

The SEASTAR Program at RIKEN-RIBF



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Volker Werner

**Institut für Kernphysik, TU Darmstadt
AG Pietralla**

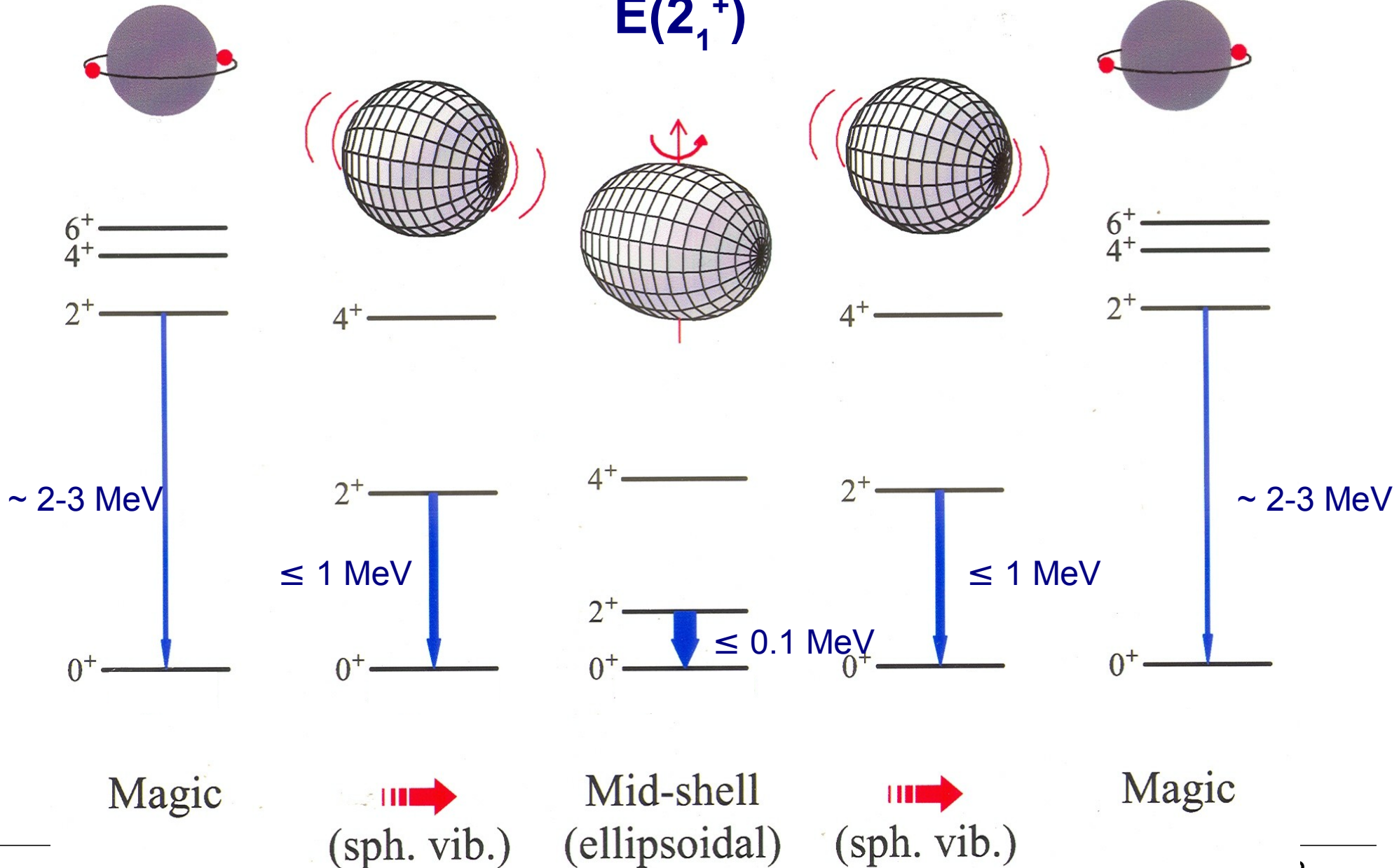
- **Basic observables**
- **Present developments toward NUSTAR @ FAIR**
 - **Shell Evolution And Search for Two-plus energies At RIBF (SEASTAR)**
 - **First Campaign in May 2014**
 - **LH2 Target / TPC (MINOS - CEA) coupled to DALI2 (RIKEN)**
 - **R4/2 ratios and evolution of structure in Cr/Fe isotopes**
 - **Preliminary results on ^{78}Ni**
 - **Inelastic scattering off Ni isotopes**
 - **Brief summary SEASTAR campaign 2 (3)**

Basic Spectroscopic Information



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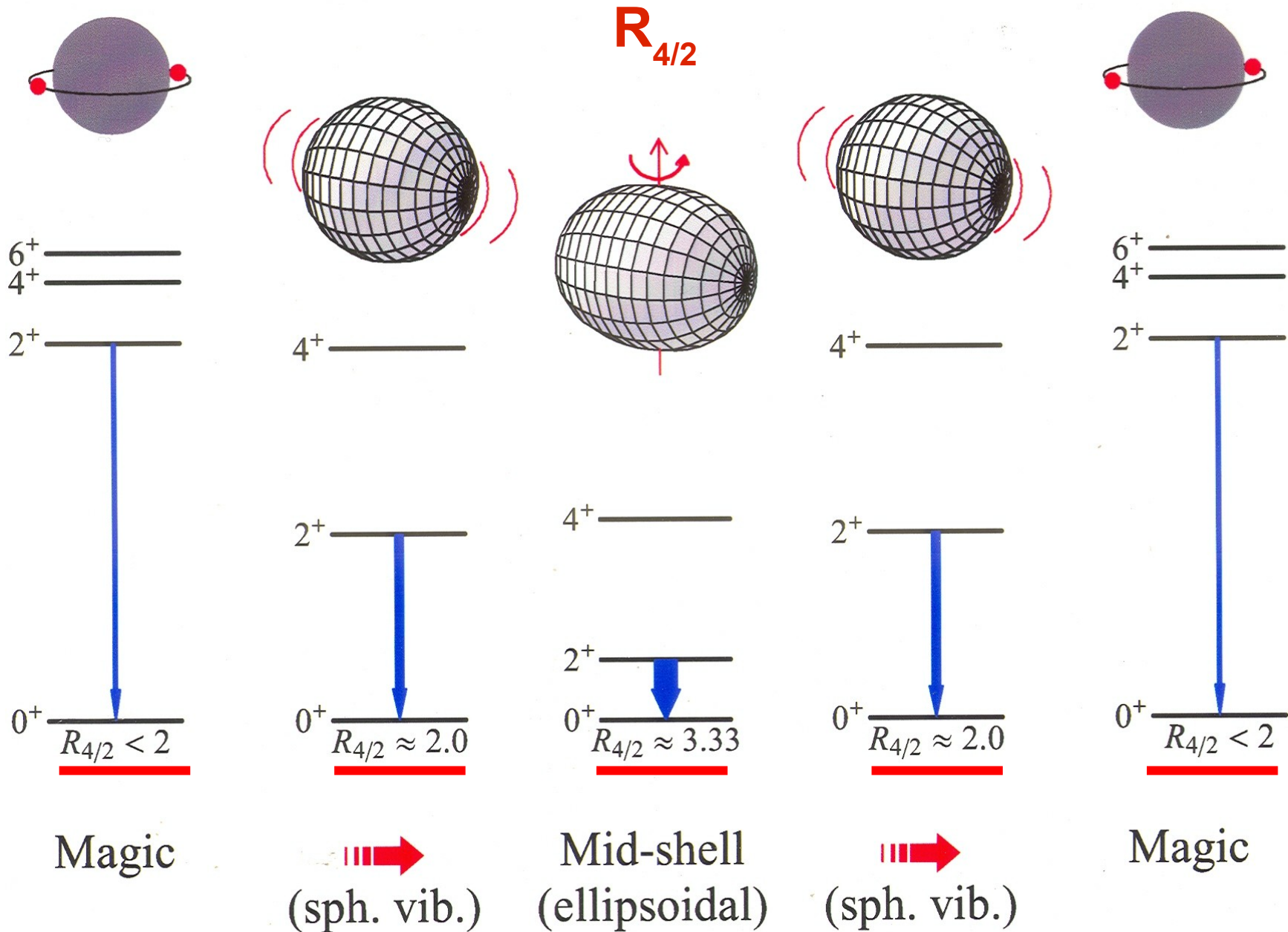
$E(2_1^+)$



Basic Spectroscopic Information



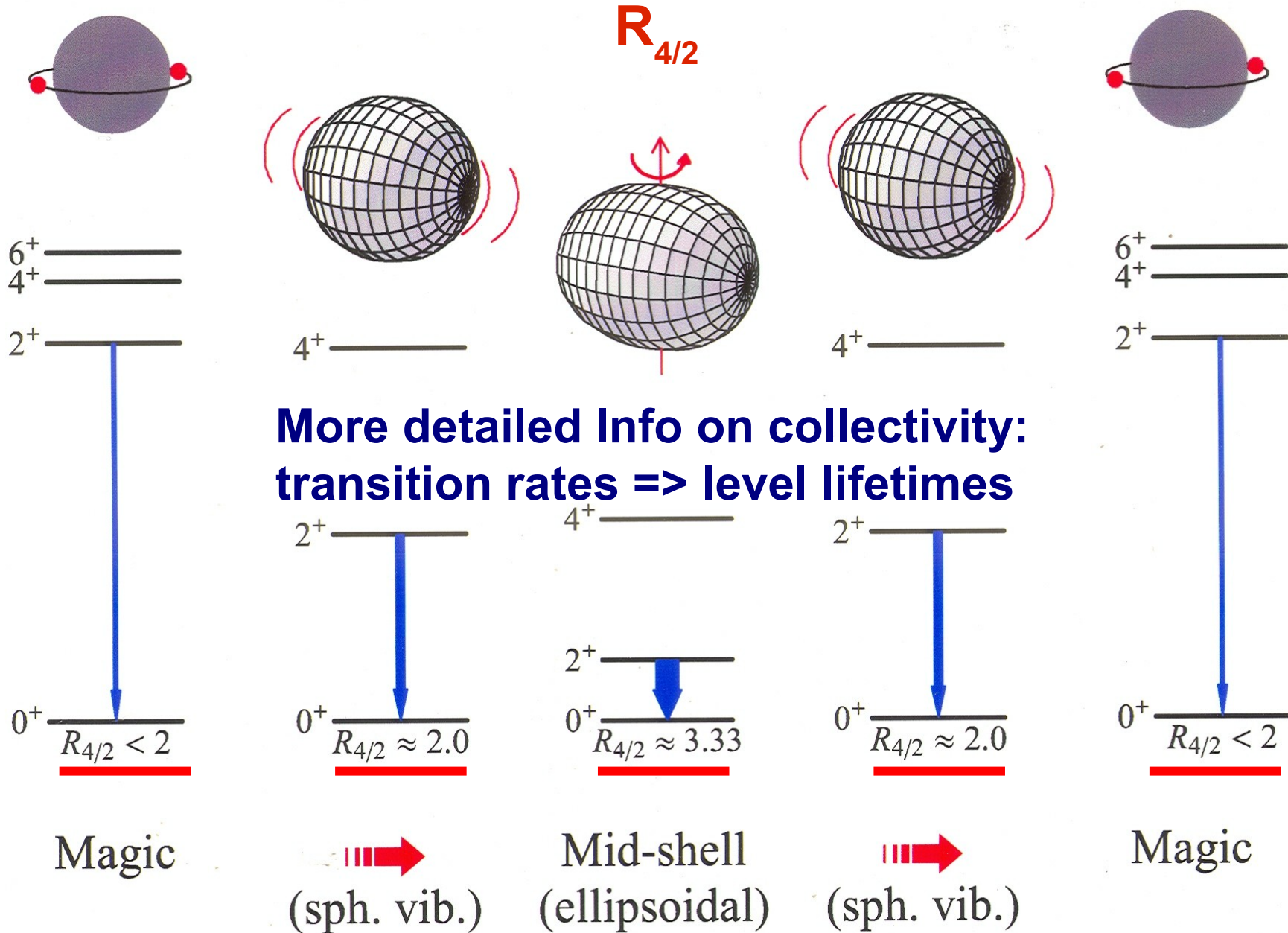
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Basic Spectroscopic Information



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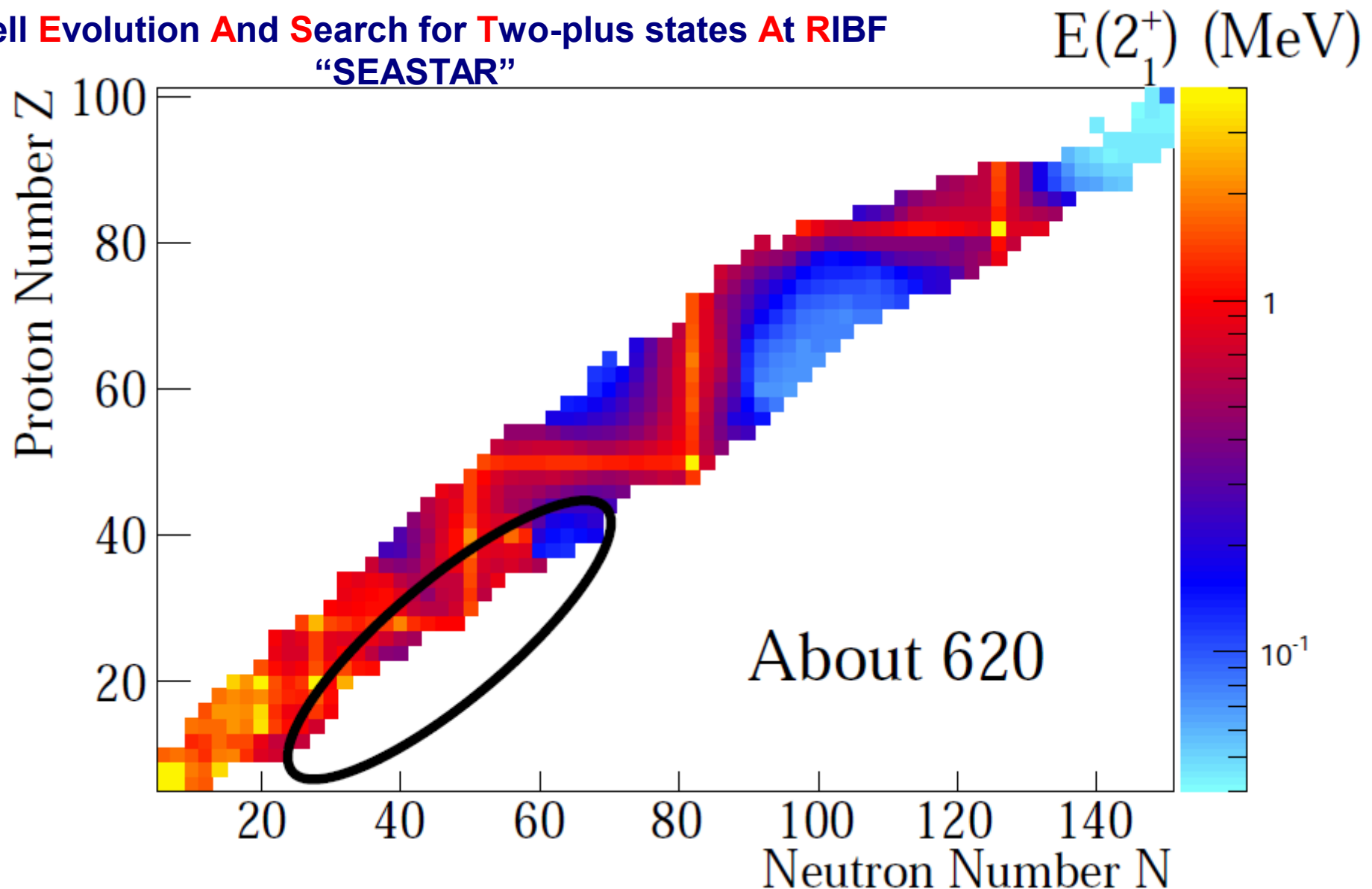


Learn from Systematic Evolution of Structure: SEASTAR @ RIBF



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Shell Evolution And Search for Two-plus states At RIBF
"SEASTAR"

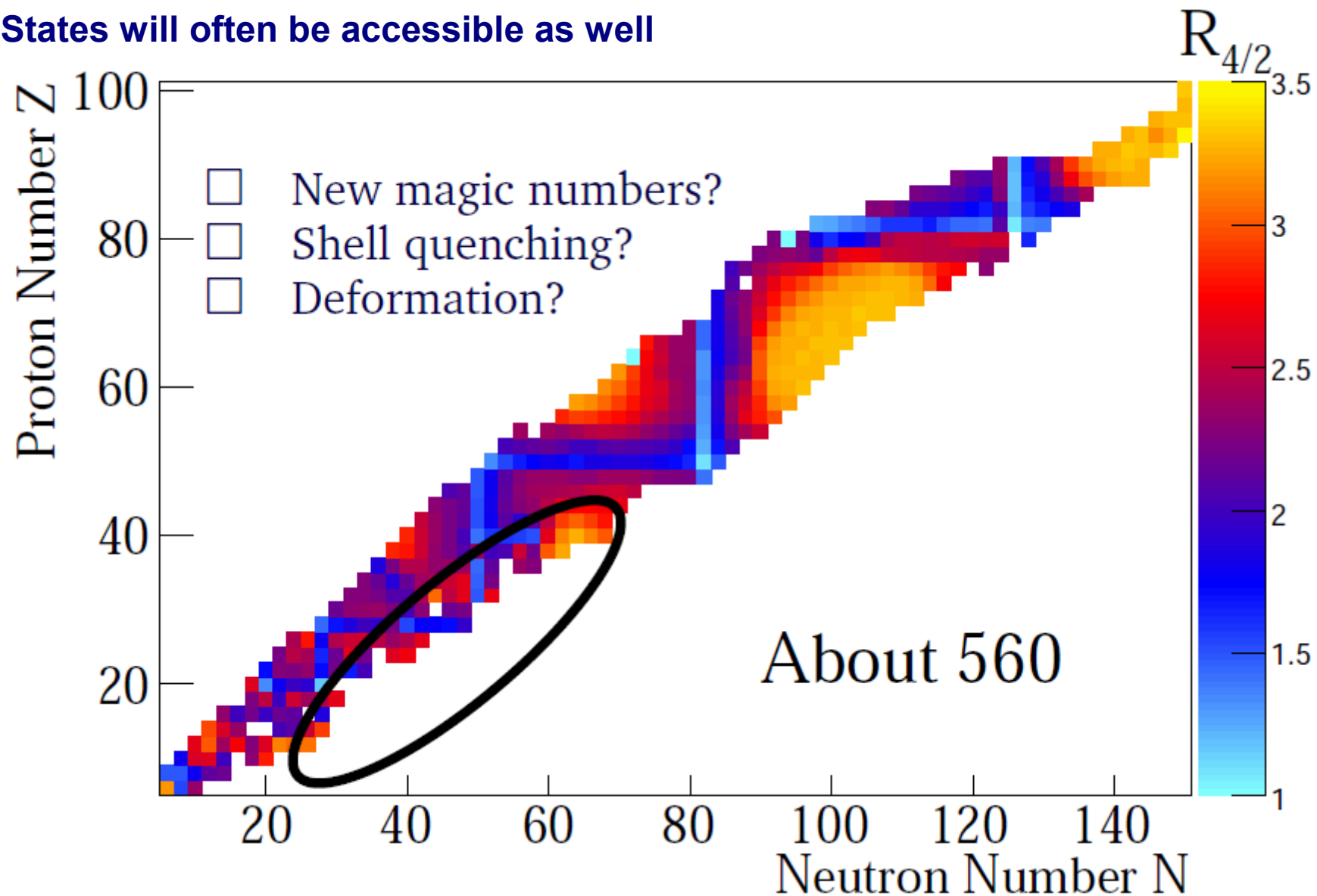


Learn from Systematic Evolution of Structure: SEASTAR @ RIBF



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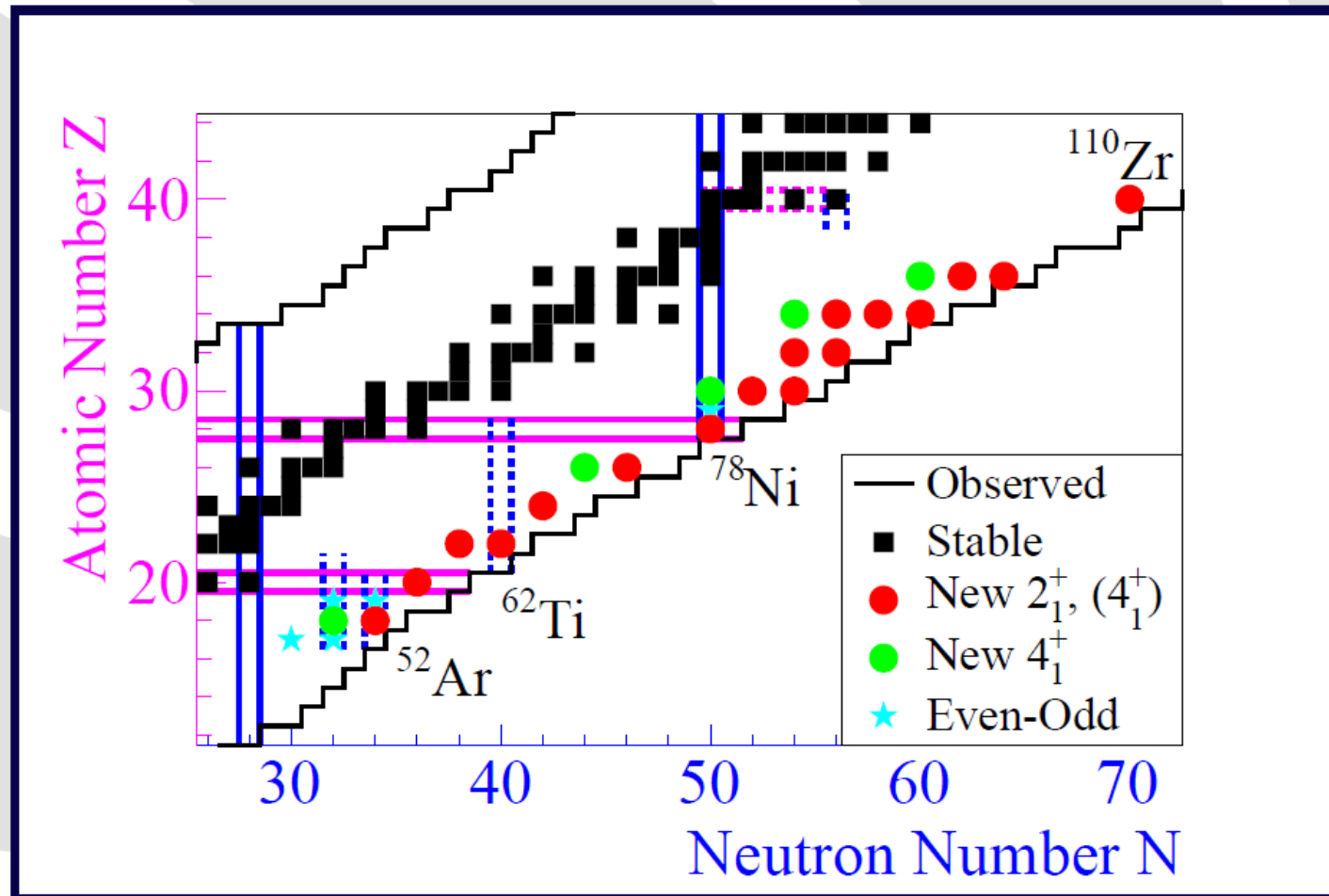
4⁺ States will often be accessible as well



SEASTAR @ RIKEN-RIBF



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- Spokespersons: PD and A. Obertelli
- ^{238}U primary beam, **average intensity 15 pA!**
- Secondary beams at 240 MeV/u, 100-mm target, $\delta\beta = 20\%$

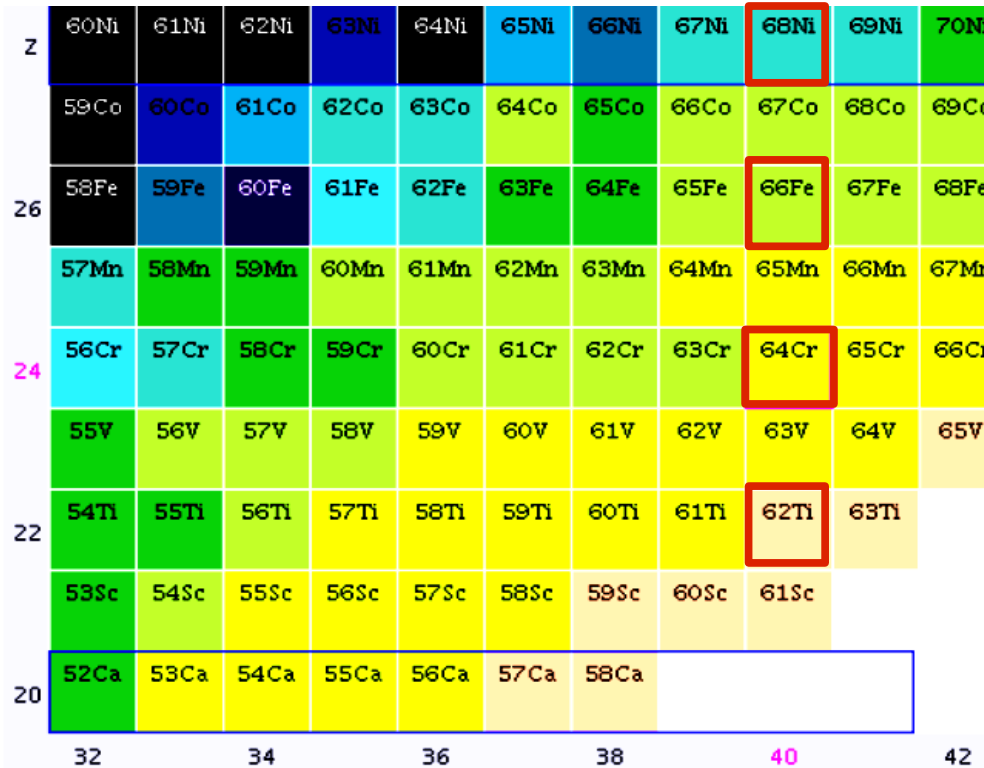
From P. Doornenbal, EGAN Workshop 2014

- Feb. 2013: 1st SUNFLOWER Workshop, Wako (physics opportunities)
- Sep. 2013: 2nd SUNFLOWER Workshop, Darmstadt (discuss umbrella proposal)
- May 2014: 1st SEASTAR campaign
- Sep. 2014: 3rd SUNFLOWER Workshop, Tokyo (discussion of 2nd campaign)
- May 2015: 2nd SEASTAR campaign
- Fall 2016: 3rd SEASTAR campaign

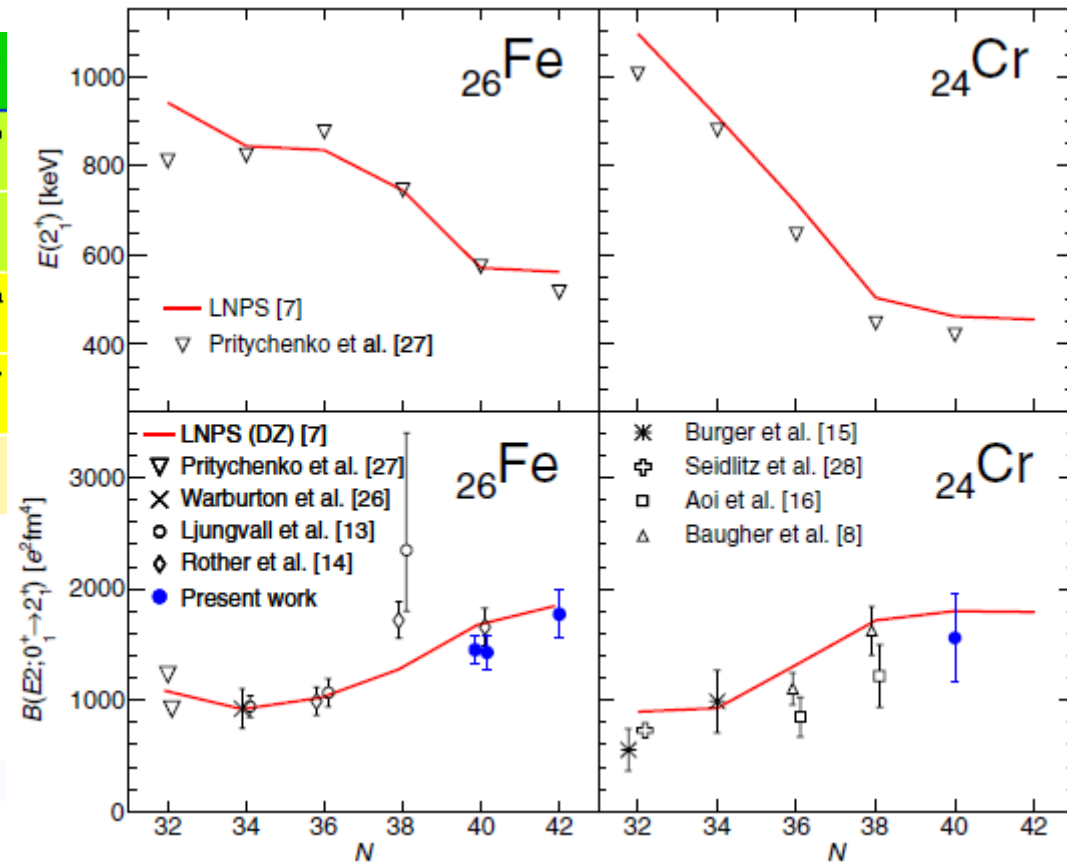
Collectivity at N=40



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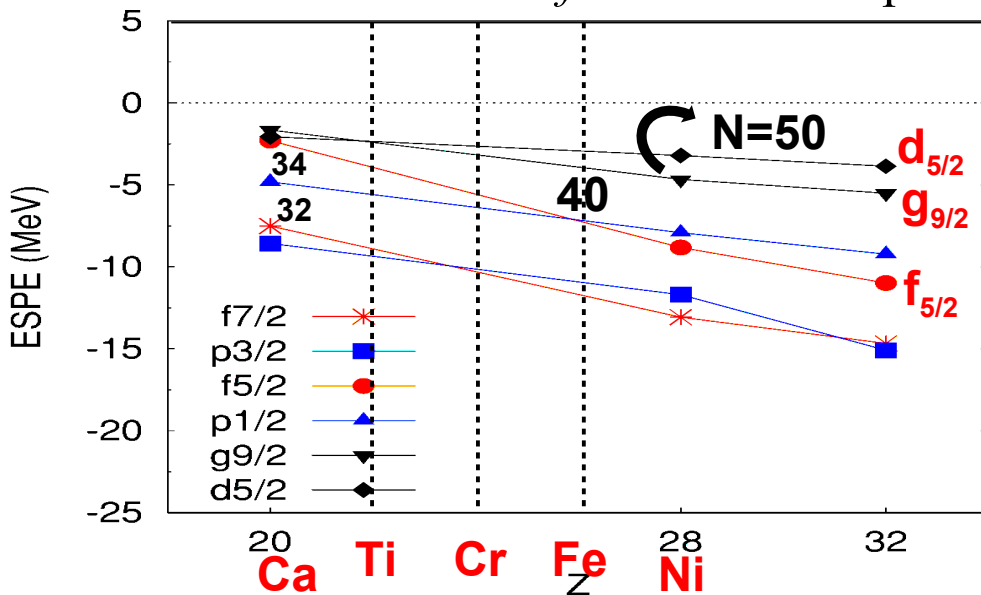
- ^{68}Ni with $N=40$ behaves as a doubly-magic nucleus.
- Enhancement of collectivity in $N=40$ isotones below ^{68}Ni .



H. Crawford et al., PRL 110

Shell Gaps vs. Correlations

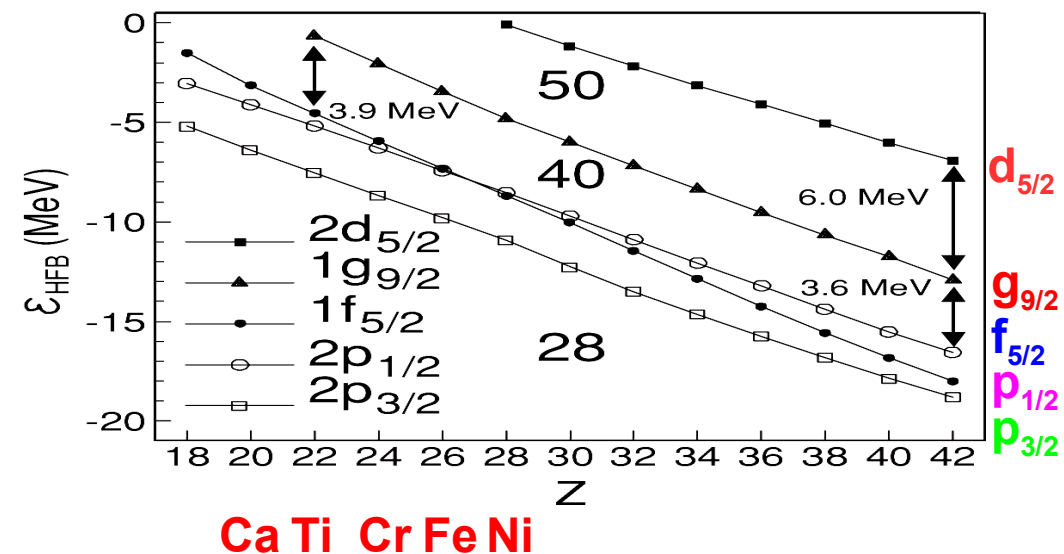
- Shell Model LNPS interaction
- A new "island of inversion" is predicted



S. Lenzi *et al.*, PRC 82, 054301, (2010)

- Weakened $N = 50$
- Q-partners $g_{9/2}$ - $d_{5/2}$
- $N = 32, 34$ sub-shell closures
- $N = 40$?

- HFB calculations



L. Gaudefroy *et al.*, PRC 80, 064313 (2009)

- $vg_{9/2}$ - $\pi f_{7/2}$ interaction
- Correlations favor $(vg_{9/2})^2$
- Strong $N = 50$
- $N = 32, 40$ sub-shell closures

RIKEN-RIBF Overview



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Intensities of 345 MeV/u beams from the SRC

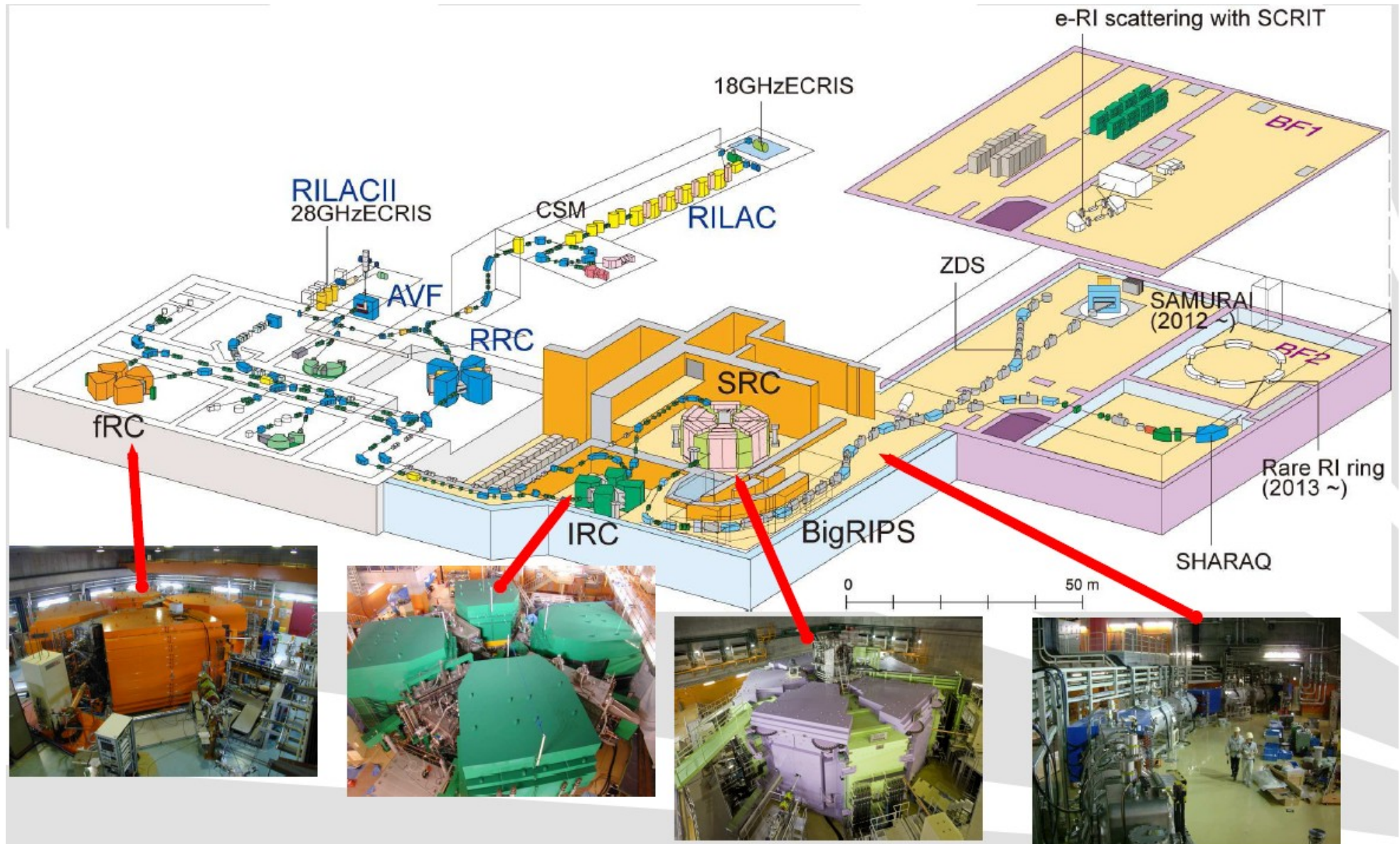
Nucleus	Goal	Beam Intensity / pnA	
		Achieved	Max
^{48}Ca	1000	415	>200
^{70}Zn	1000	123	100
^{78}Kr	1000	—	—
^{124}Xe	100	38	30
^{238}U	100	25	15

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

RIKEN-RIBF Overview



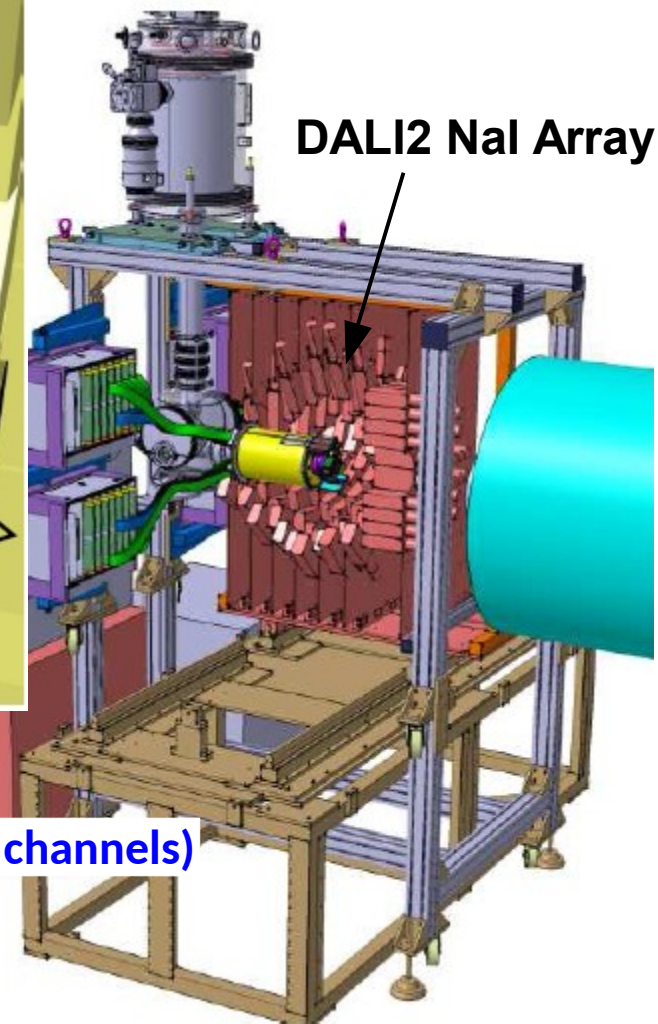
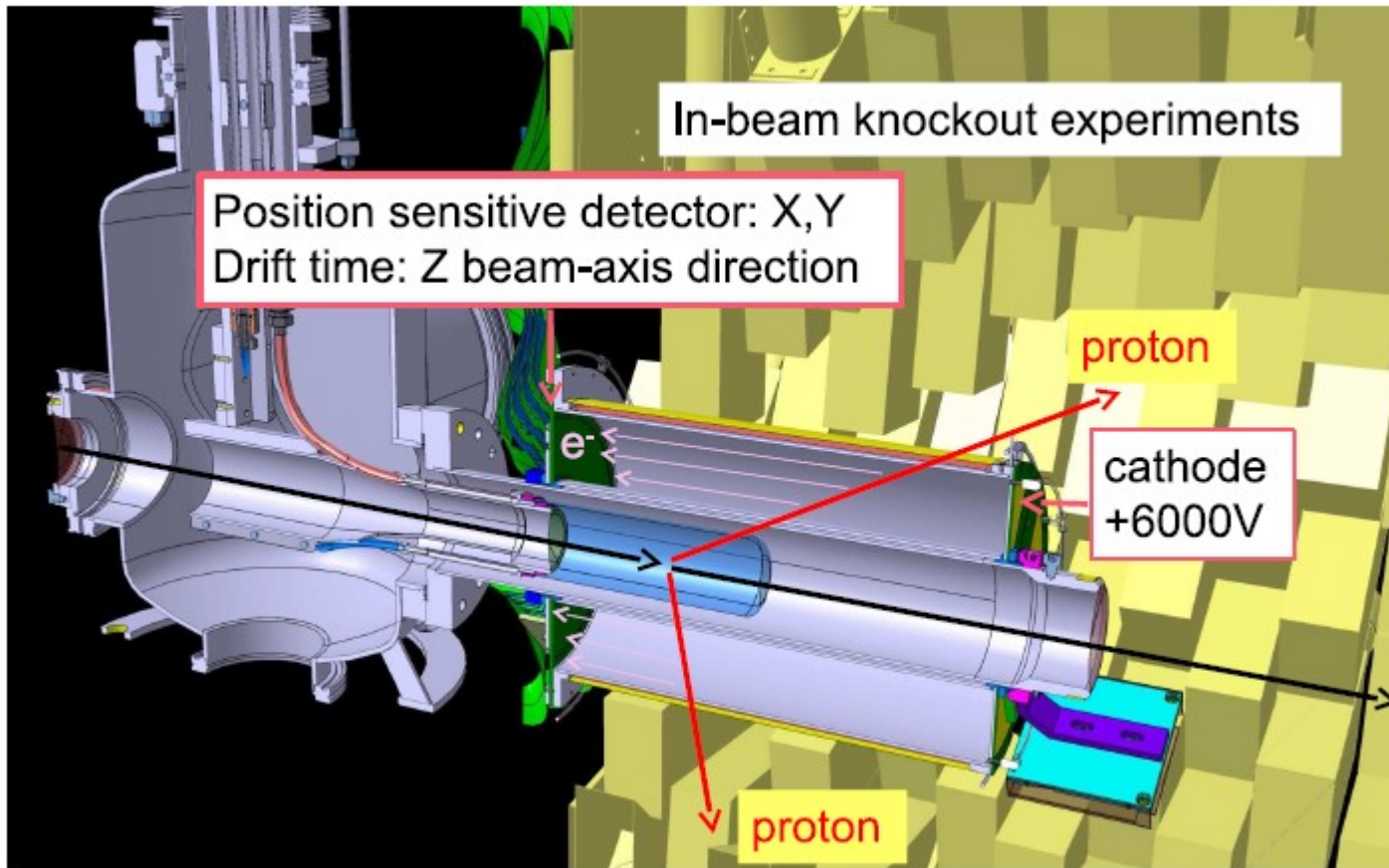
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MINOS + DALI2



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LH2 target length = 100 mm

Time Projection Chamber equipped with MicroMegas detector (3604 channels)

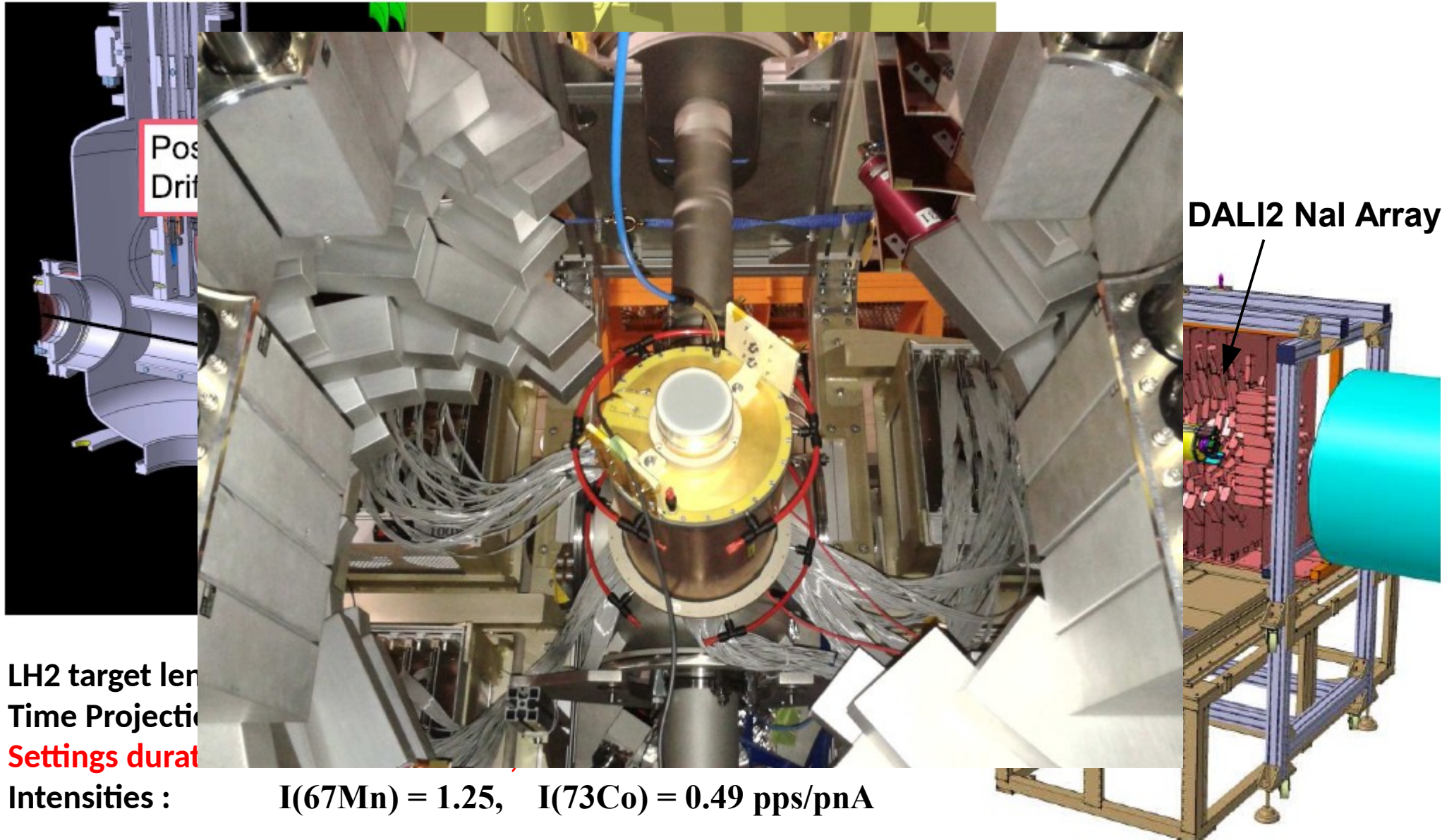
Settings duration : 22.7 hours for Cr, 26 hours for Fe

Intensities : $I(67\text{Mn}) = 1.25$, $I(73\text{Co}) = 0.49$ pps/pnA

MINOS + DALI2



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LH2 target len
Time Projection
Settings durat
Intensities :

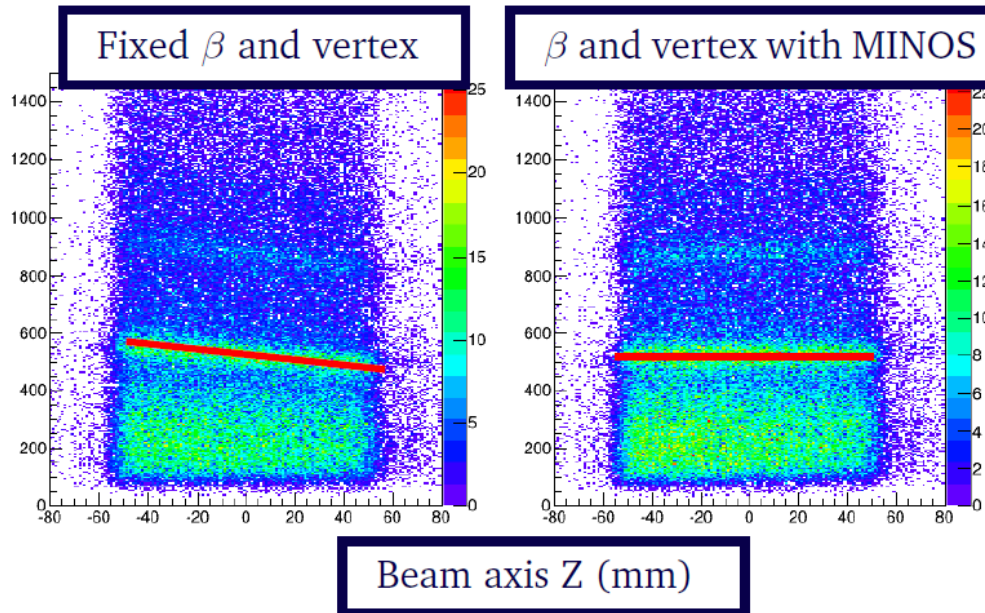
$I(67\text{Mn}) = 1.25, \quad I(73\text{Co}) = 0.49 \text{ pps/pnA}$

$^{69}\text{Co}(p,2p)^{68}\text{Fe}$ @ 200 MeV/u

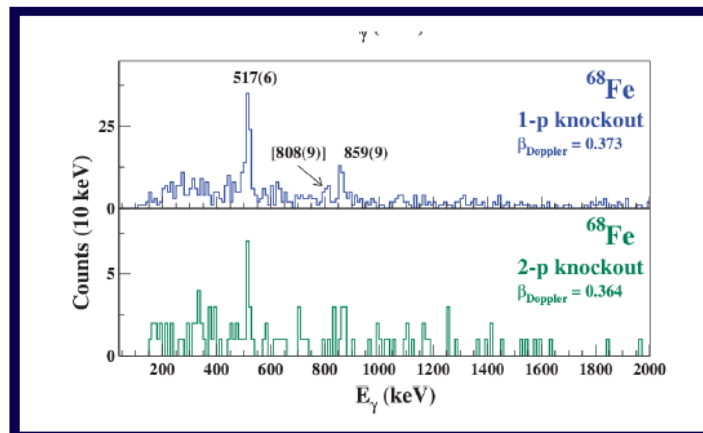
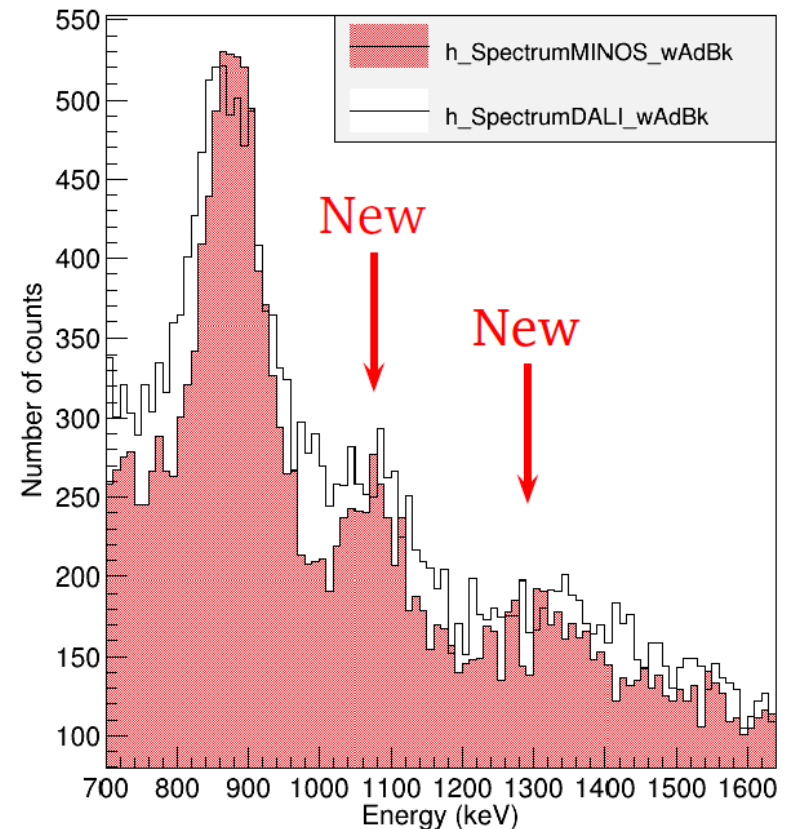
Proof of Principle



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BigRIPS setting on ^{67}Mn , 22 h of beam time



P. Adrich *et al.*, PRC 77, 054306 (2008).

Successful 1st SEASTAR campaign. Physics results for ^{66}Cr , $^{70,72}\text{Fe}$, ^{78}Ni and others available soon

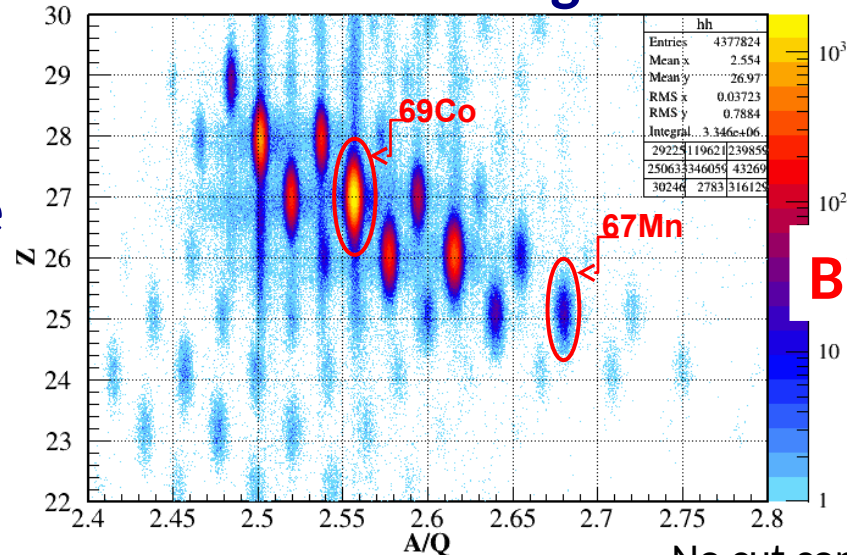
Particle Identification



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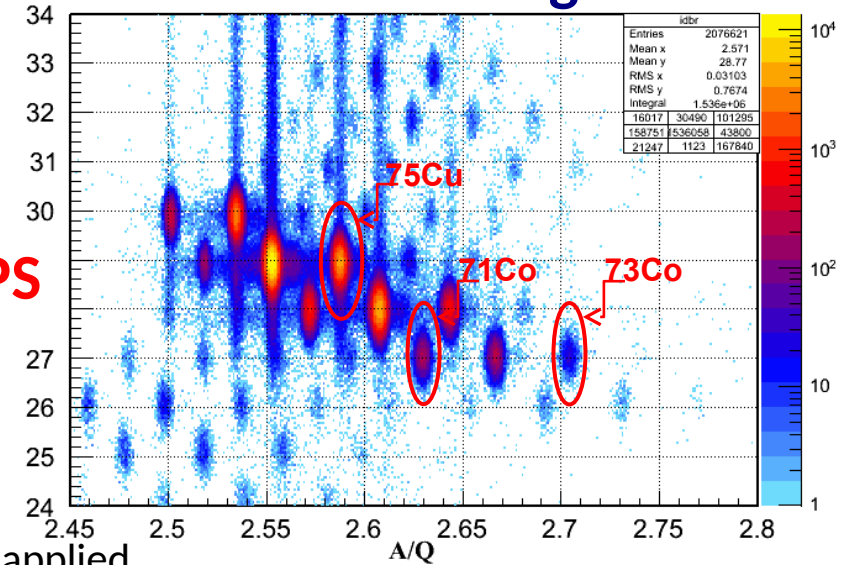
Cr Setting

Before
Target



BigRIPS

Fe Setting



No cut condition applied

Particle Identification

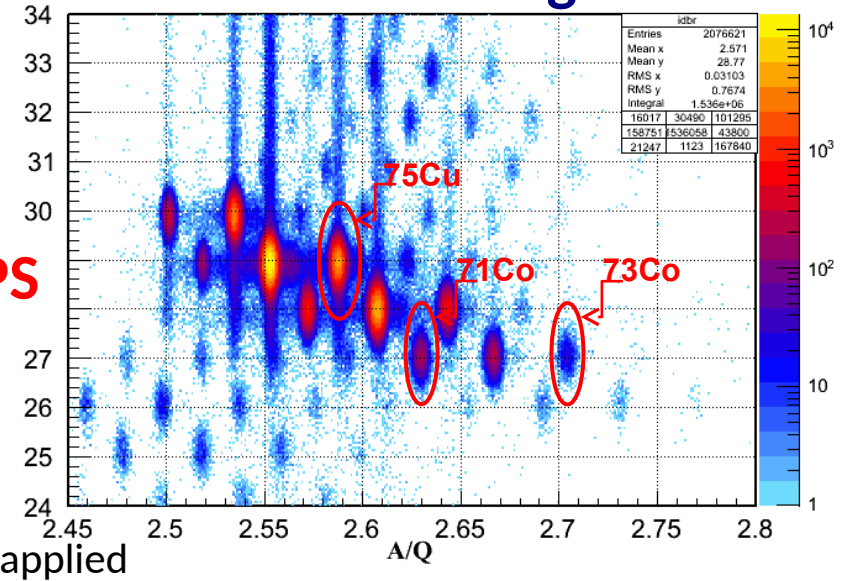
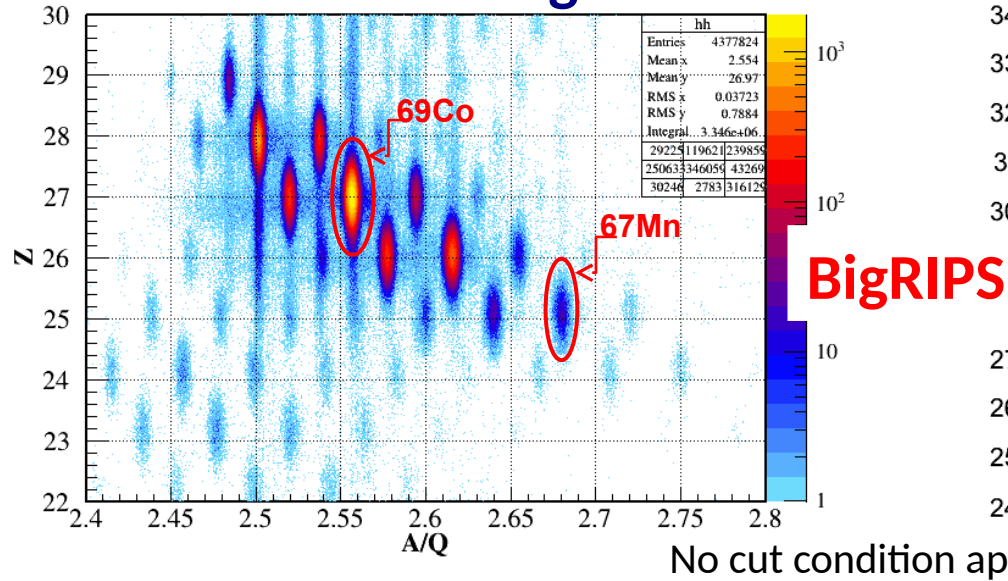


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Cr Setting

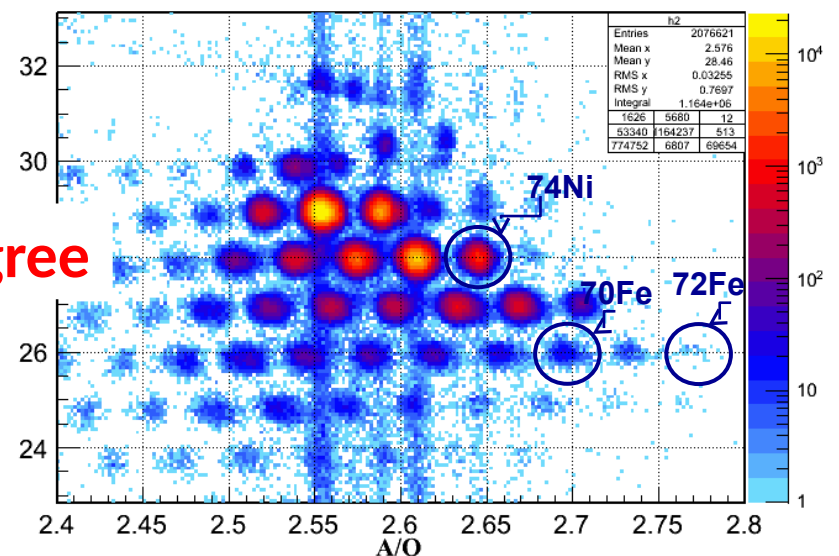
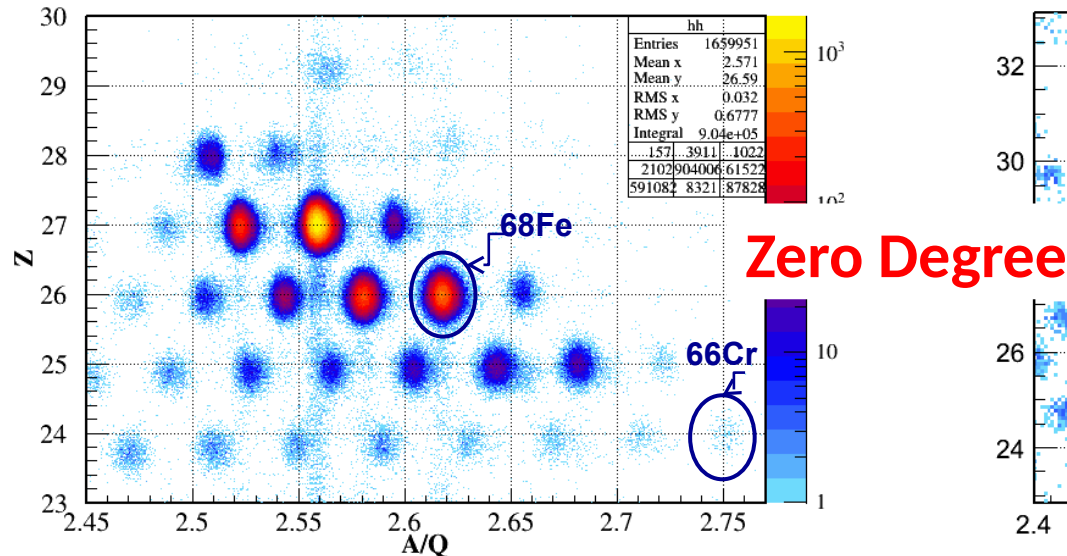
Fe Setting

Before
Target



No cut condition applied

After
Target

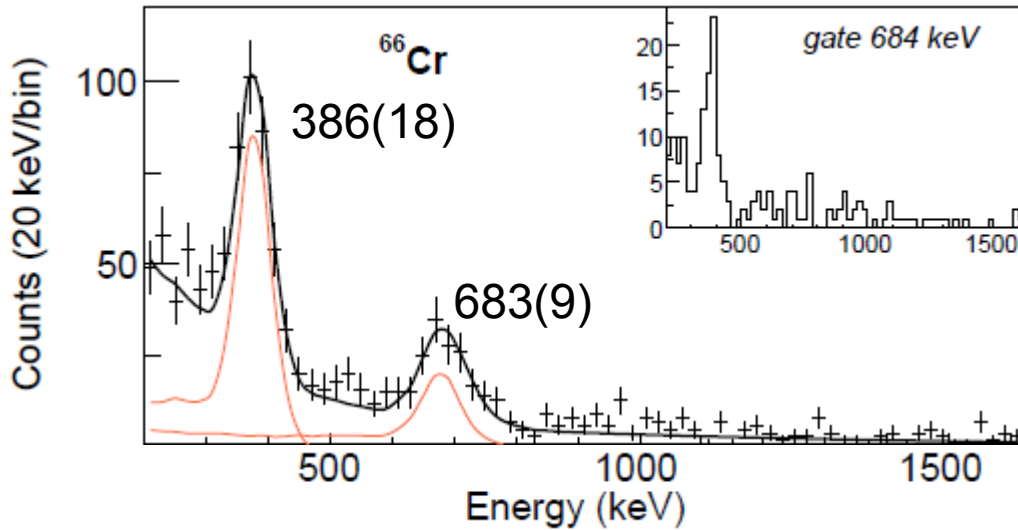


^{66}Cr and $^{70,72}\text{Fe}$

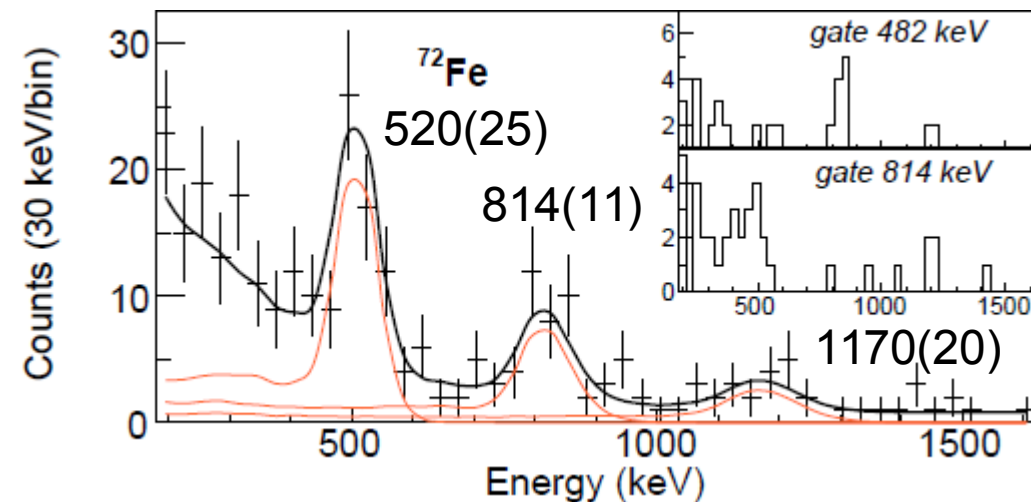
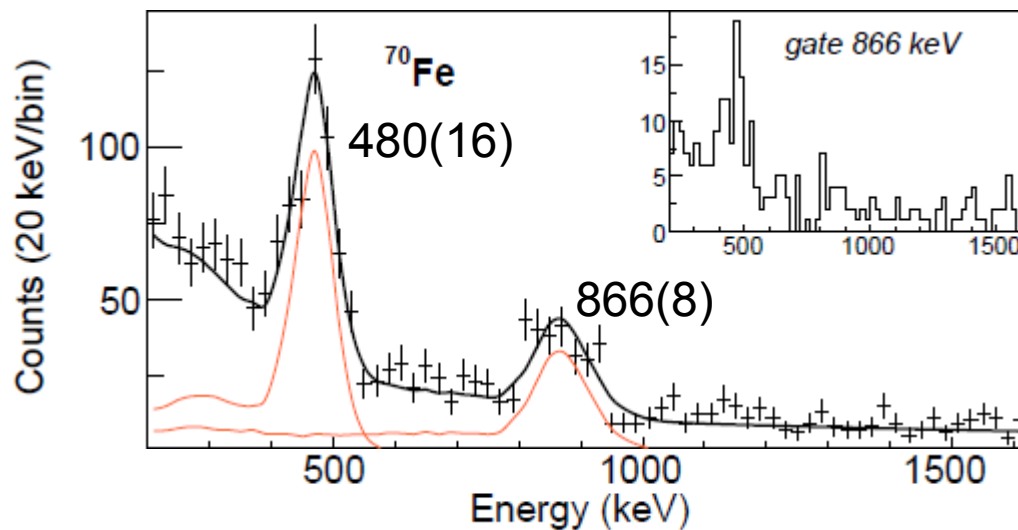


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C. Santamaria (CEA)



C. Louchart (TUD)



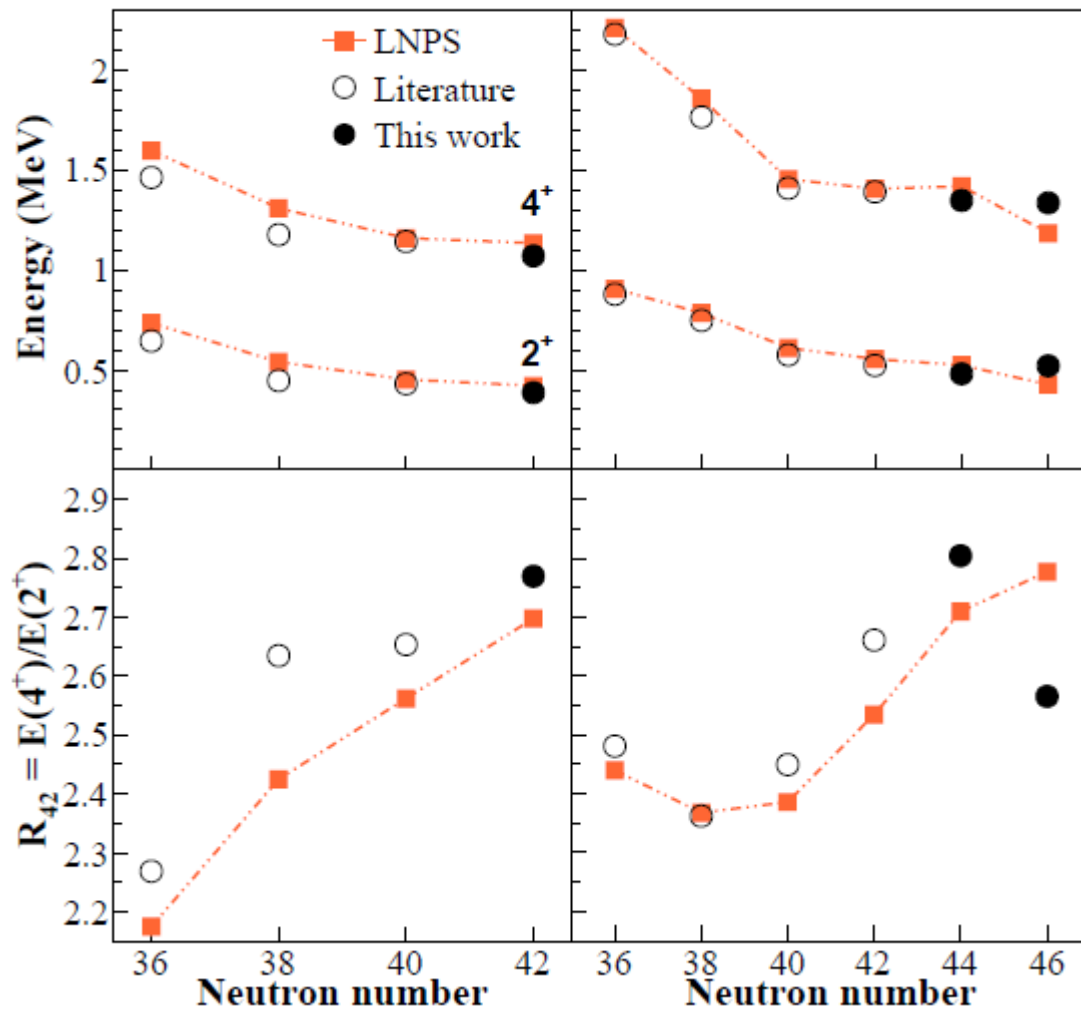
Collectivity between N=40-50



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Cr isotopes

Fe isotopes



Naive interpretation:

- $E(2^+)$ minimizes at N=44 - mid- $g_{9/2}$
- $R_{4/2}$ maximizes at N=44
- Decrease of collectivity toward N=50 starts beyond mid- $g_{9/2}$

Slightly modified LNPS → F. Nowacki, Strasbourg

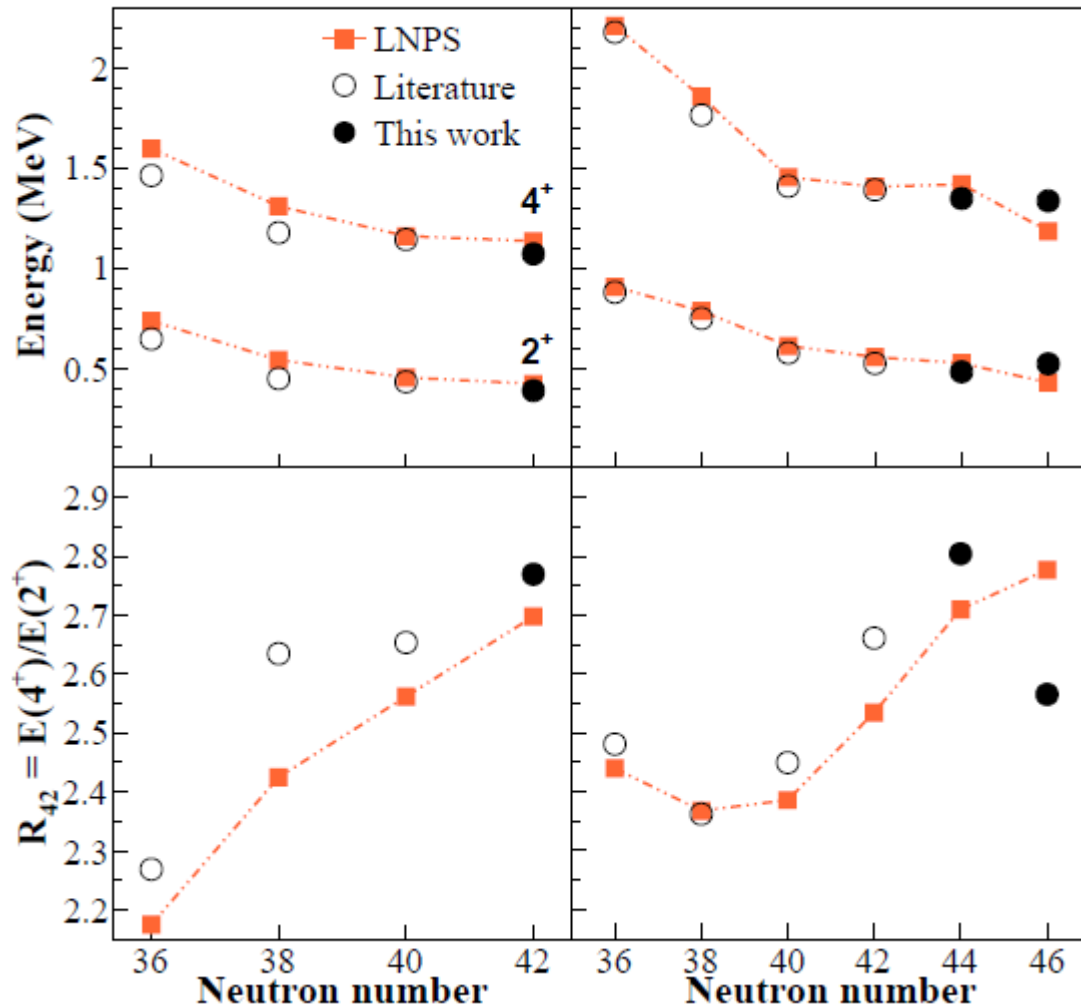
Collectivity between N=40-50



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Cr isotopes

Fe isotopes



Nucleus	$n^{\nu}(g_{9/2} + d_{5/2})$	0p0h	2p2h	4p4h	6p6h	$E_{Pairing}^*$
^{60}Cr	1.66	17	71	6	0	1.30
^{62}Cr	3.1	0	40	54	1	1.30
^{64}Cr	3.9	0	10	75	10	1.52
^{66}Cr	4.5	0	68	27	1	1.30
^{68}Cr	5.7	15	71	6	0	1.33

Shell Model:

- Maximum collectivity not reflected by minimum 2^+ energy
- $\langle H_{pair} \rangle$ maximizes at N=40
 - More np-nh excitations

Slightly modified LNPS → F. Nowacki, Strasbourg

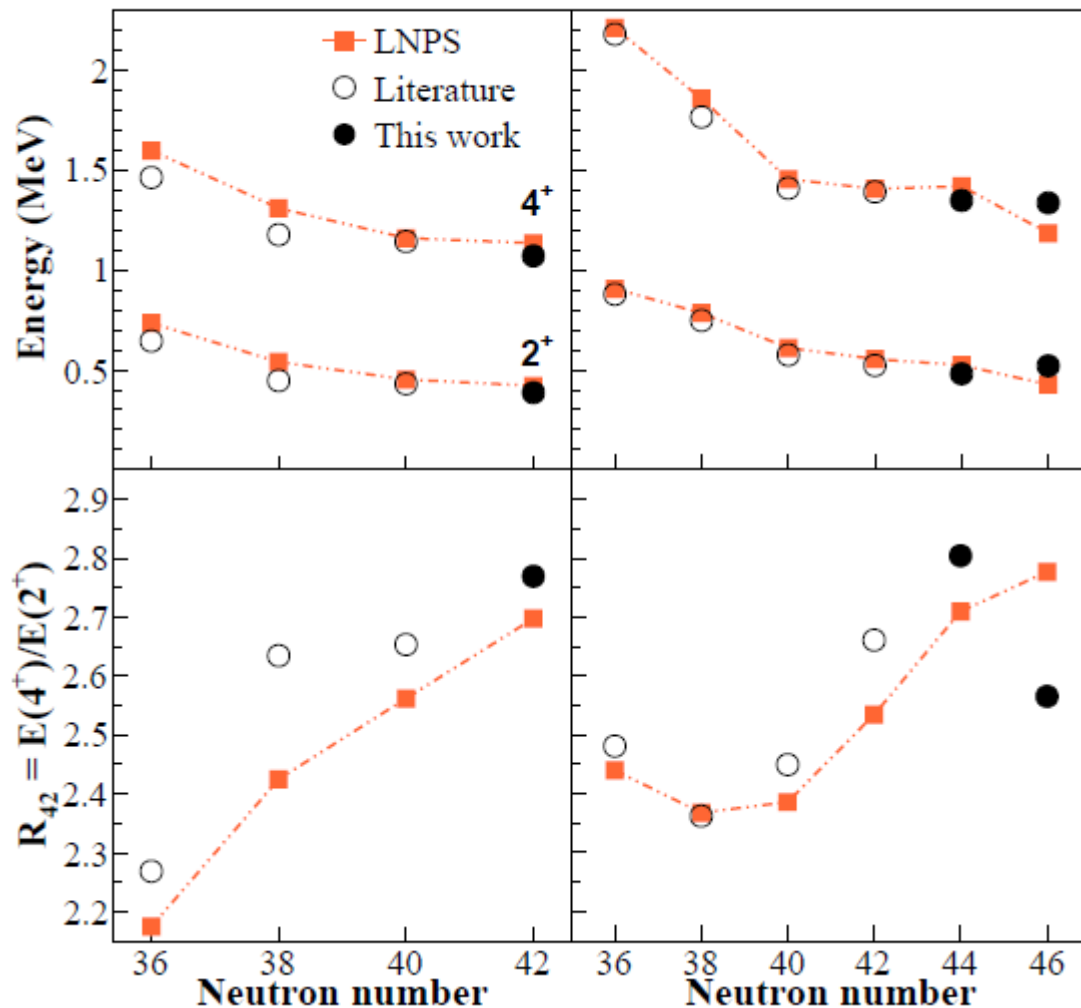
Collectivity between N=40-50



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Cr isotopes

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Shell Model:

- Maximum collectivity not reflected by minimum 2^+ energy
- $\langle H_{pair} \rangle$ maximizes at N=40
 - More np-nh excitations
- First attempt to fix ^{72}Fe :
 - 0p0h dominant (as opposed to N<46)
 - Enhance gd-gd monopole strength

Slightly modified LNPS → F. Nowacki, Strasbourg

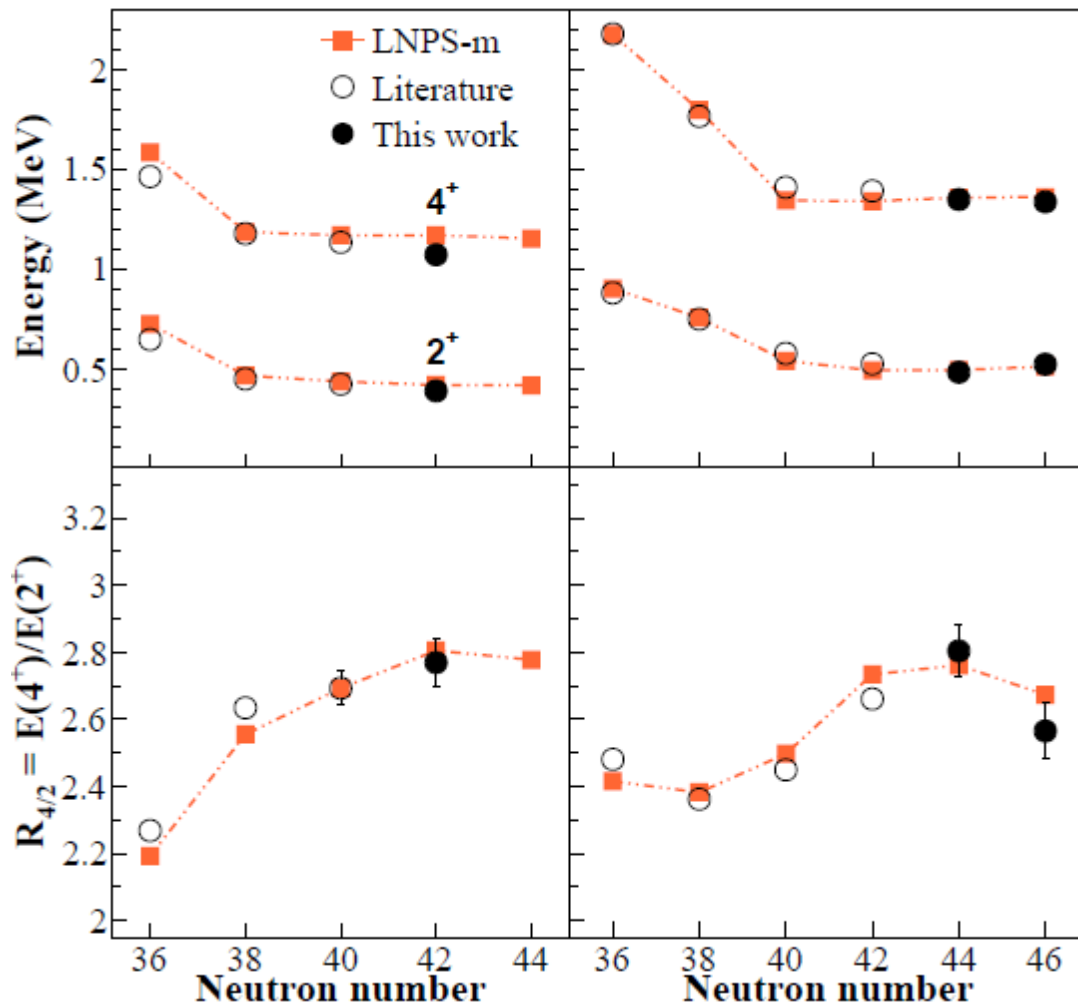
Collectivity between N=40-50



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Cr isotopes

Fe isotopes



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Shell Model:

- Maximum collectivity not reflected by minimum 2^+ energy
- $\langle H_{pair} \rangle$ maximizes at N=40
 - More np-nh excitations
- First attempt to fix ^{72}Fe :
 - 0p0h dominant (as opposed to N<46)
 - Enhance gd-gd monopole strength
 - min. $E(2^+)$ shifted to N=44, perfect agreement !

Slightly modified LNPS → F. Nowacki, Strasbourg

News on ^{78}Ni



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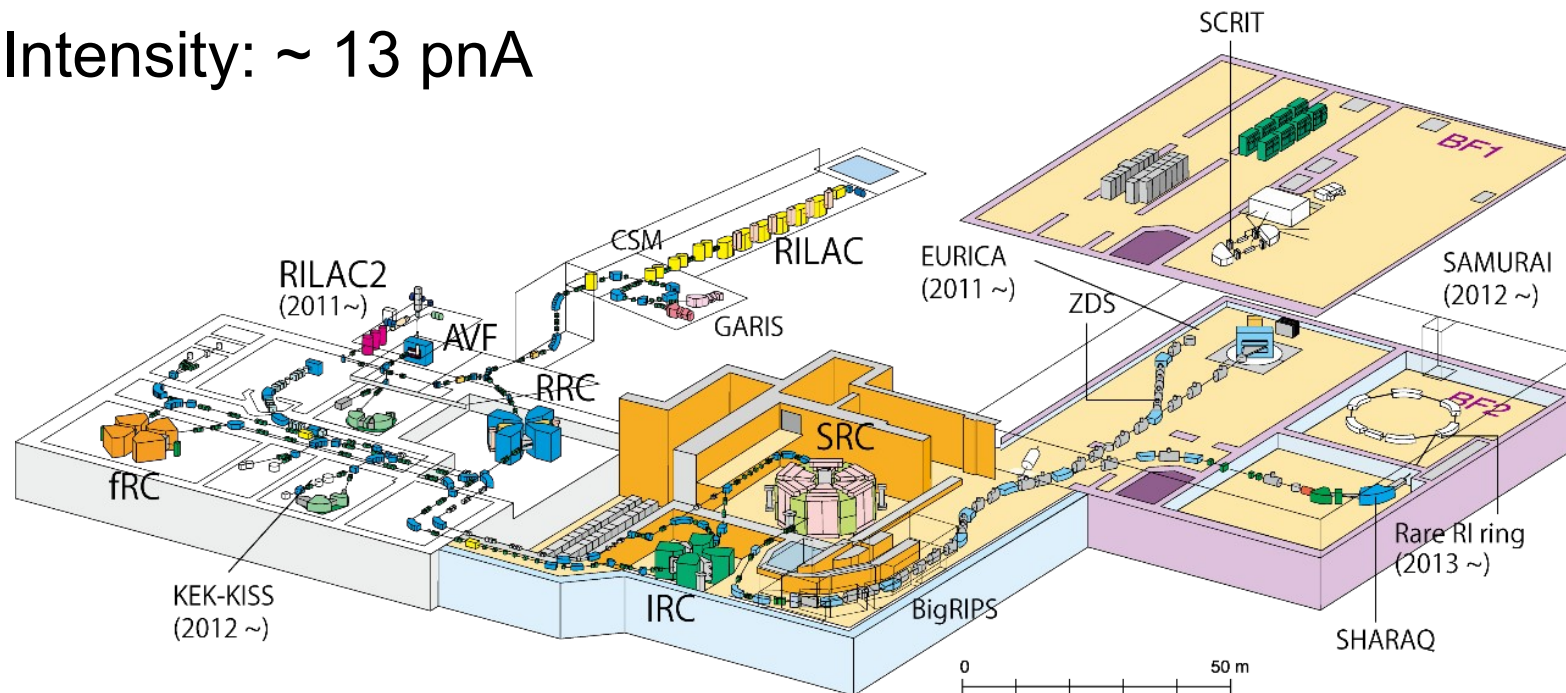
Experiment: for 6 days May 2014

^{238}U primary beam
Energy : 345 MeV/u



Main reaction:
 $^{79}\text{Cu}(p, 2p\gamma)^{78}\text{Ni}$

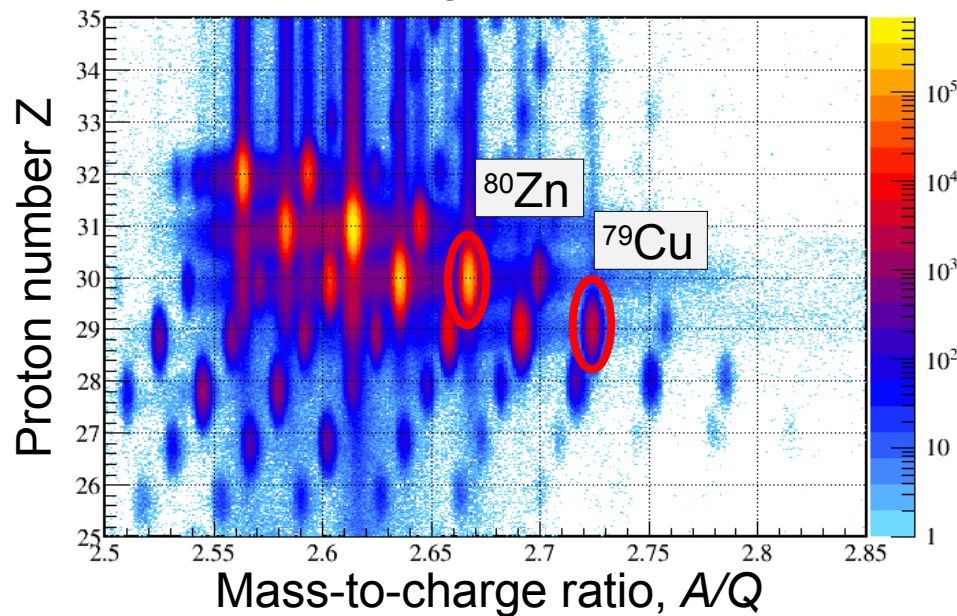
Intensity: ~ 13 pnA



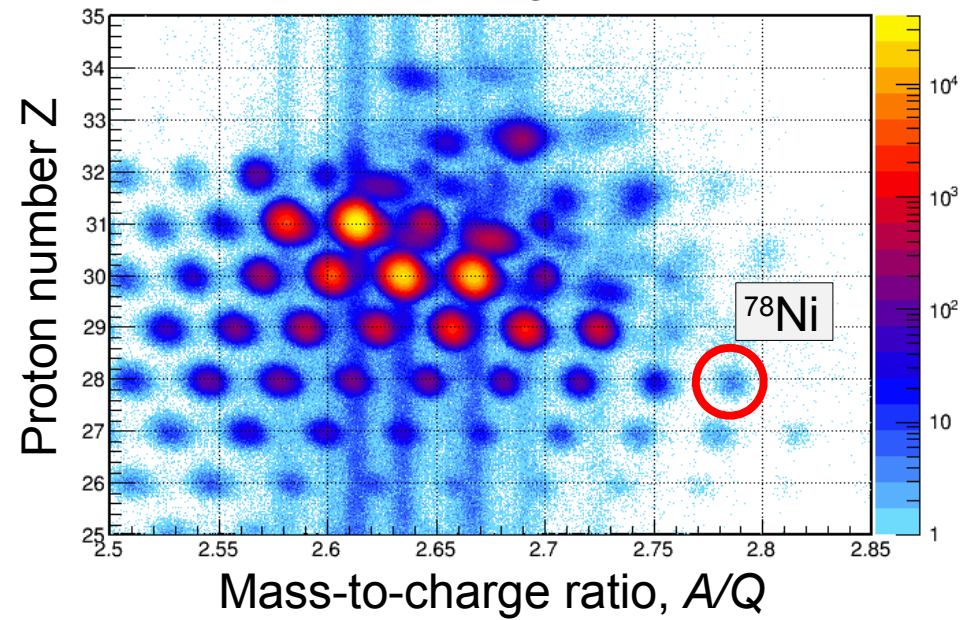
Coutesey R. Taniuchi (U Tokyo / RIKEN-RIBF)

PIDs for ^{78}Ni

BigRIPS



ZeroDegree



Typical BigRIPS rates:

$^{79}\text{Cu} \sim 6\text{-}7$ pps
[Purity $\sim 0.3\%$]

$^{80}\text{Zn} \sim 300$ pps
[Purity $\sim 15\%$]

Coincident events:

1p Knock out
 $^{79}\text{Cu} \rightarrow ^{78}\text{Ni} + \gamma \sim 690$ events

2p Knock out
 $^{80}\text{Zn} \rightarrow ^{78}\text{Ni} + \gamma \sim 530$ events

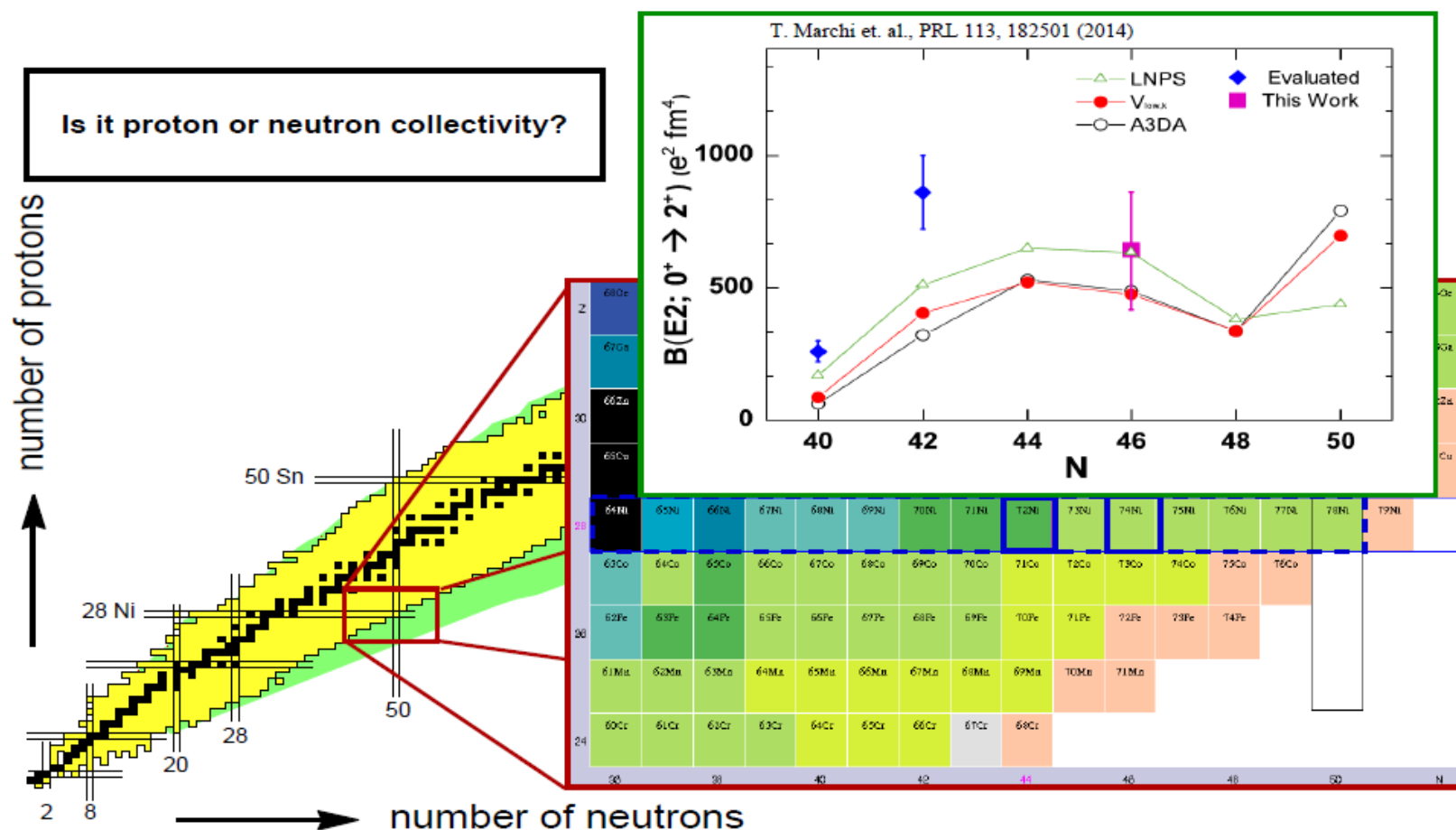
Coutesey R. Taniuchi (U Tokyo / RIKEN-RIBF)

By-Products Example: Inelastic Scattering around ^{78}Ni



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Collectivity of protons and neutrons



M.L. Cortes (TU Darmstadt)

(p,p') Deformation Lengths vs. Deformation from CoulEx



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Proton and neutron collectivity

$$\frac{M_n}{M_p} = \frac{N}{Z} \left[\frac{\delta_{p,p'}}{\delta_C} + \frac{Zb_p}{Nb_n} \left(\frac{\delta_{p,p'}}{\delta_C} - 1 \right) \right]$$

[A. M. Bernstein, V. R. Brown, and V. A. Madsen, Phys. Lett. B103, 255 (1981).]

$$\text{If } \delta_{p,p'} = \delta_C \rightarrow M_n/M_p = N/Z$$

For ^{74}Ni :

$$\delta_C = 0.78 \pm 0.13 \text{ fm} \quad \delta_{p,p'} = 1.04 \pm 0.16 \text{ fm}$$

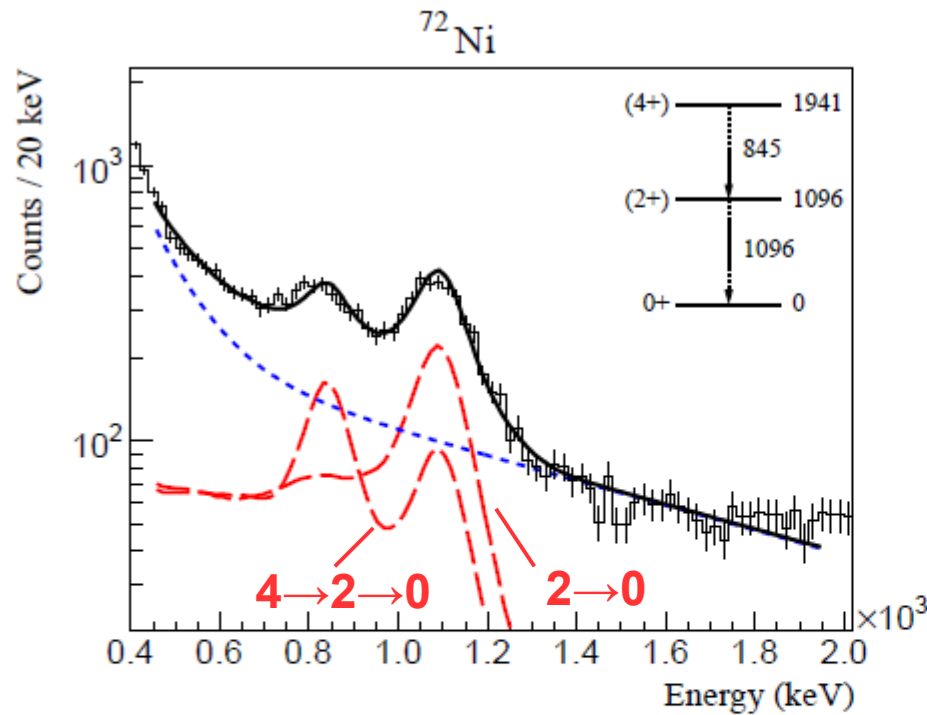
[T. Marchi, et. al., PRL 113, 182501 (2014)]

[N. Aoi, et. al., PLB 692, 302 (2010)]

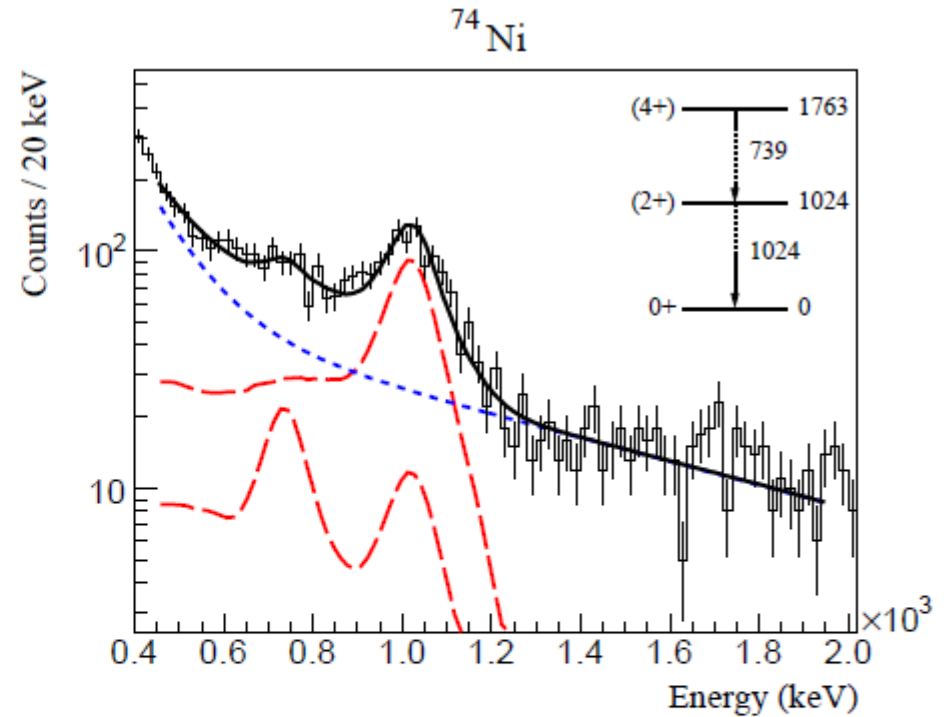
$$\frac{M_n}{M_p} = 2.4 \pm 0.8$$

M.L. Cortes (TU Darmstadt)

(p,p') Deformation Lengths vs. Deformation from CoulEx



- Error from the fit
- 6% error in DALI2 efficiency
- 2% error in target thickness



$$\sigma_{p,p'} = 3.8 \pm 0.5 \text{ mb for } ^{72}\text{Ni}$$

$$\sigma_{p,p'} = 4.3 \pm 0.6 \text{ mb for } ^{74}\text{Ni}$$

M.L. Cortes (TU Darmstadt)

(p,p') Deformation Lengths vs. Deformation from CoulEx

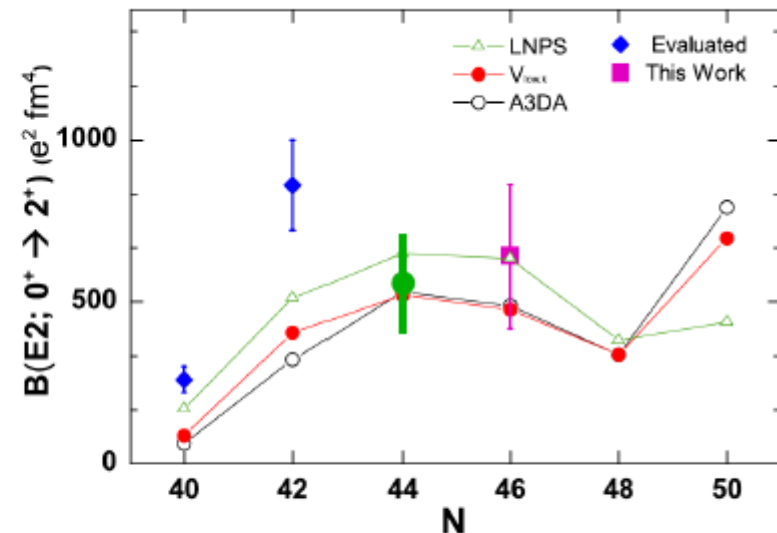


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- ▶ Using the same parameters:

$$M_n/M_p = 2.2 \pm 0.6$$

- ▶ Assuming the same ratio of deformation length for ^{72}Ni :



$$B(E2; 0^+ \rightarrow 2^+) = 610 \pm 152 \text{ e}^2\text{fm}^4$$

- Now extracting M_n/M_p For several Ni and Zn isotopes
- Work on optical potentials (RIKEN), mean-field formalism (CEA)

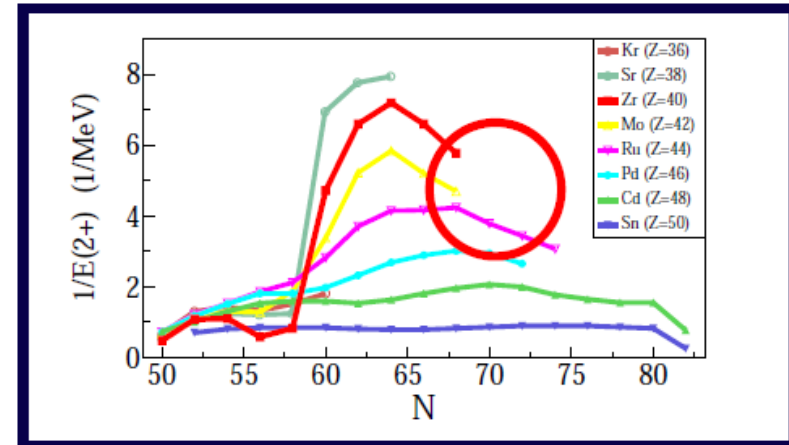
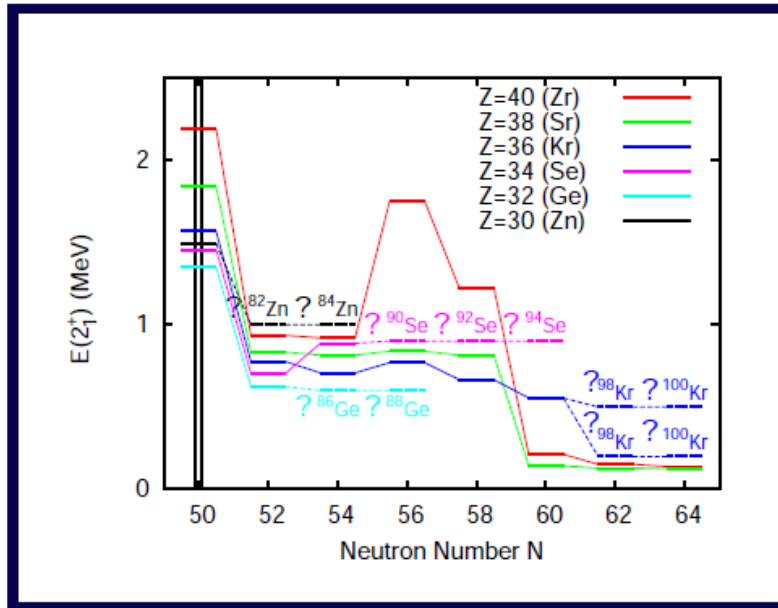
M.L. Cortes (TU Darmstadt)

Campaign 2: April/May 2015

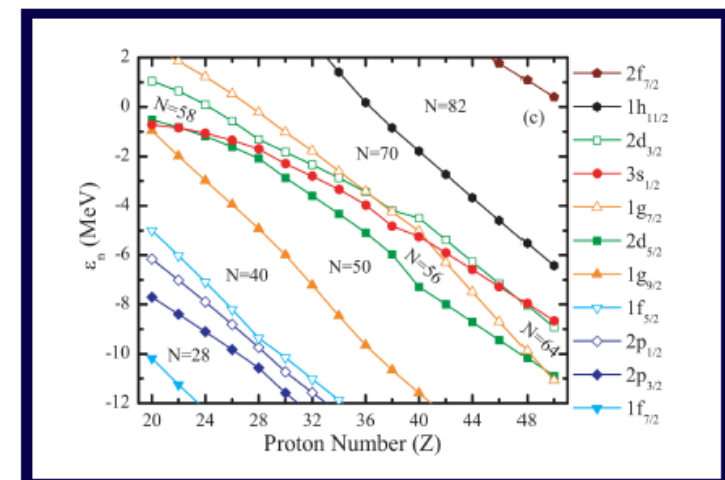


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Courtesy P. Doornenbal, PAC 12/2013



- ☐ **Surrey/GSI** **RIKEN**
Orbital migration beyond $N = 50$ ($^{82-84}\text{Zn}$, $^{86,88}\text{Ge}$, $^{90,92}\text{Se}$)
 – Possible $N = 56, 58$ sub-shell closures
 – Lowering of the $s_{1/2}$ orbital when approaching $Z = 28$?
TUDA
- ☐ **Orsay**
Rise in collectivity at $N \geq 60$ (^{94}Se , $^{98,100}\text{Kr}$)
- ☐ **Saclay**
Evidence for a $N = 70$ sub-shell effect (^{110}Zr)



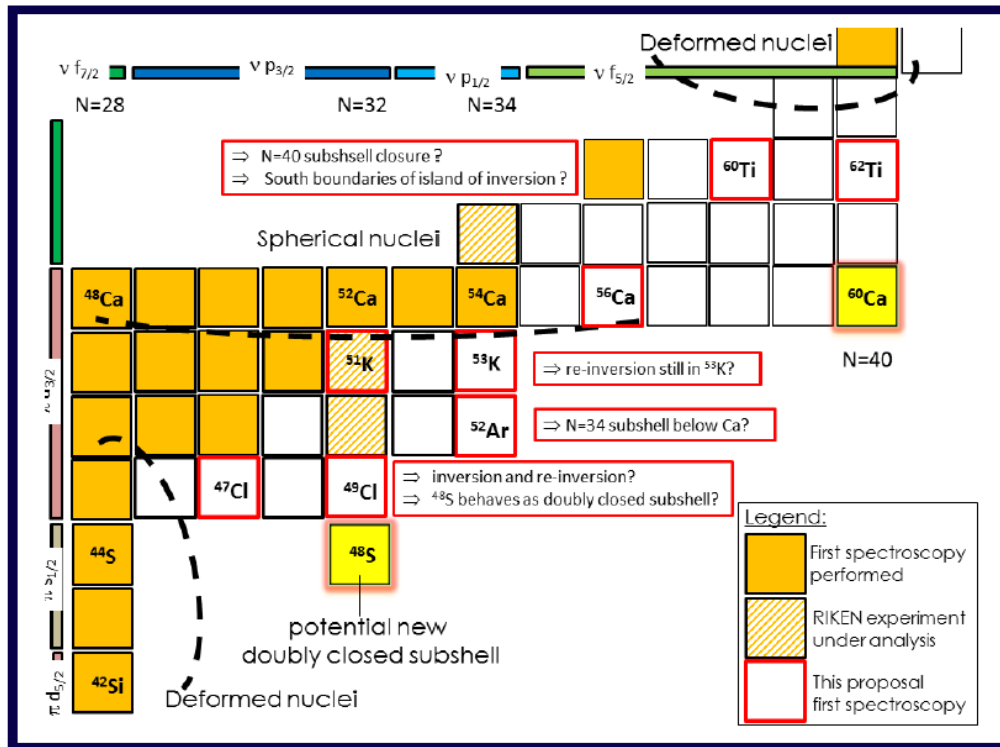
+ EURICA isomer decay data available: Se-Kr (**TUDA, IFIN-HH, RIKEN**)

Campaign 3 Plans

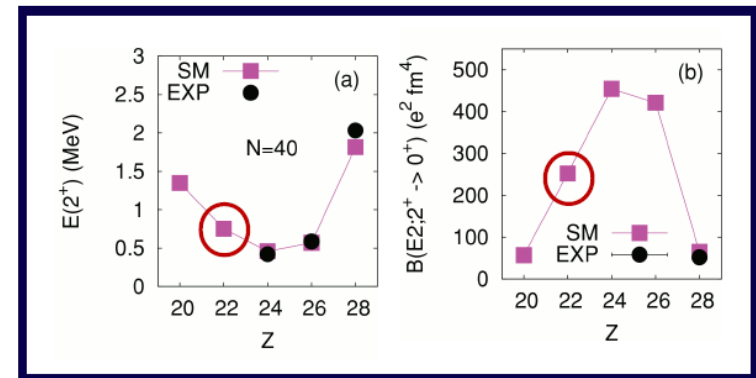
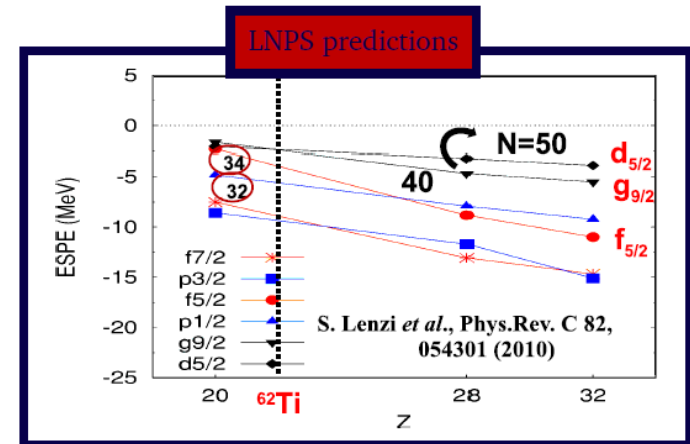
^{70}Zn primary beam



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- 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" ($^{60,62}\text{Ti}$)



$N = 32, 34$ shell gaps with SDPF-MU

	Ti	Ca	Ar
$N = 32$	2.54 MeV	2.43 MeV	2.27 MeV
$N = 34$	1.77 MeV	2.64 MeV	3.13 MeV

SEASTAR Collaboration



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- Preparations for γ -spectroscopy @ FAIR:
 - *use of liquid-hydrogen target at RIKEN-RIBF*
(similar conditions as at FAIR, lower energies/intensities)
- Charting the Nuclear Chart
 - **SEASTAR** will *guide future experiments*
 - Test stage for **Physics** and future FAIR **Instrumentation**
 - First SEASTAR results: **Cr/Fe** collectivity toward N=50
 - Preliminary: 2_1^+ state in ^{78}Ni confirms double-magicity
 - **Inelastic scattering**: test of neutron/proton contributions

Thank you !



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