In-beam gamma-ray spectroscopy of ^{68}Fe

L.X. Chung [1], B.D. Linh[1], A. Gillibert [2], P. Doornenbal [3], A. Obertelli [2], F. Nowacki [4], G. Authelet [2], H. Baba [3], D. Calvet [2], F. Château [2], A. Corsi [2], A. Delbart [2], J.-M. Gheller [2], T. Isobe [3], V. Lapoux [2], M. Matsushita [5], S. Momiyama [3,6], T. Motobayashi [3], M. Niikura [6], H. Otsu [3], C. Péron [2], A. Peyaud [2], E.C. Pollacco [2], J.-Y. Roussé [2], H. Sakurai [3,6], C. Santamaria [2,3], M. Sasano [3], Y. Shiga [3,7], S. Takeuchi [3], R. Taniuchi [3,6], T. Uesaka [3], H. Wang [3], K. Yoneda [3], F. Browne [8], Zs. Dombradi [9], S. Franchoo [10], F. Giacoppo [11], A. Gottardo [10], K. Hadynska-Klek [11], N.T. Khai [1], Z. Korkulu [9], S. Koyama [3,6], Y. Kubota [3,5], C. Louchart [12], J. Lee [13], M. Lettmann [12], R. Lozeva [4], K. Matsui [3,6], T. Miyazaki [3,6], S. Nishimura [3], L. Olivier [10], S. Ota [5], Z. Patel [14], N. Pietralla [12], E. Sahin [11], C. Shand [14], P.-A. Söderström [3], G.L. Stefan [10], D. Steppenbeck [5], T. Sumikama [15], D. Suzuki [10], N.D. Ton [1], Zs. Vajta [9], V. Werner [12], J. Wu [3,16], and Z. Xu [13]

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Outline

1. Introduction
   - Introduction to "Shell Evolution And Search for 2^+ energies At RIBF (SEASTAR)" project at RIKEN
   - Curent knowledge in ^{68}Fe
2. Facilities: RIKEN accelerators +MINOS active target +DALI2 detector
3. Data analysis of ^{68}Fe
   - ^{69}Co(p,2p)^{68}Fe
   - ^{68}Fe(p,p')^{68}Fe
   - ^{69}Fe(p,pn)^{68}Fe
   - ^{70}Ni(p,3p)^{68}Fe

Nucleonic-rich nuclei

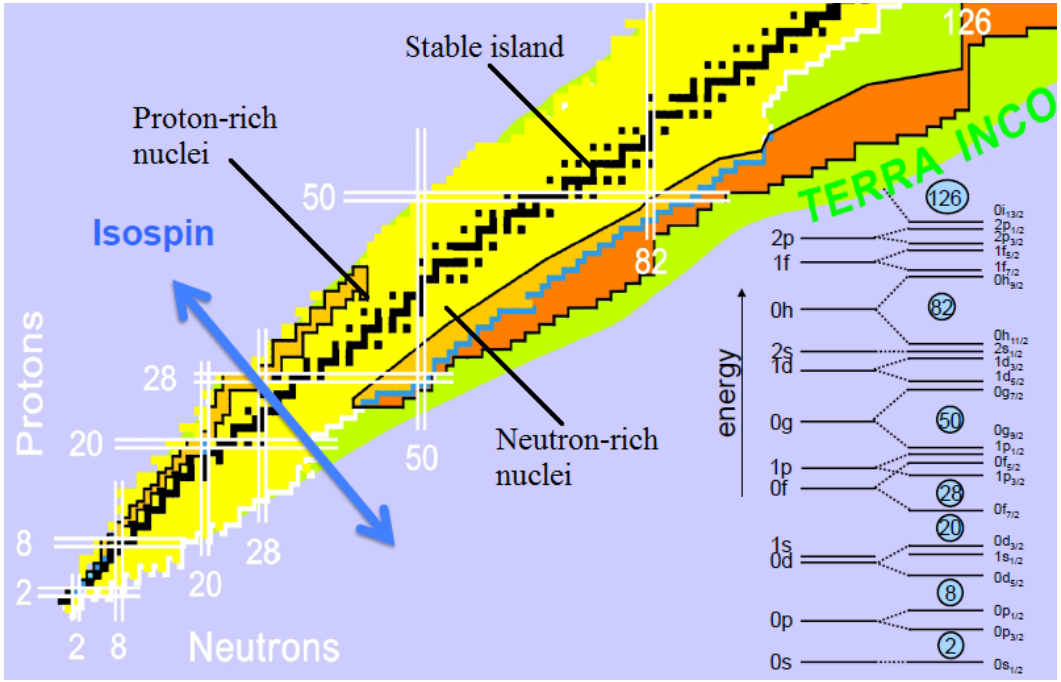

Chart of nuclei.

- For stable nuclei, nucleus is called "magic nucleus" if Z or $N = 2, 8, 20, 28, 50, ...$
- Nucleonic-rich nuclei have large $|Z - N|$, magic number may be different.
- Their half-live is very short (^{68}Fe: $T_{1/2}$=187(6) ms).
- They can be created only in laboratory (accelerator, ...).

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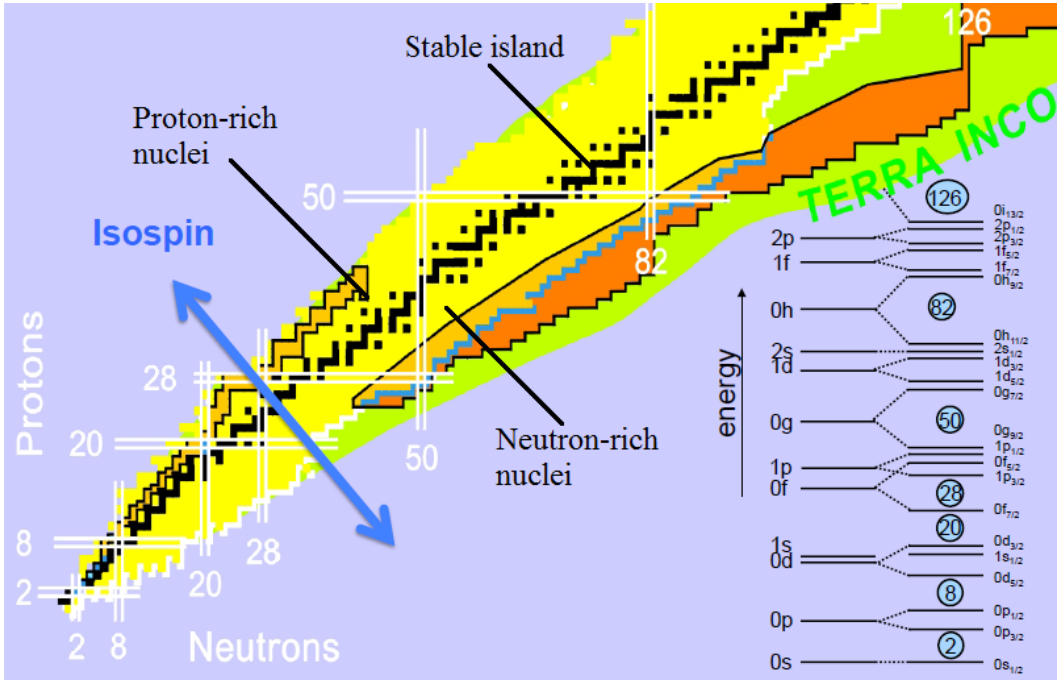

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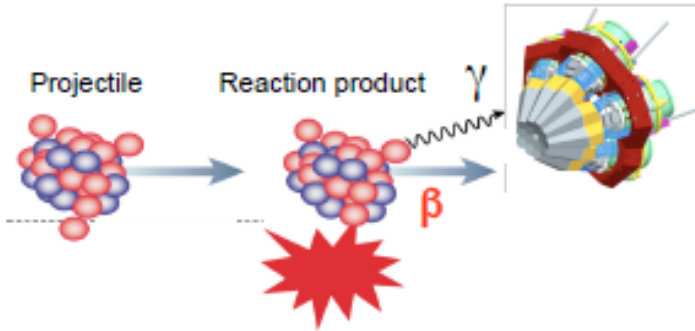
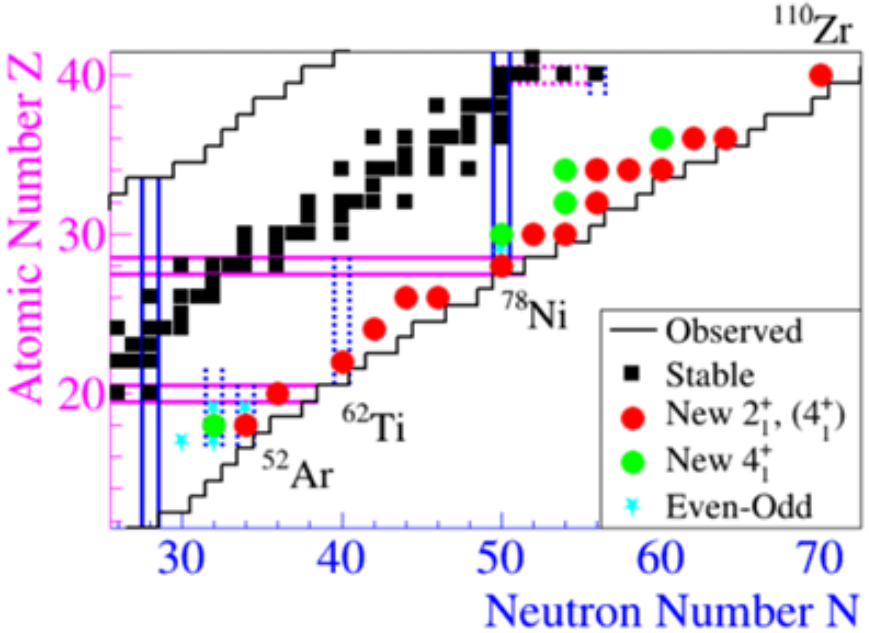


SEASTAR measurements

+ Measuring 2_1^+ states, systematically, from ^{52}Ar to ^{110}Zr. Where the physics interests can be mentioned as:

- Neutron sub-shell at $N = 34$ below ^{54}Ca (^{52}Ar)
- Correlation in Ca isotopes beyond ^{54}Ca (^{56}Ca)
- Low-Z shore of the $N = 40$ (^{60,62}Ti)
- Collectivity evolution beyond $N = 40$ (^{66}Cr, ^{72}Fe)
- Anticipated new doubly-magic nucleus ^{78}Ni.



+ Detailed shell evolution via levels of even-odd isotopes (byproducts) through their spectroscopy

For example of: ^{47,49}Cl, ^{51,53}K, ^{67}Fe, ^{79}Cu, ...

+ In addition, E(4_1^+) will be measured for many nuclei (^{60,62}Ti, ^{66}Cr, ^{82}Zn, ^{86,88}Ge...).

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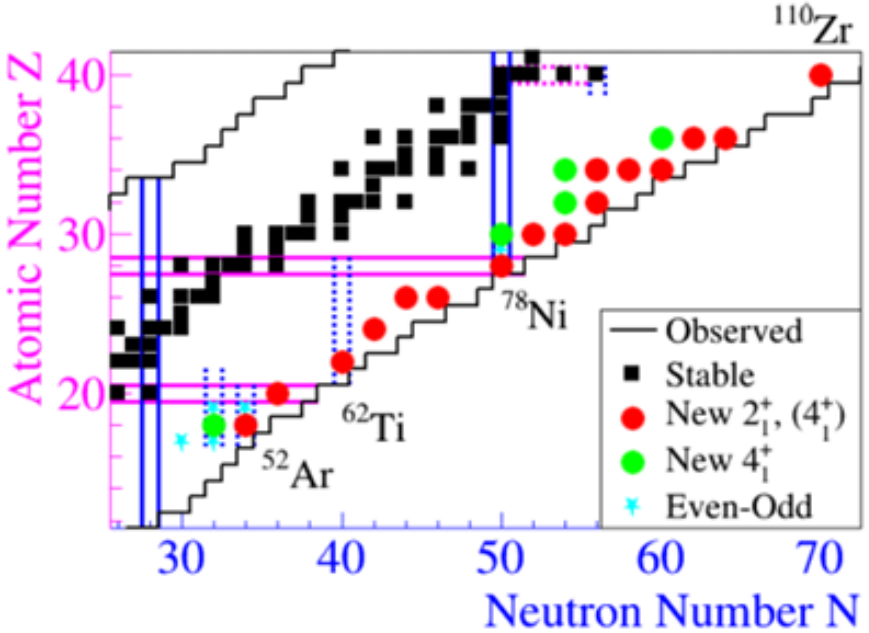

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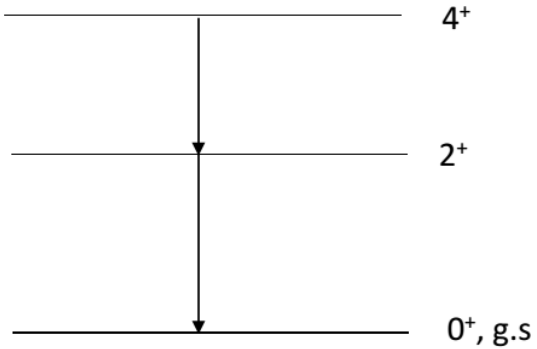
In which, the analysis of ^{67,68,69,71}Fe and ^{63,65}Cr data are performed by Vietnamese group at INST (Institute for Nuclear Science and Technology).

$E(2_1^+)$ measurement - a tool for nuclear structure study



- $E(2_1^+)$ is needed to level up to the first excited state
- Measure $E(2_1^+)$ systematically, if $E(2_1^+)$ is high $\Rightarrow$ evidence of "new magic number"

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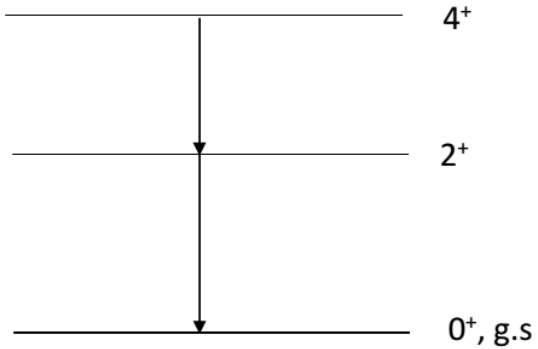

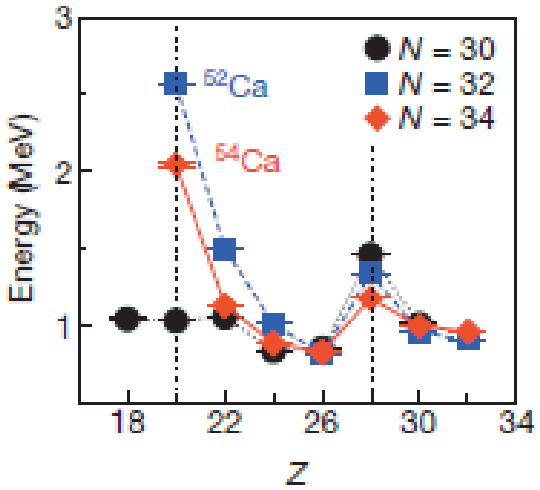

Exa.: Systematics of $E(2_1^+)$ around Ca.
$\Longrightarrow$ **Doubly-magic evidence of ^{52,54}Ca**

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

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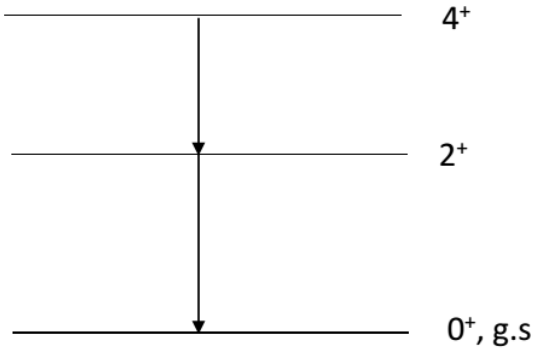

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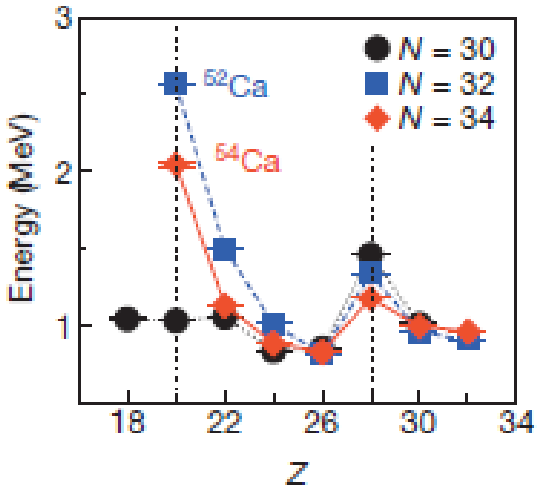

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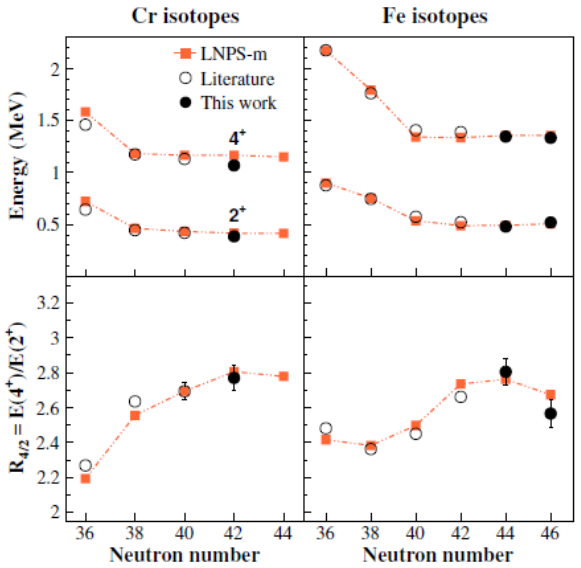
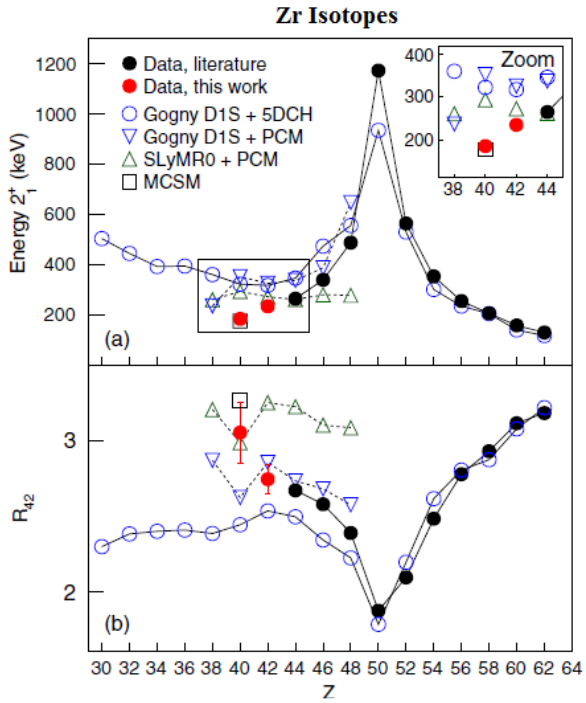


S. Clementine *et al.*, PRL **115** (2015) 192501

- **SEASTAR measurements**



P. Nancy *et al.*, PRL **118** (2017) 032501

- **SEASTAR measurements**

Why RIKEN+MINOS+DALI2?

- Radioactive Isotope Beam Factory (RIBF) at RIKEN:
  - Provided high intensities of primary beams (^{70}Zn and ^{238}U) at energies up to 350 MeV/u, and capability of
  - Beam identification with BigRIPS.
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  Using the above Z_v as the input for Doppler-shift correction $\Longrightarrow$ precisely E_γ determination.
- The 1^{st} and 2^{nd} SEASTAR experiments were in May 2014 and 2015, respectively. (The 3^{rd} one will be on May 8-14 2017.)

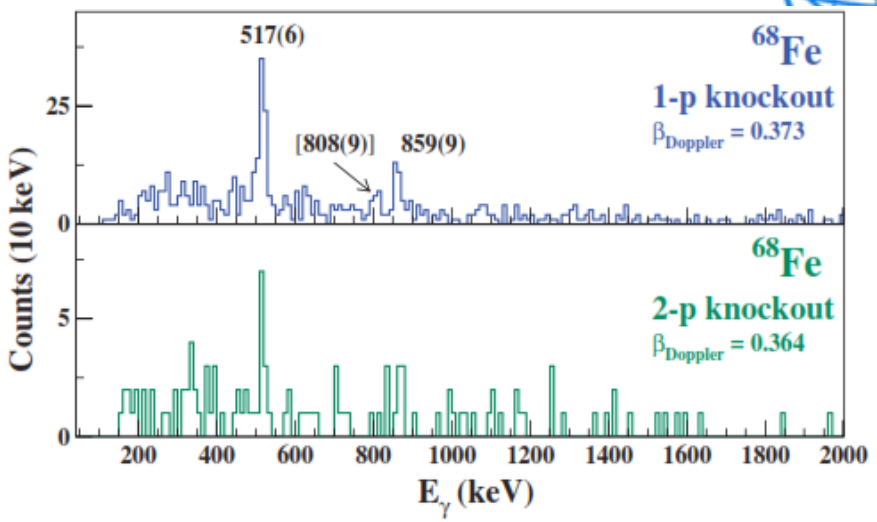
It is noted that for such search in this nuclear region, the experiments can only be conducted if the current primary beam intensities increase by at least **one order of magnitude**.

Current knowledge in ^{68}Fe

- The first spectroscopy of ^{68}Fe has been reported via one- and two-proton knockout from ^{69}Co and ^{70}Ni at NSCL.

- Two transitions were observed at 517(6) keV and 859(9) keV.

- There was a week indication at 808(9) keV but not concluded yet.



P. Adrich *et al.*, Phys. Rev. C 77 (2008) 054306

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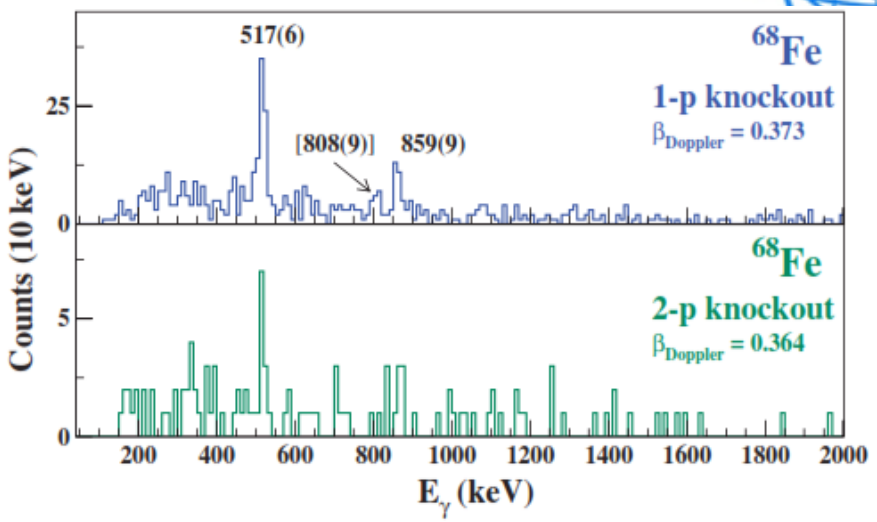
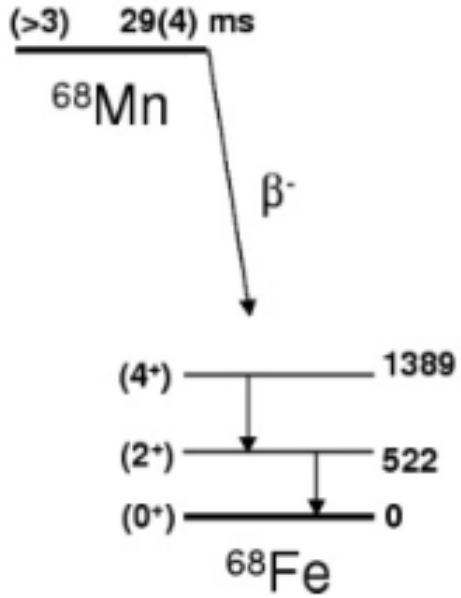


P. Adrich *et al.*, Phys. Rev. C 77 (2008) 054306

- The above two levels were then confirmed by the experiment at GANIL by detecting β-delayed γ-ray emission of ^{68}Mn.

- These transition were associated with $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$, respectively, in collective model.

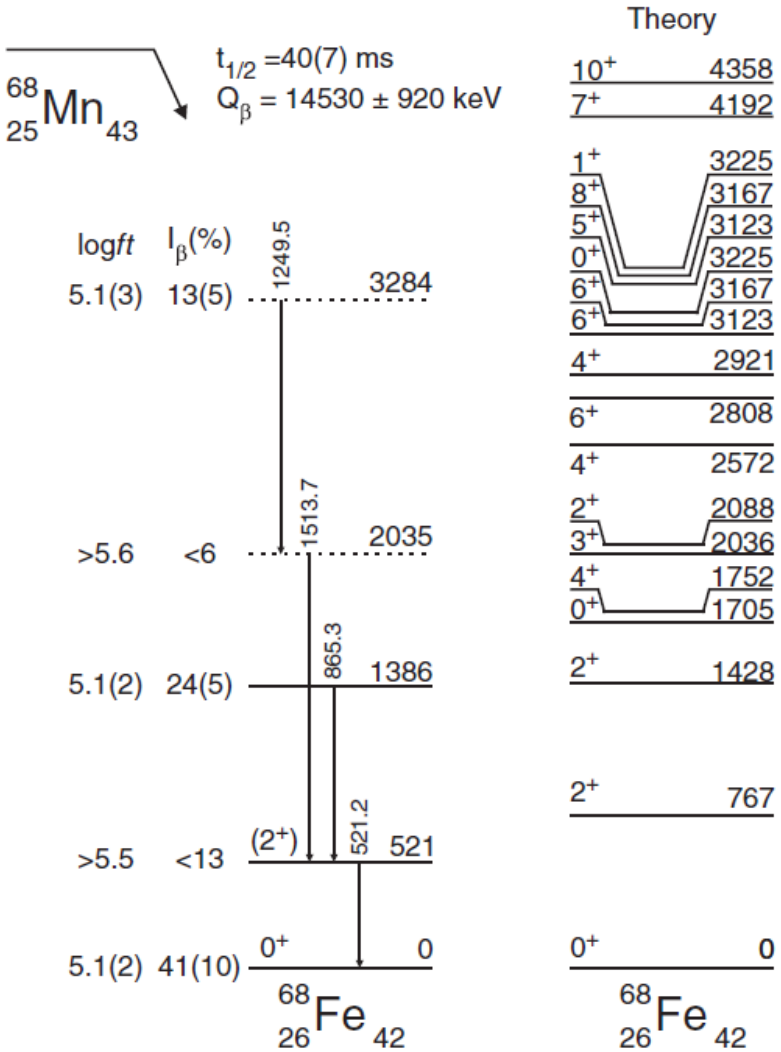


J. M. Daugas *et al.*, Phys. Rev. C 83 (2011) 054312

Current knowledge in ^{68}Fe

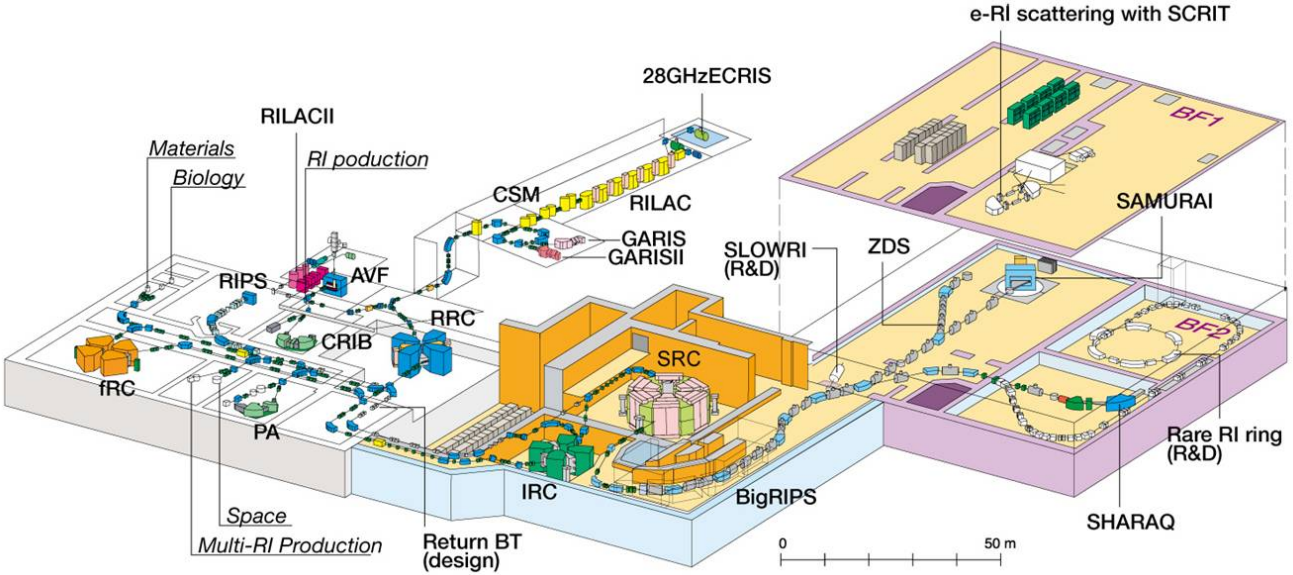
- More observed levels were 1249.5 and 1513.7 keV besides 521.2 and 865.3 keV via β-delayed γ-ray emission of ^{68}Mn at NSCL.

- However, the transition states are unkown: 865.3 keV (? $\rightarrow 2^+$), 1249.5 keV (? $\rightarrow$?), 1513.7 keV (? $\rightarrow$?) except, 521.2 keV ($2^+ \rightarrow 0^+$).

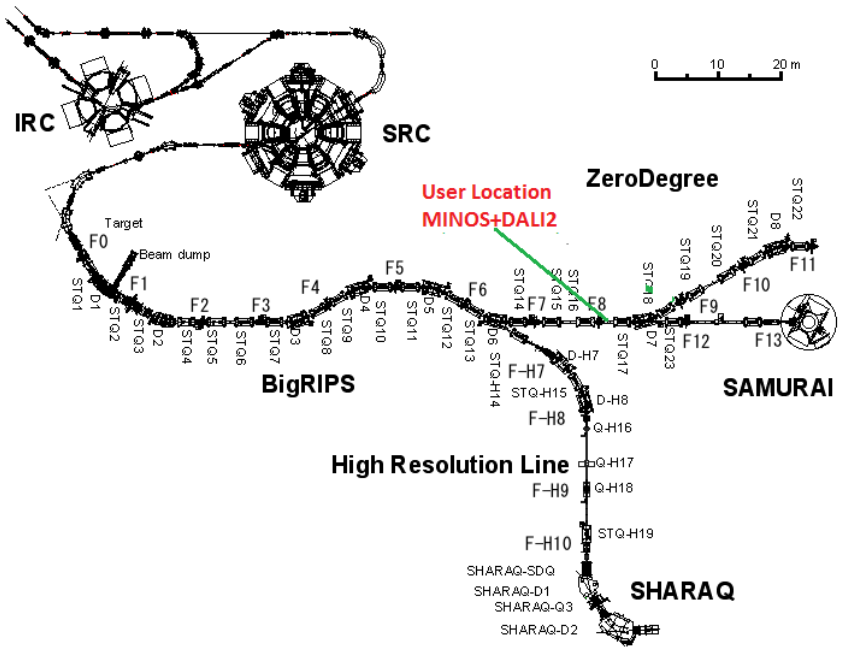


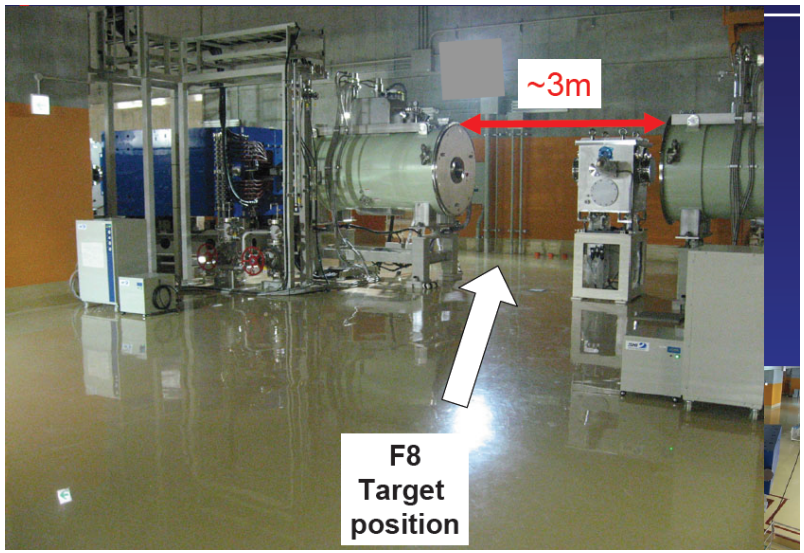
S. N. Liddick *et al.*, Phys. Rev. C 87 (2013) 014325

RIKEN Facility

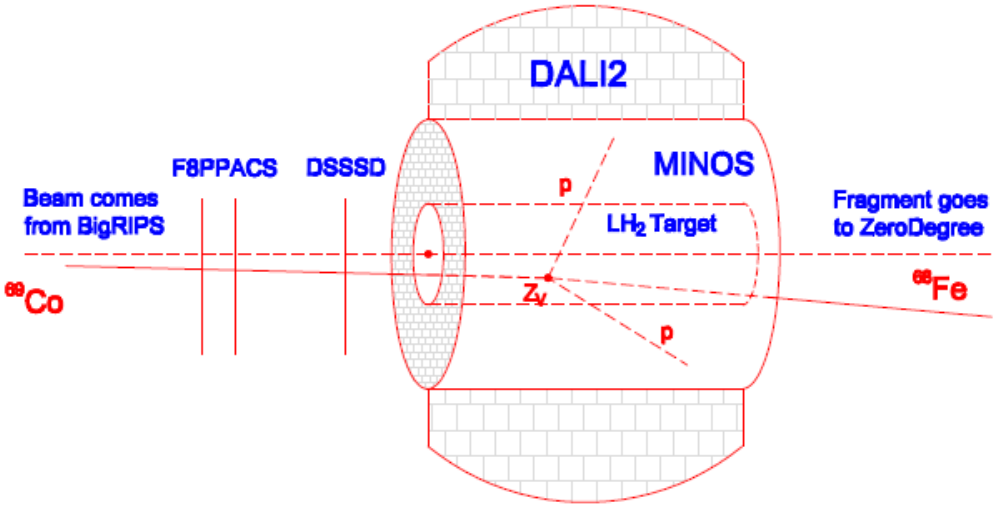


- RIPS: an in-flight type radioactive isotope (RI) separator.
- IRC: Intermediate-stage Ring Cyclotron.
- SRC: Superconducting Ring Cyclotron.

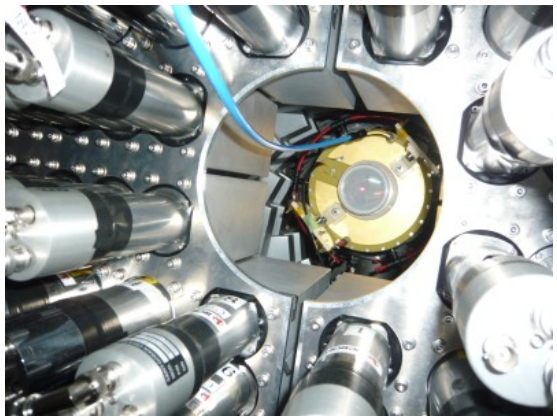




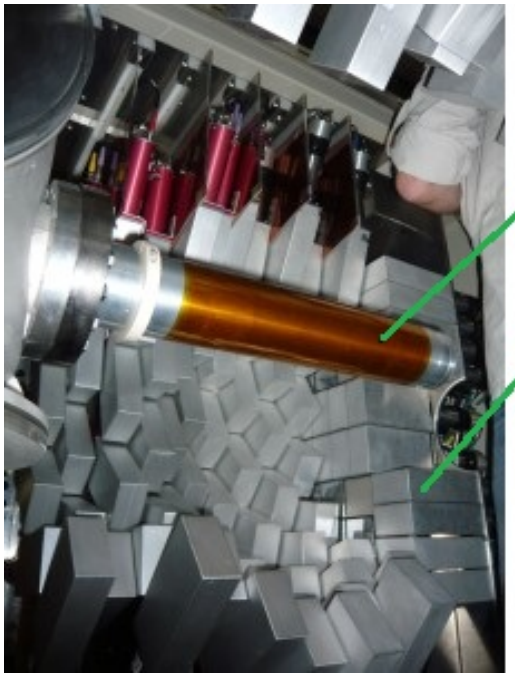
SEASTAR Setup: MINOS + DALI2



MINOS⊕DALI2 installed at user location



MINOS inside DALI2



MINOS: Recoiled proton detection
(nuclear Maglc Number Off Stability)

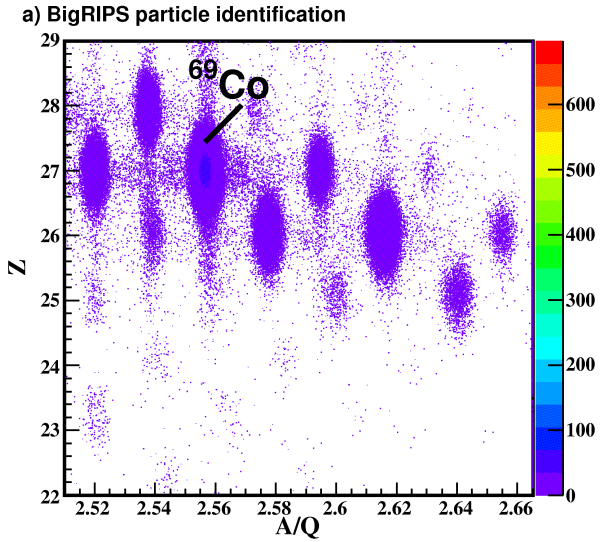
BigRIPS (Big Radioactive-IsotoPe beam Separator)

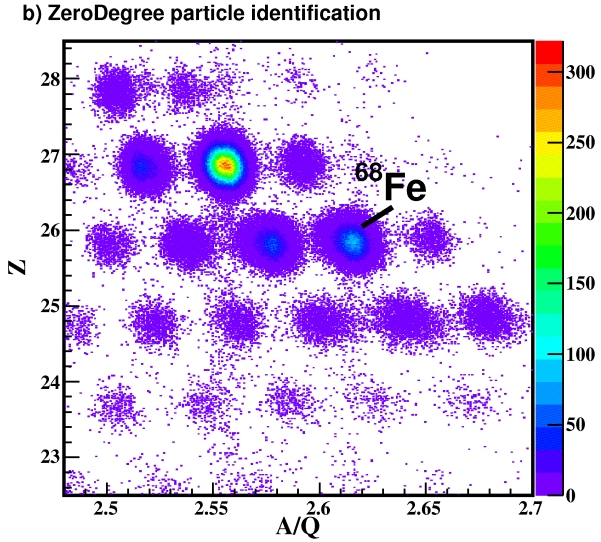
$$\mathrm{TOF} = \frac{L}{\beta c},$$

$$\frac{A}{Q} = \frac{B\rho}{\beta\gamma}\frac{c}{m_u},$$

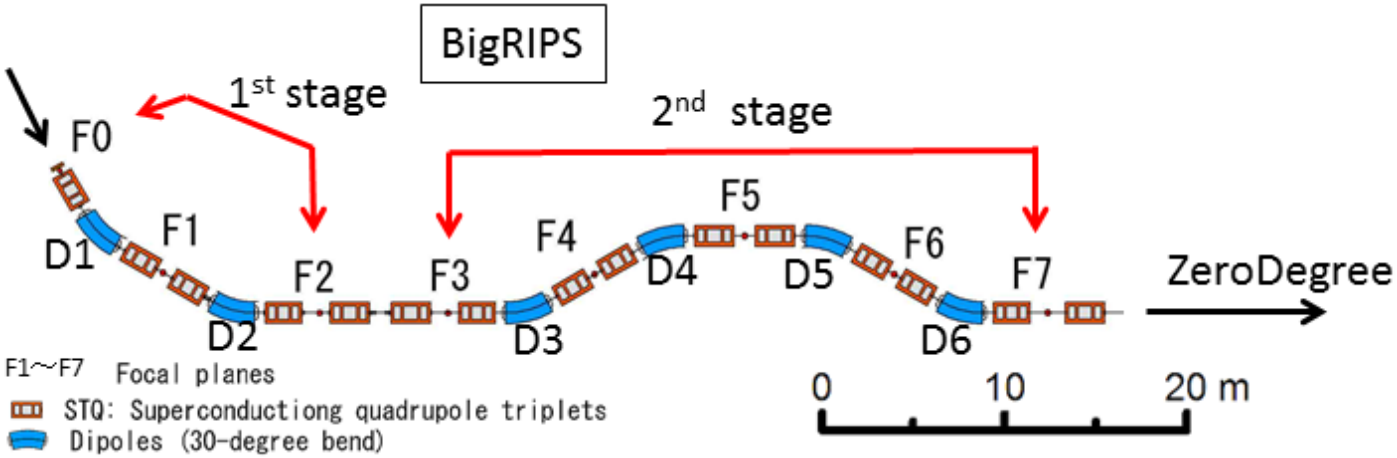
$$\frac{dE}{dx} = \frac{4\pi e^4 Z^2}{m_e v^2} Nz\left[\ln\frac{2m_e v^2}{I} - \ln(1-\beta^2) - \beta^2\right].$$

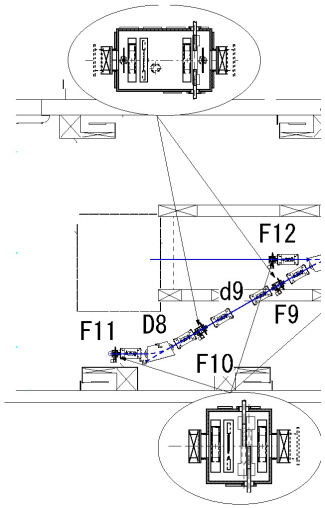
N. Fukuda *et al.*, Nucl. Instr. Meth. in Phys. Res. B 317



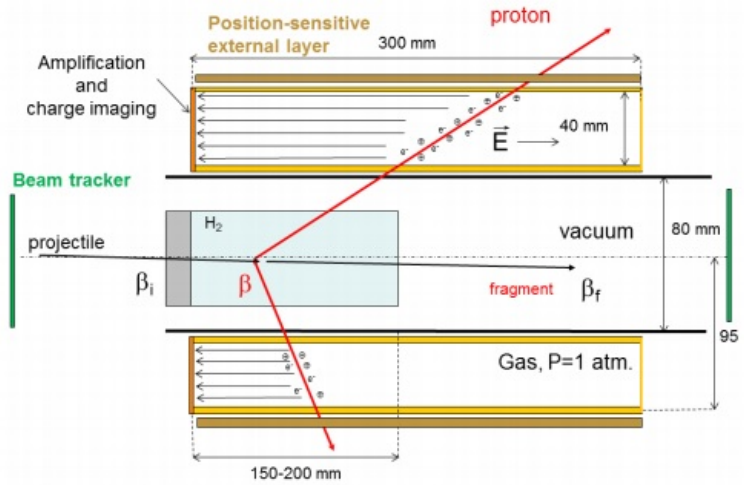


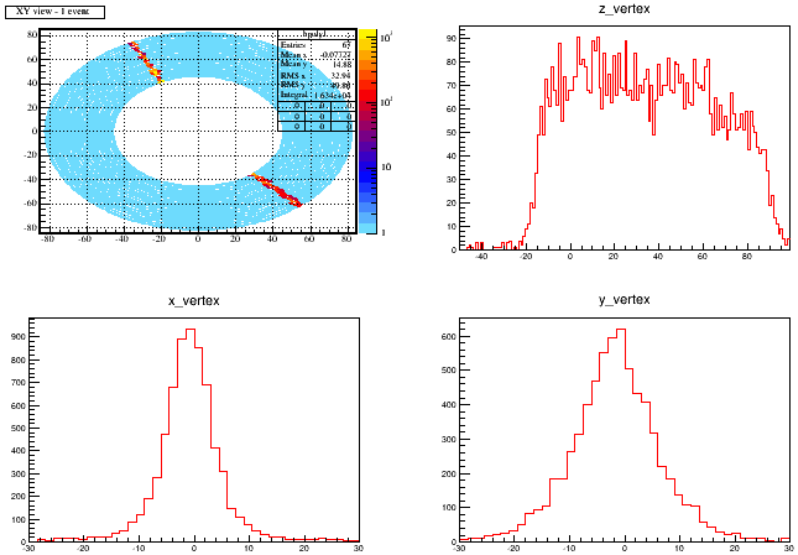
Beam and fragment dentification
(The same technique for both.)

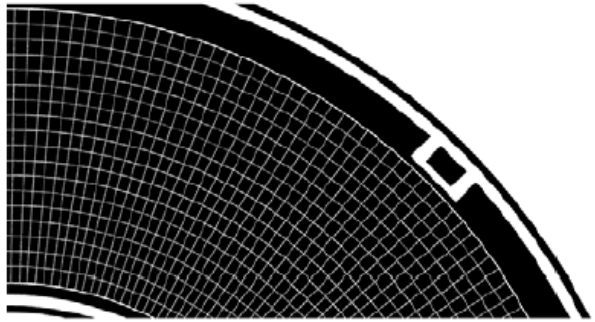




Detector MINOS (nuclear MagIc Number Off Stability)



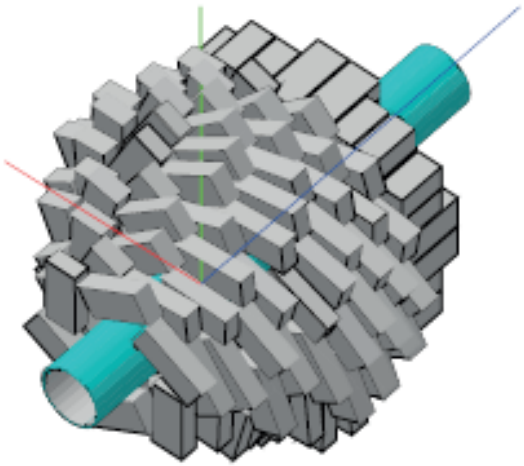




Time Projection Chamber (TPC) electrode:
18 rings divided into number of identical pads,
3604 electronics channels.
(O. Alexandre *et al.*, Eur. Jour. Phys. A **50** (2014) 8)

- 2-proton track observed by TPC.
- Z_v reconstruction by TPC.

DALI2: Detector Array for Low Intensity radiation



- DALI2 consists of 186 NaI crystals,
- For γ-ray detection.
- Doppler-shift correction:
  $E_{\gamma 0} = E_{\gamma} \frac{1-\beta cos\vartheta_{\gamma}}{\sqrt{1-\beta^2}}$
  $E_{\gamma 0}, E_{\gamma}$ are de-excited γ-ray energy in the rest frame and observed γ-ray energy, respectively, ϑ_{γ} is γ-ray emission angle, $\beta = v/c$, v is the nucleus' velocity

Conclusion and perspective

The in-beam gamma spectroscopy of ^{68}Fe was analysed via (p,2p), (p,p'), (p,n) and (p,3p) channels.

- 5 excited gamma rays of ^{68}Fe were observed at 277(3), 519(5), 868(8), 1066(11) and 1301(17) keV.
- 3 new transitions have been observed at 277(3), 1066(11) and 1301(17) keV.
- The level scheme of ^{68}Fe was proposed and the state quantum number was assigned preliminarily derived from gamma-gamma coincidence and the comparison with the shell model calculation.
- The inclusive and exclusive cross sections of (p,2p), the inclusive cross sections of (p,p') and (p,pn) were derived.

Spectroscopy of the neutron-rich iron isotopes ^{67,68}Fe

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The in-beam gamma-ray spectroscopy of ^{67}Fe and ^{68}Fe from hydrogen-induced neutron and proton knockout and inelastic scattering at 250 MeV/nucleon is reported. The experiment was performed at the Radioactive-Isotope Beam Factory of RIKEN with a setup composed of the MINOS target-tracker and the DALI2 NaI scintillator array. New transitions were observed and level schemes are proposed. The proposed level schemes are analyzed within the shell-model framework using a modified version of the LNPS interaction in the valence space. Inclusive and exclusive cross sections have been extracted and are interpreted using the distorted-wave impulse approximation and the eikonal assumption combined with shell model spectroscopic factors.

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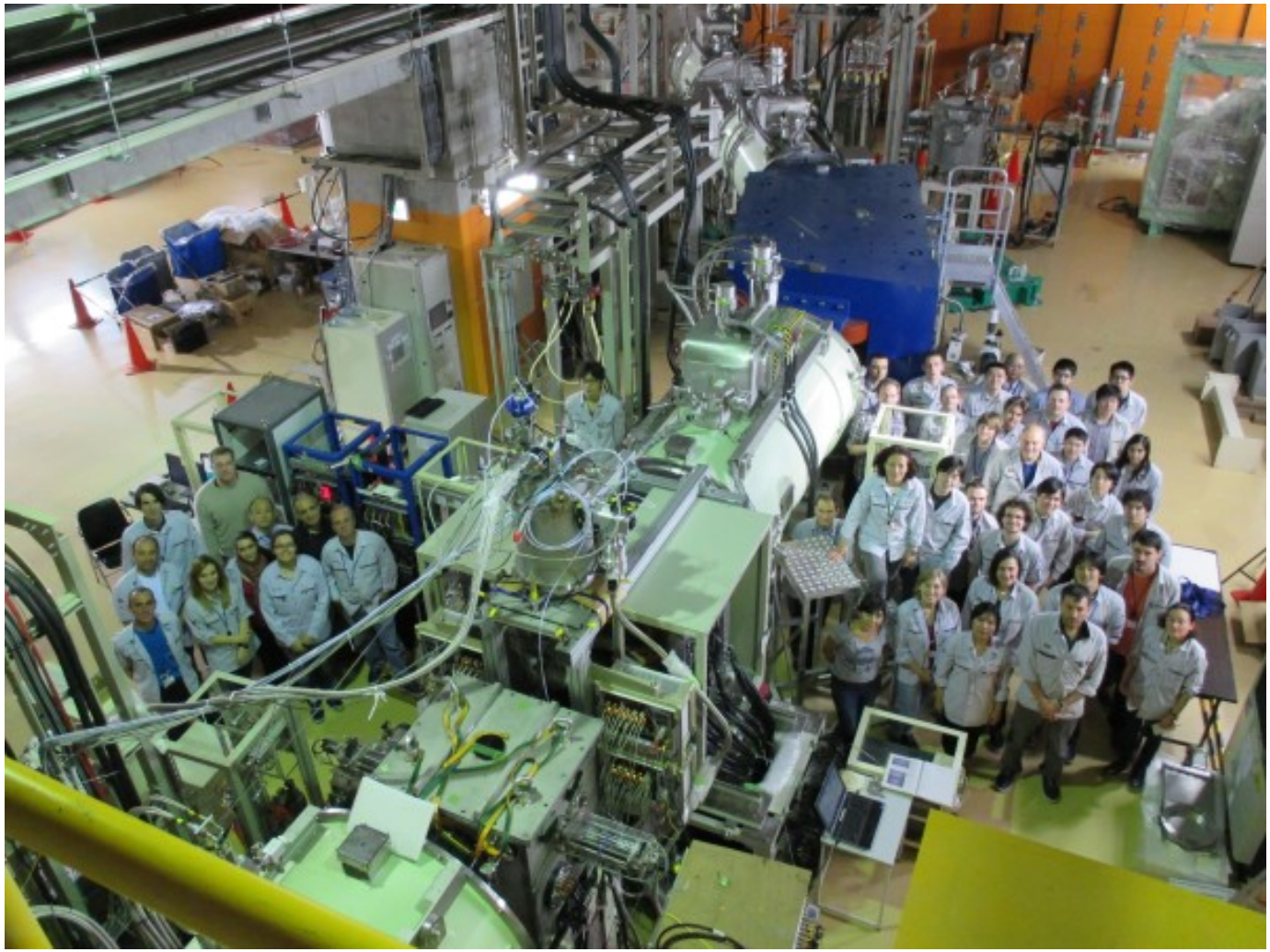
I. INTRODUCTION

Nuclear structure is characterized by few spherical nuclei located around shell closures and large deformation regions. The appearance or onset of quadrupole deformation as a function of neutron (proton) number along

of deformation has been evidenced to a larger region [4] extending up to ^{38}Mg. This deformation area has been qualified as Island of Inversion from the interpretation of a shell-model 2p-2h configuration with two neutron holes in the *sd* shell and two neutrons in the intruder *fp* shell, energetically favored compared to the normal

to be submitted to PRC!

Thanks for your attention!



SEASTAR Collaborators.