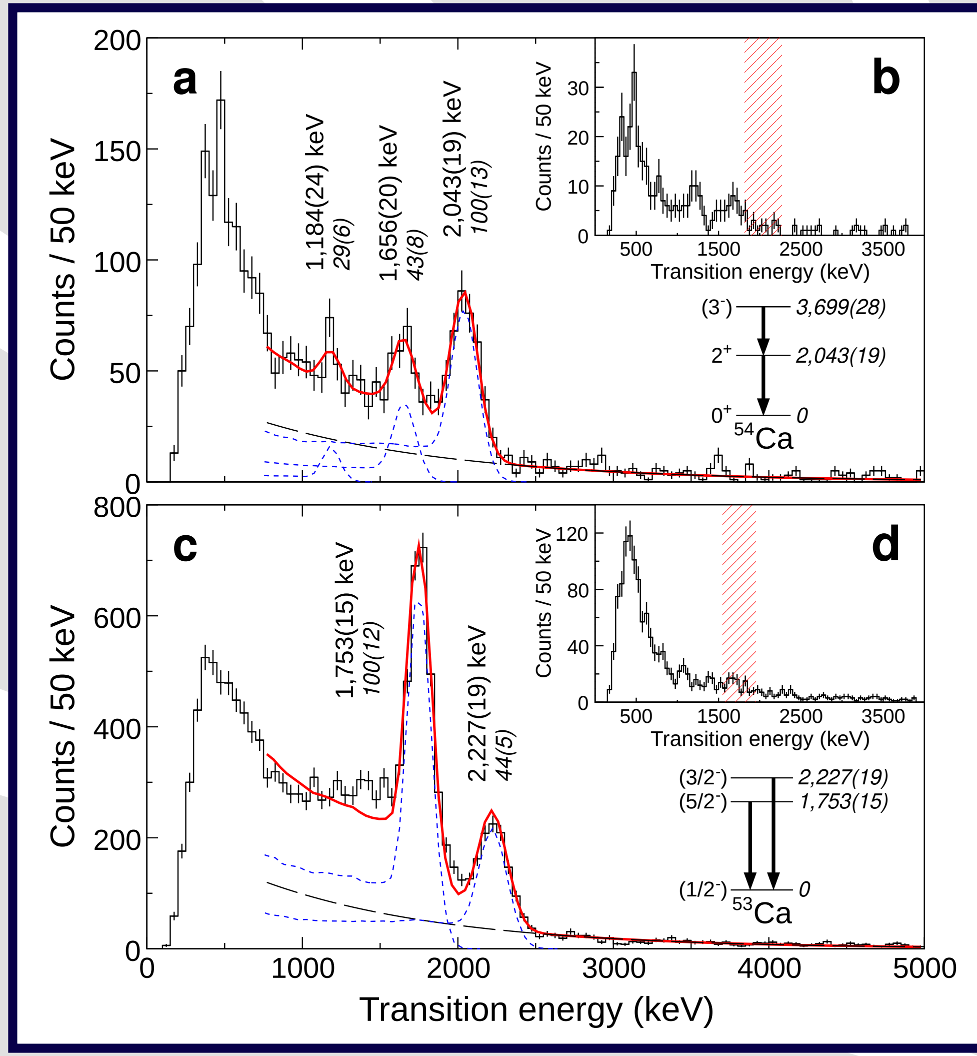


- Reduced attractive interaction between $\pi f_{7/2}$ and $\nu f_{5/2}$
- Possible development of new sub-shell closures at N = 32 and N = 34
- Observation of N = 32 sub-shell closure for ^{52}Ca, ^{54}Ti.

D. Steppenbeck *et al.*, Nature 502, 207 (2013).

Significant Shell Closures at $N = 32, 34$

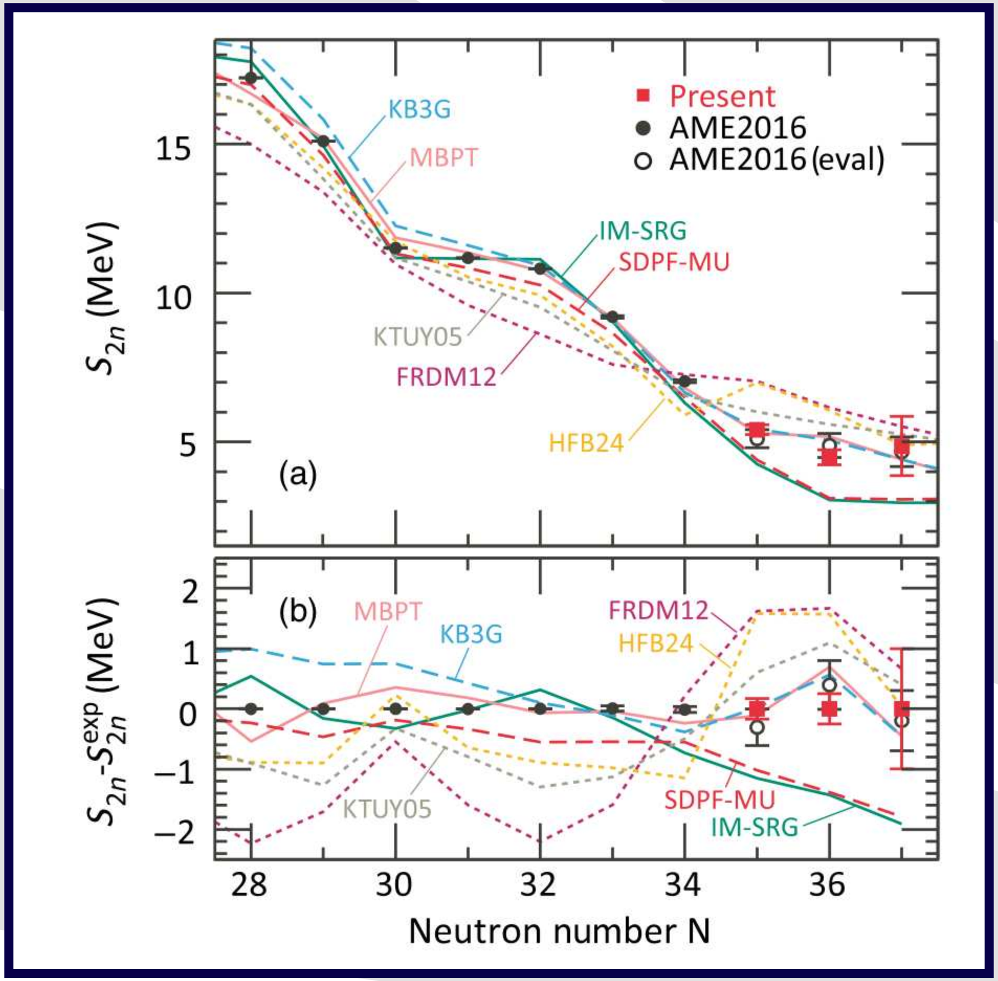


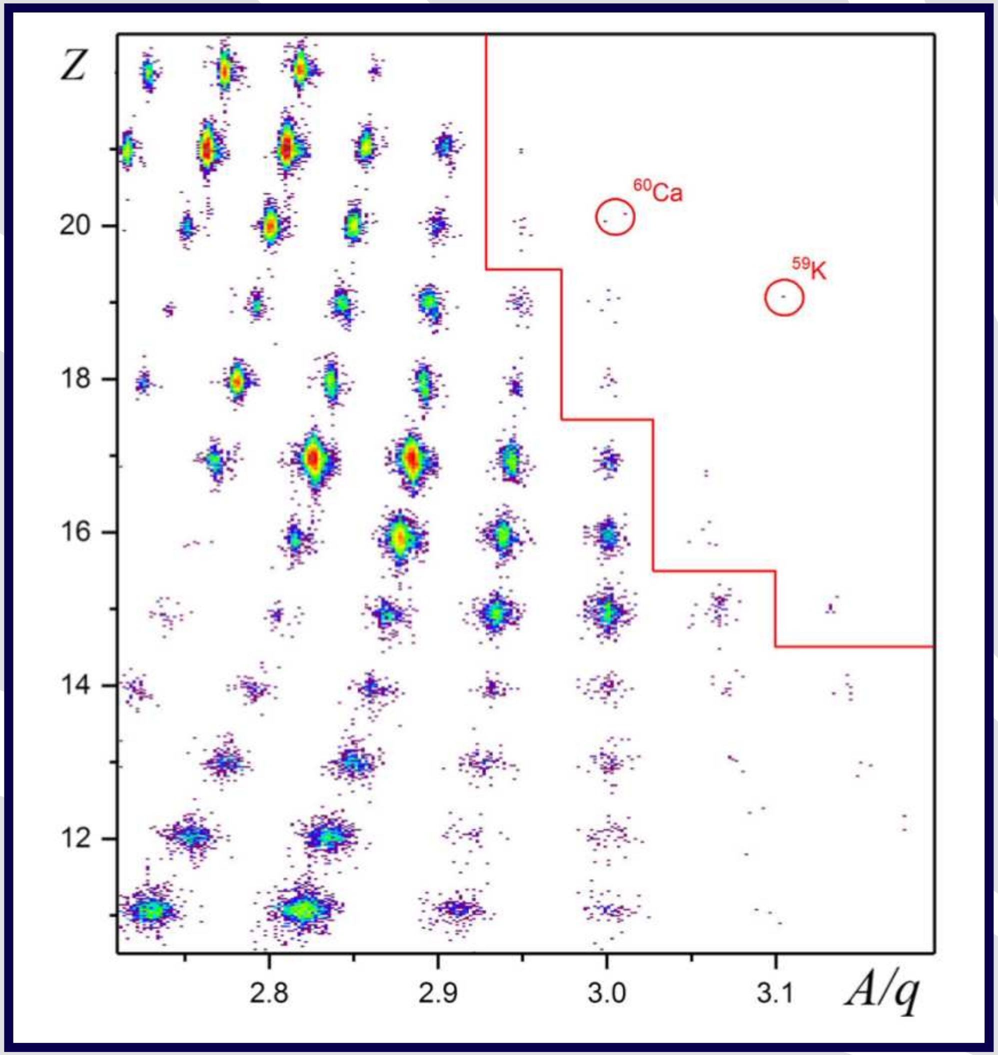


- Masses of ^{53,54}Ca
  - Significant gap between $p_{3/2}$ and $p_{1/2}$
- $E(2_1^+)$ Spectroscopy of ^{54}Ca
  - Gap between $p_{1/2}$ and $f_{5/2}$

F. Wienholtz *et al.*, Nature 498, 346 (2013).
D. Steppenbeck *et al.*, Nature 502, 207 (2013).

Towards Physics of ^{60}Ca

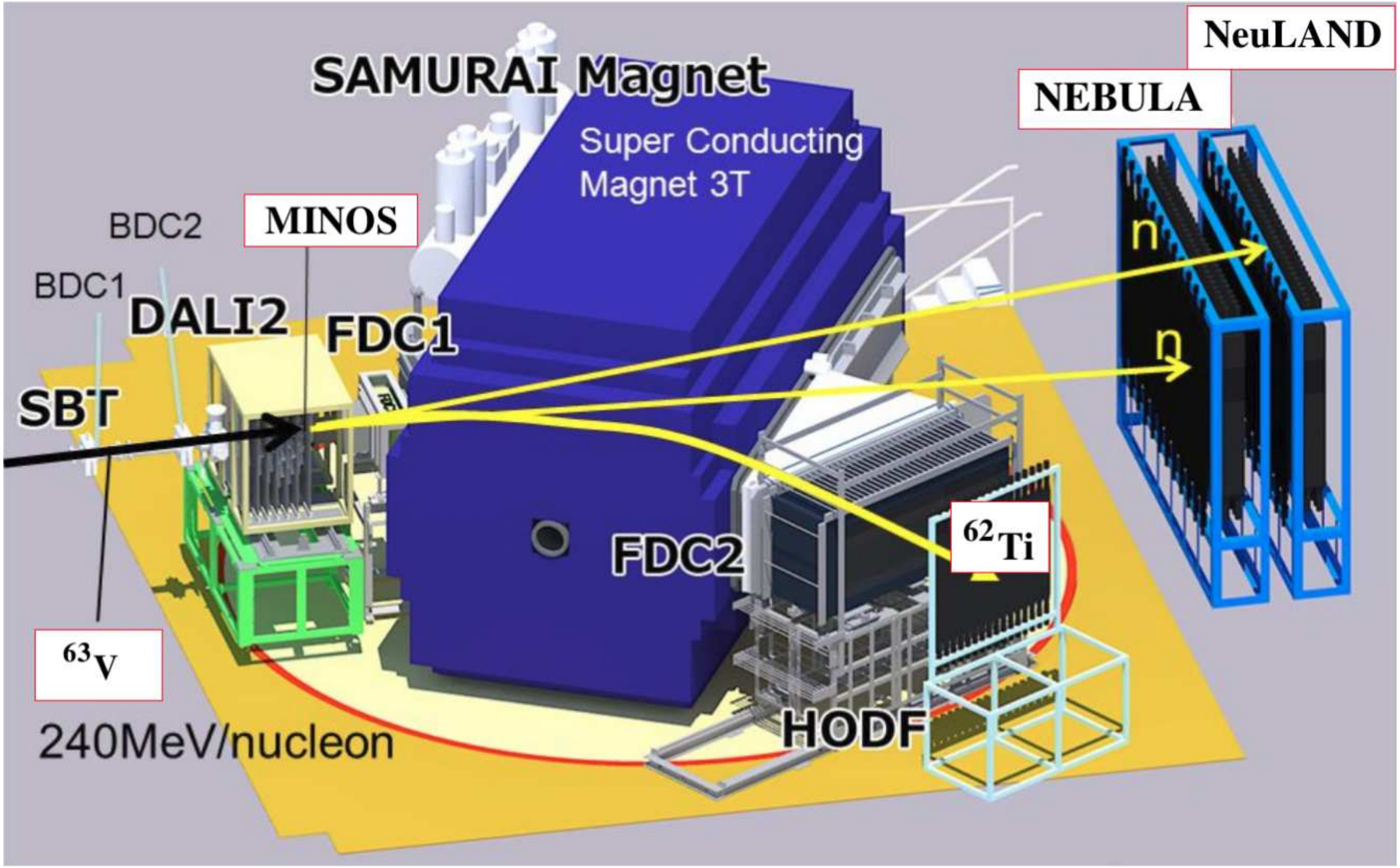




- Masses of $^{55–57}$Ca
  - Significant gap between $p_{1/2}$ and $f_{5/2}$
- Discovery of ^{60}Ca

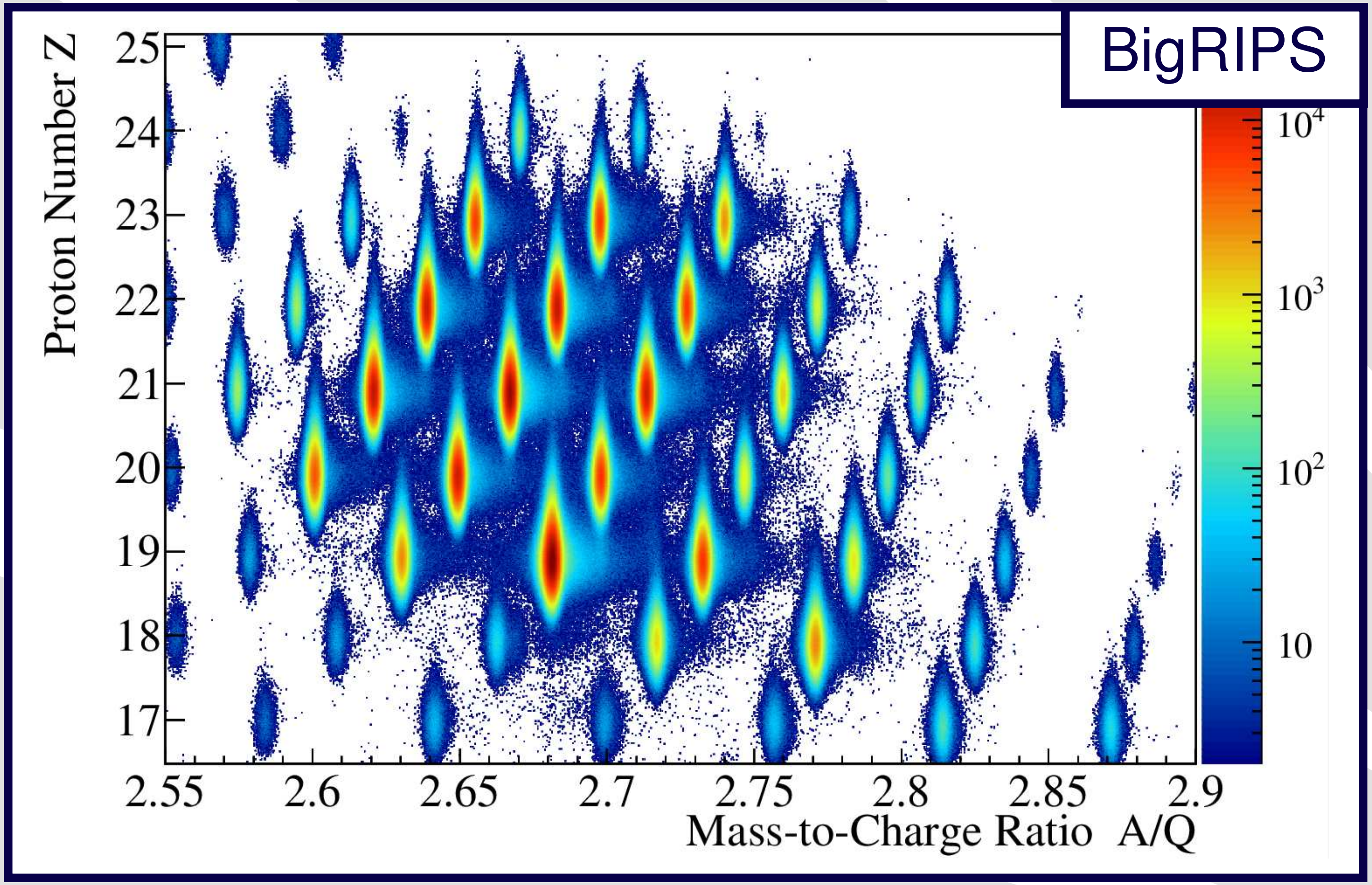
S. Michimasa *et al.*, PRL 121, 022506 (2018).
O. Tarasov *et al.*, PRL 121, 022501 (2018).

SEASTAR at SAMURAI



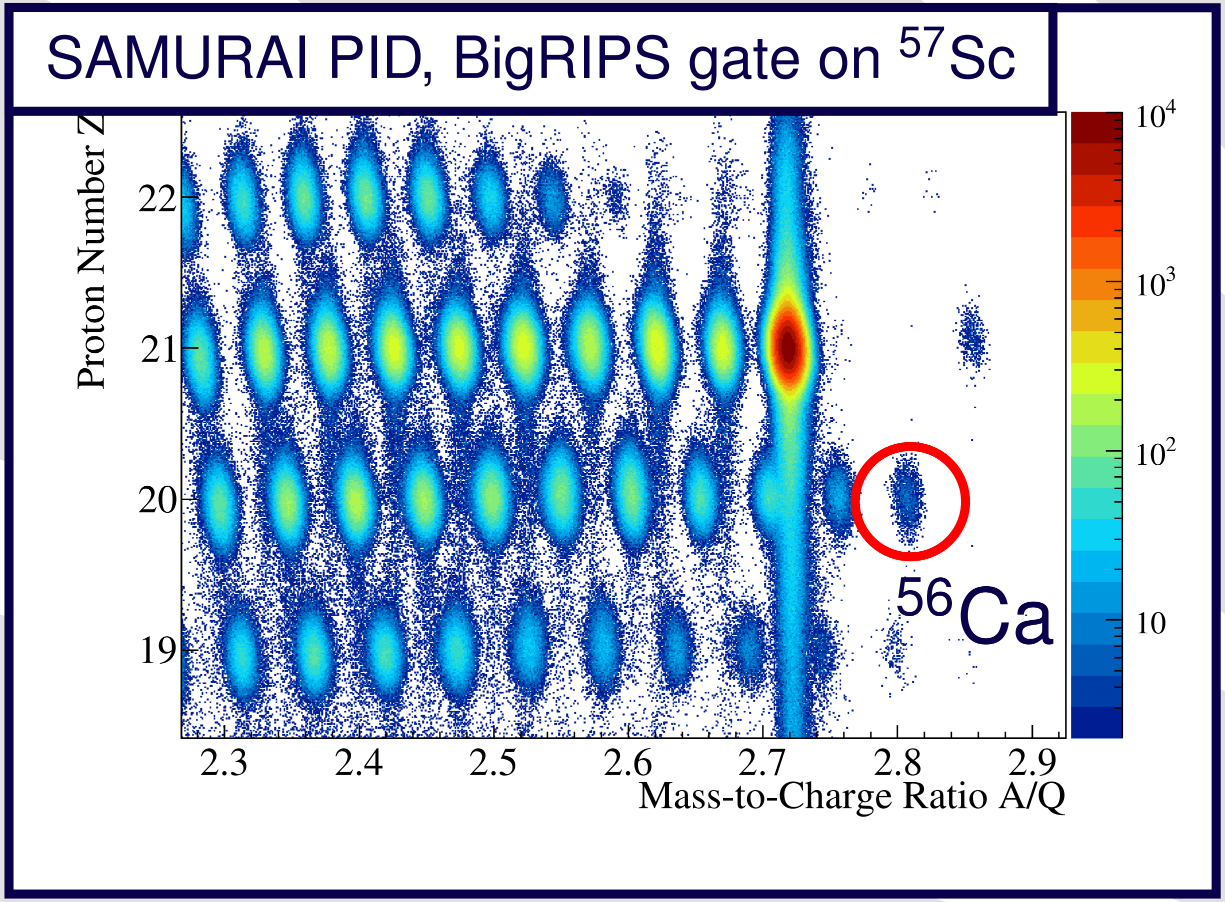
- Large acceptance
  - Simultaneous measurement of ^{52}Ar, ^{56}Ca, and ^{62}Ti

SEASTAR at SAMURAI
Particle Identification



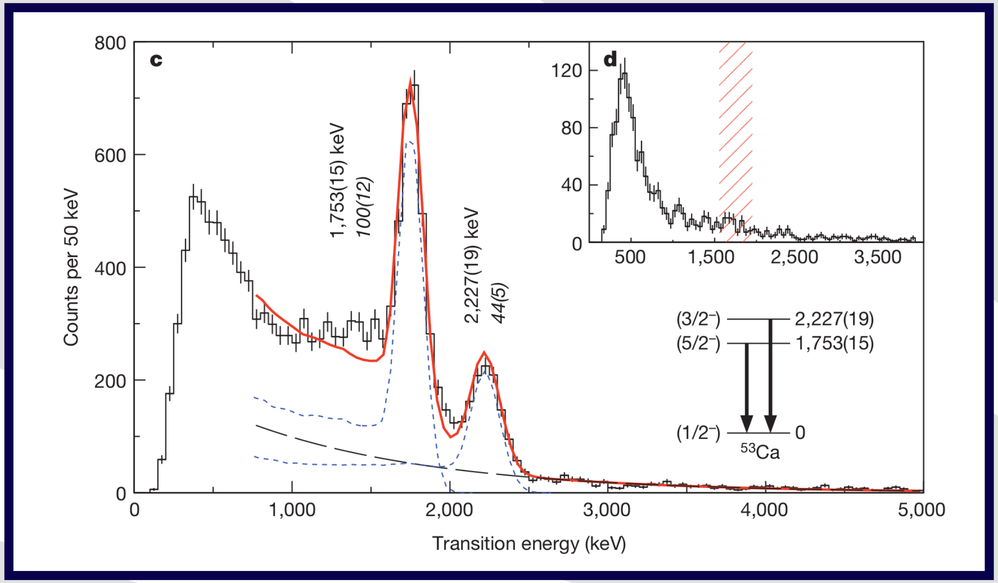
- ^{70}Zn primary beam, 345 MeV/u, 240 pnA
- Secondary beam at 240 MeV/nucleon
- **ONE unique setting**
- Total beam intensity: 200 pps; ^{53}K: 0.8 pps, ^{57}Sc: 13 pps, ^{63}V: 3 pps

SEASTAR at SAMURAI
Particle Identification

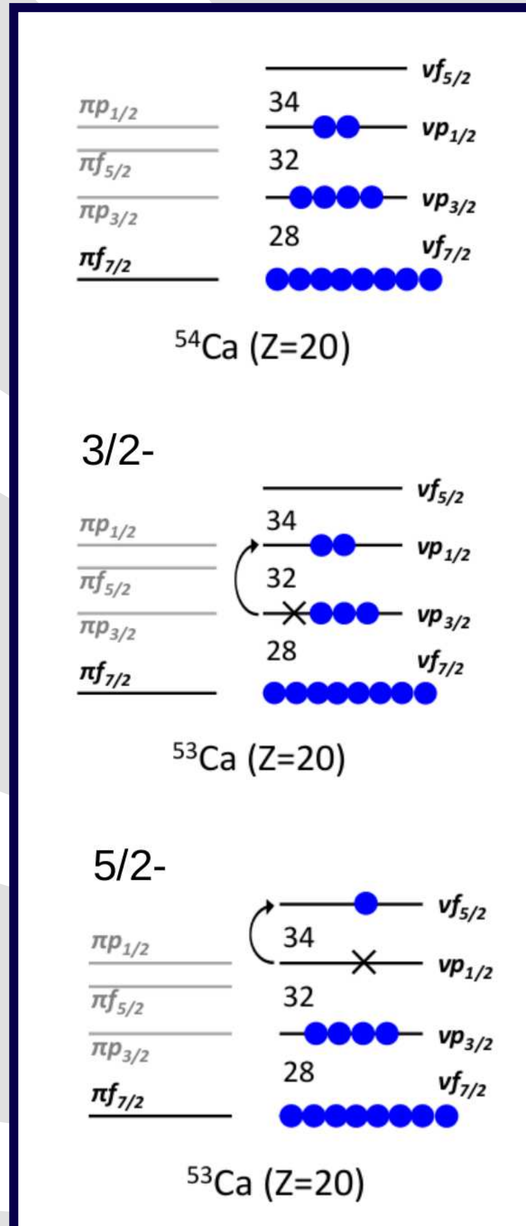


- ^{70}Zn primary beam, 345 MeV/u, 240 pnA
- Secondary beam at 240 MeV/nucleon
- **ONE unique setting**
- Total beam intensity: 200 pps; ^{53}K: 0.8 pps, ^{57}Sc: 13 pps, ^{63}V: 3 pps

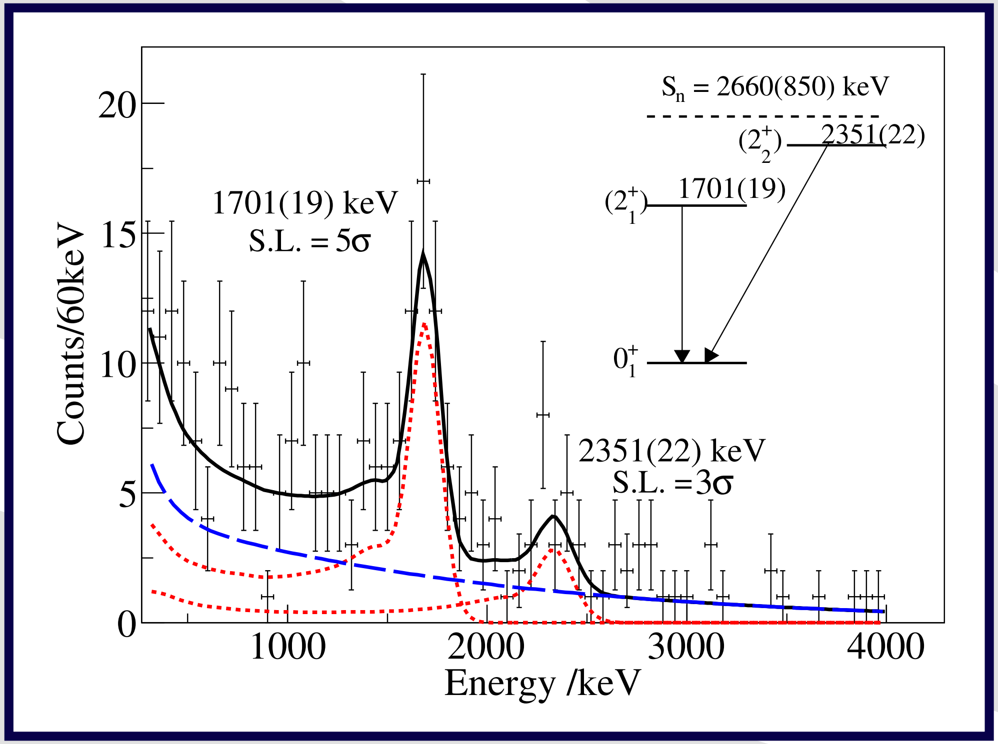
Spectroscopy of ^{53}Ca



- E_x = 2220 keV via β decay.
  F. Perrot *et al.*, PRC 74, 014313 (2006).
- ^{53}Ca not directly populated
  Be(^{55}Sc,^{53}Ca+γ)
  D. Steppenbeck *et al.*, Nature 502, 207 (2013).
- Use direct reaction ^{54}Ca(p,pn)^{53}Ca
  - Direct probe of g.s. wave function of ^{54}Ca
    - Cross sections $\rightarrow$ SFs
    - Only one strong 2220 keV transition $\rightarrow$ shell closure at N = 34



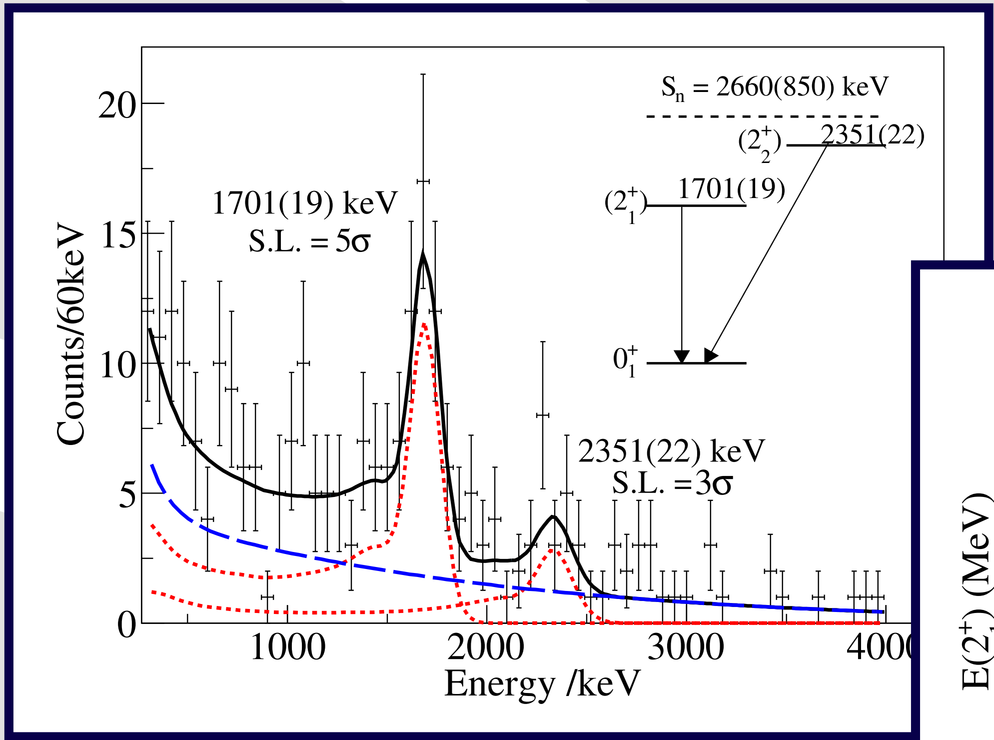
$N = 34$ gap "South" of ^{54}Ca
^{53}K(p,2p)^{52}Ar

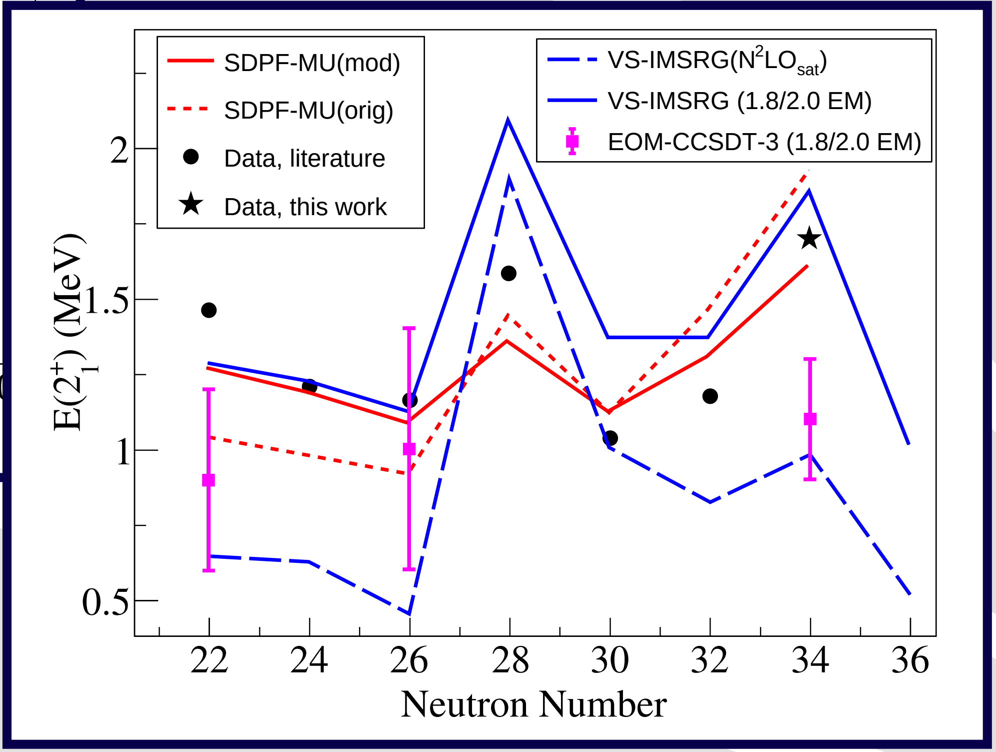


- Largest $E(2_1^+)$ in Ar isotopes beyond N = 20

H. Liu *et al.*, PRL 122, 072502 (2019).

$N = 34$ gap "South" of ^{54}Ca
$^{53}K(p,2p)^{52}Ar$



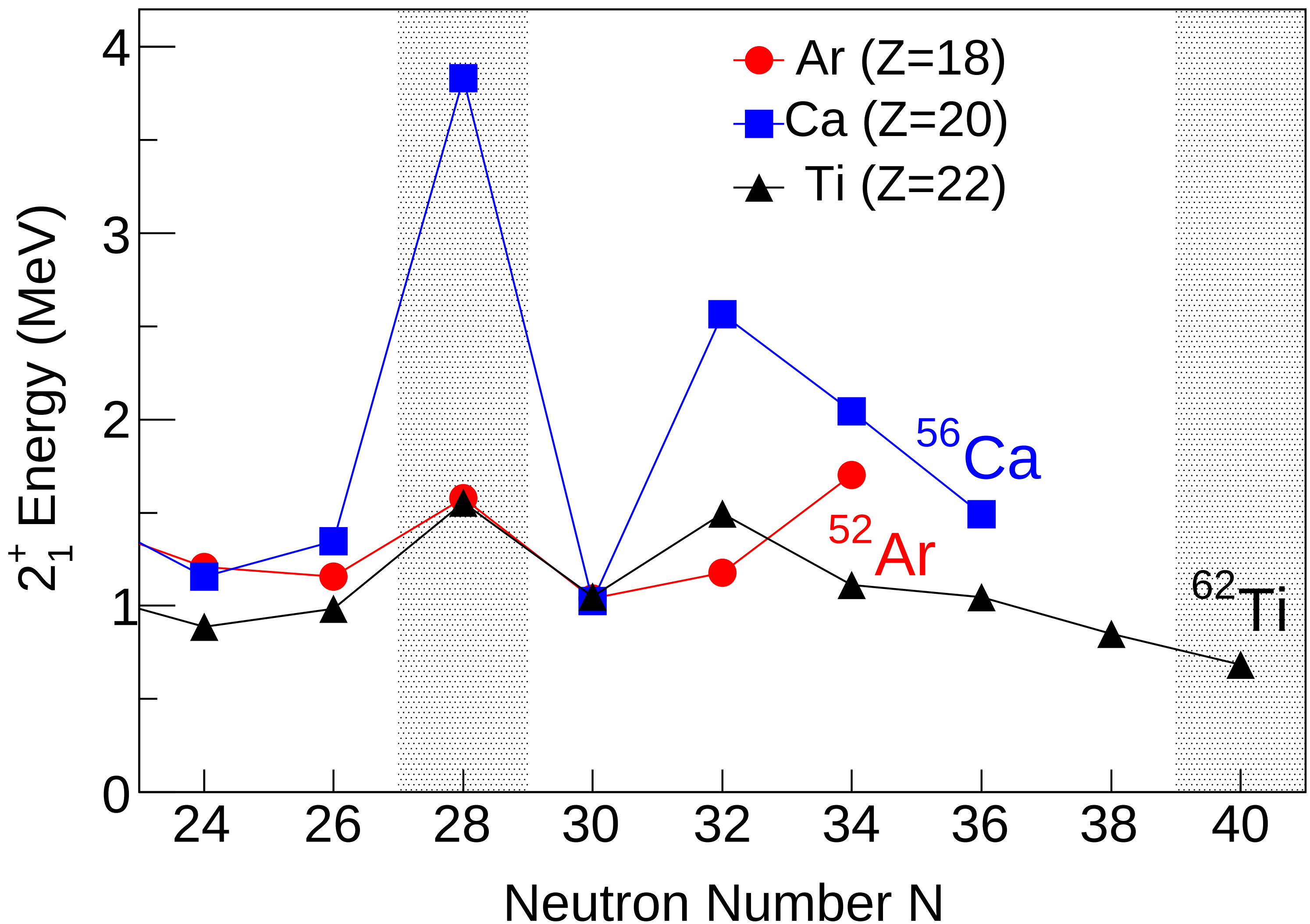


- Largest $E(2_1^+)$ in Ar isotopes beyond N = 20

SDPF-MU (orig): Y. Utsuno *et al.*, PRC 86, 051301(R) (2012).
SDPF-MU (mod): D. Steppenbeck *et al.*, PRL 114, 252501 (2015).
VS-IMSRG: J.D. Holt, R.Stroberg *et al.*
EOM-CCSDT-3: G. Hagen, T. D. Morris *et al.*

H. Liu *et al.*, PRL 122, 072502 (2019).

$E(2_1^+)$ Systematics



^{52}Ar: H. Liu *et al.*, ^{56}Ca: S. Chen *et al.*, ^{62}Ti: M.L. Cortés *et al.*

Summary and Outlook

Summary

- ^{78}Ni doubly magic
  - Indication for shape coexistence
  - Onset of deformation expected
- N = 34 shell closure in ^{54}Ca and lighter isotones
  - N = 34 better developed than N = 32
- Approaching ^{60}Ca
  - Deformation seems maintained
  - Phenomenological interactions reproduce structure along N = 40
  - Doubly-magic ^{60}Ca is disfavored
- Quasifree (p,pn) and (p,2p) knockout-reactions
  - Transversal and parallel momentum distributions
  - Can employ thick target due to vertex tracking
  - No quenching of partial cross sections

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