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AGATA@RIBF

P. Doornenbal, T. Motobayashi, M. Niikura, S. Nishimura,
A. Obertelli, H. Sakurai, and T. Uesaka

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Outline

RIBF

In-beam Spectroscopy at RIBF

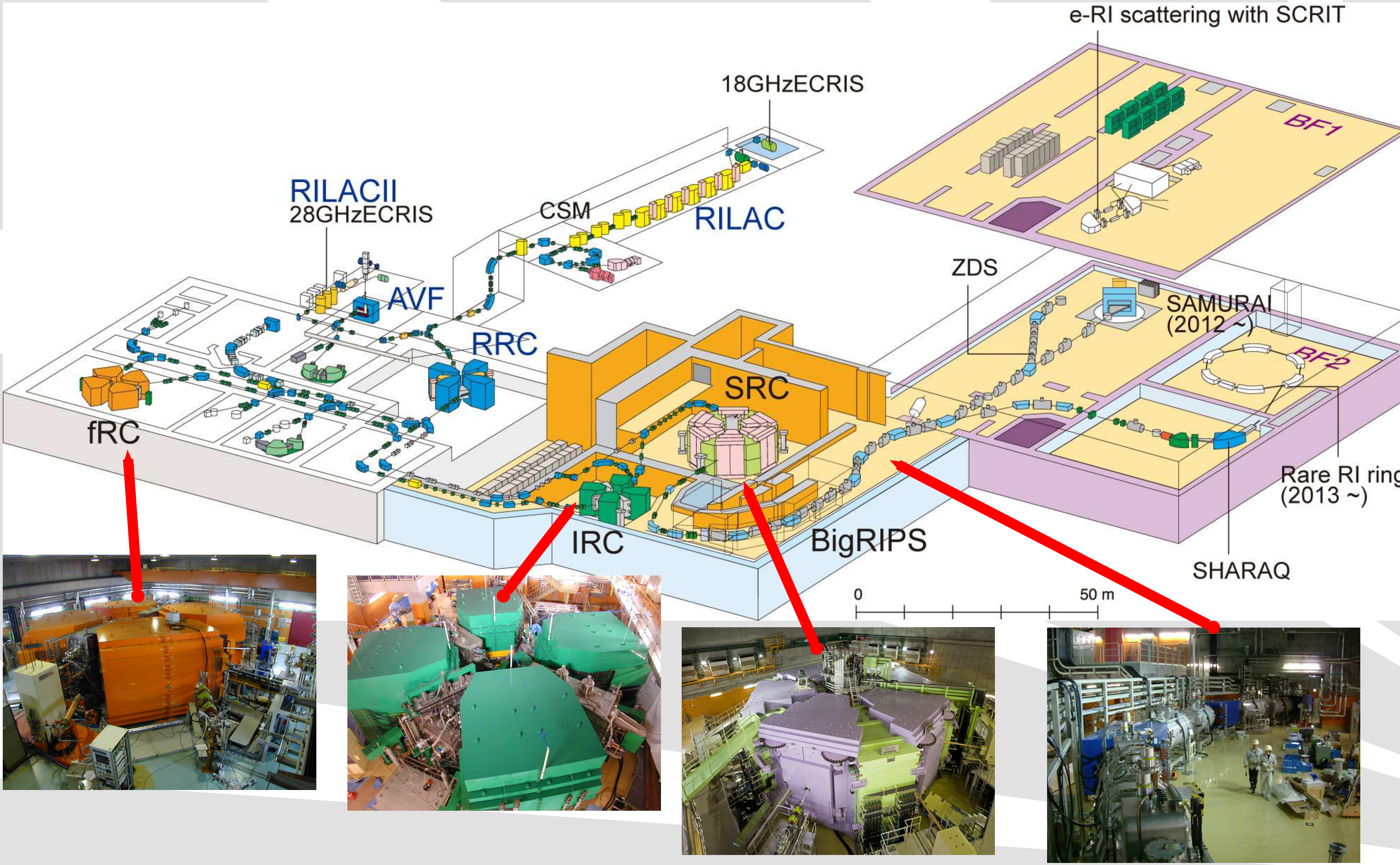
AGATA@RIBF

Summary

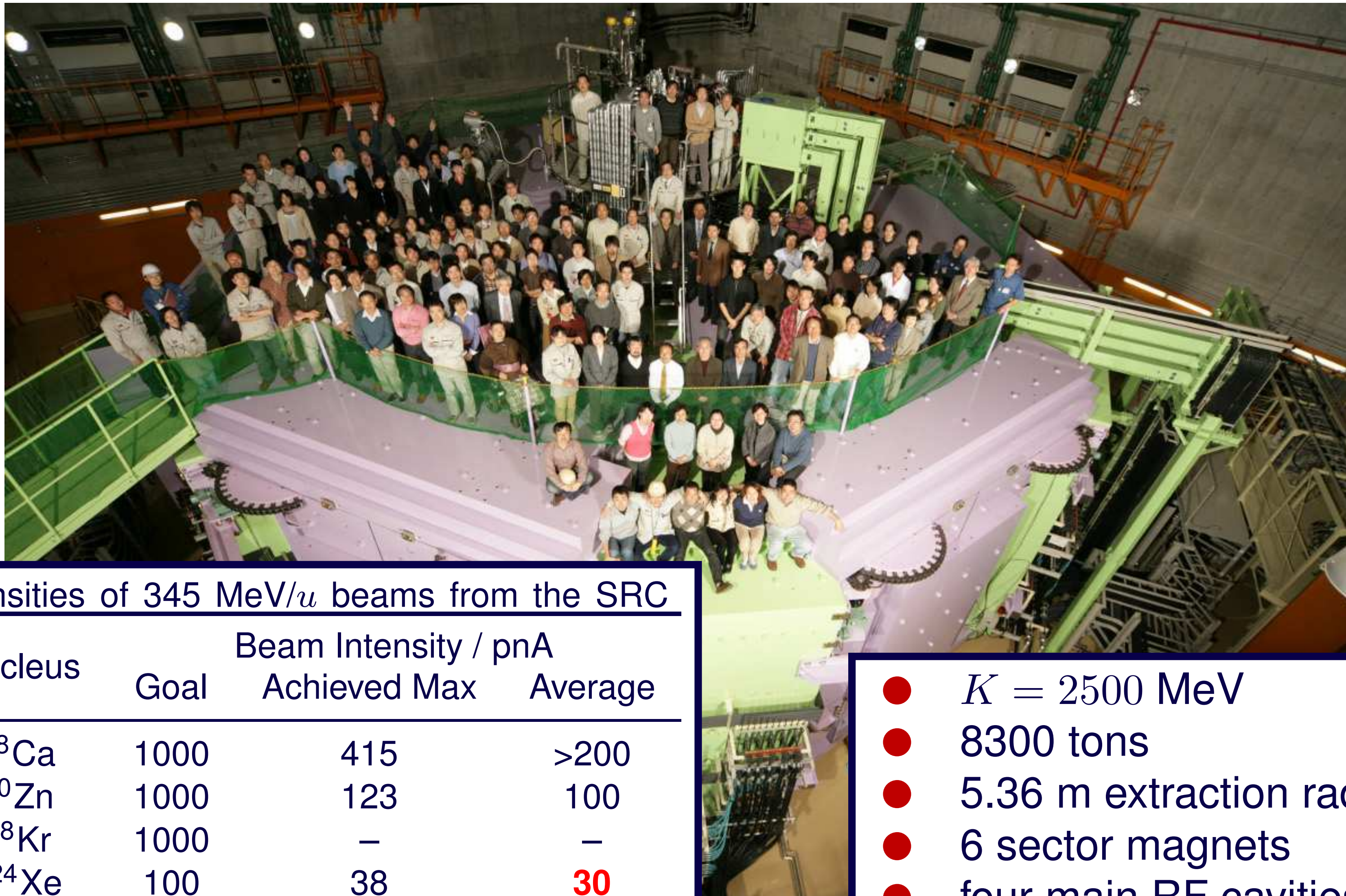
- In-beam γ-ray spectroscopy at RIBF
  - BigRIPS, ZeroDegree
  - DALI2, F8 area
- Example results
- AGATA@RIBF
  - Physics Case
  - Organizational points

Overview of the RIBF

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	415	>200
^{70}Zn	1000	123	100
^{78}Kr	1000	–	–
^{124}Xe	100	38	**30**
^{238}U	100	25	**15**

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

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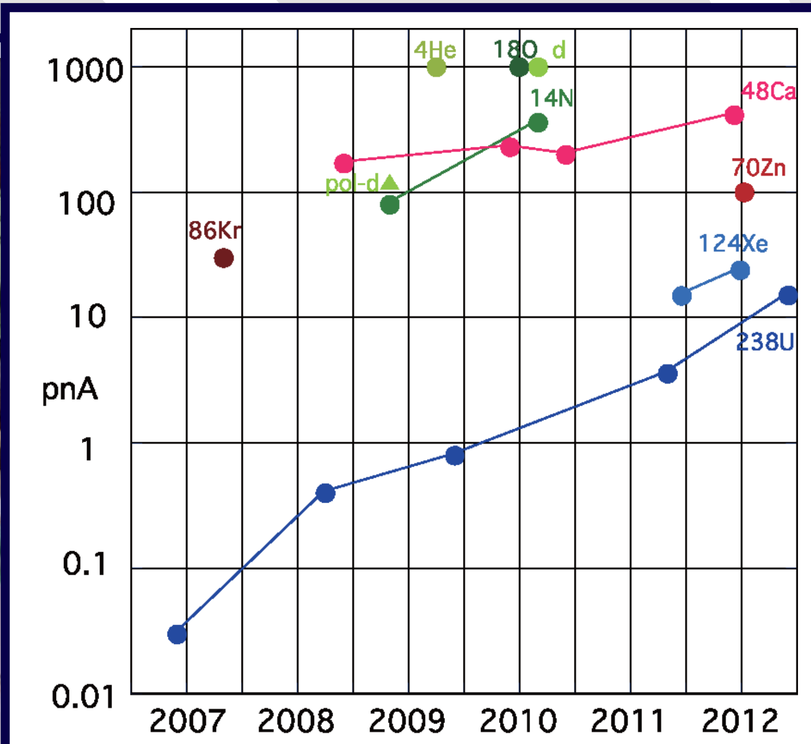

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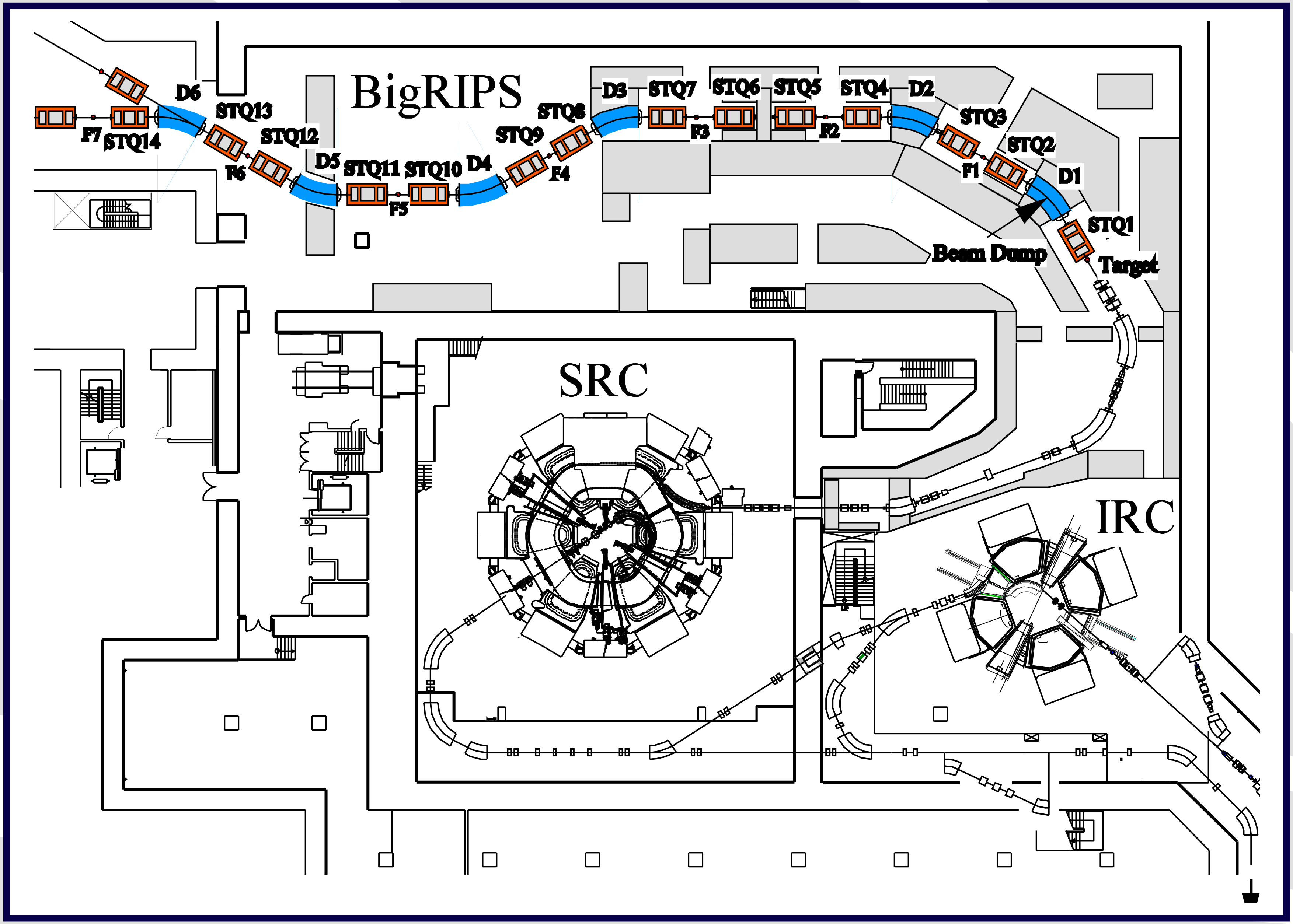
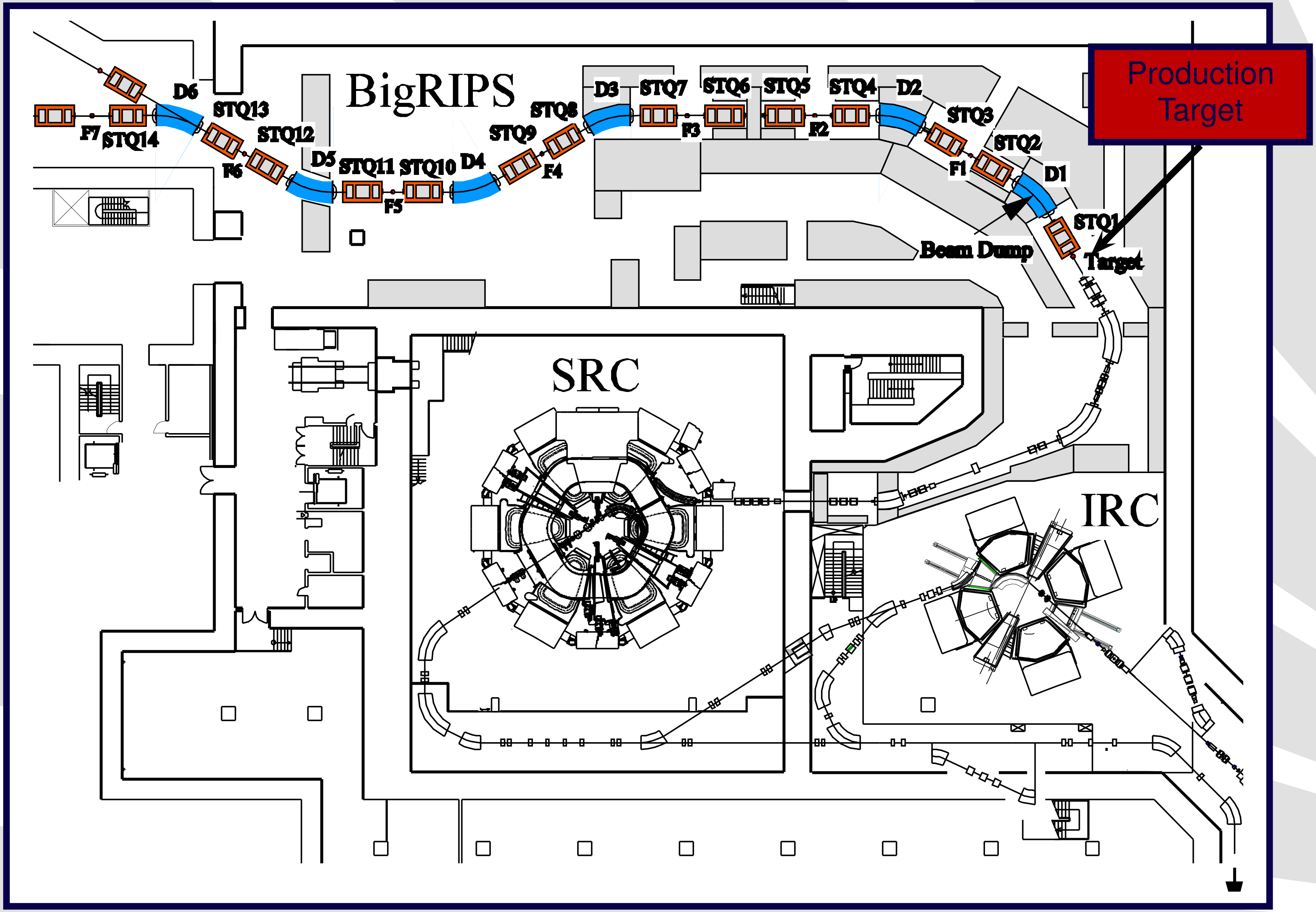
BigRIPS Overview



BigRIPS Overview



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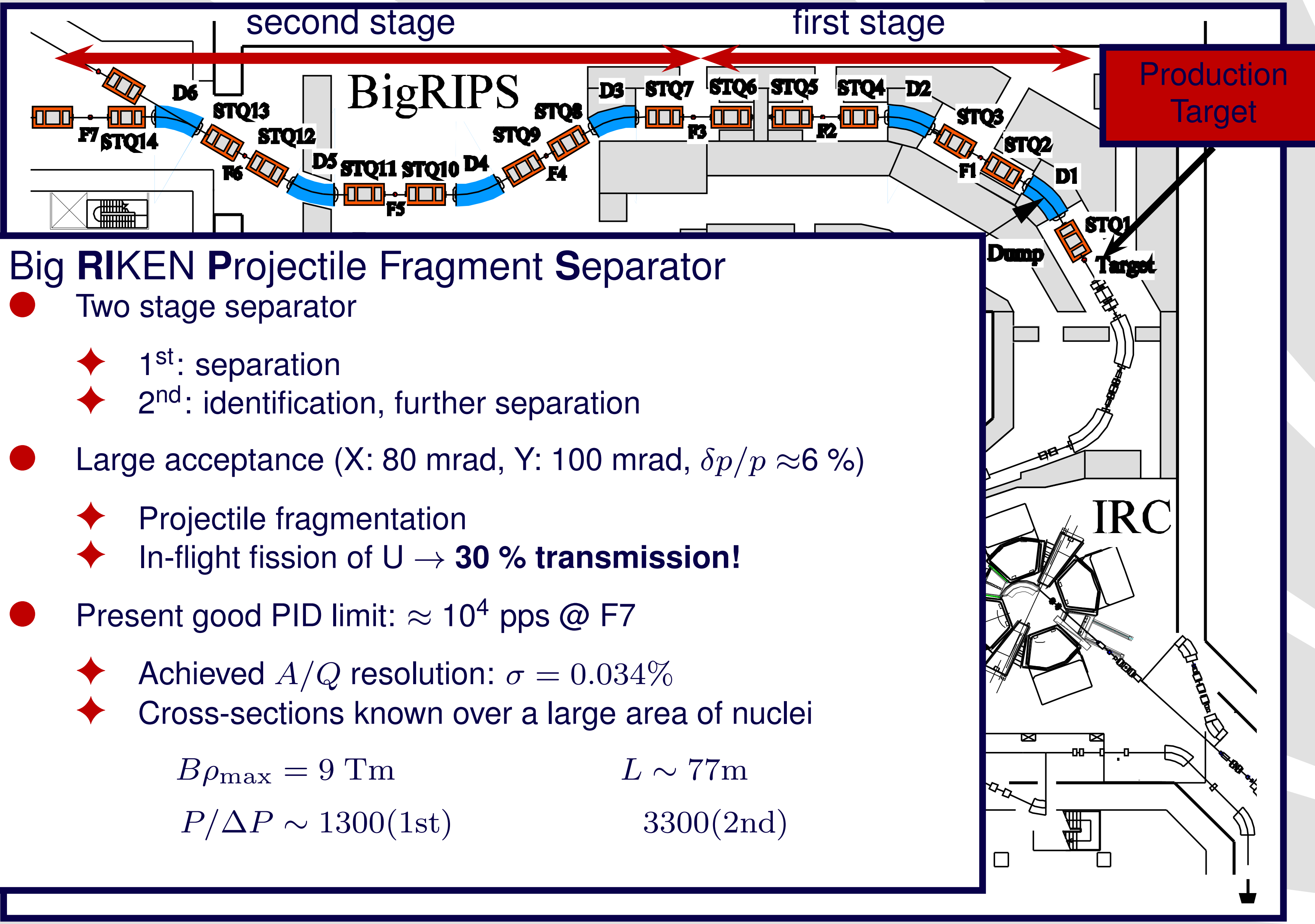


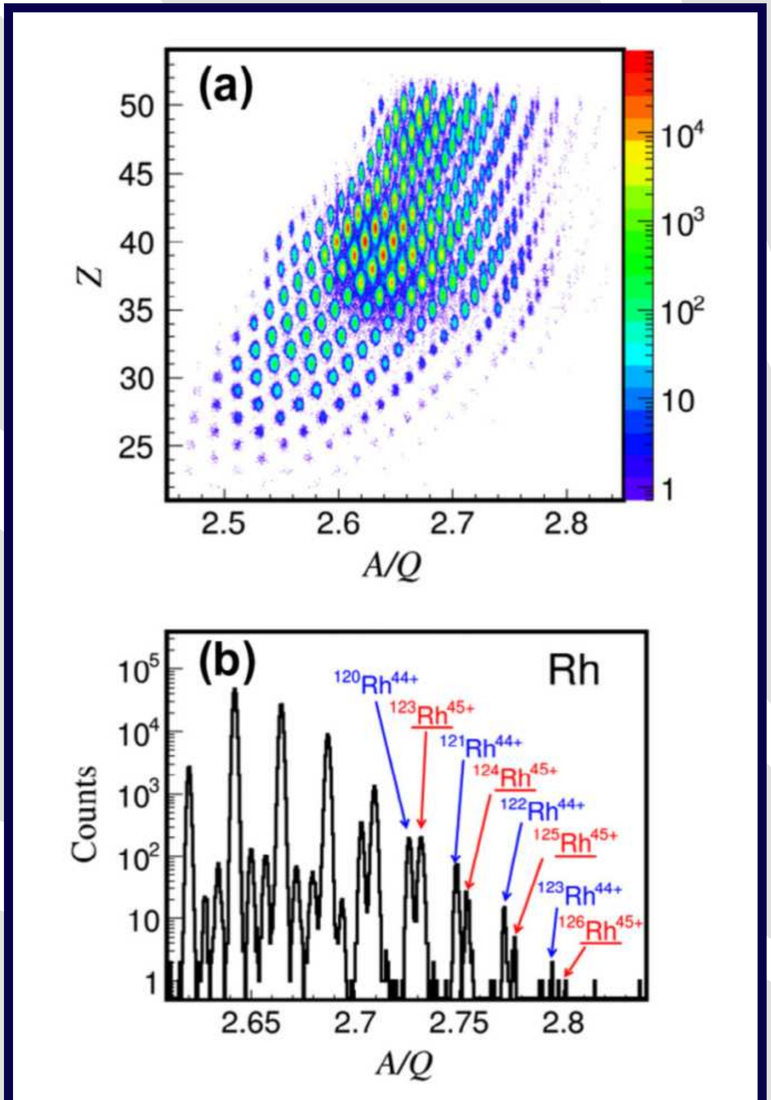
Big **RI**KEN **P**rojectile Fragment **S**eparator

- Two stage separator
  - 1st: separation
  - 2nd: identification, further separation
- Large acceptance (X: 80 mrad, Y: 100 mrad, $\delta p/p$ ≈6 %)
  - Projectile fragmentation
  - In-flight fission of U $\rightarrow$ **30 % transmission!**
- Present good PID limit: $\approx 10^4$ pps @ F7
  - Achieved A/Q resolution: $\sigma = 0.034\%$
  - Cross-sections known over a large area of nuclei

$B\rho_{\max} = 9$ Tm $\qquad L \sim 77$m

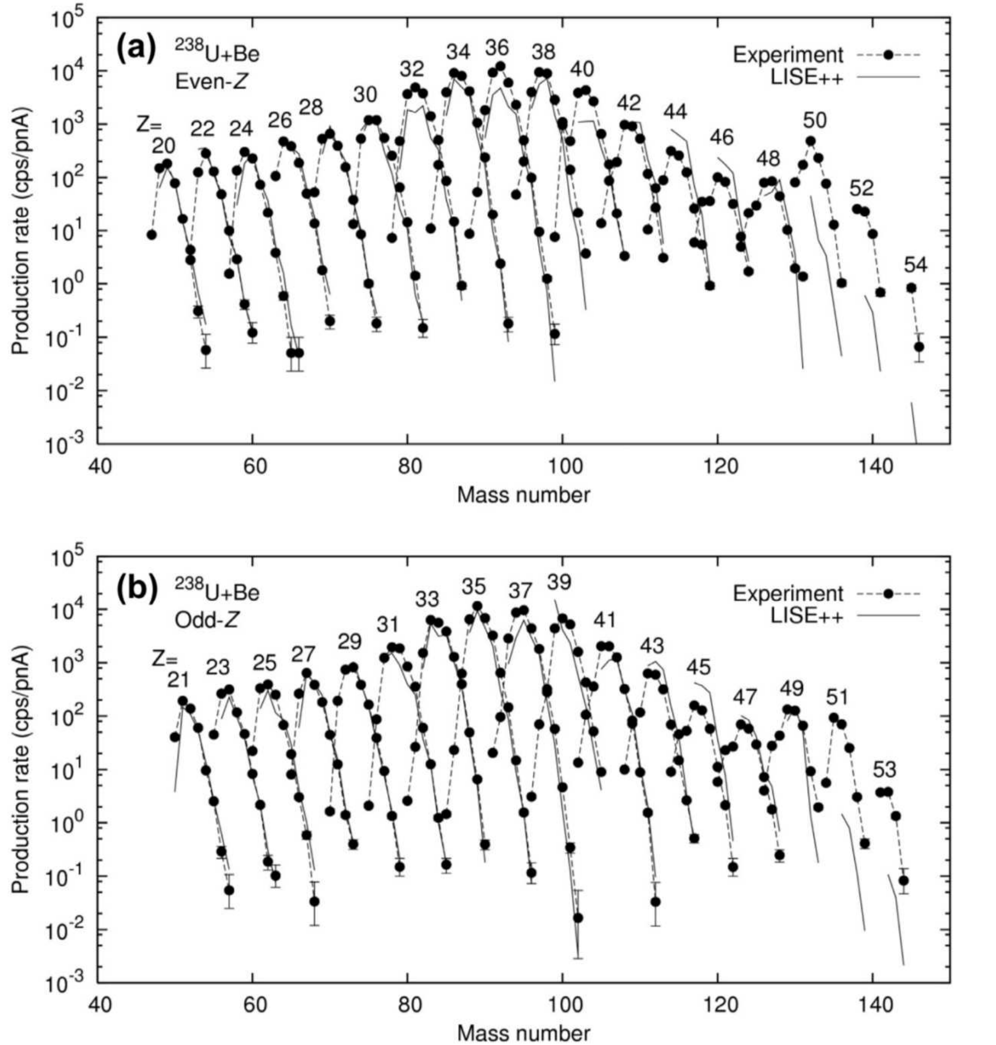
$P/\Delta P \sim 1300$(1st) $\qquad 3300$(2nd)

BigRIPS Overview

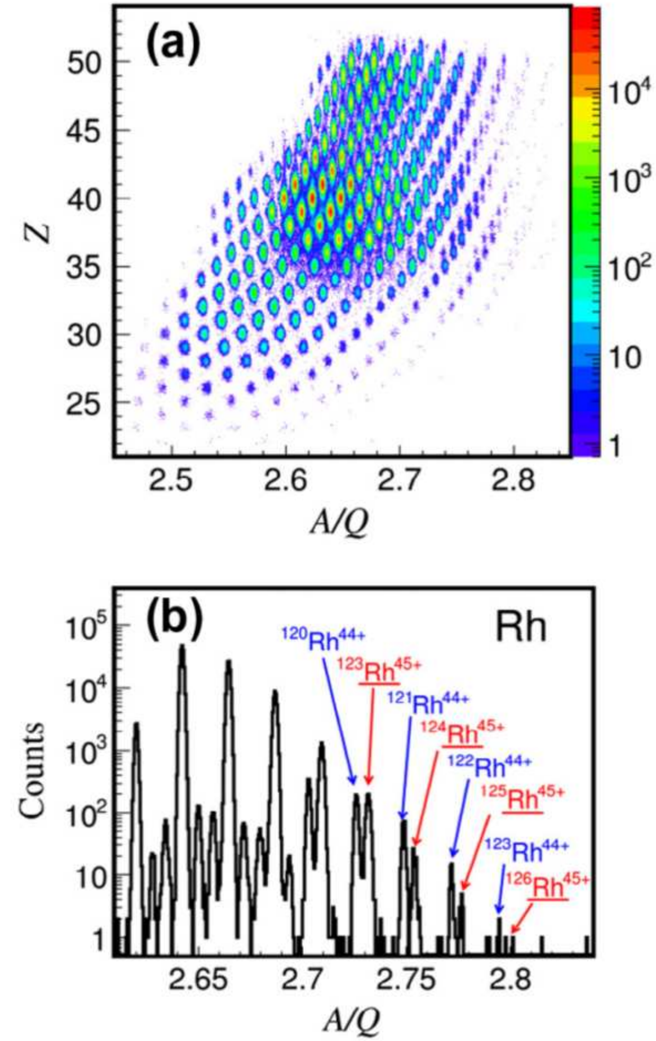


N. Fukuda *et al.*, NIMB 317, 323 (2013)

BigRIPS Overview

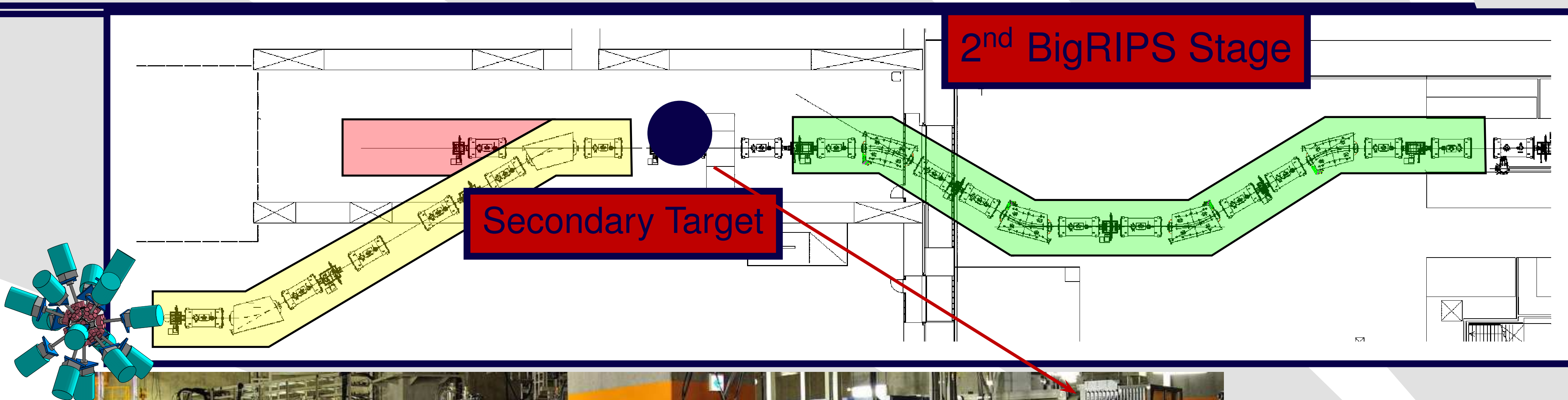


H. Suzuki *et al.*, NIMB 317, 756 (2013)



N. Fukuda *et al.*, NIMB 317, 323 (2013)

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)

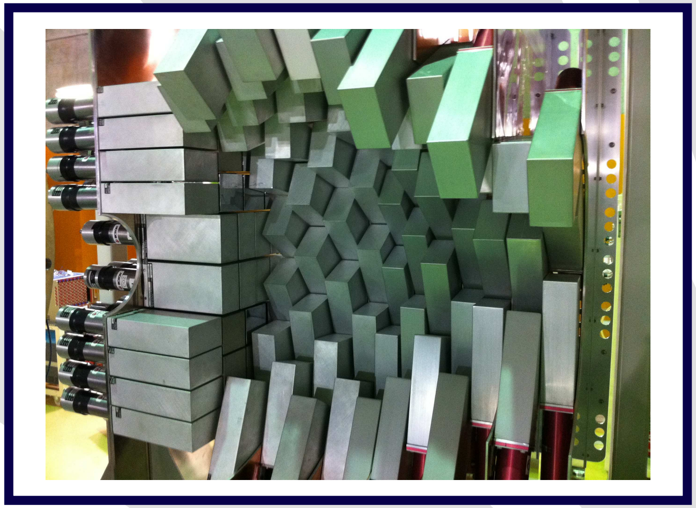
~ 3 m between Q-poles

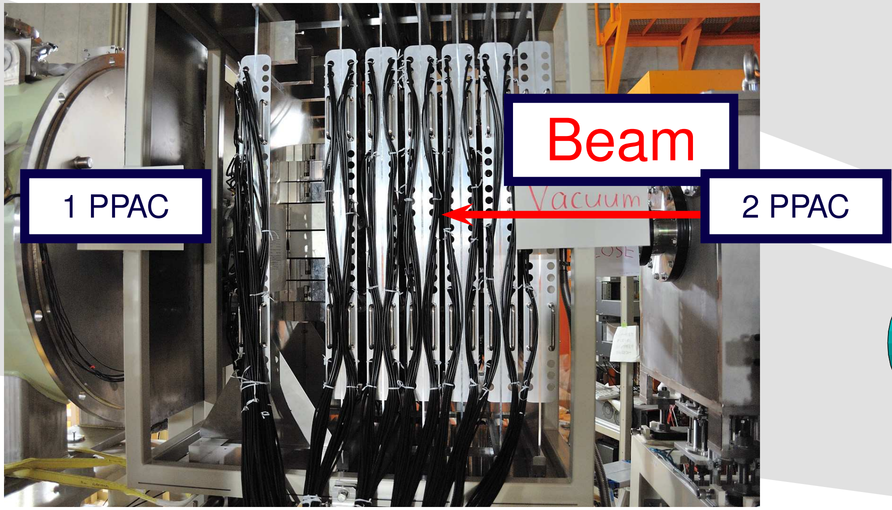
- DALI2 array, 186 NaI(Tl)
- GRAPE HPGe array
- $E_{\text{beam}} \sim 100 - 250$ MeV/u

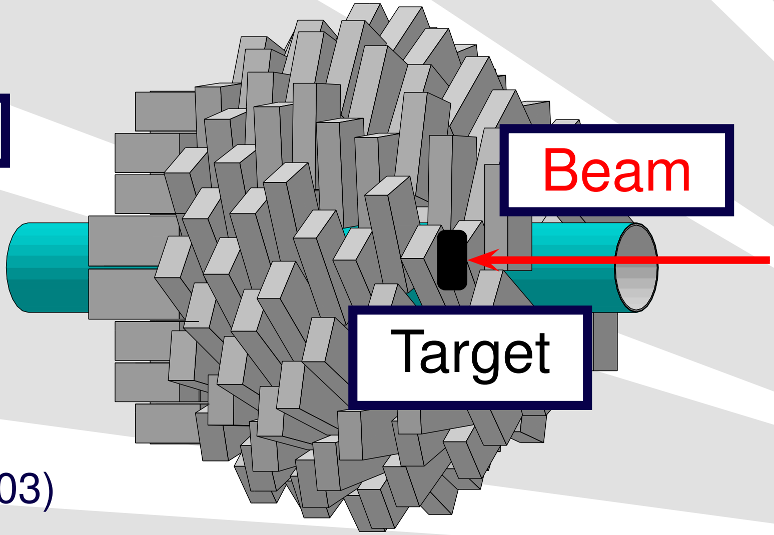
In-Beam γ-Ray Spectroscopy at the RIBF

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, $\sigma_\vartheta = 5$ mrad
- 1mm Pb (+1mm Sn) shielding







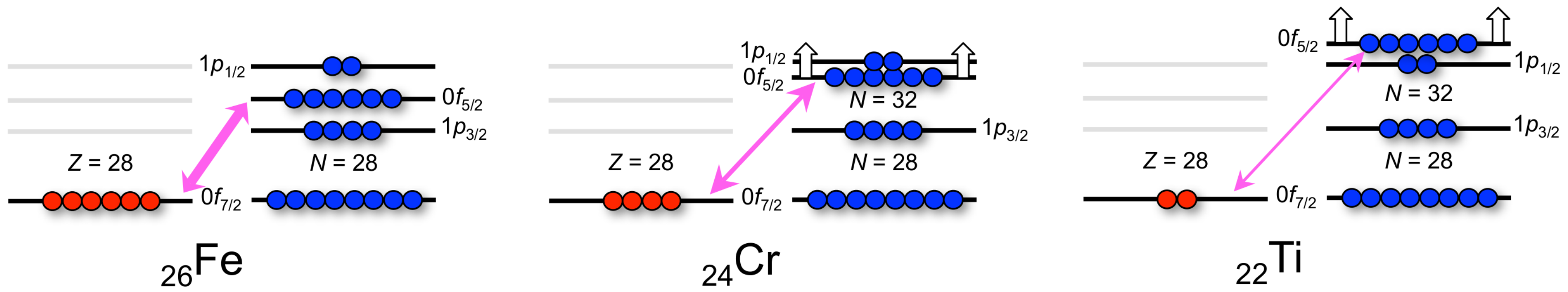
S. Takeuchi *et al.*, RIKEN Pr. Rep. 36, 148 (2003)

Evolution in fp Shell for Neutron-Rich Nuclei

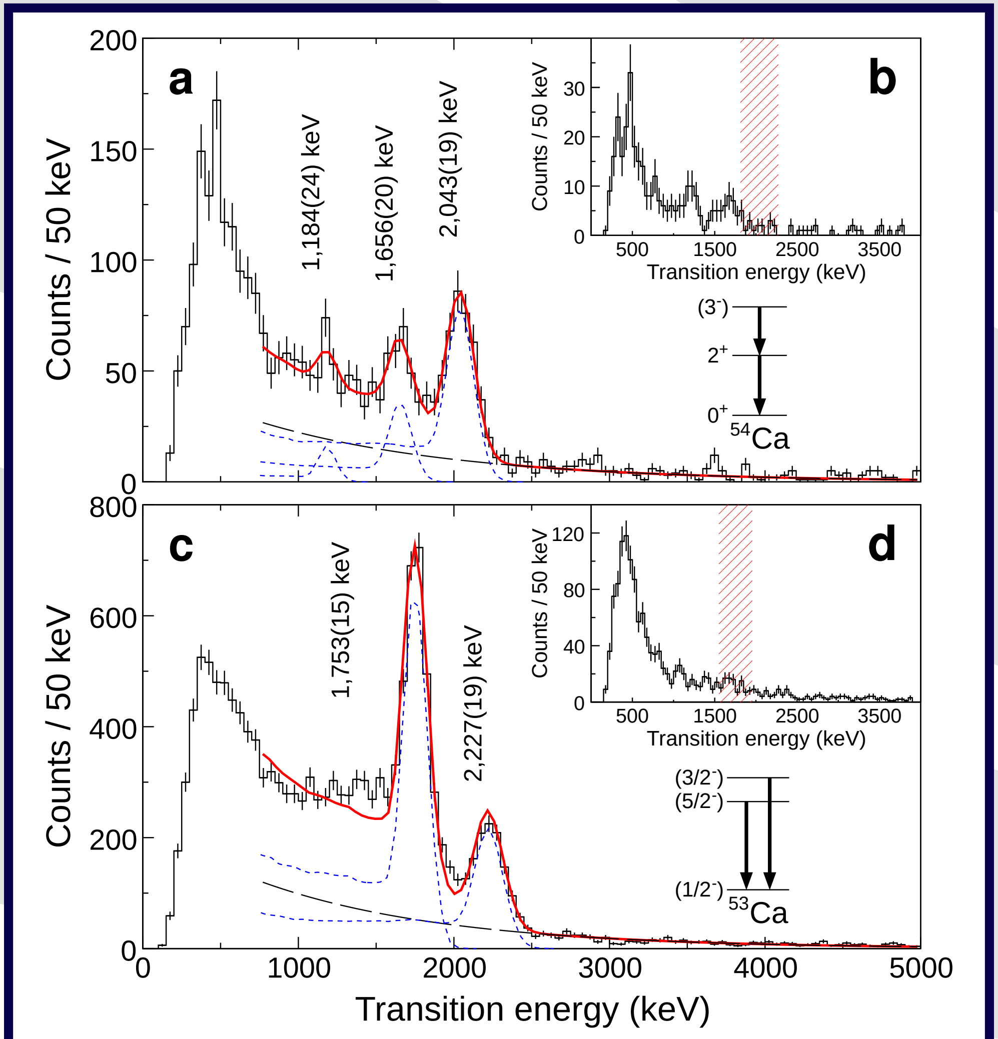
- Neutron-rich *fp* shell (bounded by $Z = 20 - 28$ and $N = 28 - 40$)
- Attractive interaction between $\pi 1f_{7/2}$ and $\nu 1f_{5/2}$ orbitals is important [1]; responsible for some features of nuclear shell evolution in this mass region

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

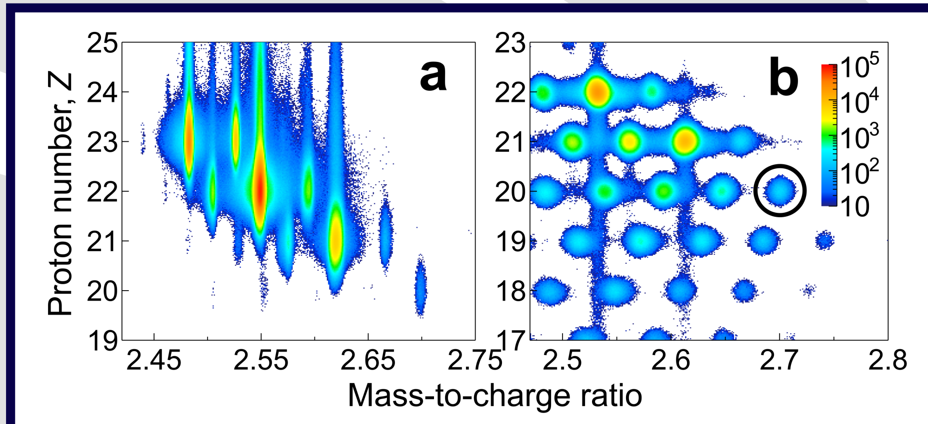
- As protons are removed from the $\pi f_{7/2}$ orbital (i.e., from $_{28}$Ni to $_{20}$Ca) the strength of the π-ν interaction weakens, causing the $\nu f_{5/2}$ orbital to shift up in energy relative to $\nu p_{1/2}$ and $\nu p_{3/2}$



In-Beam γ-Ray Spectra of ^{53,54}Ca

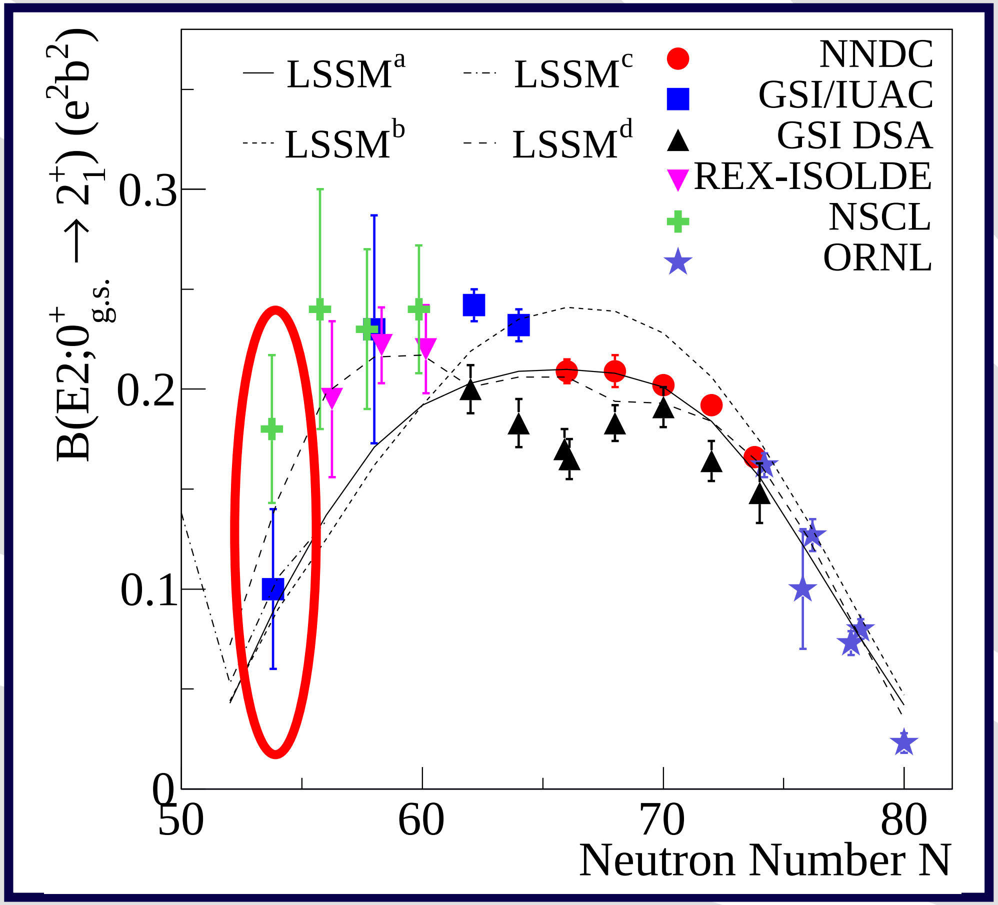


- ^{70}Zn, 60 pnA primary beam
- Be(^{55}Sc,^{54}Ca*), Be(^{56}Ti,^{54}Ca*)
- F8 target: ^{9}Be, 1.85 g/cm^2
- 124 pps/pnA ^{56}Ti
- 12 pps/pnA ^{55}Sc
- **40 hours data taking**
- $E(2_1^+)$ at 2043(19) keV in ^{54}Ca



^{53}Ca: 2200(1) keV level observed, F. Perrot *et al.*, PRC **74**, 014313 (2006)
D. Steppenbeck, S. Takeuchi *et al.*, Nature 502, 207 (2013)

$B(E2)\uparrow$ Systematics in the Sn Isotopes



^{104}Sn GSI, $B(E2)\uparrow$ relative to ^{112}Sn: G. Guastalla *et al.*, PRL 110, 172501

^{104}Sn NSCL, $B(E2)\uparrow$ relative to ^{102}Cd: V. M. Bader *et al.*, PRC 88, 051301(R) (2013)

LSSM^a: ^{100}Sn core, $e_\nu = 1.0e$, A. Banu *et al.*, PRC 72, 061305(R) (2005)

LSSM^b: ^{90}Zr core, $e_\nu = 0.5e$, $e_\pi = 1.5e$, A. Banu *et al.*, PRC 72, 061305(R) (2005)

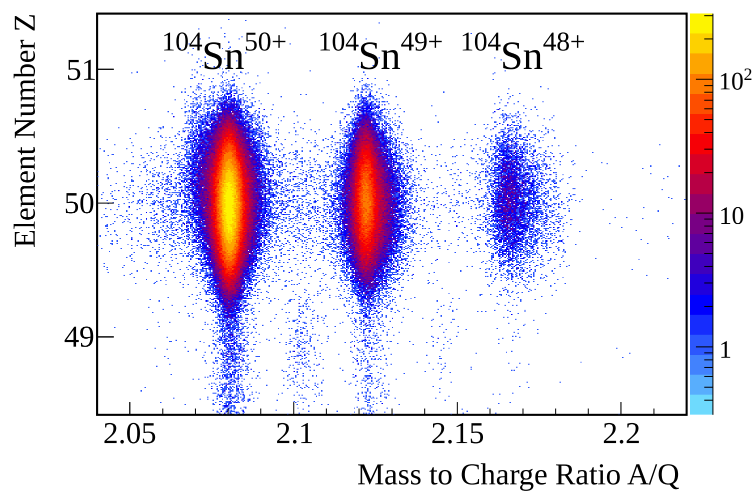
LSSM^c: ^{80}Zr core, $e_\nu = 0.5e$, $e_\pi = 1.5e$, G. Guastalla *et al.*, PRL 110, 172501 (2013)

LSSM^d: ^{90}Sn core, isospin dependent e_ν, T. Bäck *et al.*, PRC 87, 031306(R) (2013)

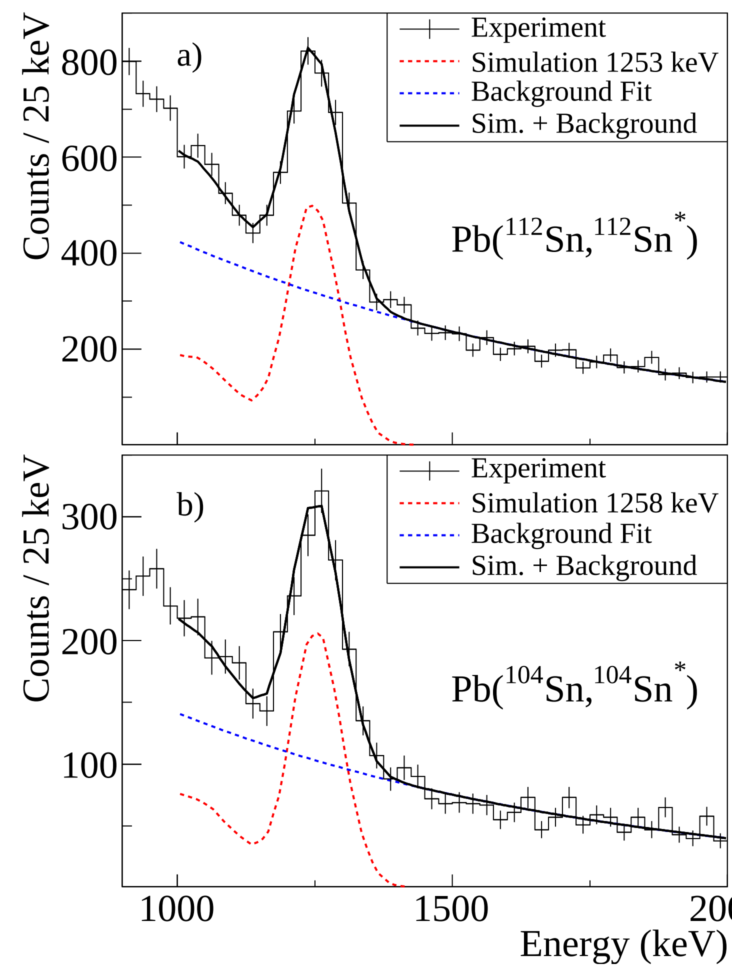
Coulomb Excitation of $^{104,112}Sn$

- ^{124}Xe, 6 pnA primary beam
- $^{nat.}$Pb(^{104}Sn,^{104}Sn*), $^{nat.}$Pb(^{112}Sn,^{112}Sn*)
- F8 target: $^{nat.}$Pb, 0.557 g/cm^2
- 150, 170 MeV/u in front of F8 target
- 5; 17 hours data taking
- Absolute $B(E2)\uparrow$ measurement
  - σ(^{104}Sn) = 298(30) mbarn
  - $B(E2)\uparrow$ = 0.163(26) e^2b^2
- Background from ^{206,208}Pb target excitations

PID in ZeroDegree, gate on ^{104}Sn in BigRIPS

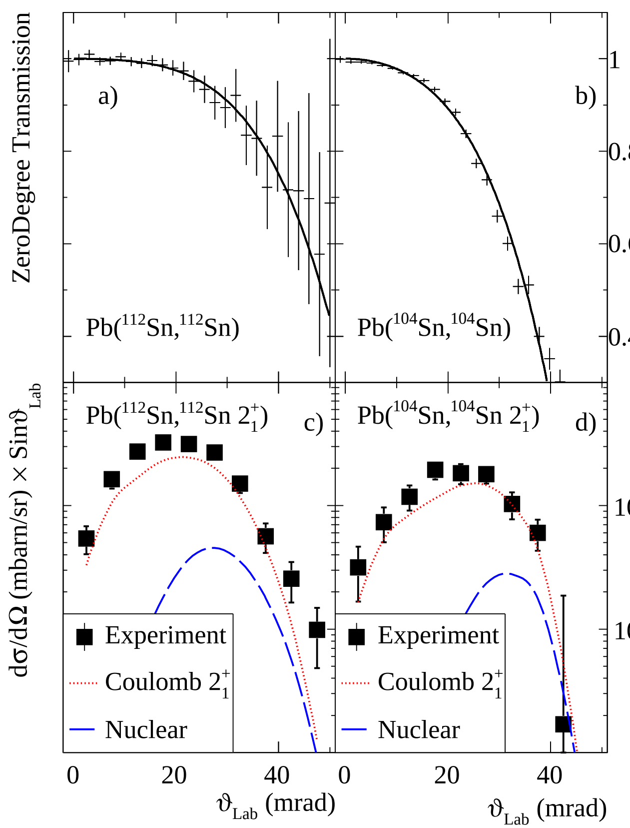


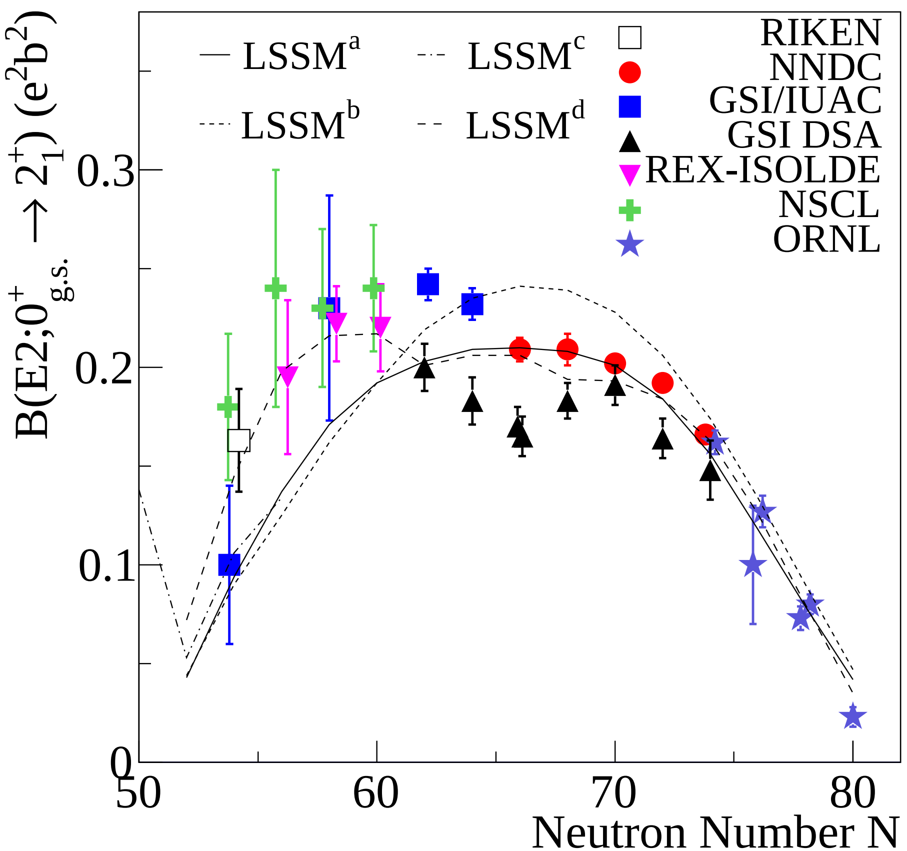
Doppler corrected γ-ray energy



$B(E2)\uparrow$ Values in Sn Isotopes

Differenetial cross-sections





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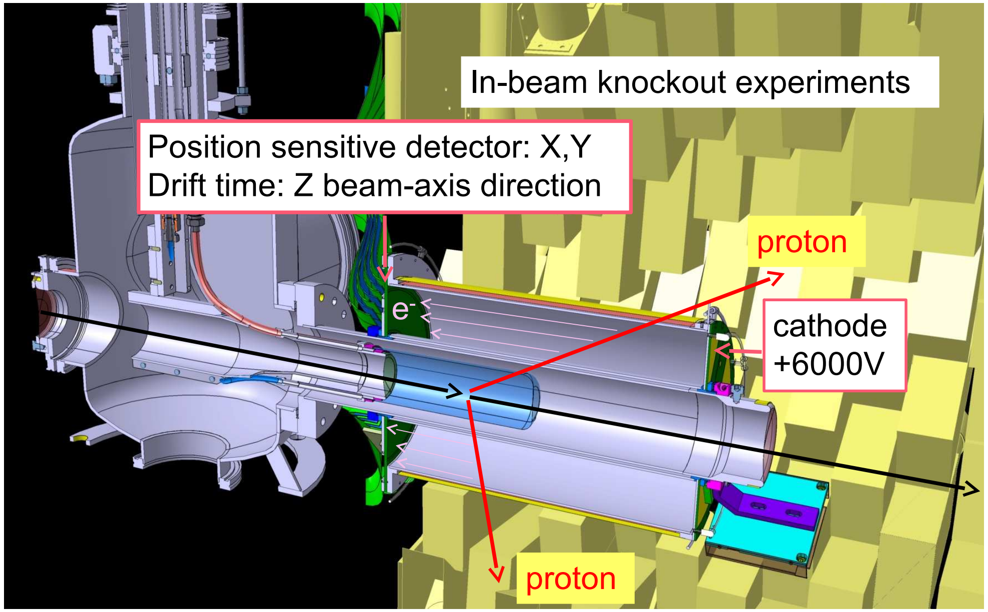
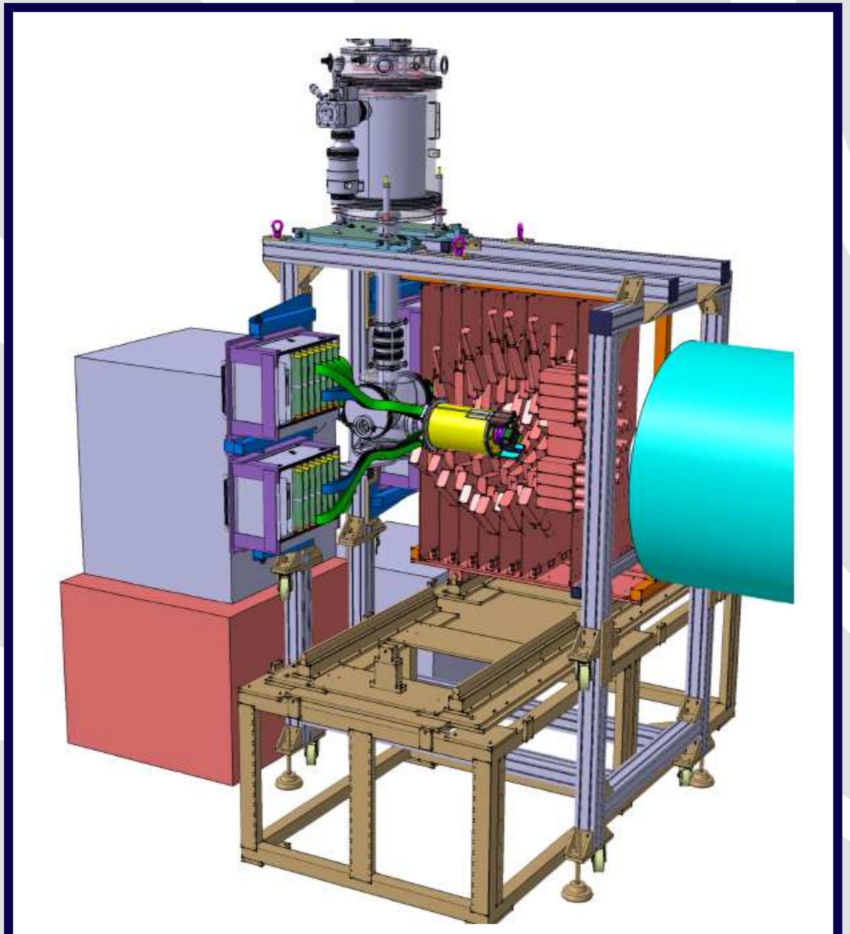
MINOS: Coupling of a Liquid Hydrogen Target with a TPC





- 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)

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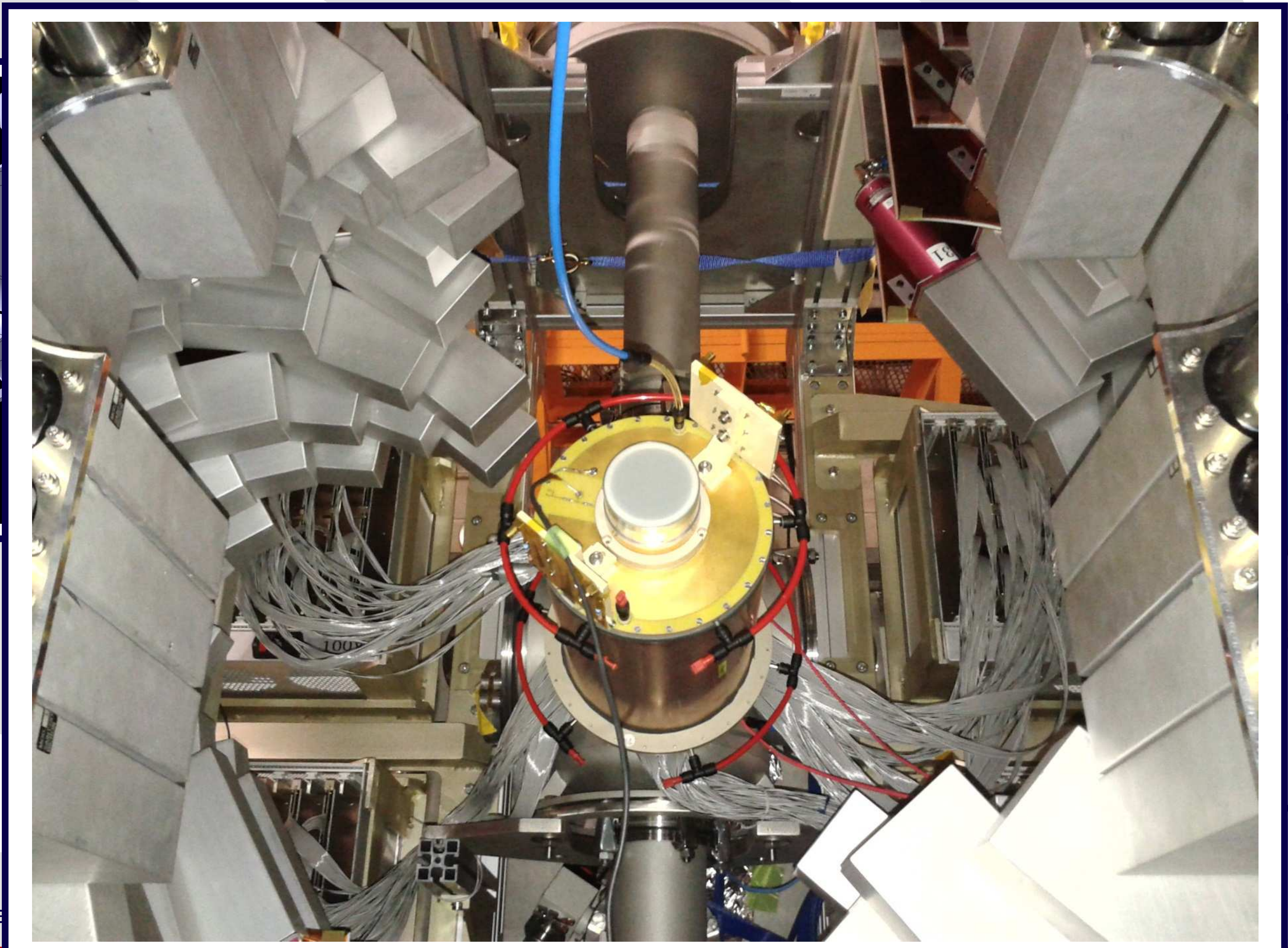
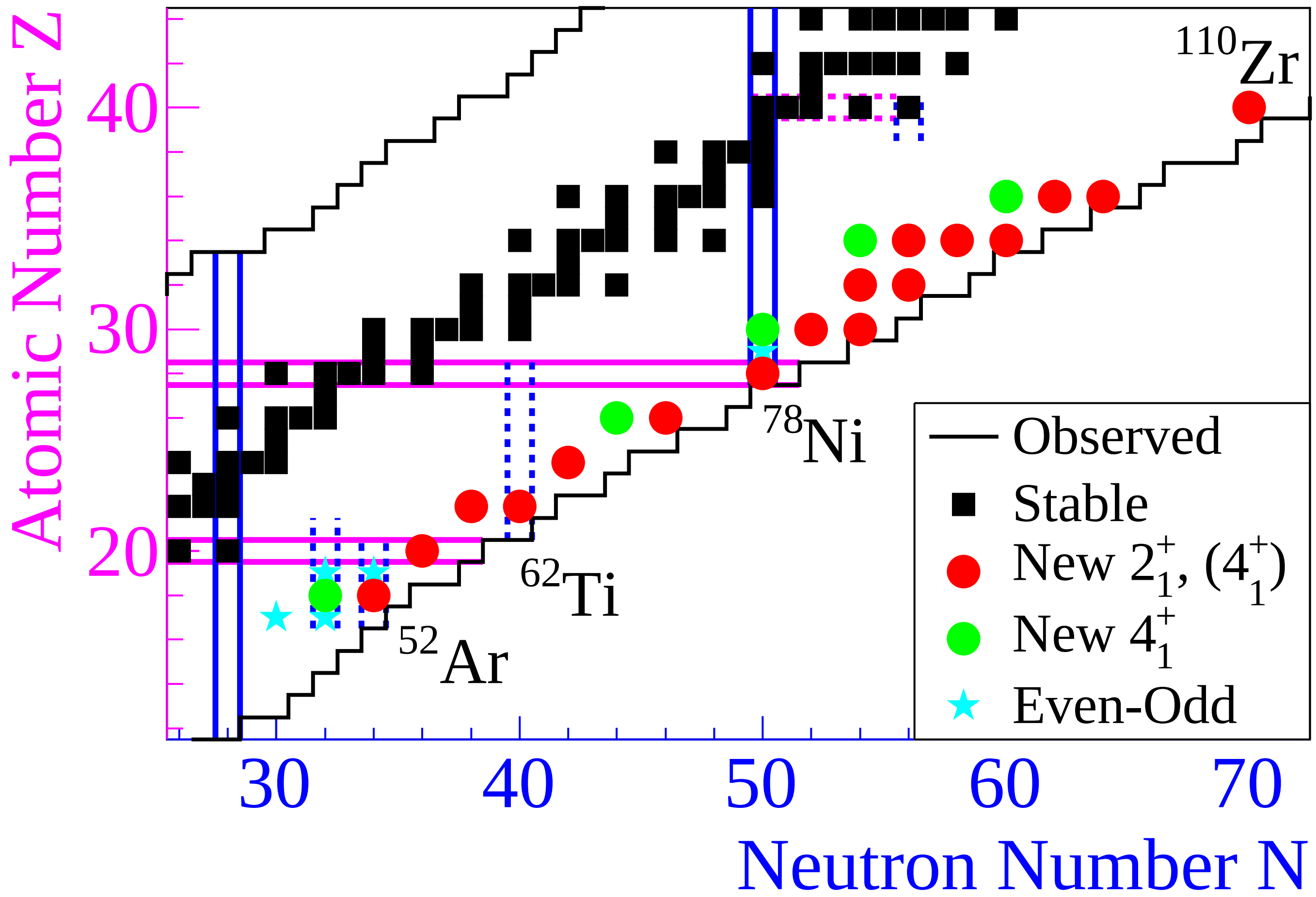


A. Obe

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



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

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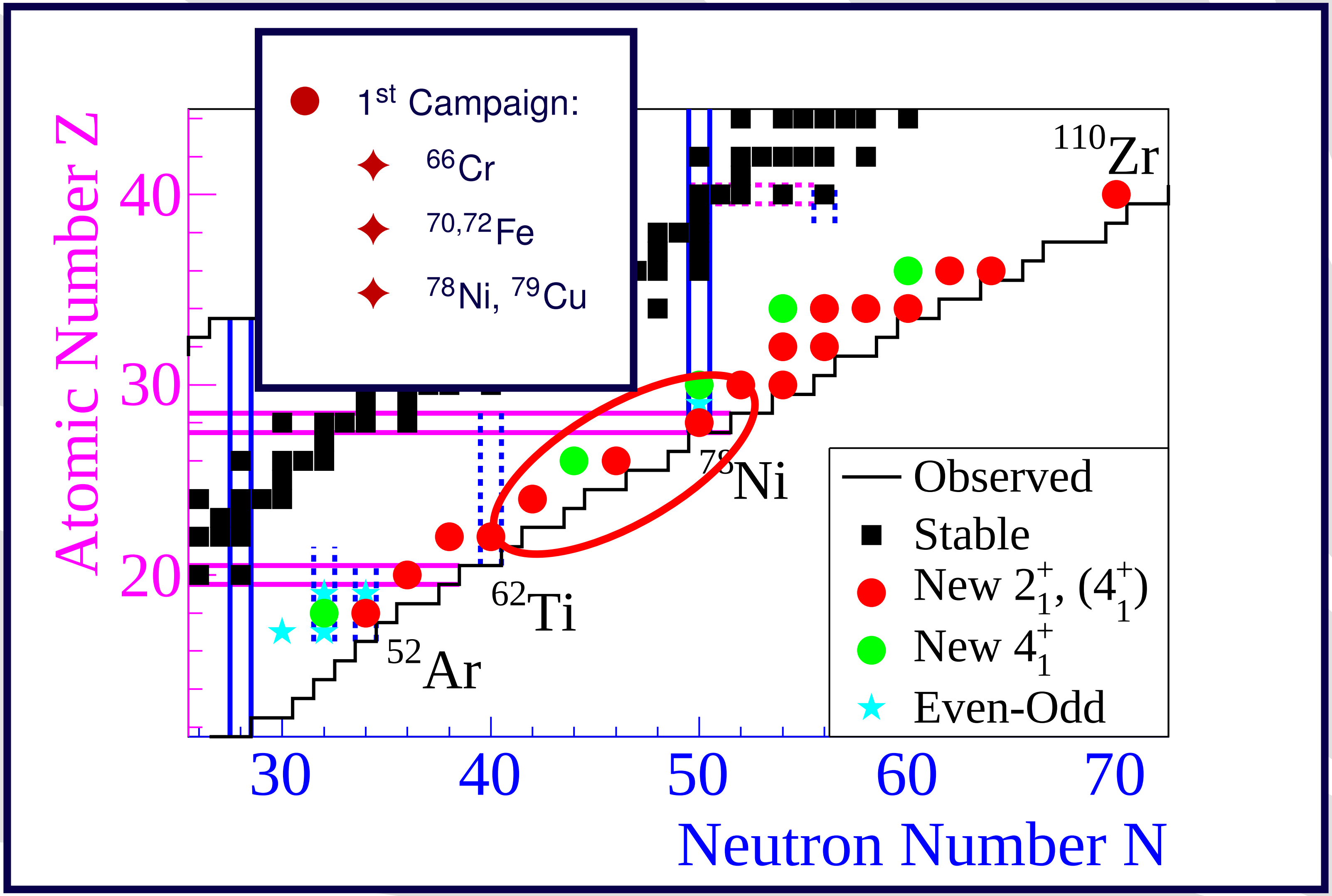

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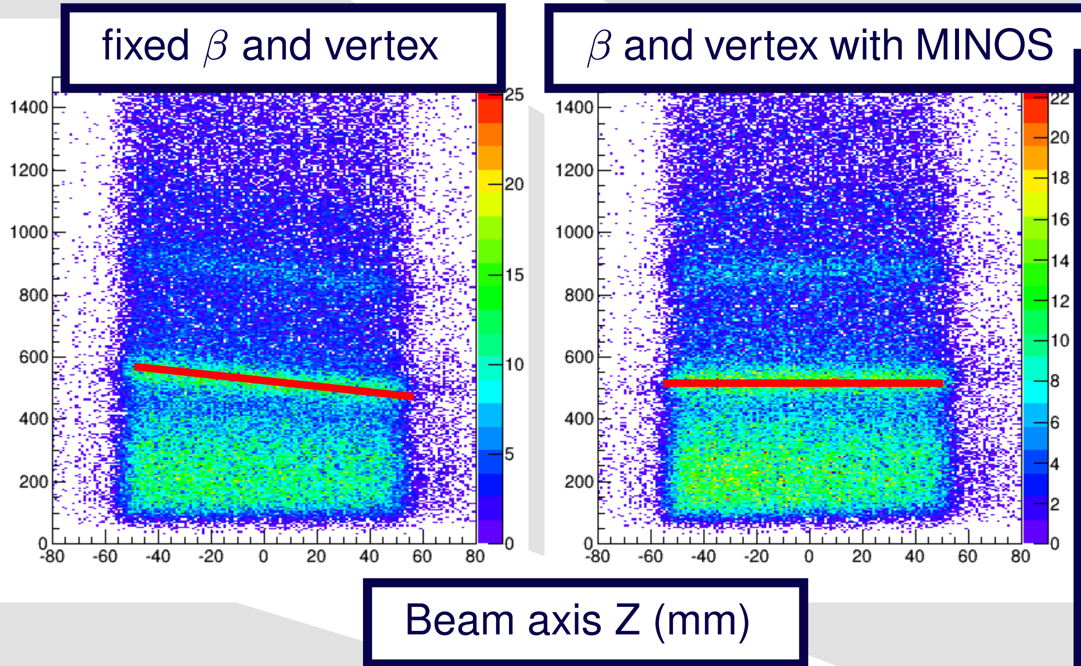
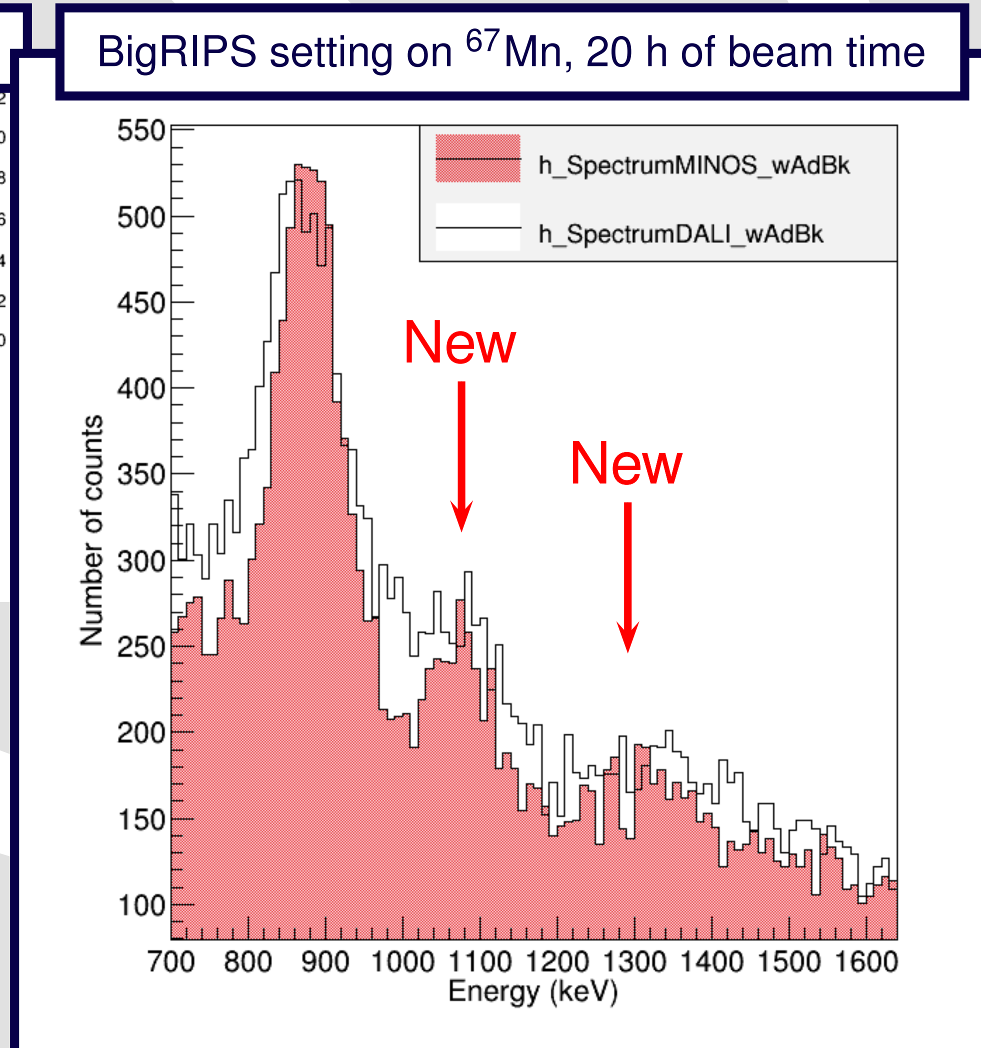
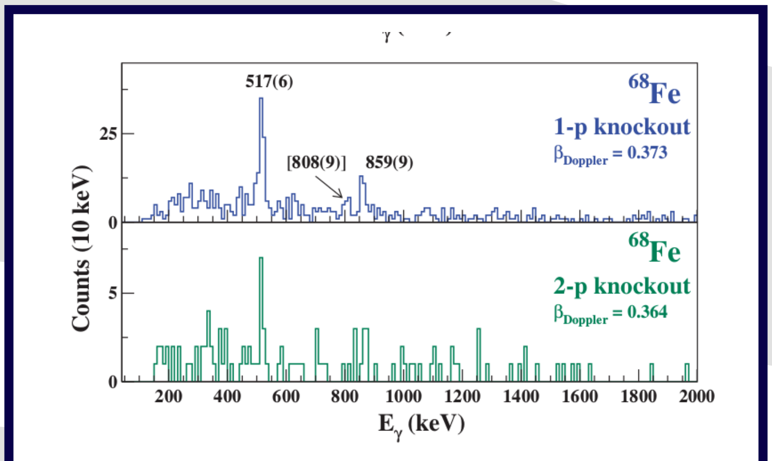
^{69}Co(p,2p)^{68}Fe @ 200 MeV/u: Proof of Principle



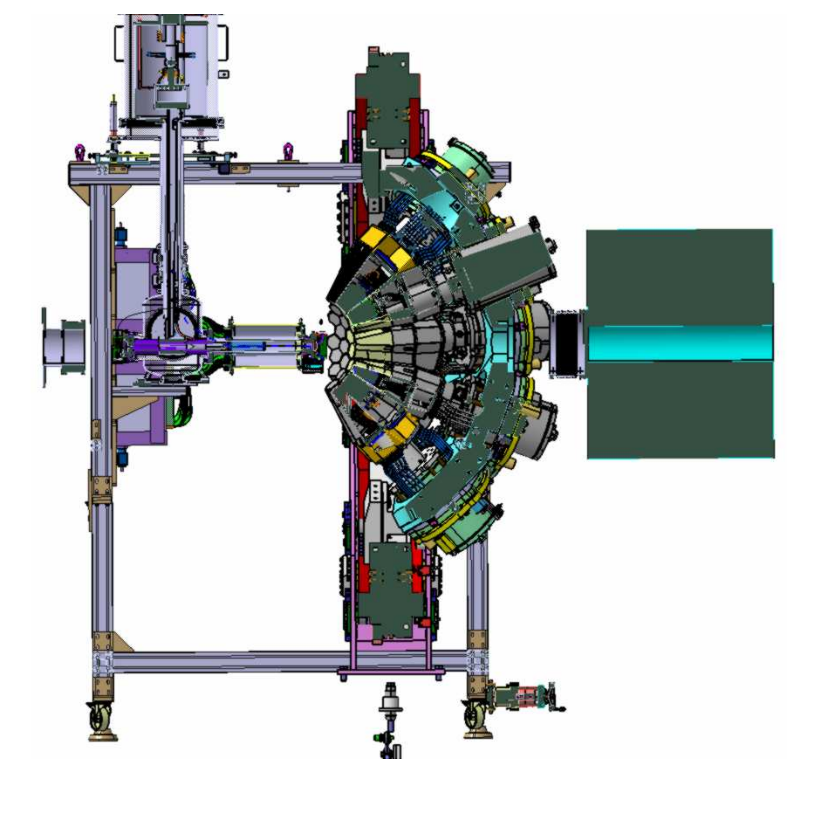




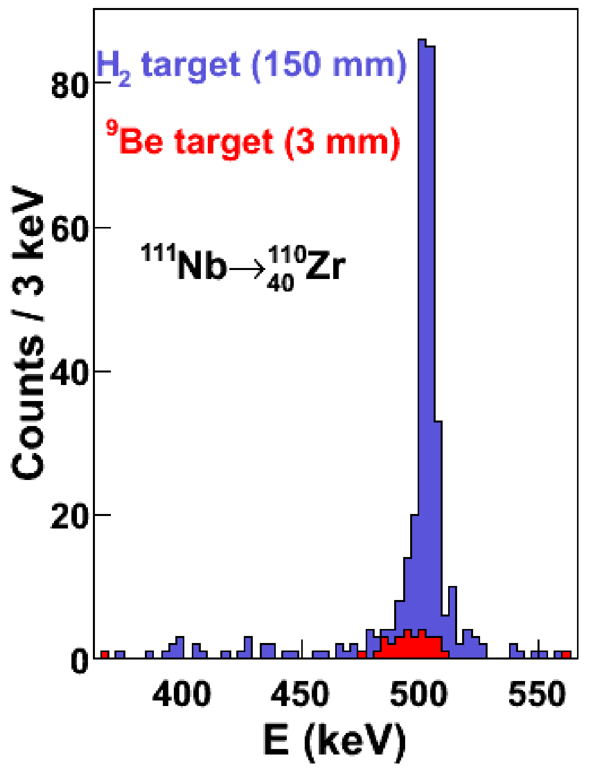
P. Adrich *et al.*, PRC 77, 054306 (2008)

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

Possibility to Couple MINOS with AGATA



- Setup between F8 chamber and Zerodegree



- Simulation at 300 MeV/u with 10 ATC

AGATA @ RIBF

Experimental Technique and Aims

- High-resolution in-beam γ-ray spectroscopy
- Secondary reaction experiments with radioactive beams
- Beam energies ranging from 100–250 MeV/u

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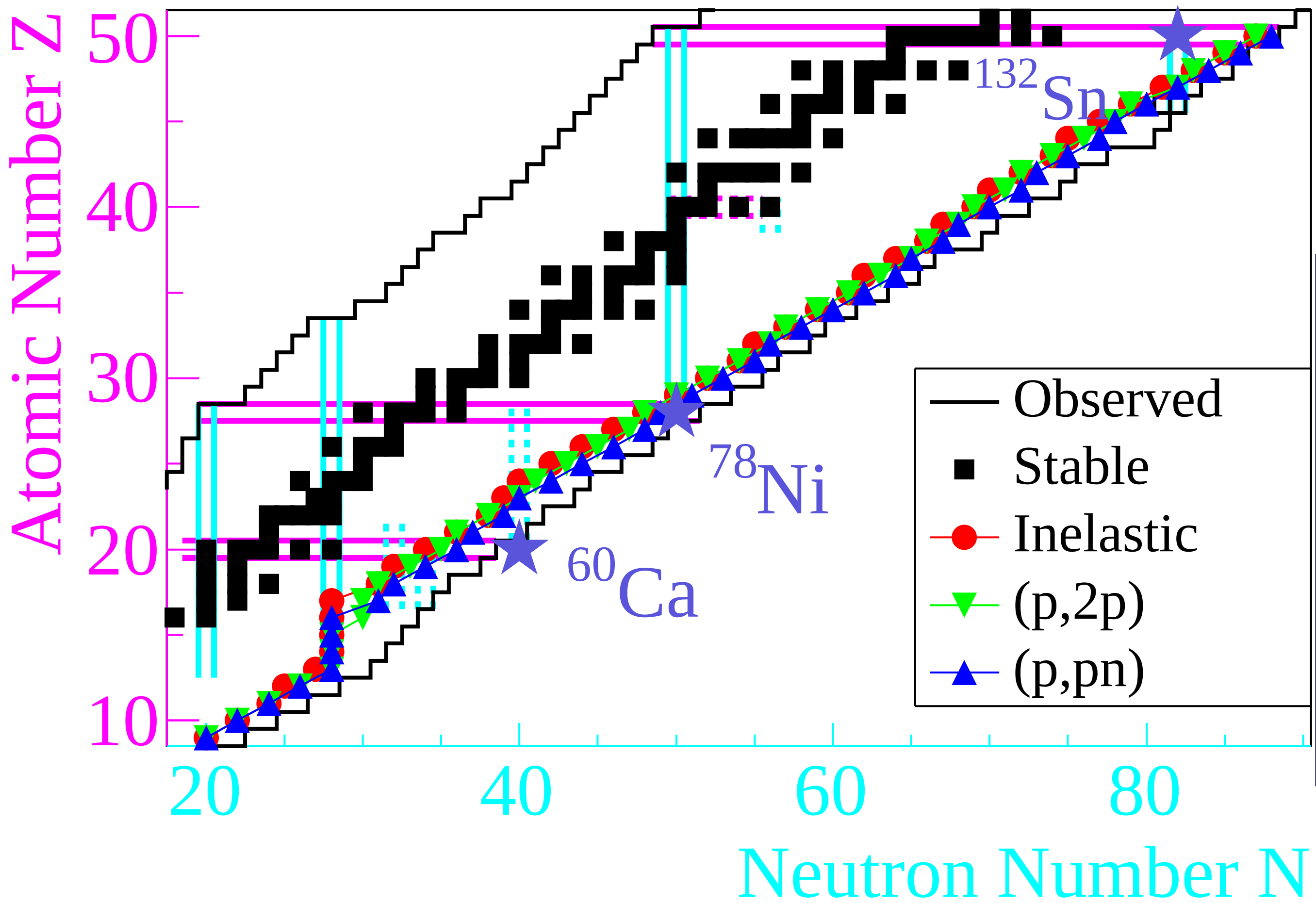
- Advantages through AGATA
  - Energy resolution $\approx 2\%$ (DALI2: $\approx 10\%$)
  - Better signal/noise ratio
- Go beyond “standard” spectroscopy of 2_1^+ and 4_1^+ states
  - **Access deformed regions with high level density**
  - **Lifetime measurements from line-shape analysis**
  - **Low cross-section Coulomb excitation: $M1$, $E3$, $E2$ of 2_2^+**
  - **Spin assignments from momentum distribution of $1p$ and $1n$ knock-out reaction residues**

Most Neutron-Rich Nuclei Accessible with AGATA@RIBF



- LISE++ simulations assuming:
  - 15 pnA ^{238}U, 100 pnA ^{70}Zn
  - max. 10^4 rate in BigRIPS
  - Exp. σ for sec. beams
- 10 % Efficiency for AGATA
- 0.5 g/cm^2 lH2 target
- At least 10 FEP events /day

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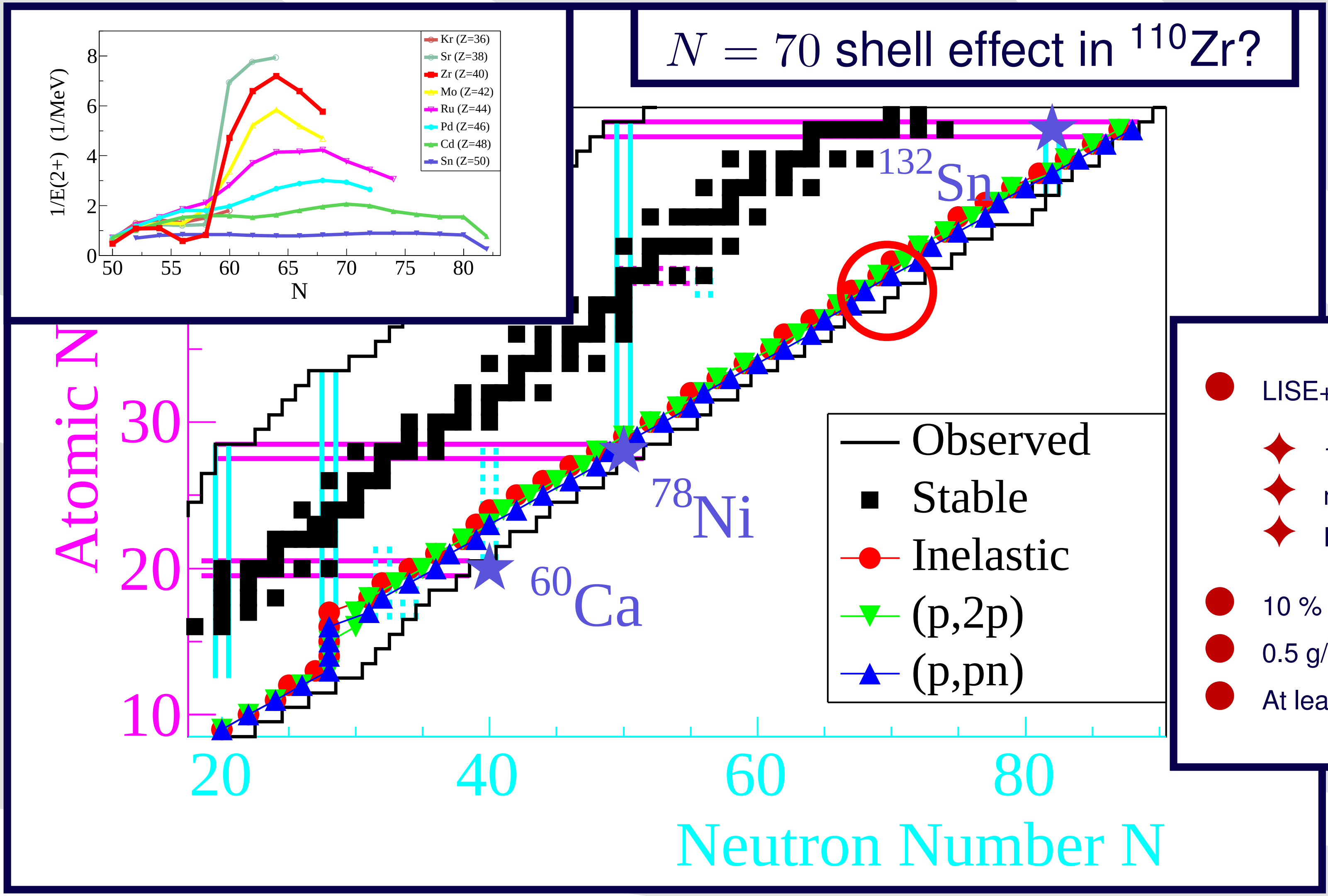

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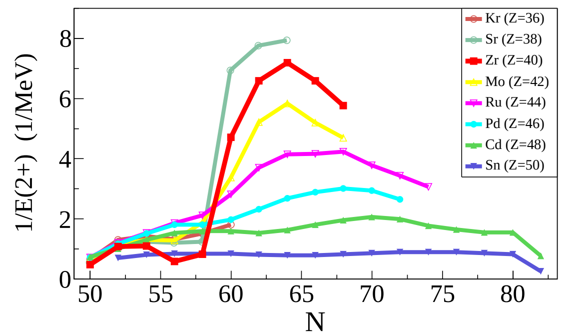

$N = 70$ shell effect in ^{110}Zr?

- **At present,** 2_1^+ **spectroscopy of ^{110}Zr via ^{111}Nb(p,2p)^{110}Zr and ^{112}Mo(p,3p)^{110}Zr**
  - 15 pnA ^{238}U
  - $\rightarrow$ 30 pps of ^{111}Nb, 400 pps of ^{112}Mo (H. Suzuki *et al.*, NIMB 2013)
  - 5 and 0.1 mbarn cross-section for (p,2p) and (p,3p) into 2_1^+
  - 65 % transmission for ZeroDegree, mainly due to target re-interactions
  - **(p,2p) $\rightarrow$ 240 counts / day**
  - (p,3p) $\rightarrow$ 60 counts / day
  - **lineshape analysis possible**

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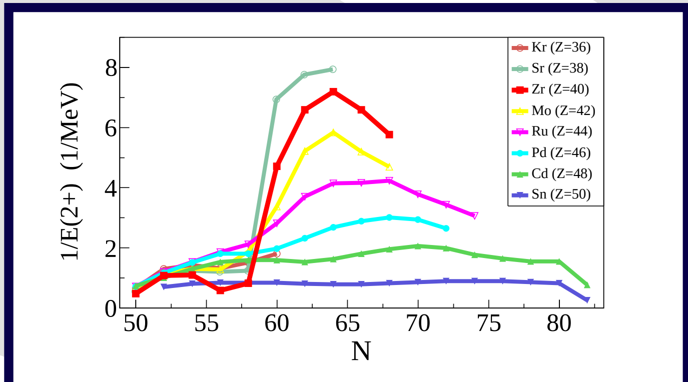

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  - **lineshape analysis possible**
- **In 2018**, 2_1^+ **spectroscopy of ^{112}Zr via ^{113}Nb(p,2p)^{112}Zr and ^{114}Mo(p,3p)^{112}Zr**
  - 100 pnA ^{238}U
  - 2.5 pps of ^{113}Nb, 55 pps of ^{114}Mo (H. Suzuki *et al.*, NIMB 2013)
  - **(p,2p) $\rightarrow$ 20 counts / day**
  - (p,3p) $\rightarrow$ **8 counts / day**

- LISE++ simulations assuming:
  - 15 pnA ^{238}U, 100 pnA ^{70}Zn
  - max. 10^4 rate in BigRIPS
  - Exp. σ for sec. beams
- 10 % Efficiency for AGATA
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Expected Manpower and Beam-time

- Several local groups from RIKEN, University of Tokyo, CNS, and RCNP are interested in actively supporting the project
- Can create International Program Associate (IPA) dedicated to AGATA@RIBF
  - PhD students can stay at RIKEN 3 – 12 months
  - **Daily allowance and accommodation paid by RIKEN**
  - IPA program already succesfully applied for EURICA, 9 European students
  - Can easily increase number of students for AGATA@RIBF

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  - Most in-beam γ-ray measurements require only 1–2 days of data taking

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- Several local groups from RIKEN, University of Tokyo, CNS, and RCNP are interested in actively supporting the project
- Can create International Program Associate (IPA) dedicated to AGATA@RIBF
  - PhD students can stay at RIKEN 3 – 12 months
  - **Daily allowance and accommodation paid by RIKEN**
  - IPA program already succesfully applied for EURICA, 9 European students
  - Can easily increase number of students for AGATA@RIBF
- At present beam time is scarce, but
  - Most in-beam γ-ray measurements require only 1–2 days of data taking
  - **Sakurai-san looks very happy recently**

Summary

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- RIBF is the world leading facility for in-flight production of exotic nuclei for next 5–10 years.
- Experience to host external and NUSTAR experimental devices
  - EURICA, since 2011, e.g. ^{100}Sn decay (M. Lewitowicz *et al.*)
  - MINOS, since 2014
  - AIDA, since 2014, test during SEASTAR campaign
  - NeuLAND, from 2015
- RIBF offers ideal secondary beam energies of 100–250 MeV/u for AGATA
- In-beam γ-ray spectroscopy at high energies is successfully applied at RIBF
  - **Low background** in knockout and inelastic scattering experiments
  - **Absolute cross-section** measurements above 100 MeV/u
  - Spin assignments from **momentum distribution**
- **All spectrometers and ancillary detectors (PID, angle, vertex, etc.) ready to use**
- 15 pnA of ^{238}U average primary beam intensity achieved, **up to 100 pnA maximum expected in a few years**
- Opportunity to perform unique experiments with AGATA
  - "standard" 2_1^+, 4_1^+, $B(E2)\uparrow$ spectroscopy
  - Spectroscopy of low cross-section scattering: $E3$, $M1$ excitations, 2_2^+
  - Nuclei with high level density, **line shapes**
  - Spin assignments from momentum distribution

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