

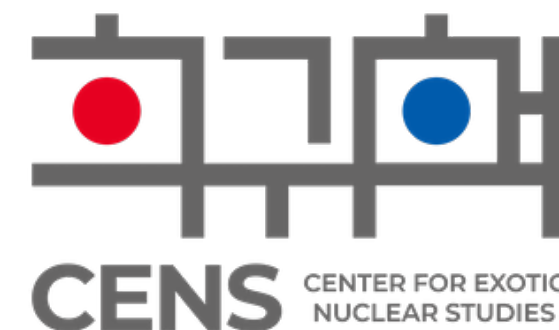
November 20, 2025

한국고에너지물리학회 및 핵-입자-천체분과 연합 워크숍

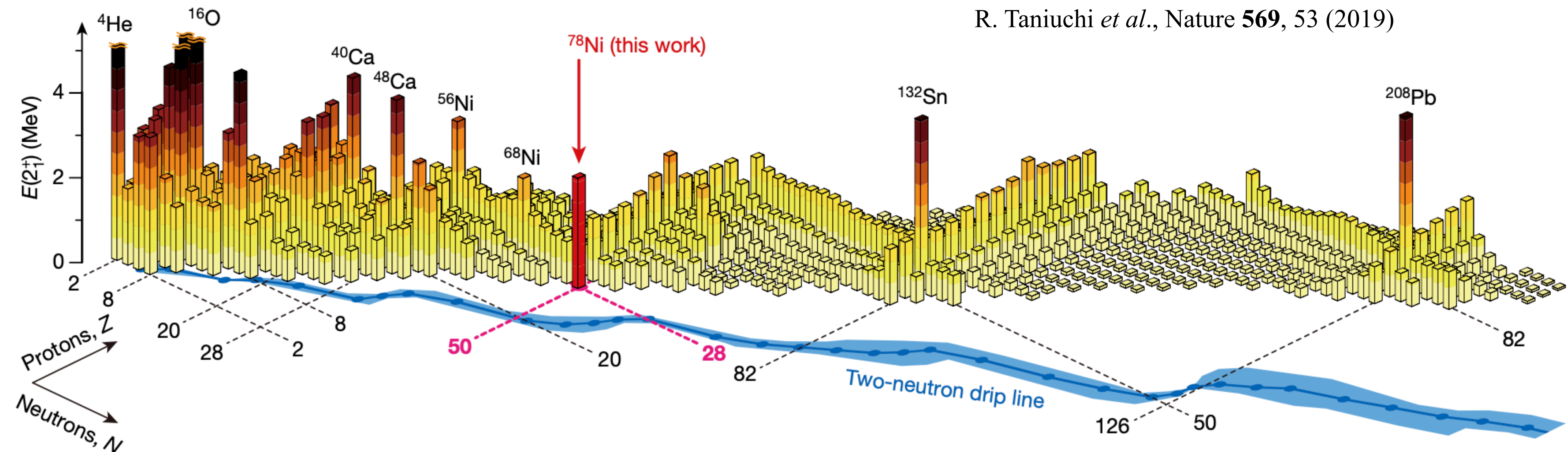
Gamma-ray spectroscopy activities at RIBF, RIKEN

Byul Moon

Center for Exotic Nuclear Studies, Institute for Basic Science



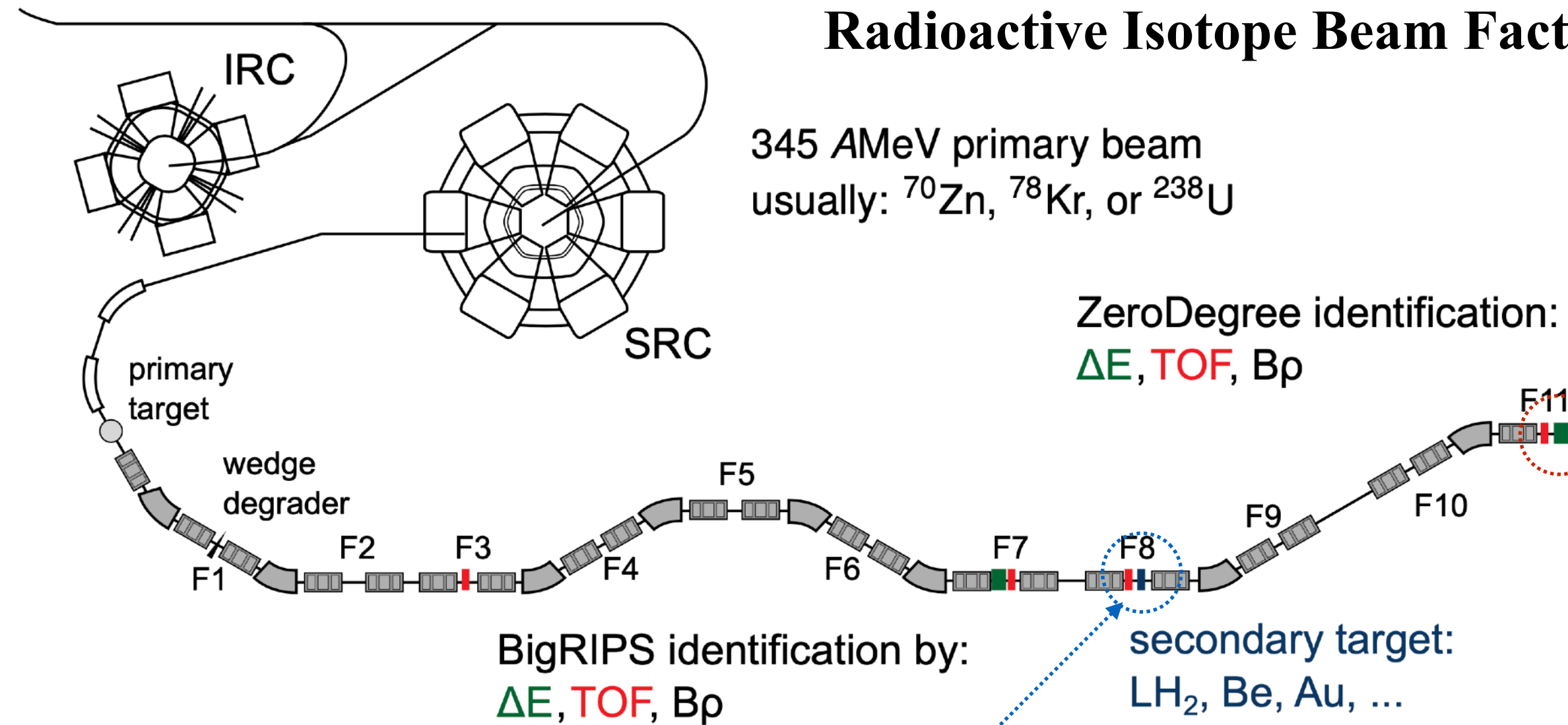
Nuclear structure with RI beam



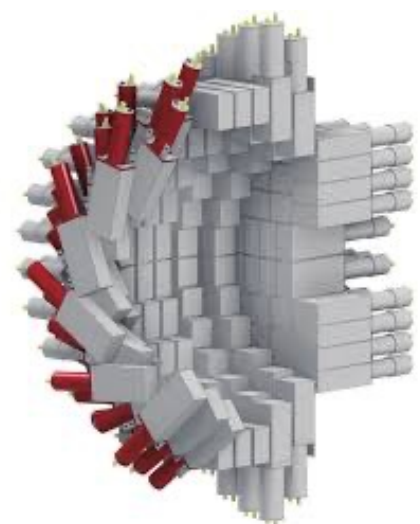
- How does an atomic nucleus transit in its shape?
- Do magic numbers change in exotic nuclei?
- How do nuclear shells change their energies depending on number of nucleons?

RI Beam Factory at RIKEN

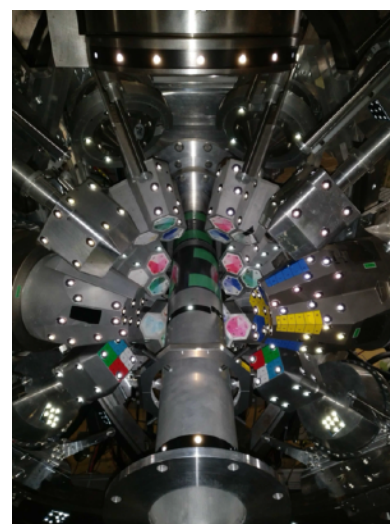
Radioactive Isotope Beam Factory (RIBF)



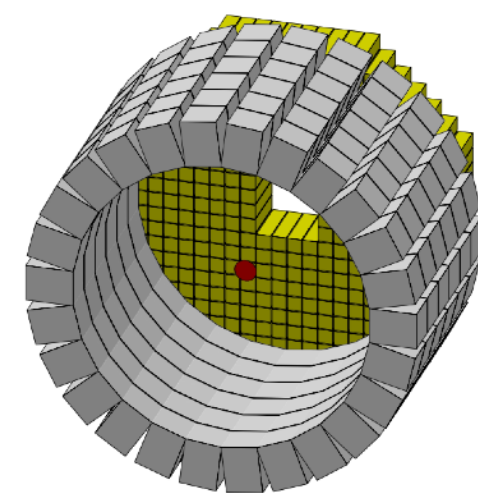
In-beam γ -ray spectroscopy



DALI2+

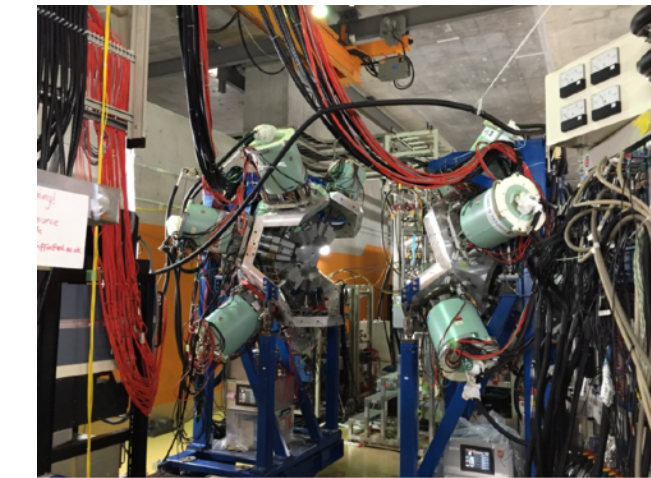


HiCARI

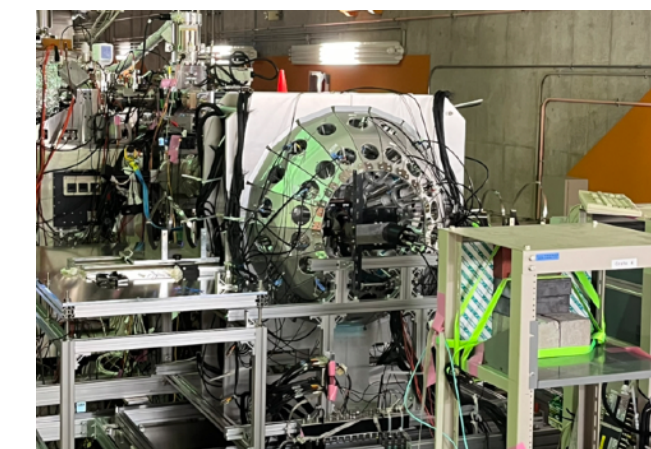


HYPATIA

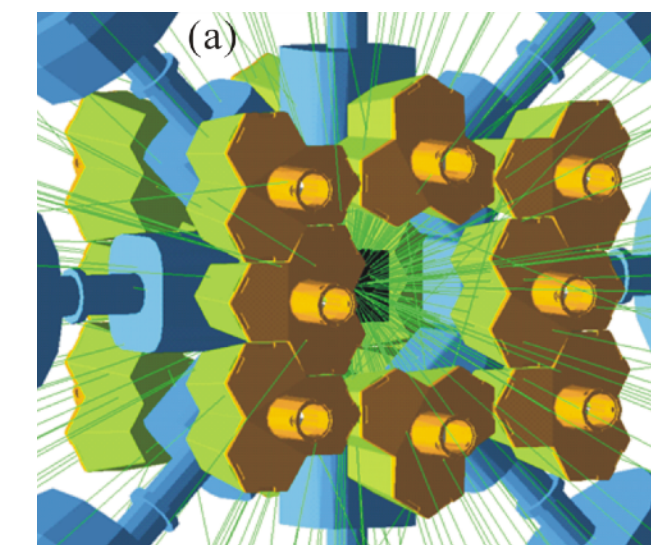
Decay spectroscopy



EURICA

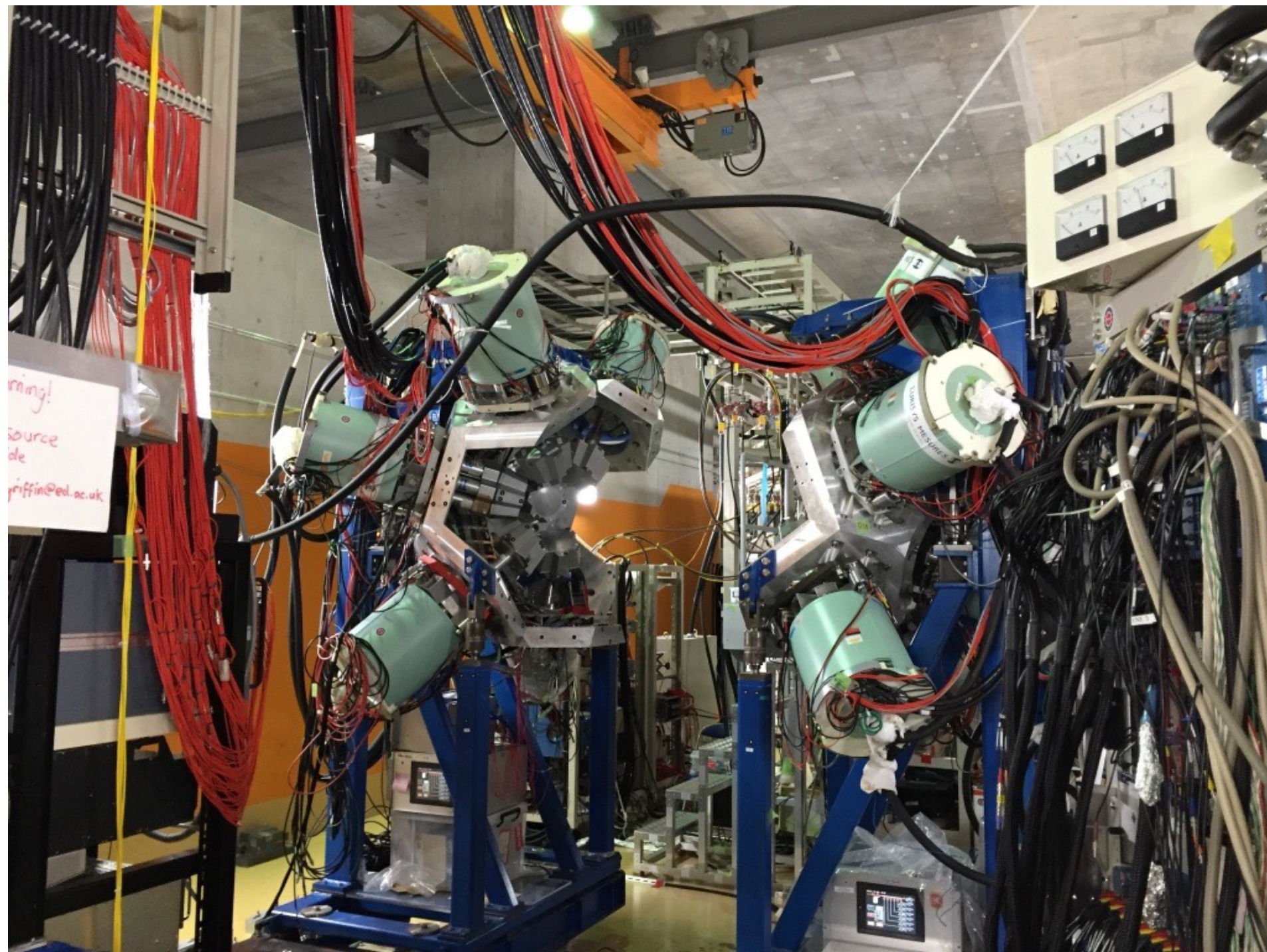


IDATEN

C²URIE

- Primary beams (^{70}Zn , ^{78}Kr , ^{124}Xe , ^{238}U) from SRC with an energy up to 345 AMeV
- RI production and selection from the in-flight fission or fragmentation method
- F1-F7: BigRIPS / F8-F11: ZeroDegree Spectrometer

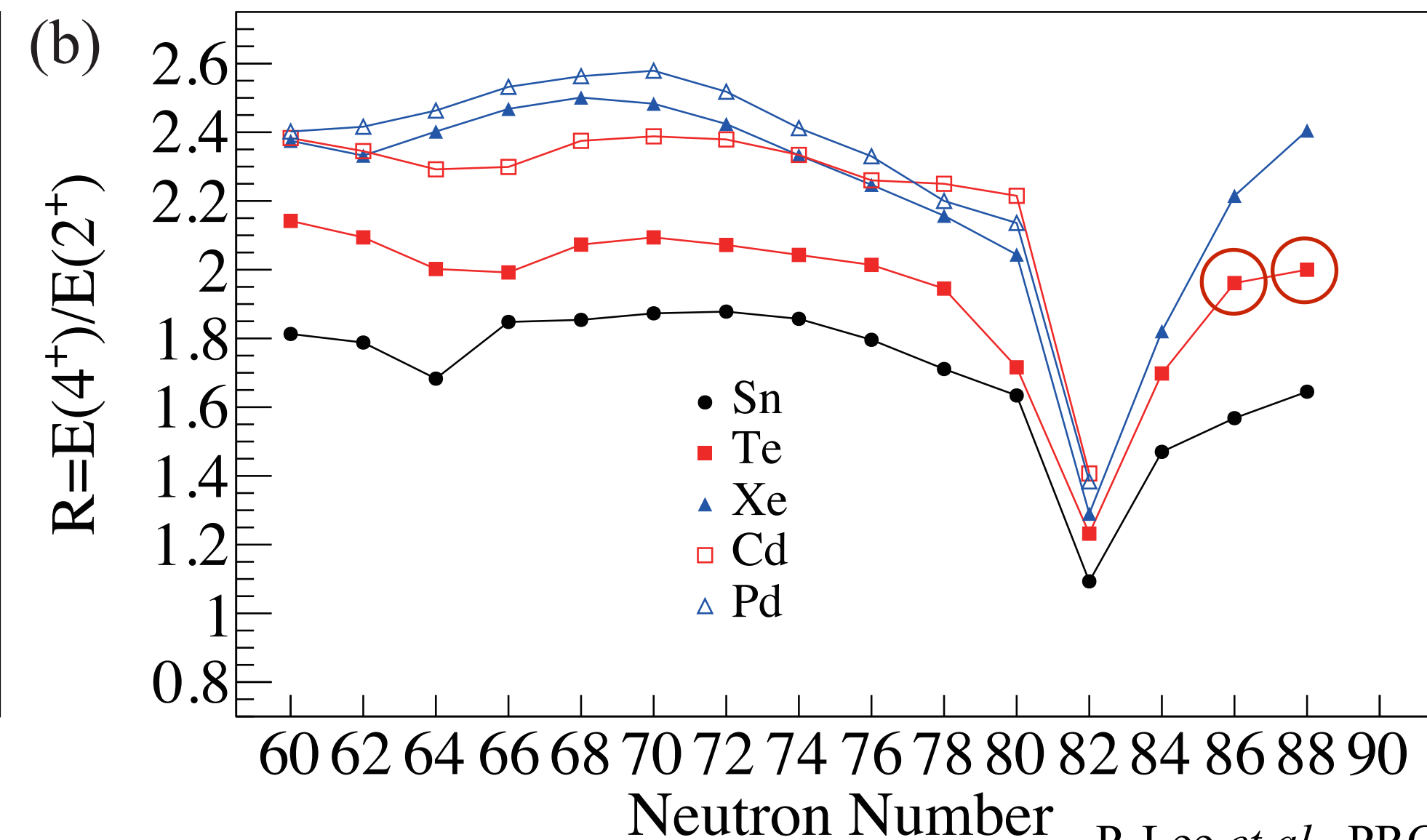
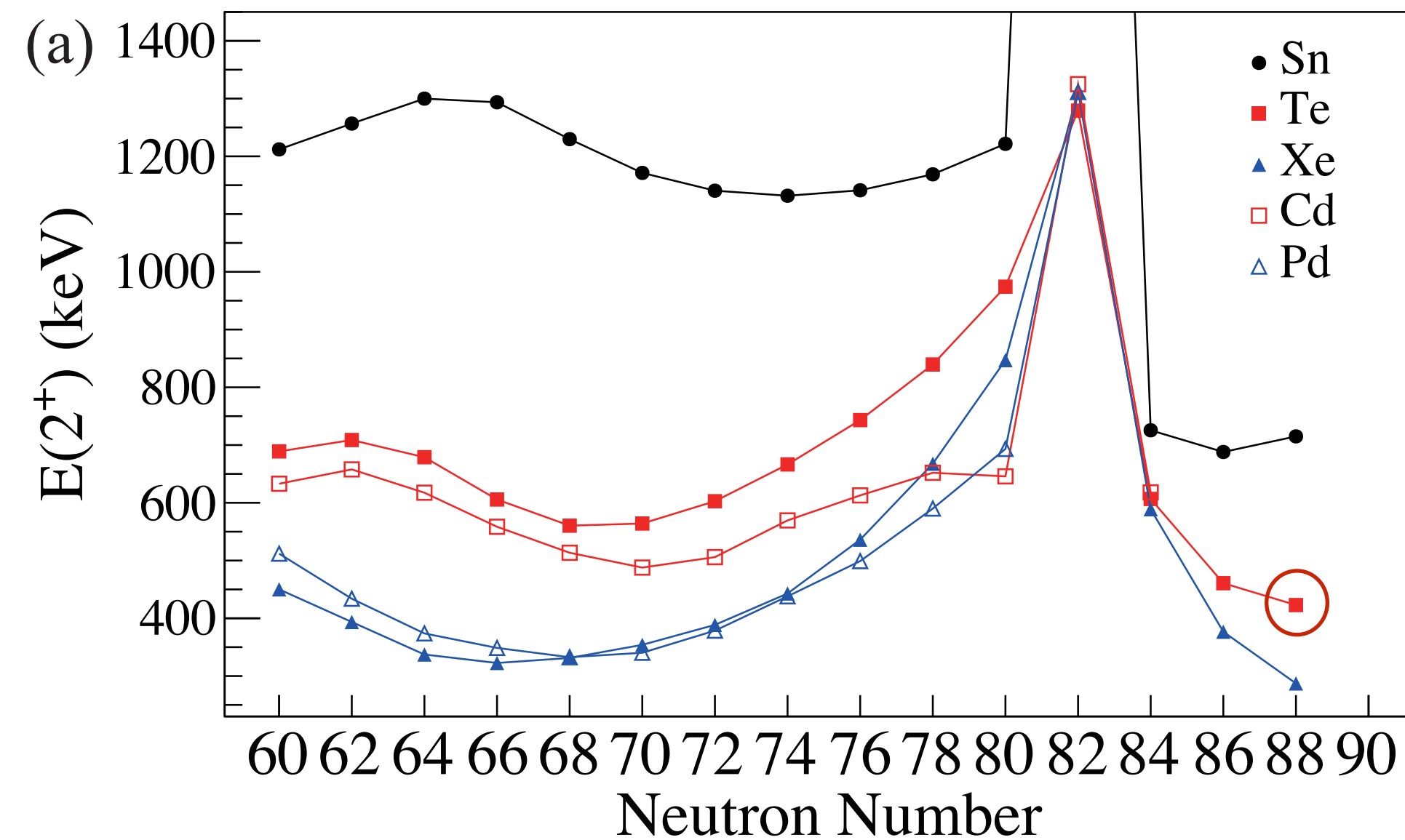
High-resolution delayed γ -ray spectroscopy



P.-A. Soderstrom *et al.*, NIM A **317**, 649
H. Watanabe, Eur. Phys. J. A **55**, 19

- Euroball-RIKEN Cluster Array (EURICA) project
 - 2012 - 2016 at RIBF
 - 18 experiments with 110 days of beam time
- 84 high-purity germanium detectors from Europe
- 5 layers of DSSDs as active stopper (WAS3ABi)
- Decay spectroscopy (beta/isomer)
- 40 new isotopes observed and tons of new half-lives in various nuclear regions
- 70 peer-reviewed papers published to date

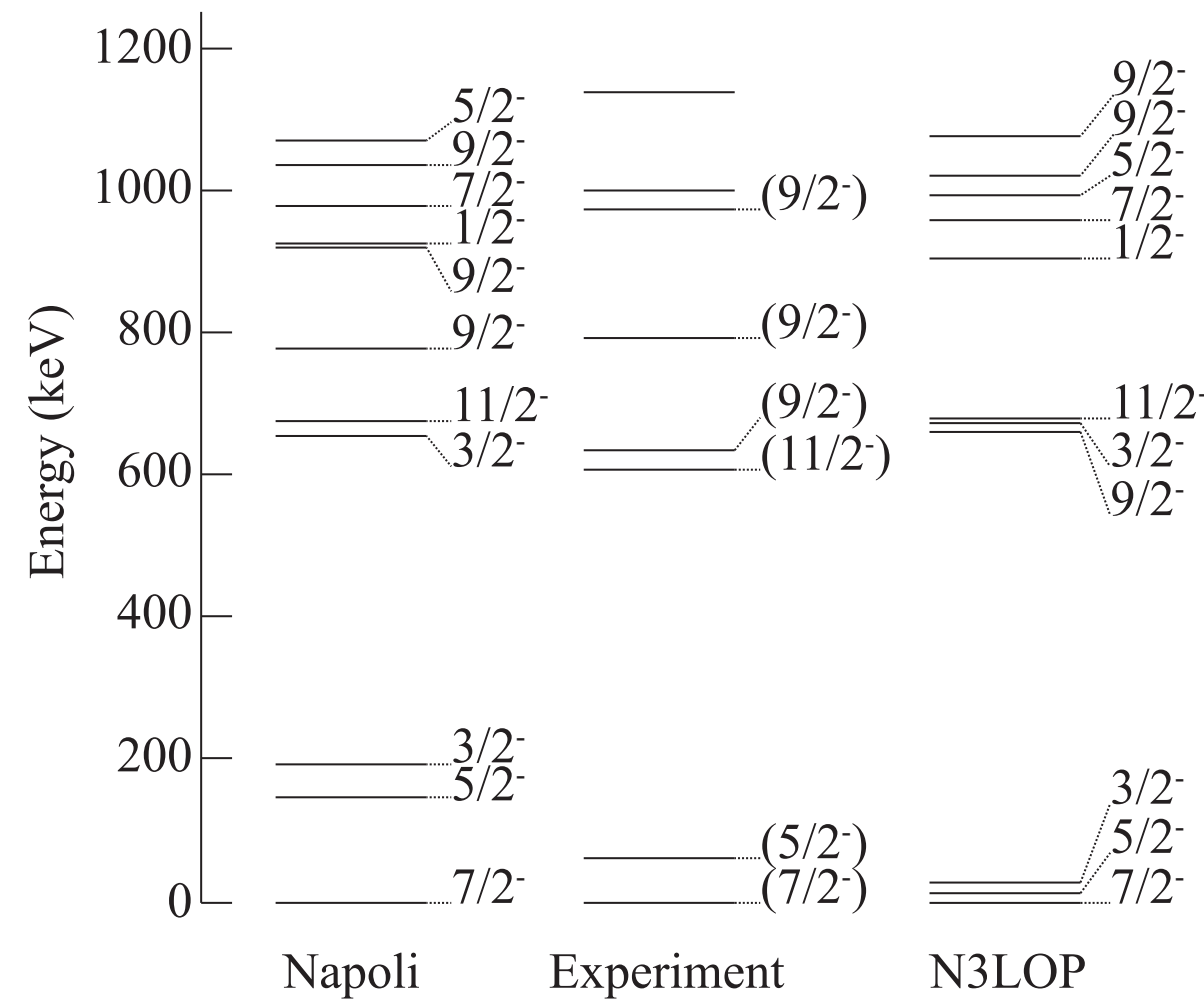
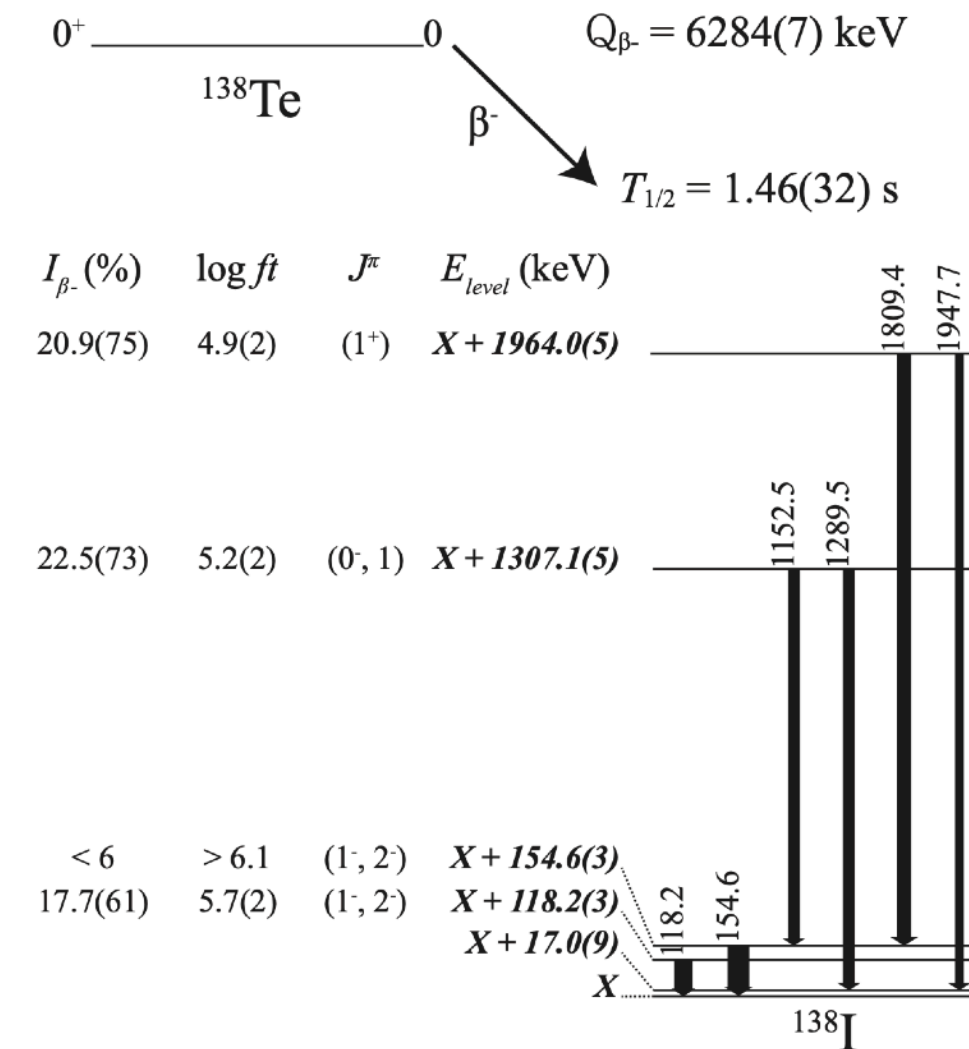
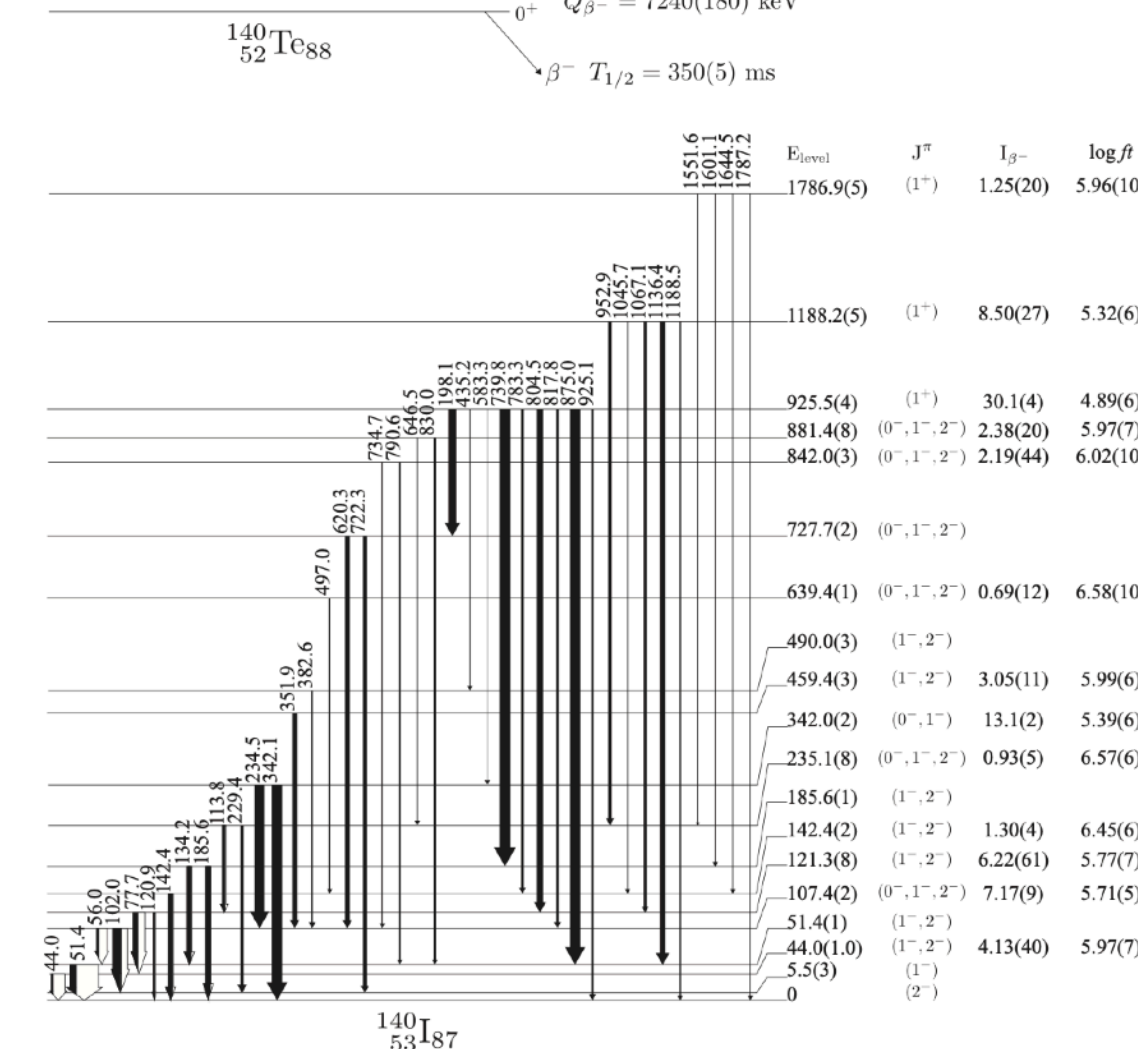
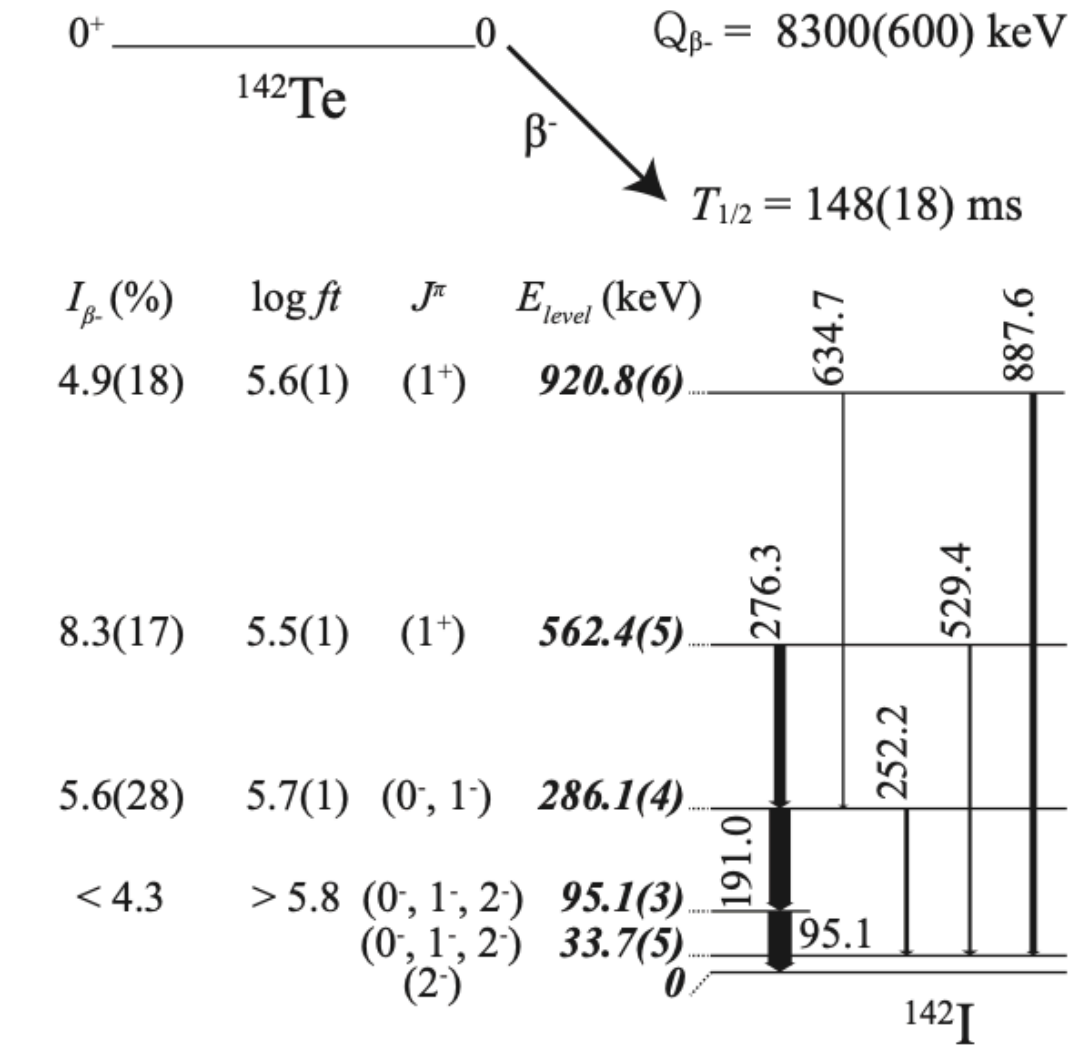
Nuclear structure beyond ^{132}Sn



P. Lee *et al.*, PRC **92**, 044320 (2015)
B. Moon *et al.*, PRC **95**, 044322 (2017)

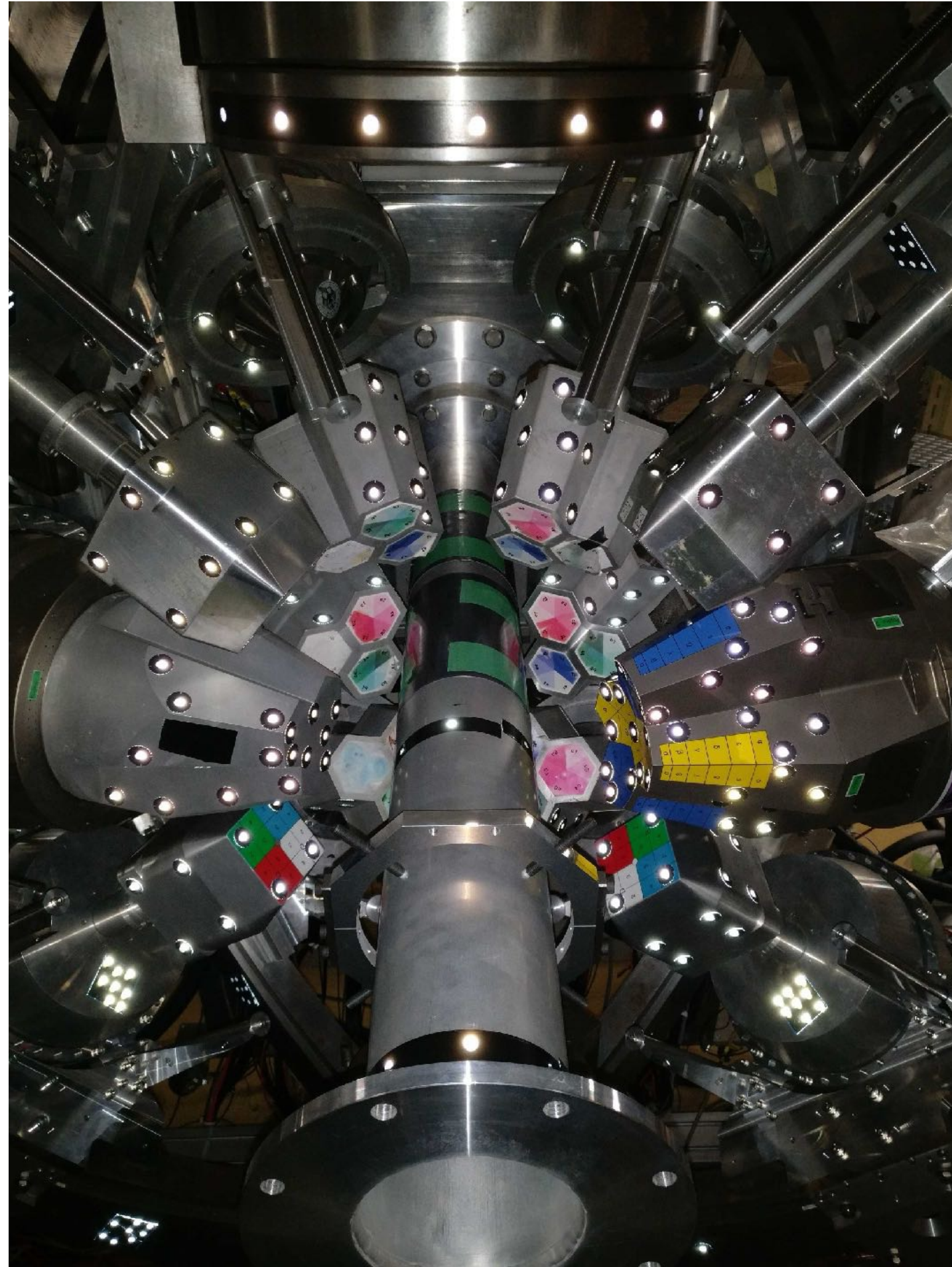
- Different pairing behaviors of protons and neutrons (^{134}Te and ^{134}Sn).
- New levels in ^{138}Te and ^{140}Te were observed from our data (red circles).
- A unique feature of the symmetric structure evolution was observed.
- $N = 90$ new magic number? Or a special physics in neutron-rich Te isotopes?

Nuclear structure beyond ^{132}Sn

B. Moon *et al.*, PRC **103**, 034320 (2021)B. Moon *et al.*, PRC **105**, 034334 (2022)B. Moon *et al.*, PRC **96**, 014325 (2017)B. Moon *et al.*, PRC **107**, 014311 (2023)

- Seniority-3 scheme of neutron $f_{7/2}$ orbital observed in ^{137}Te
- Two different natures in $9/2^-$ states:
 - $\nu 1f_{7/2} \otimes 2^+$ of ^{136}Te core excitation.
 - $\nu 0h_{9/2} \otimes 0^+$ of ^{136}Te , single particle. First observation of β decay of ^{138}Te and ^{140}Te
- Newly observed 1^+ states in ^{138}I , ^{140}I , and ^{142}I
- Shell model calculations predict this 1^+ state as a candidate of $\pi h_{11/2} \otimes \nu h_{9/2}$ proton-neutron configuration.

High-resolution in-beam γ -ray spectroscopy

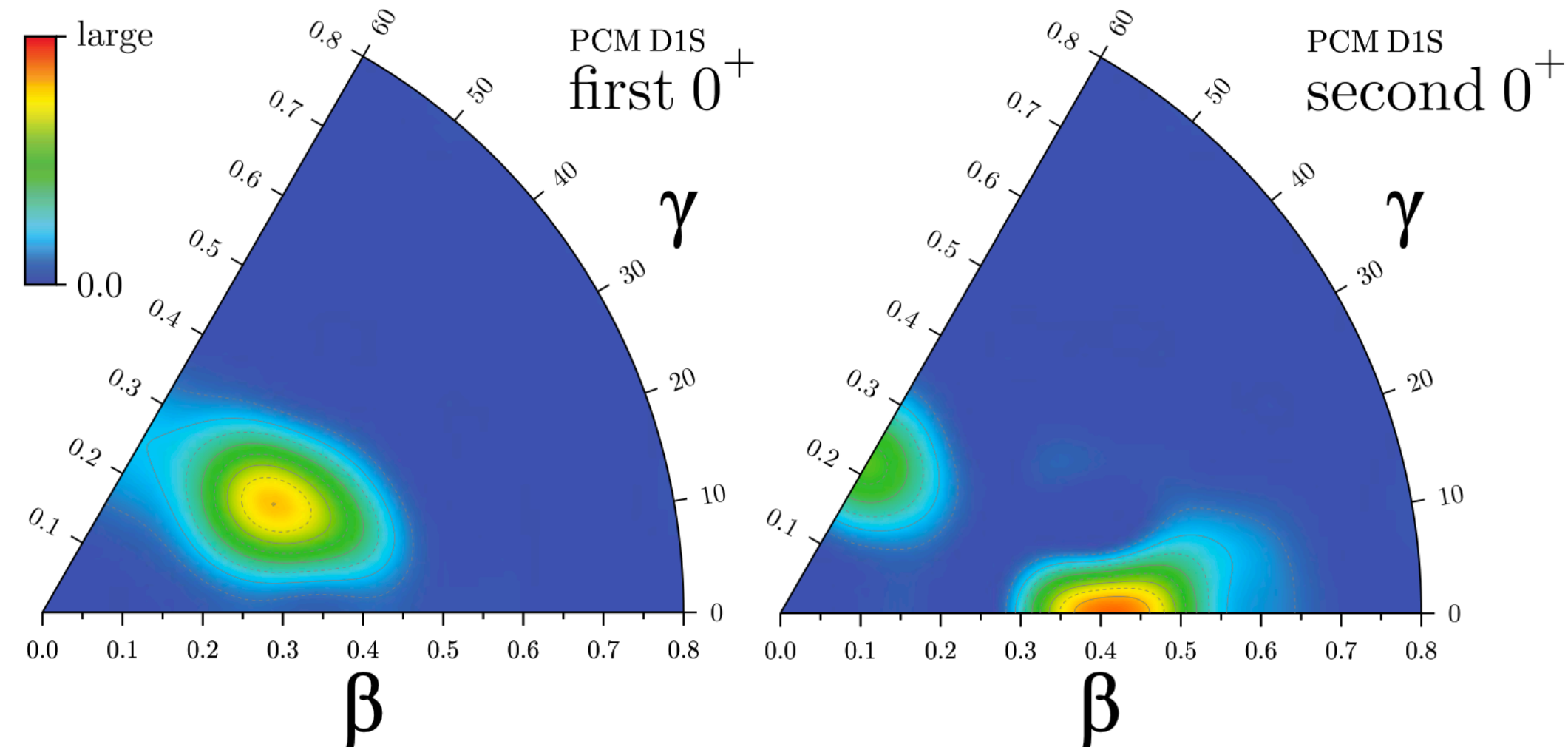


- High-resolution Cluster Array at RIBF (HiCARI) campaign was performed in 2020 and 2021.
(Spokespersons: P. Doornenbal and K. Wimmer)
- Large international collaboration
 - 6 Miniball triple clusters, 4 segmented clovers, and 2 GRETINA-type tracking detectors
- $\sim 3\%$ detection efficiency @ 1 MeV
- 8 experiments with 31.5 days of beam time

K. Wimmer et al., RIKEN Accel. Prog. Rep. 54 (2021) S27

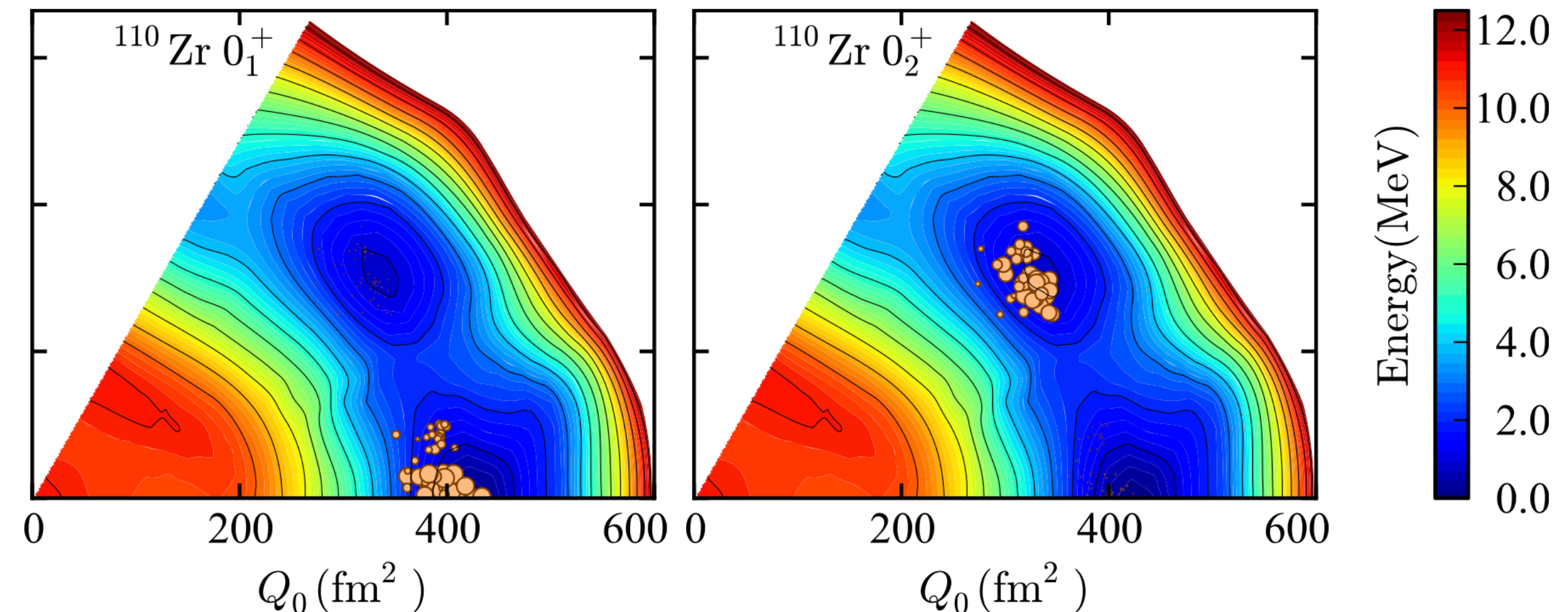
Axial or triaxial deformation in ^{110}Zr ?

- Predicted nuclear shape of ^{110}Zr



M. Borrajo *et al.*, PLB **746**, 341 (2015)

N. Paul *et al.*, PRL **118**, 032501 (2017)

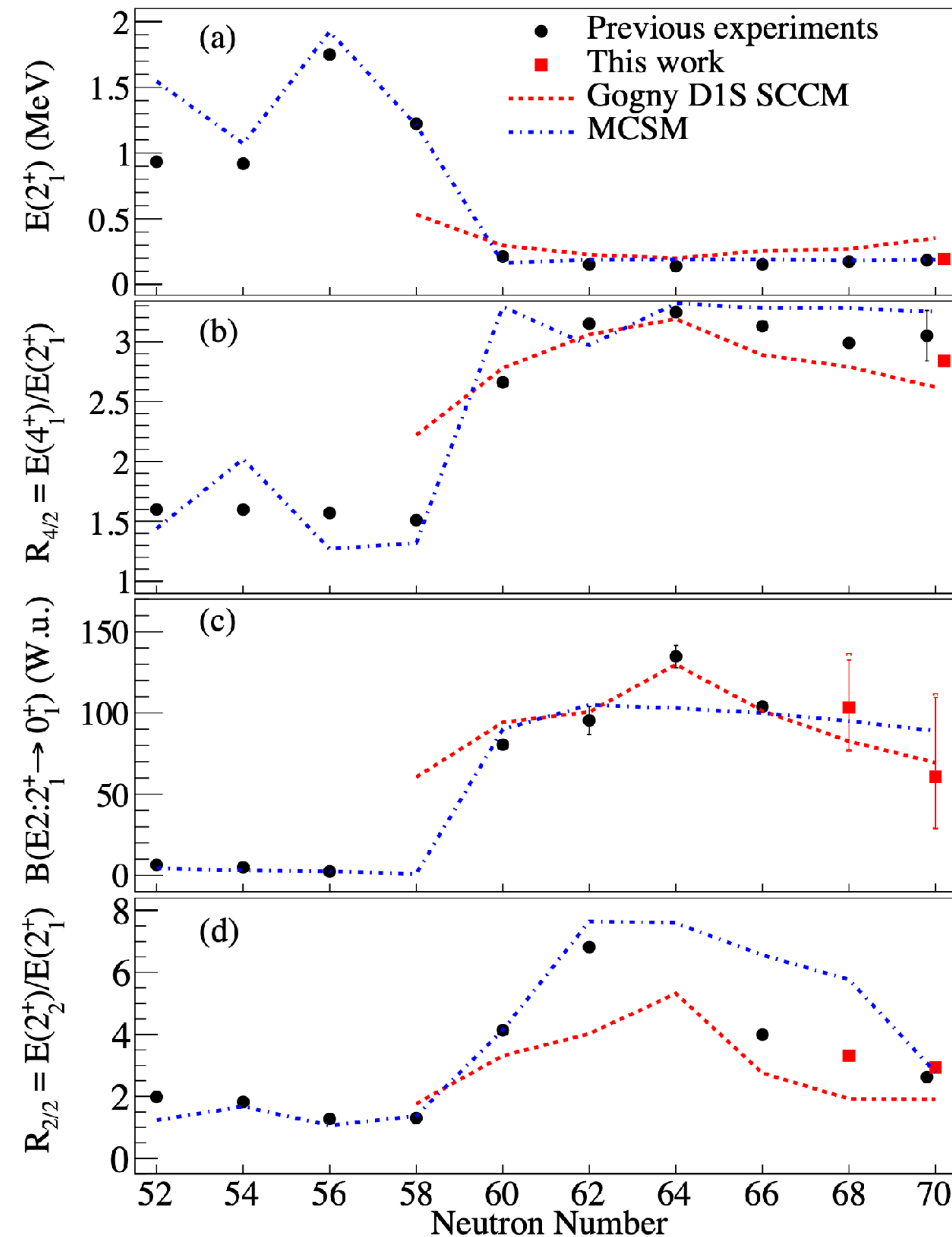


T. Togashi *et al.*, PRL **117**, 172502 (2016)

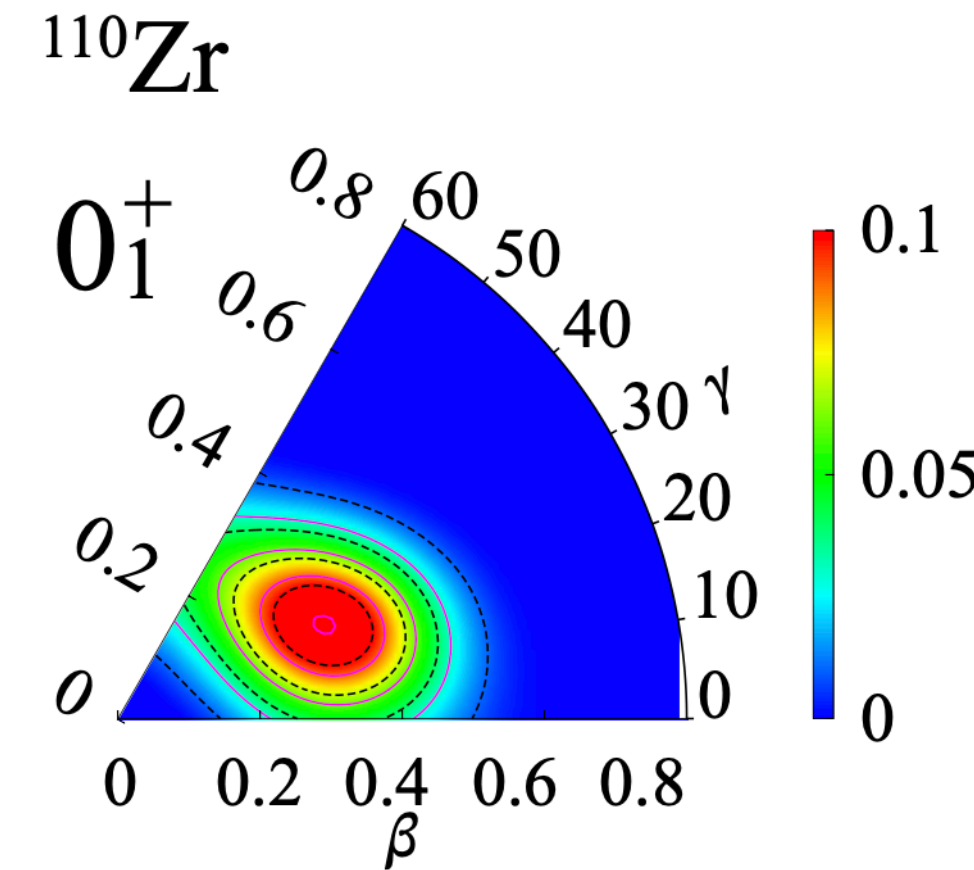
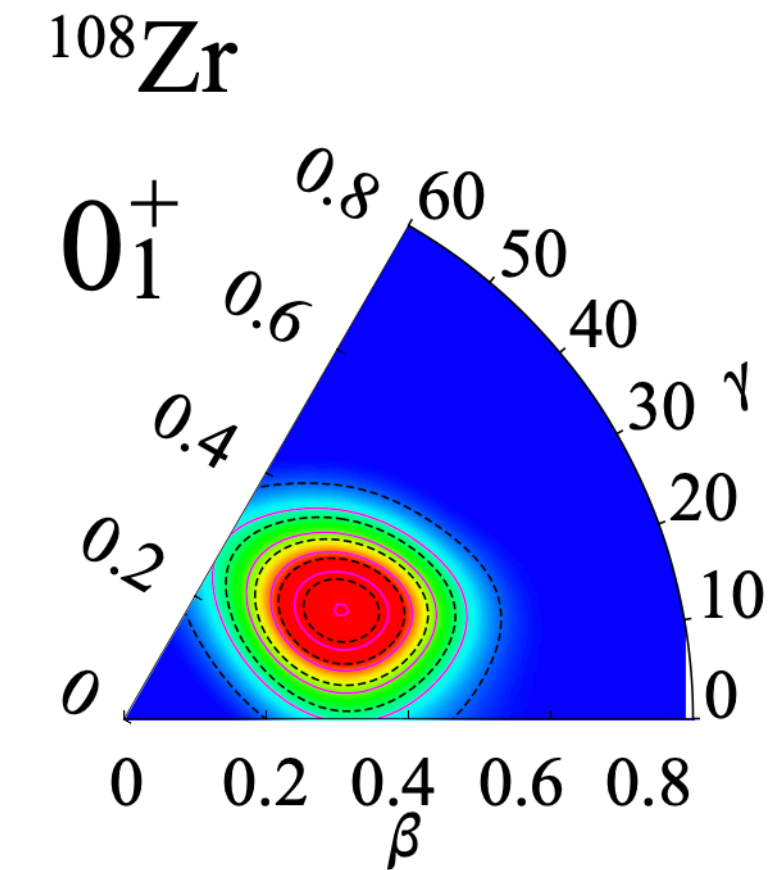
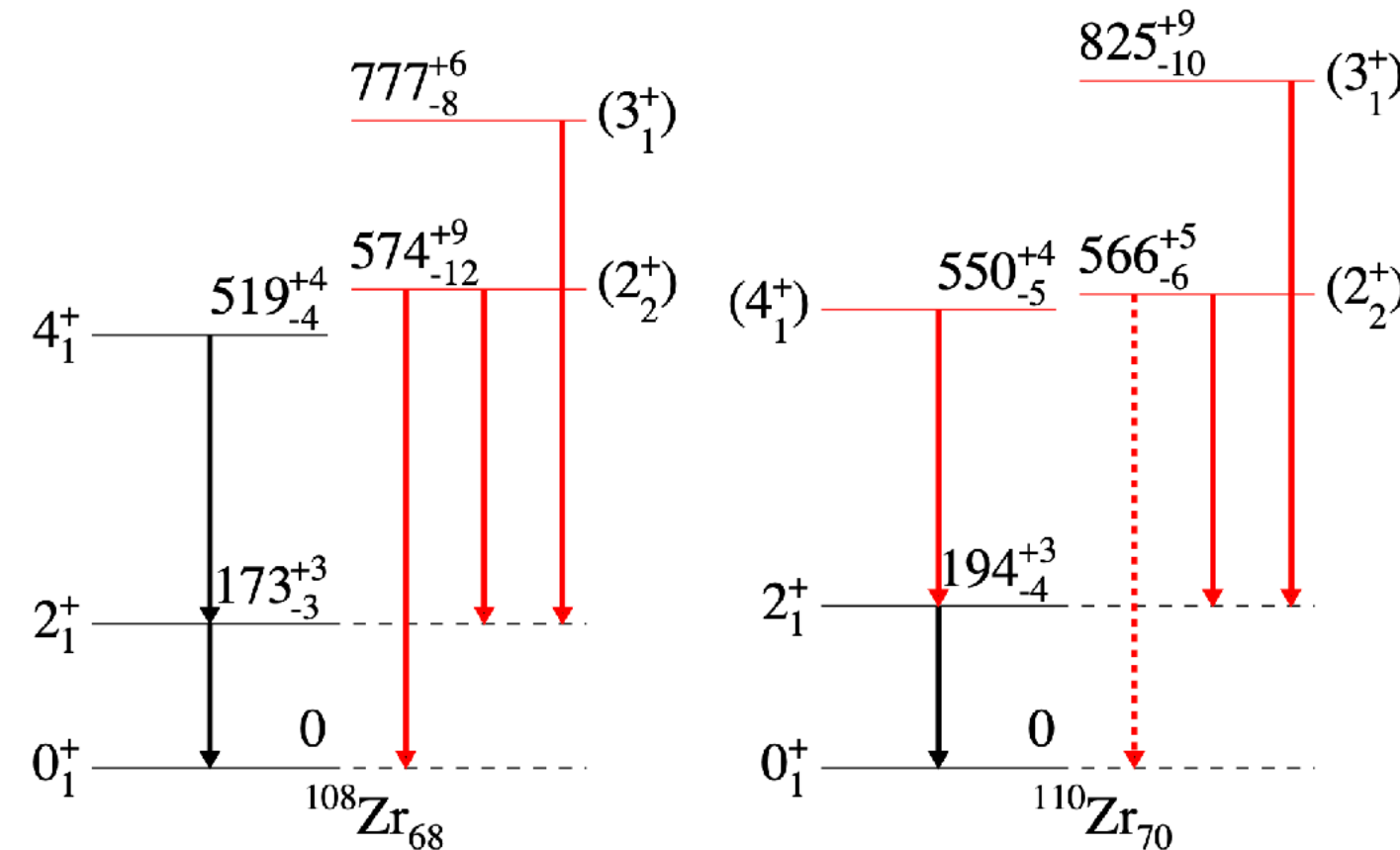
- Two theoretical models showed similar level schemes, but with different structures.
- BMF calculations predict triaxial ground states with γ -softness.
- MCSM calculation predicts the prolate deformed ground state with triaxial excited state.
- Need the transition rate information to investigate the nuclear shape.

Lifetime measurements are essential to discriminate between different theoretical predictions!

Triaxial deformation in $^{108, 110}\text{Zr}$

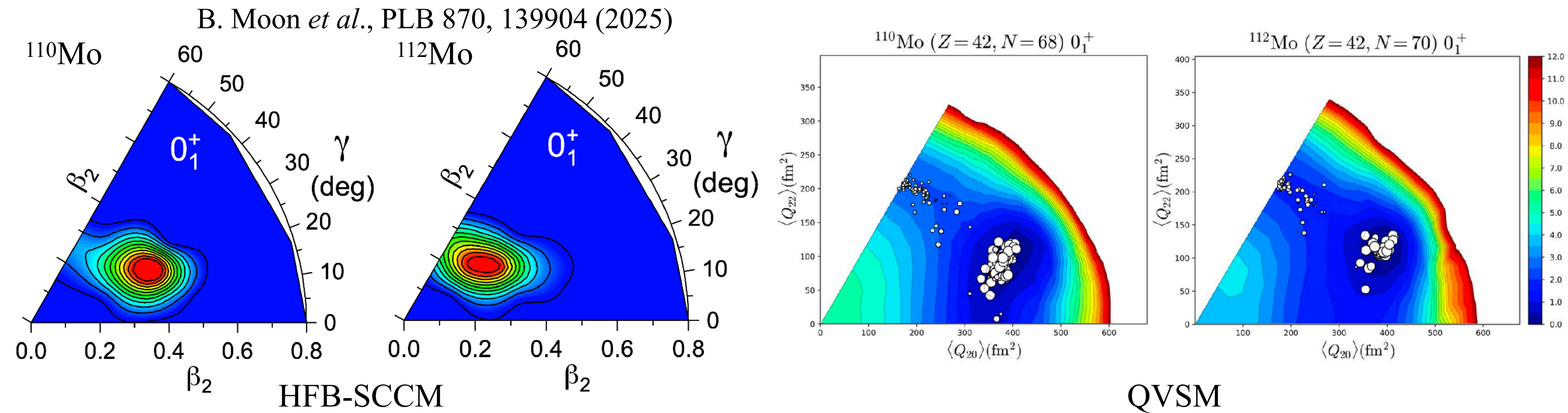
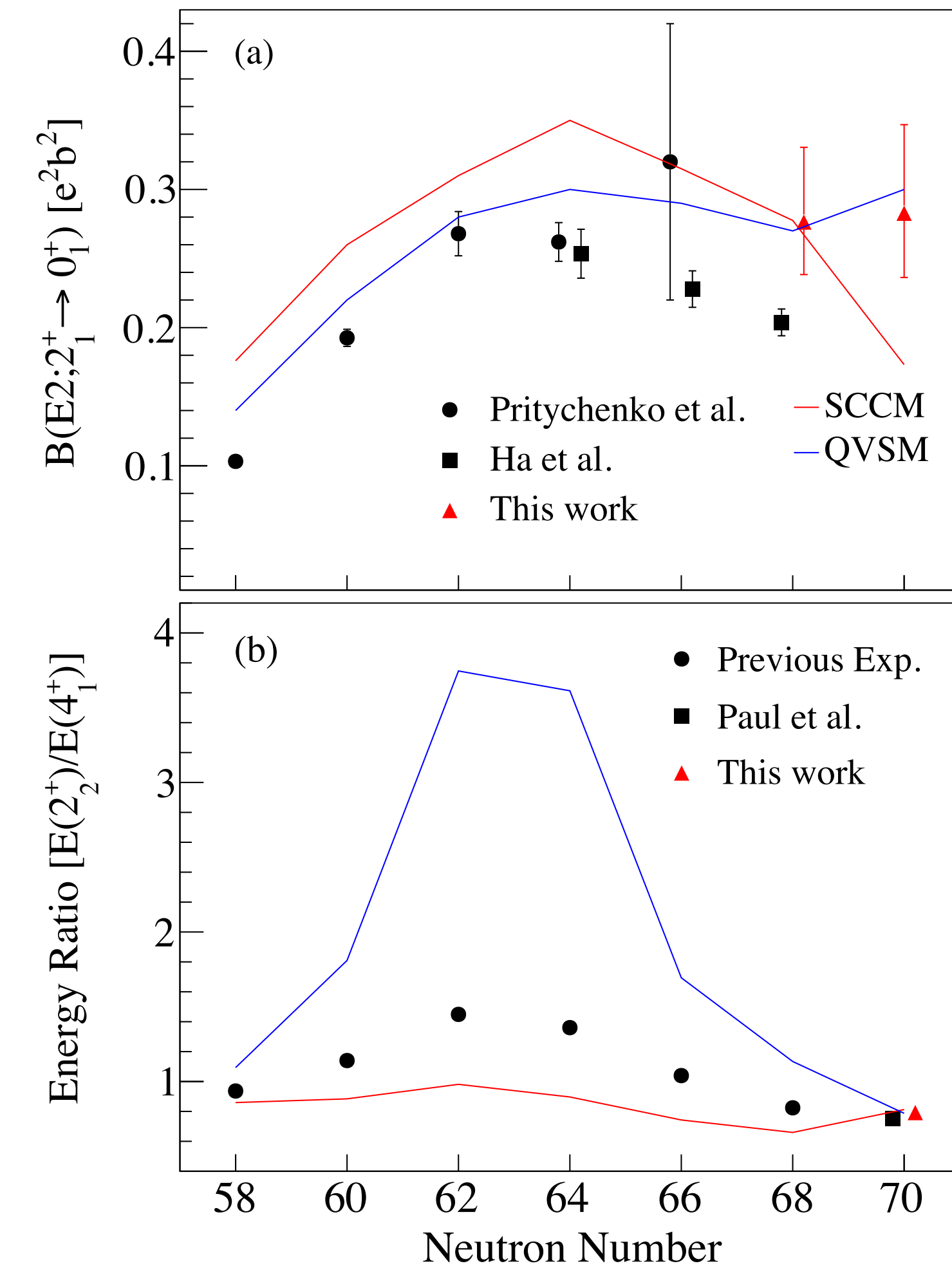


B. Moon *et al.*, PLB 858, 139047 (2024)



- Decrease of collectivity in Zr isotopes toward $N = 70$ in terms of $R_{4/2}$ and $B(E2)$ values
- Certain γ degree of freedom needs to be considered, i.e., triaxial deformation in ground states from HFB-SCCM.
- New QVSM (advanced MCSM) also predicts the triaxial ground states in $^{108, 110}\text{Zr}$.

Triaxial deformation in $^{110,112}\text{Mo}$



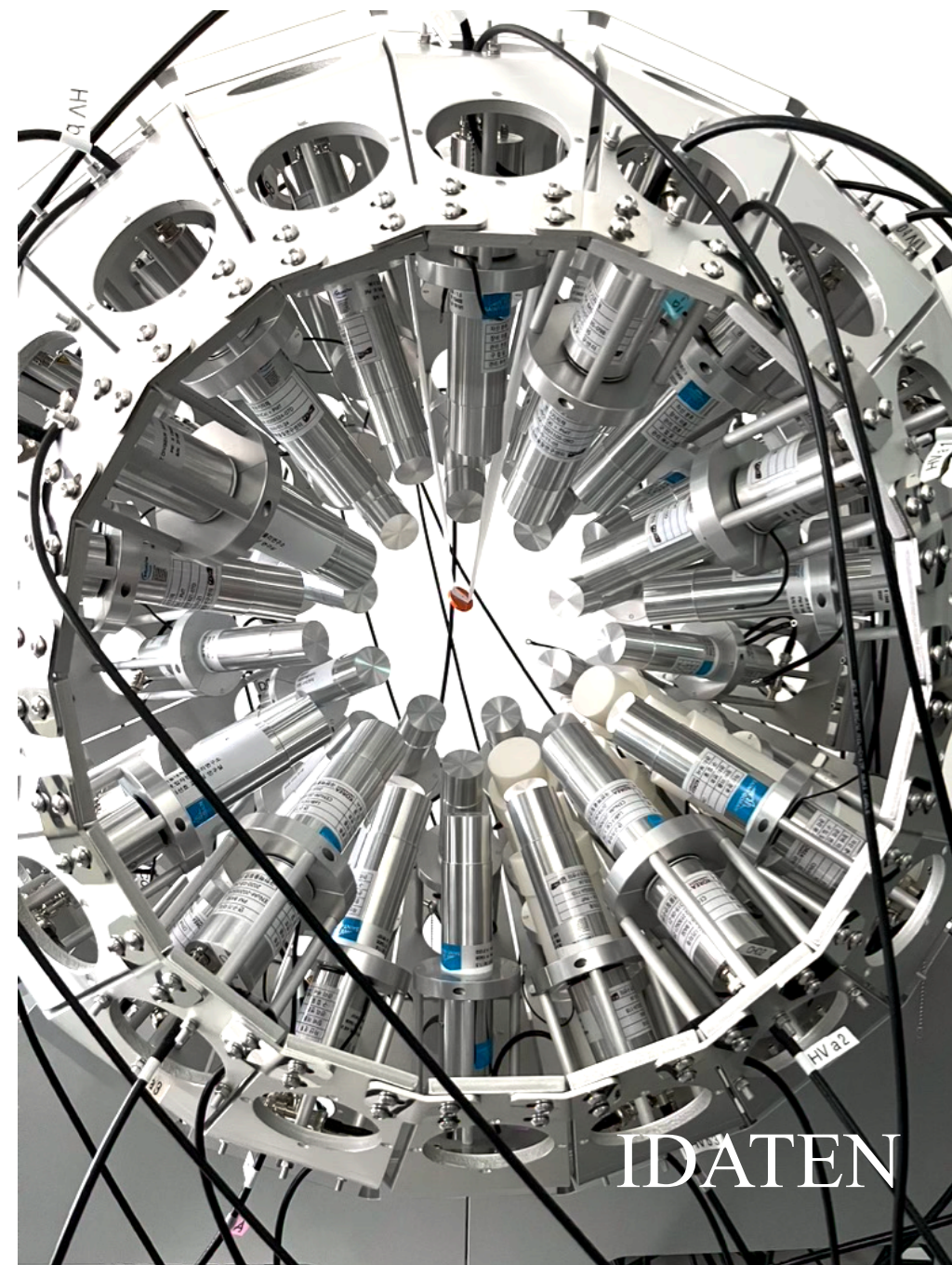
- Different trend of the B(E2) values in ^{110}Mo and ^{112}Mo from the previous measurements.
- Both HFB-SCCM and QVSM could not fully describe the Mo isotopic chain.
- ^{110}Mo and ^{112}Mo may have triaxial deformation in ground states.
- Both models predict the shape coexistence on the top of the 0_2^+ states.

Fast-timing measurement

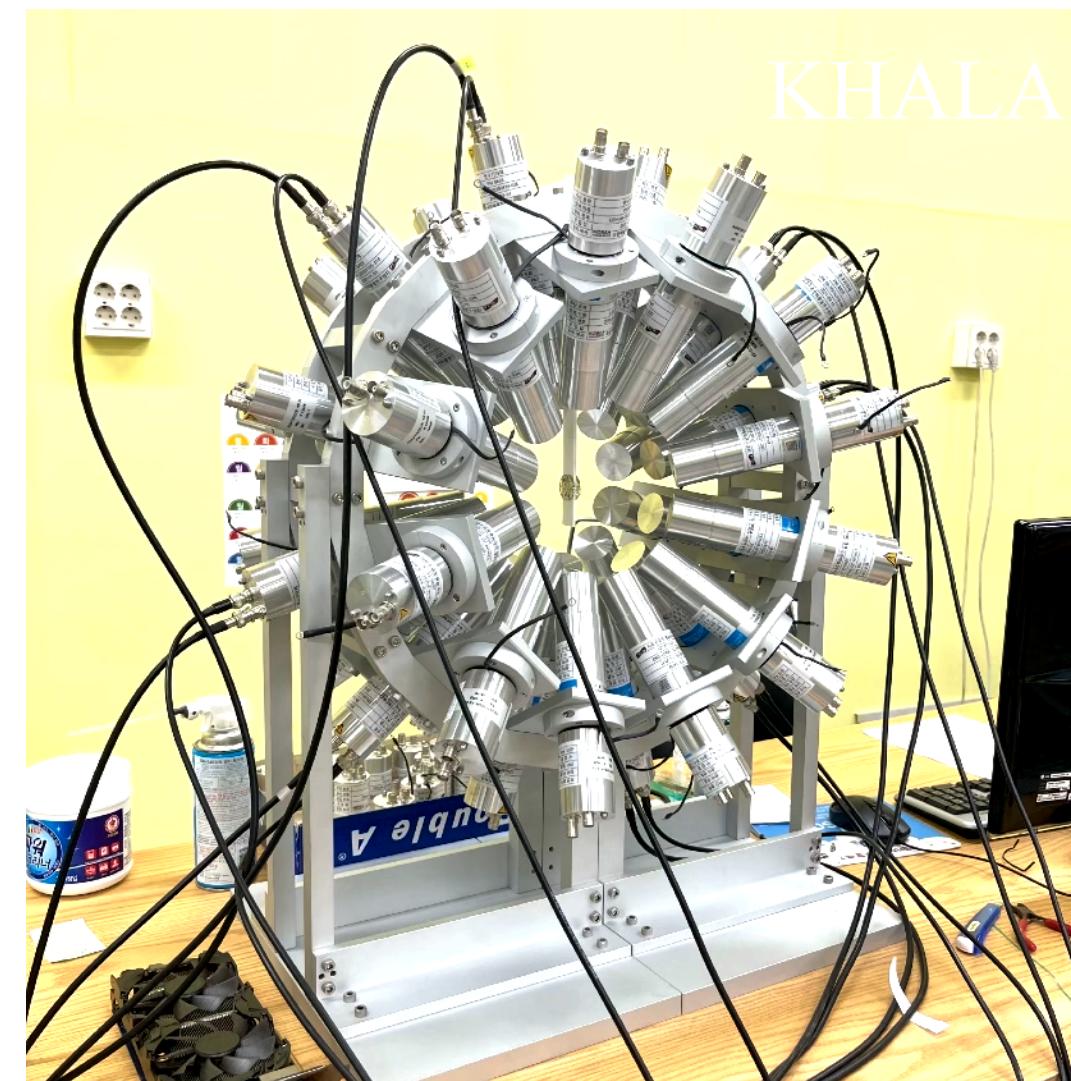
NP2112-RIBF212

Fast-timing γ -ray spectroscopy of exotic nuclei at RIBF

H. Watanabe, P. H. Regan, and B. Moon

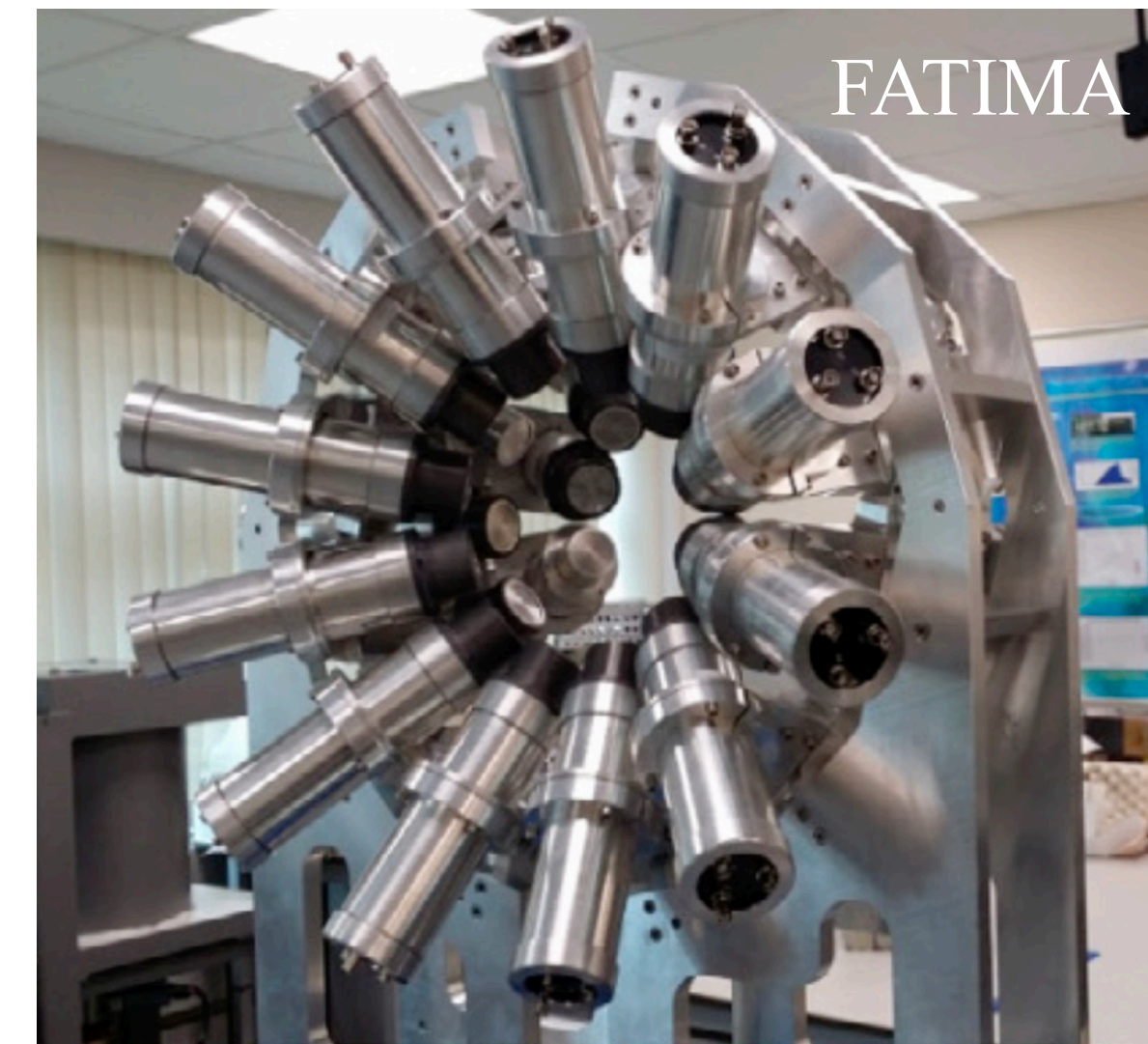


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B. Moon *et al.*, NIMB **541**, 253 (2023)

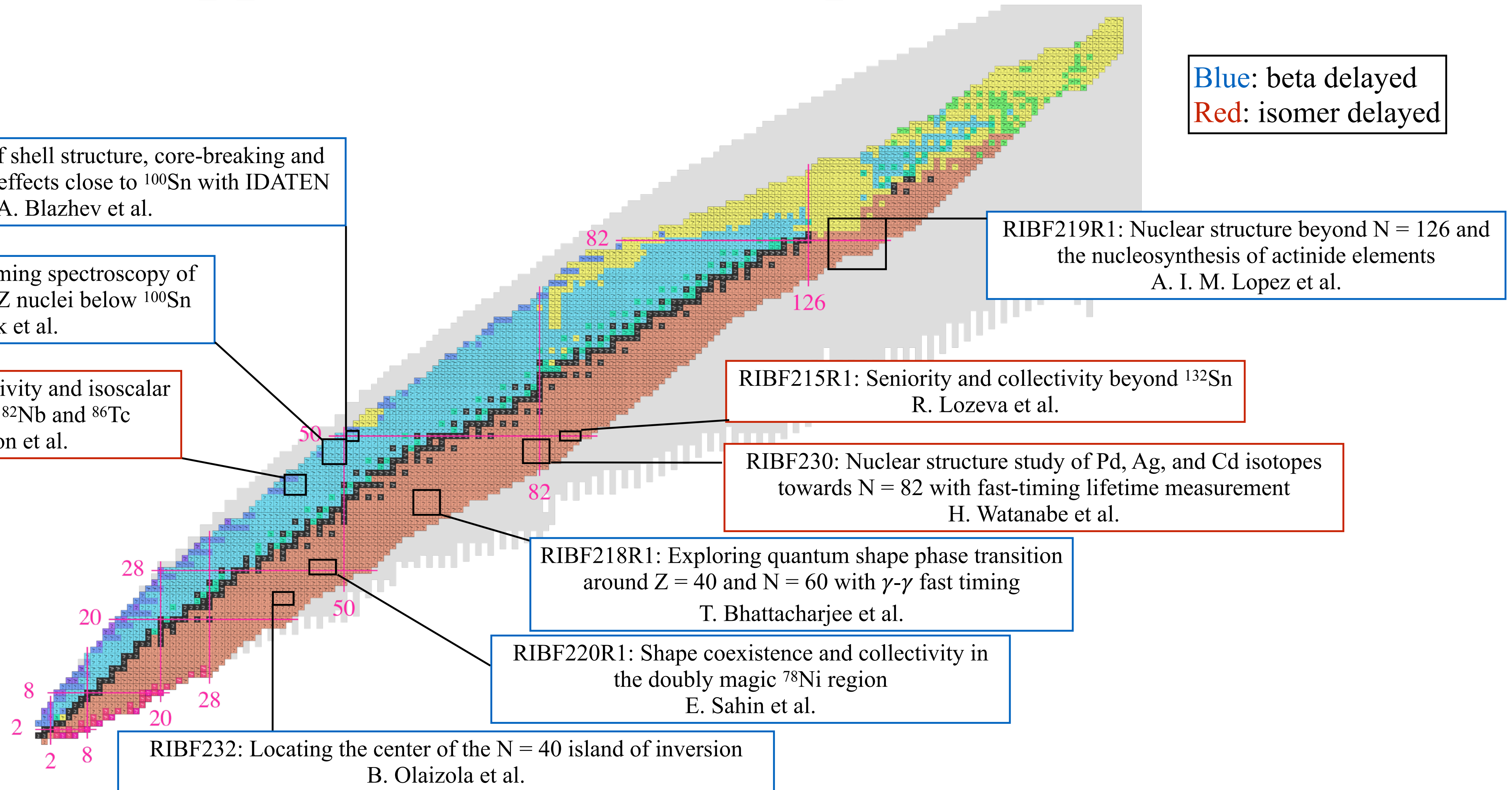
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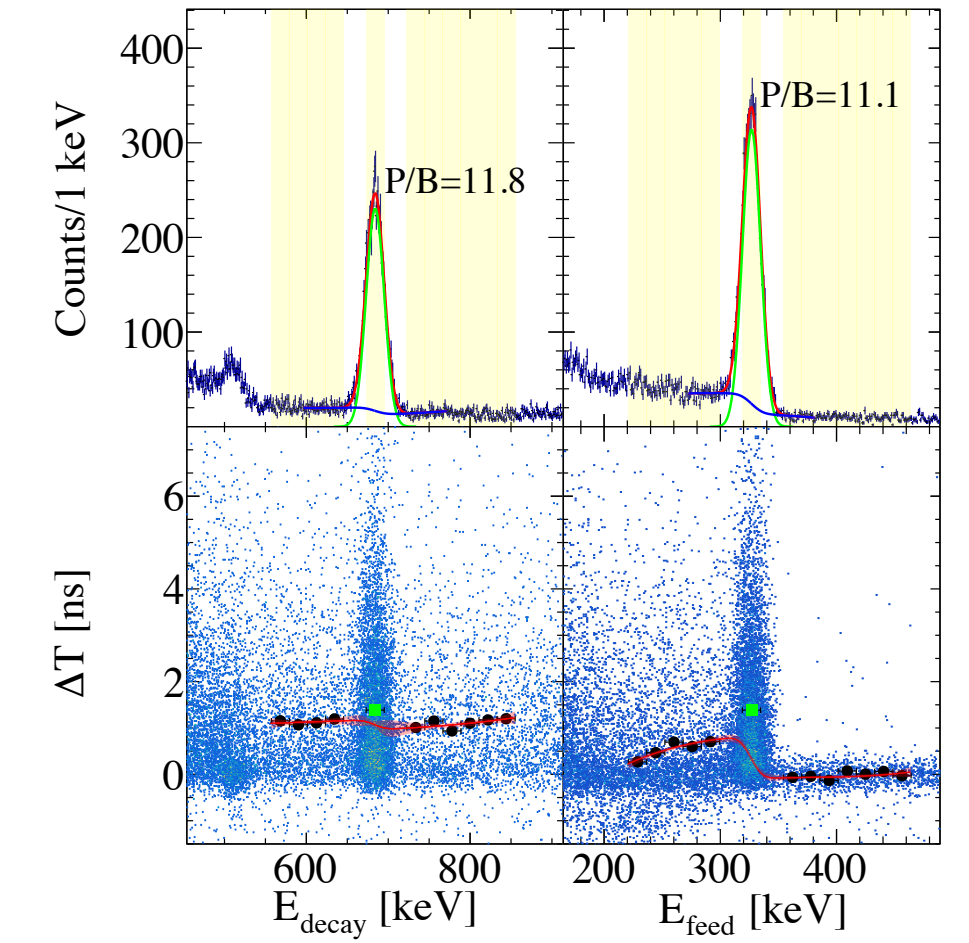
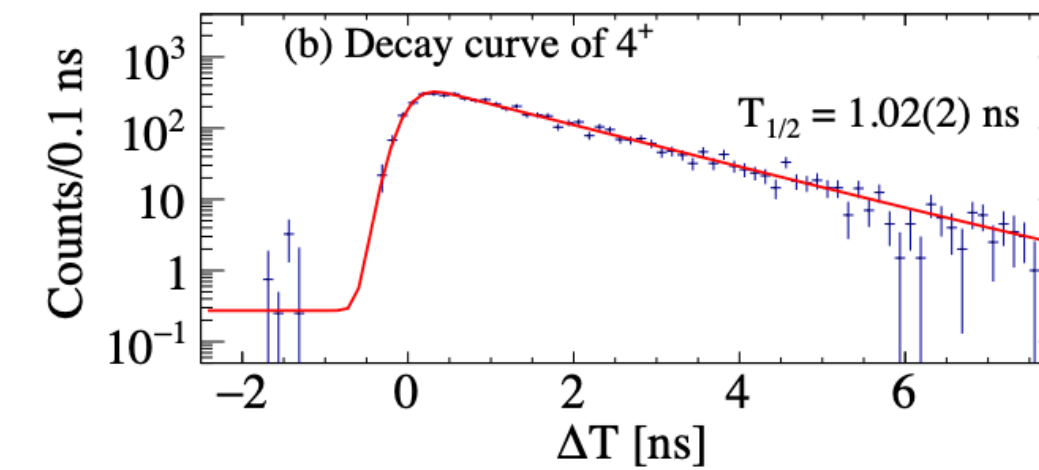
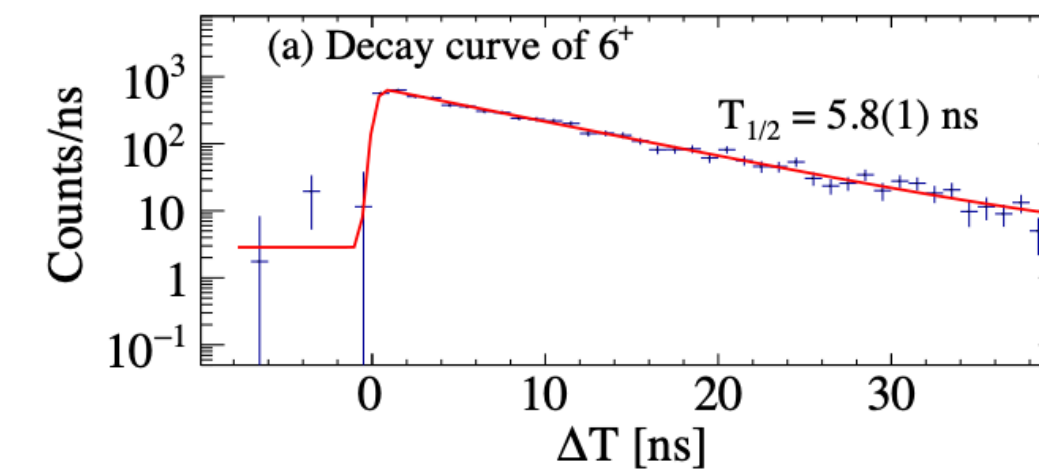
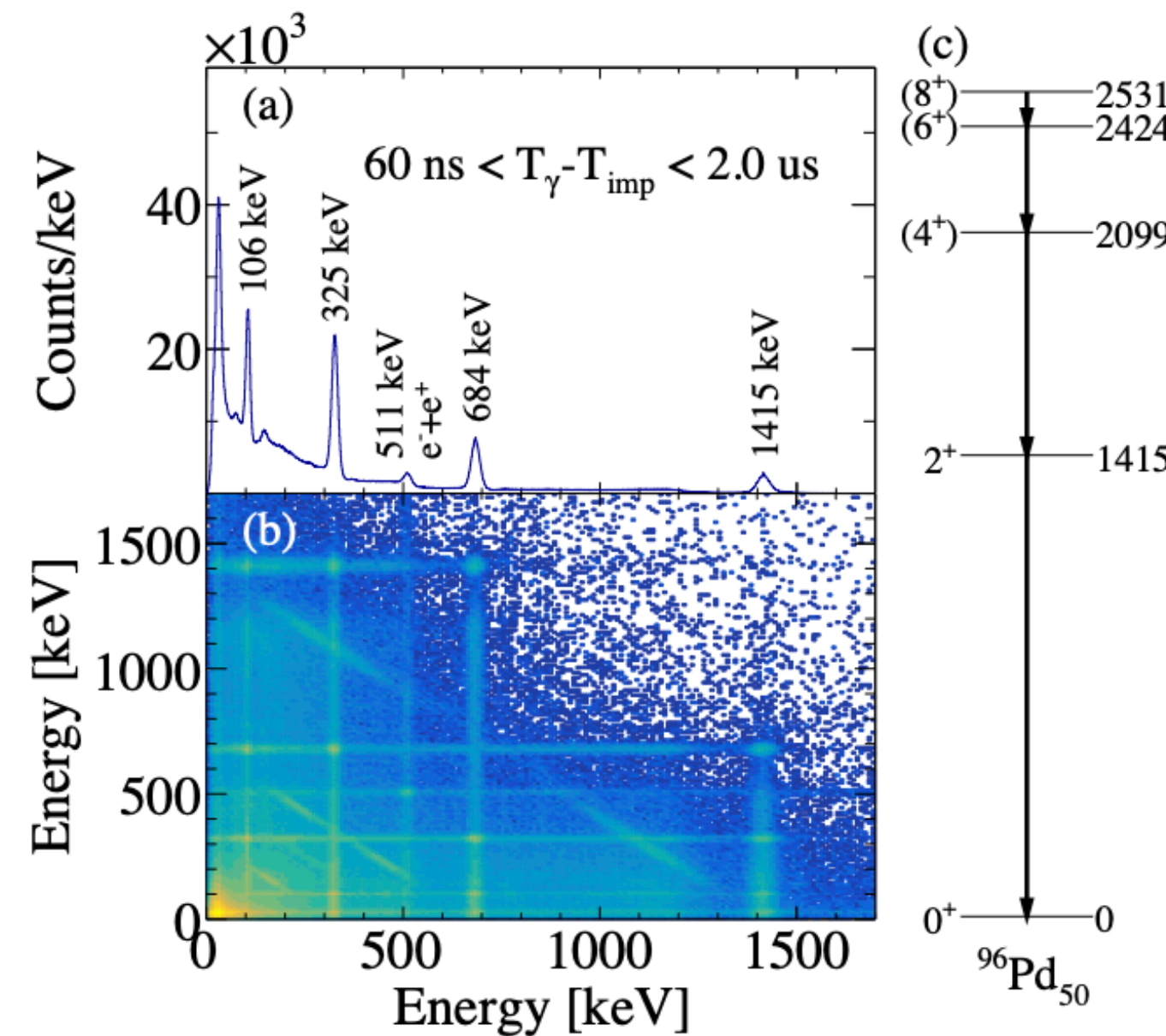
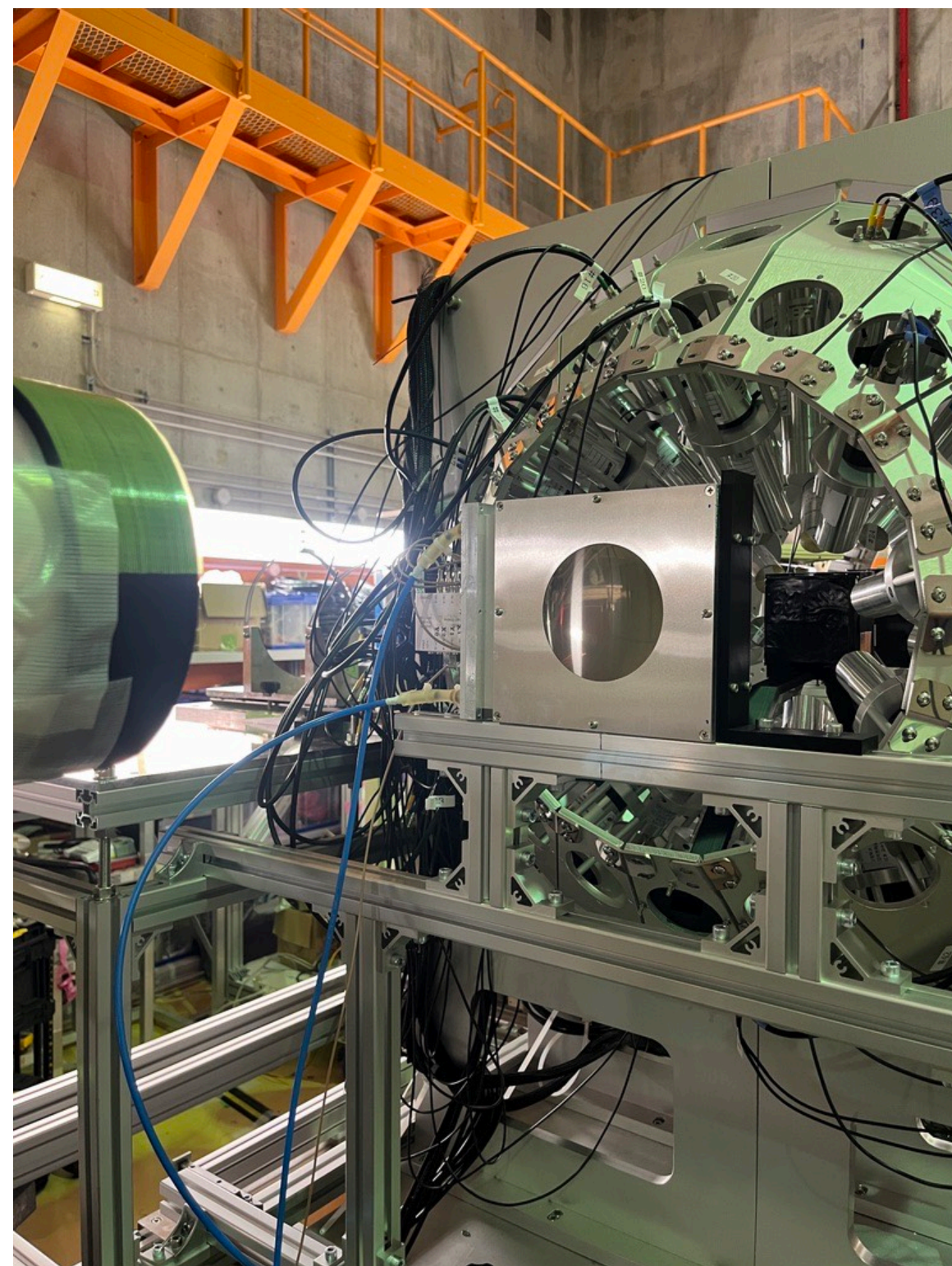
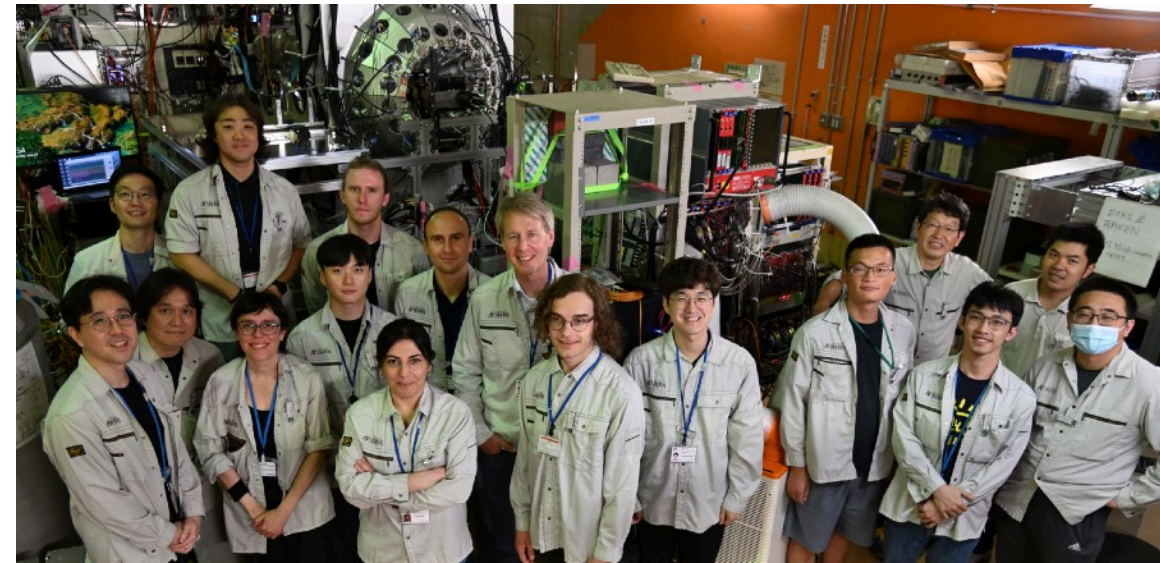
M. Rudigier *et al.*, NIMA **969**, 163967 (2020)

- World largest fast-timing array IDATEN (International Detector Assembly for fast-Timing measurements of Exotic Nuclei)
- 36 KHALA (Korea Univ.) + 36 FATIMA (U. Surrey, U. Brighton) + 12 LaBr₃ (SNU)
- 10 experiments with 43 days of beam time approved by PAC (including a commissioning experiment)

Approved IDATEN experiments



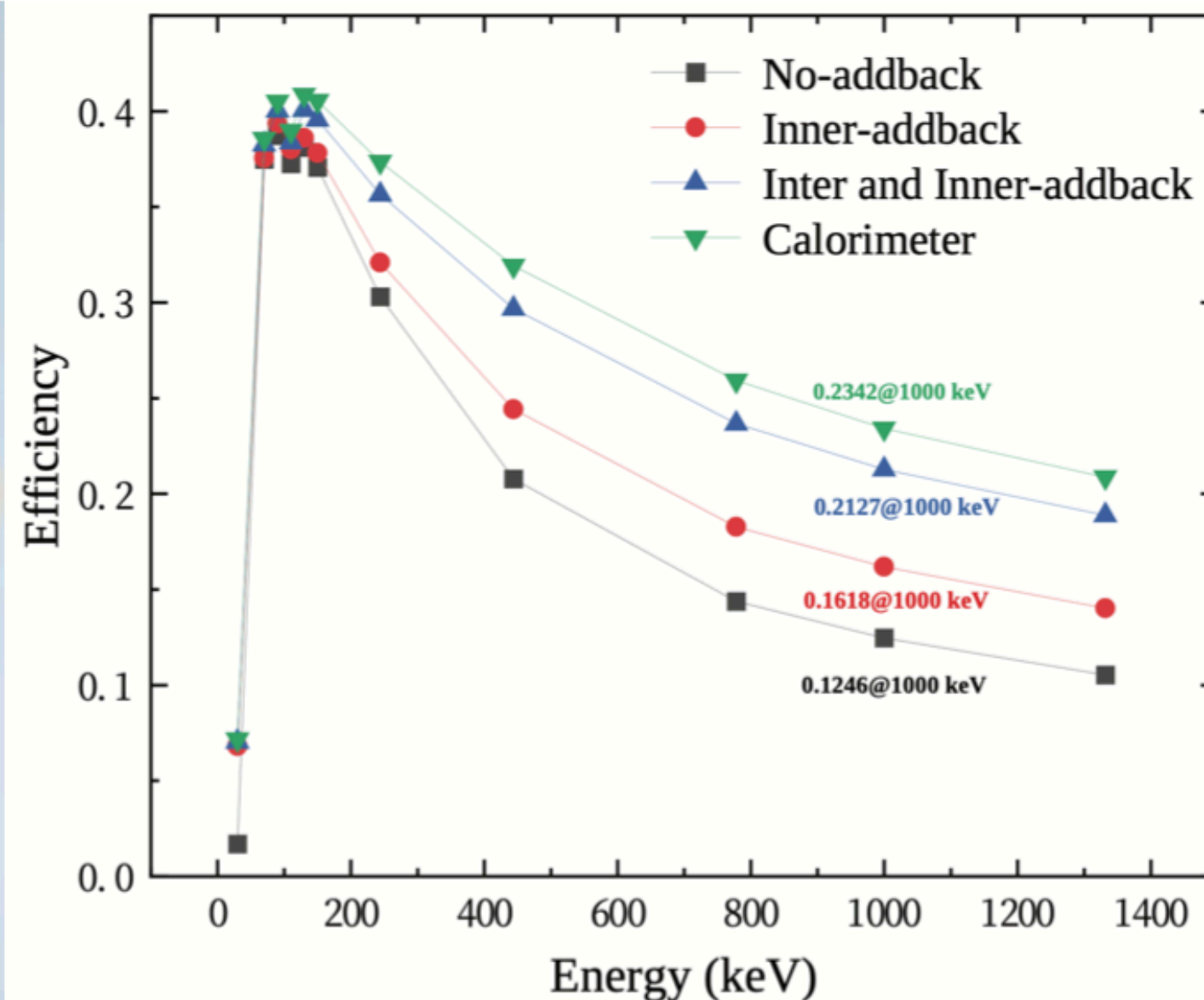
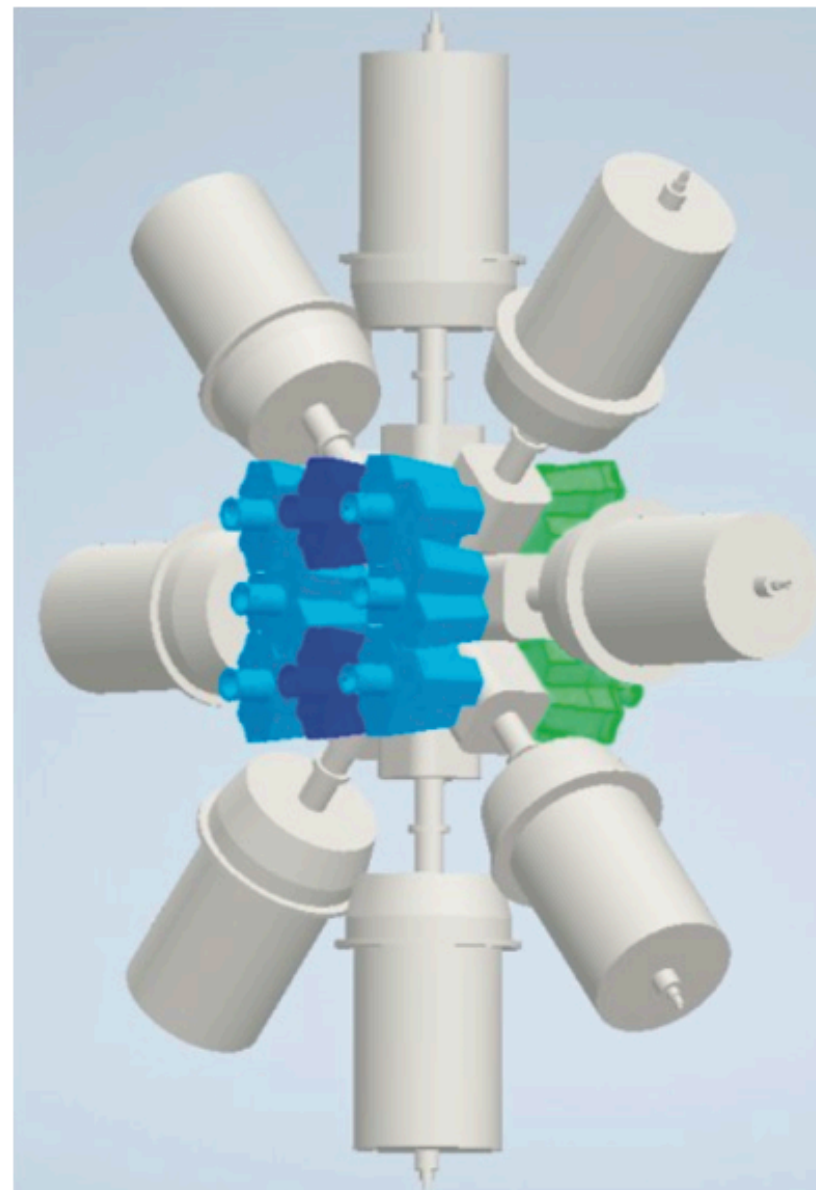
IDATEN commissioning experiment



B. Moon *et al.*, submitted to NIMA (2025)

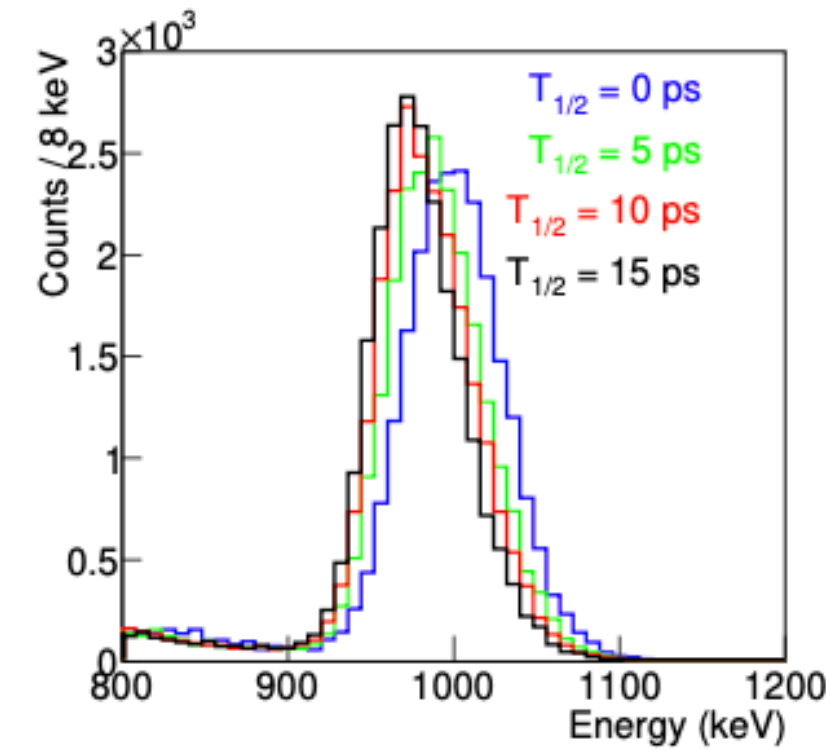
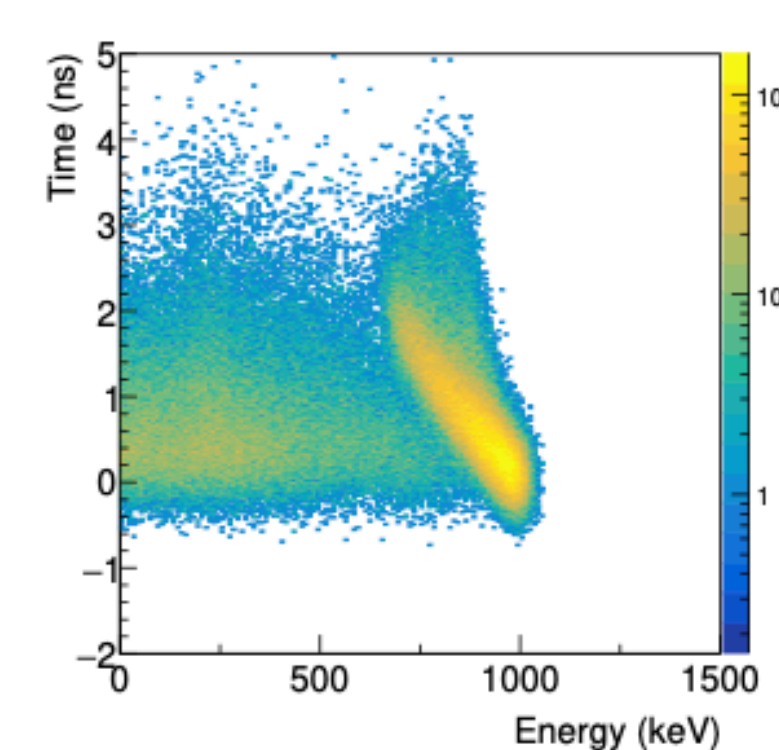
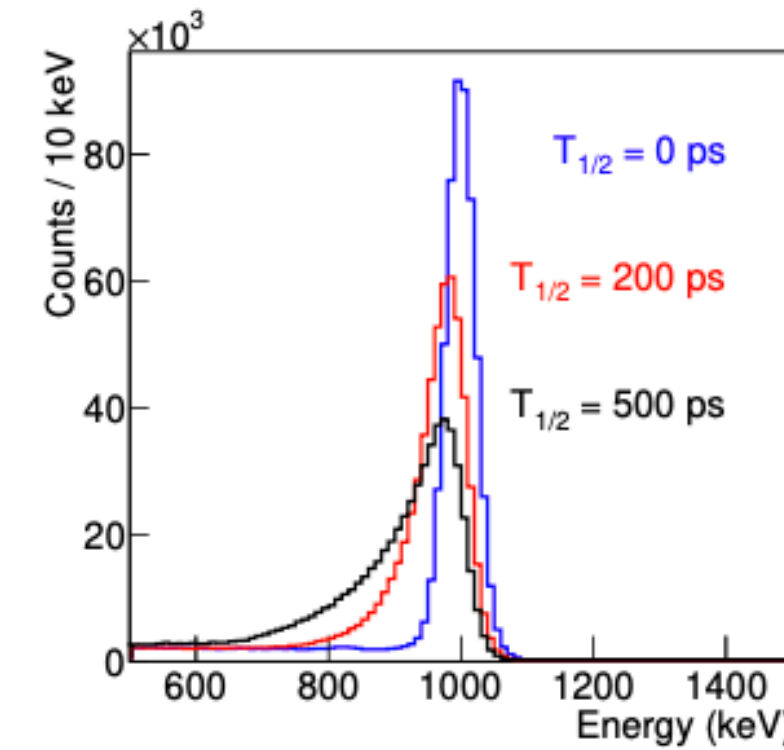
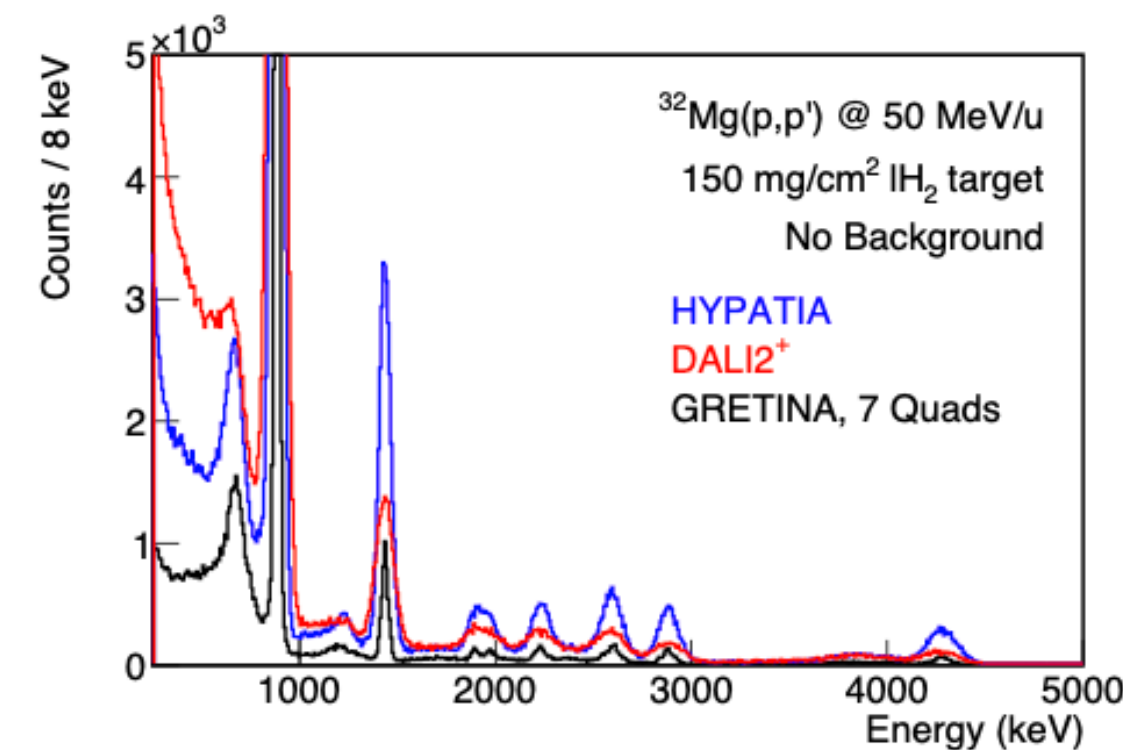
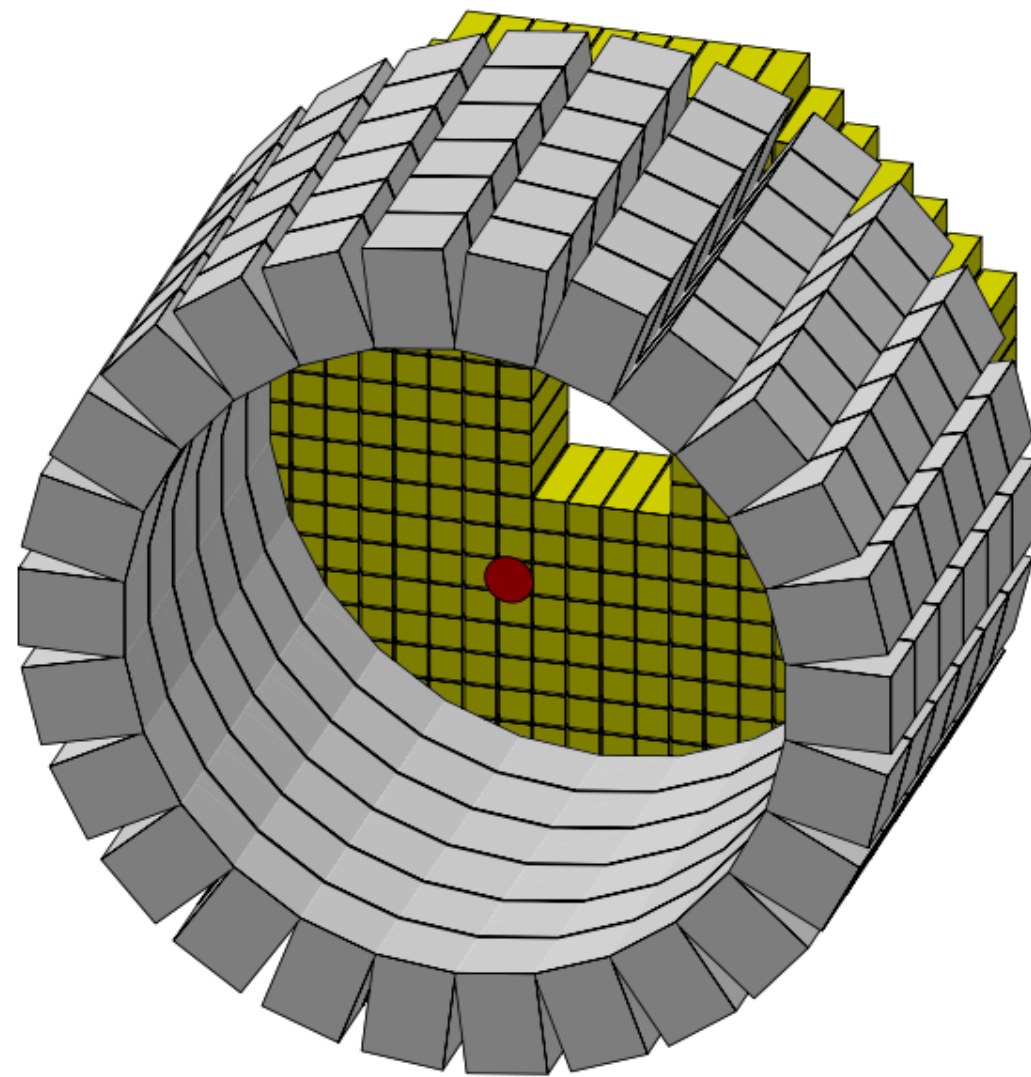
- 29.5 hours of beam time in June 2024
- Test fast-timing measurements, compatibility of readout electronics, and ion-beta correlation with two different beam modes (high and low rates)
- A technical paper for ^{96}Pd was recently submitted to NIMA, and the first revision is being prepared.
- Two physics papers are being prepared by two Ph.D. students.

Future γ -ray spectroscopy project at RIBF

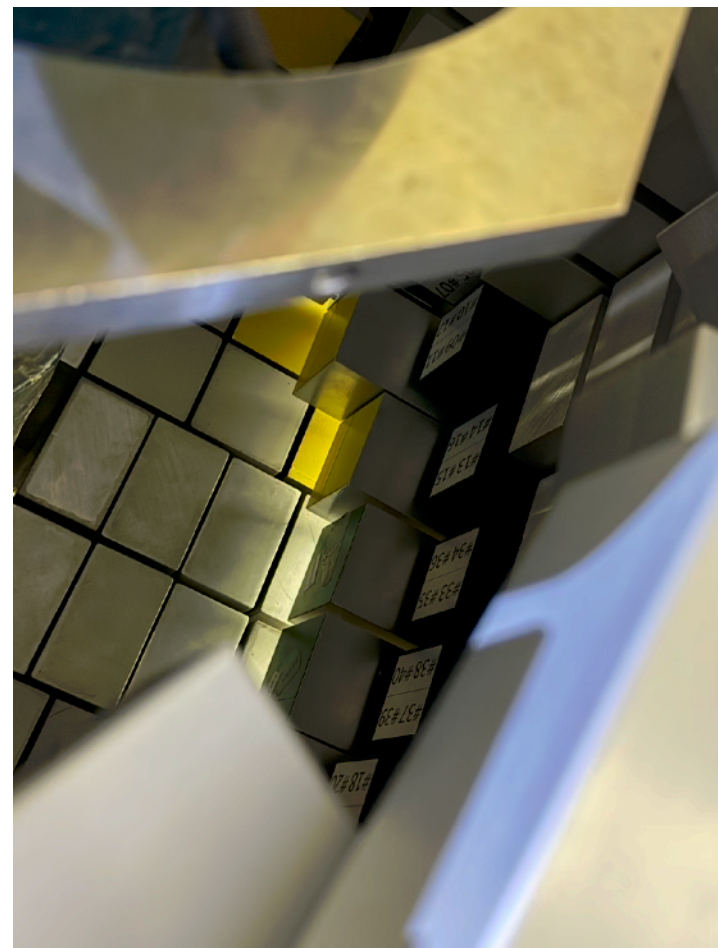


- C²URIE (Clover and Cluster Units for RIBF's Implantation Experiments) project is being prepared for high-resolution high-efficiency delayed γ -ray spectroscopy experiments at RIBF.
- 8 clover detectors from CENS and IMP, 16 DEGAS-type triple clusters from Europe will be installed in the most compact geometry to maximize the efficiency.
- 11 proposals were submitted to NP-PAC26 of RIKEN from the collaborators.
- The approved experiments will be conducted in 2027.

Future γ -ray spectroscopy project at RIBF

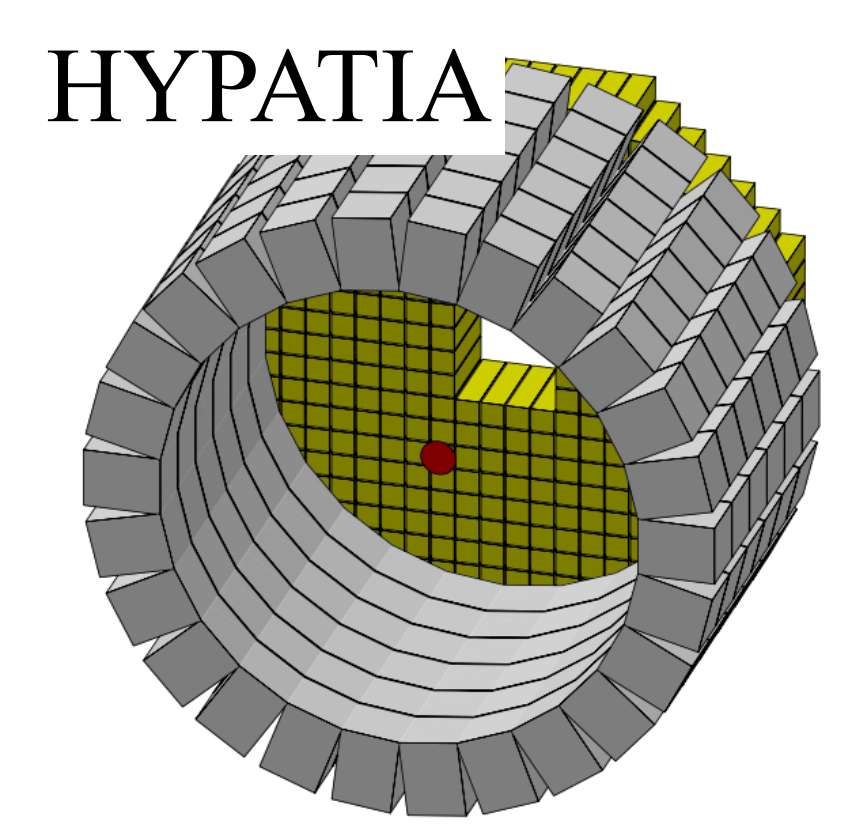
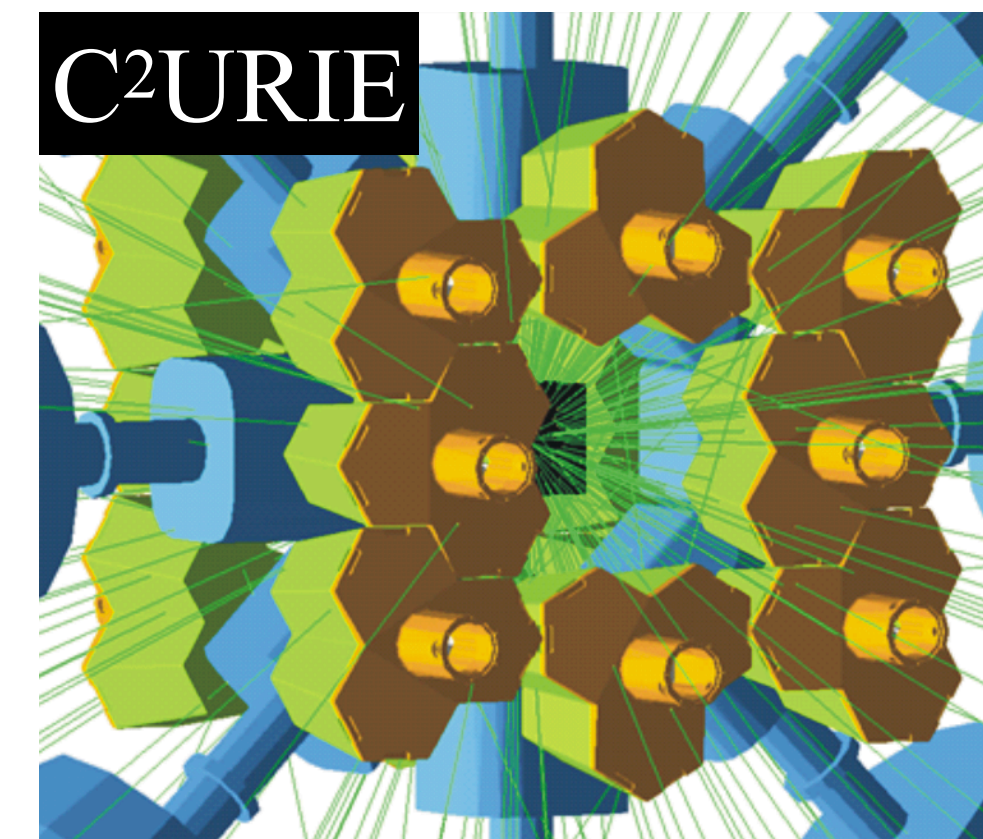
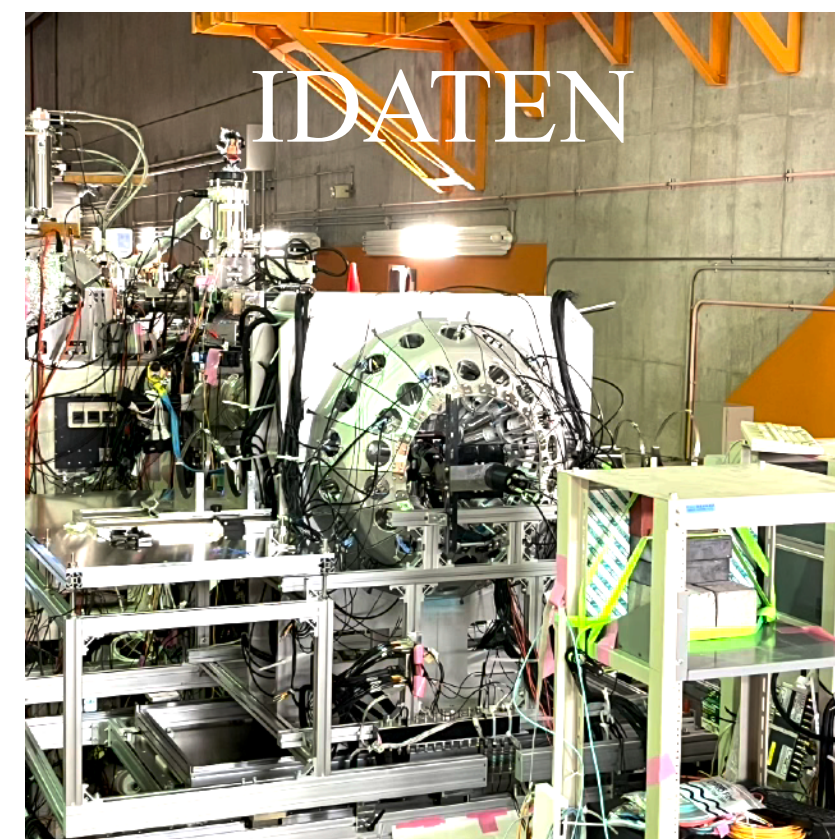
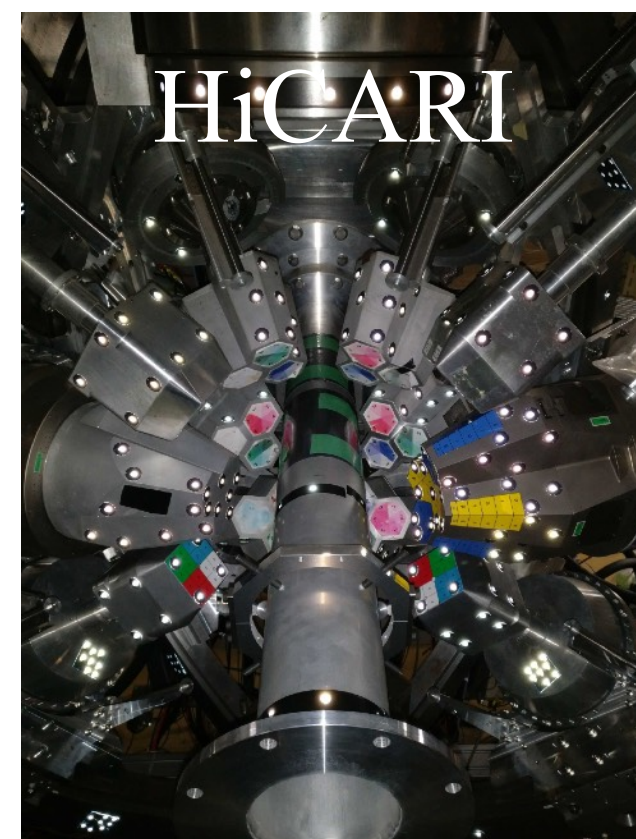
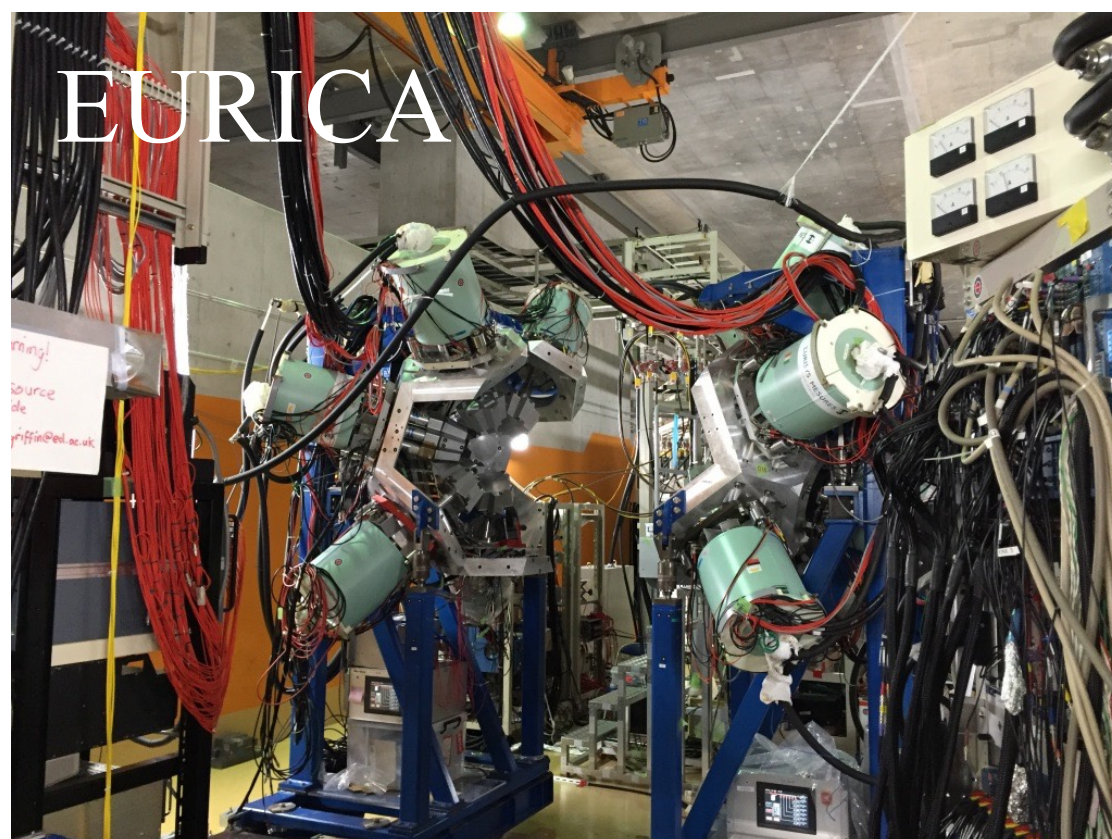


- HYPATIA (Hybrid Photon detector Array To Investigate Atomic nuclei) project for high-efficiency high-resolution in-beam γ -ray spectroscopy experiments using relativistic RI beams
- 386 GAGG(Ce) and 624 CeBr₃ scintillator crystals in total
- Two experiments were performed by replacing several DALI2+ detectors by HYPATIA modules in 2024 (¹⁰⁰Sn, removal) and 2025 (neutron-rich Ca, Coulex).
- CENS is contributing to the collaboration by supplying GAGG(Ce) crystals.



Summary

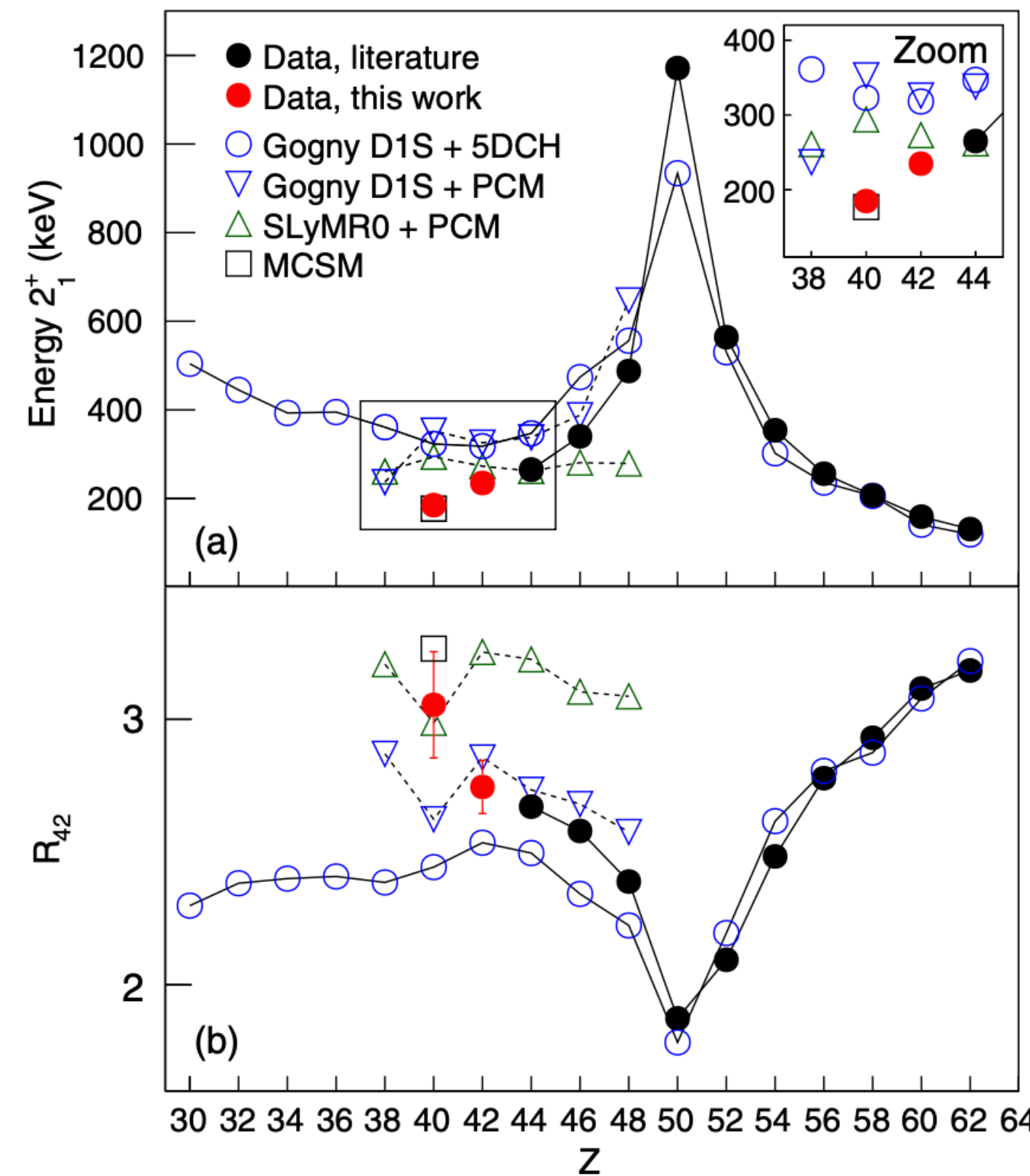
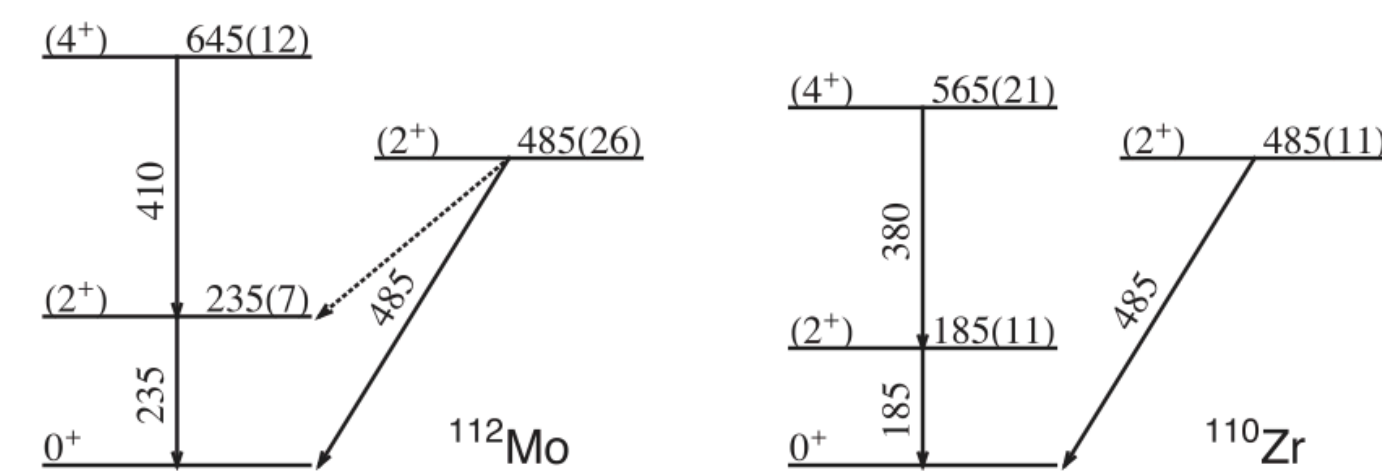
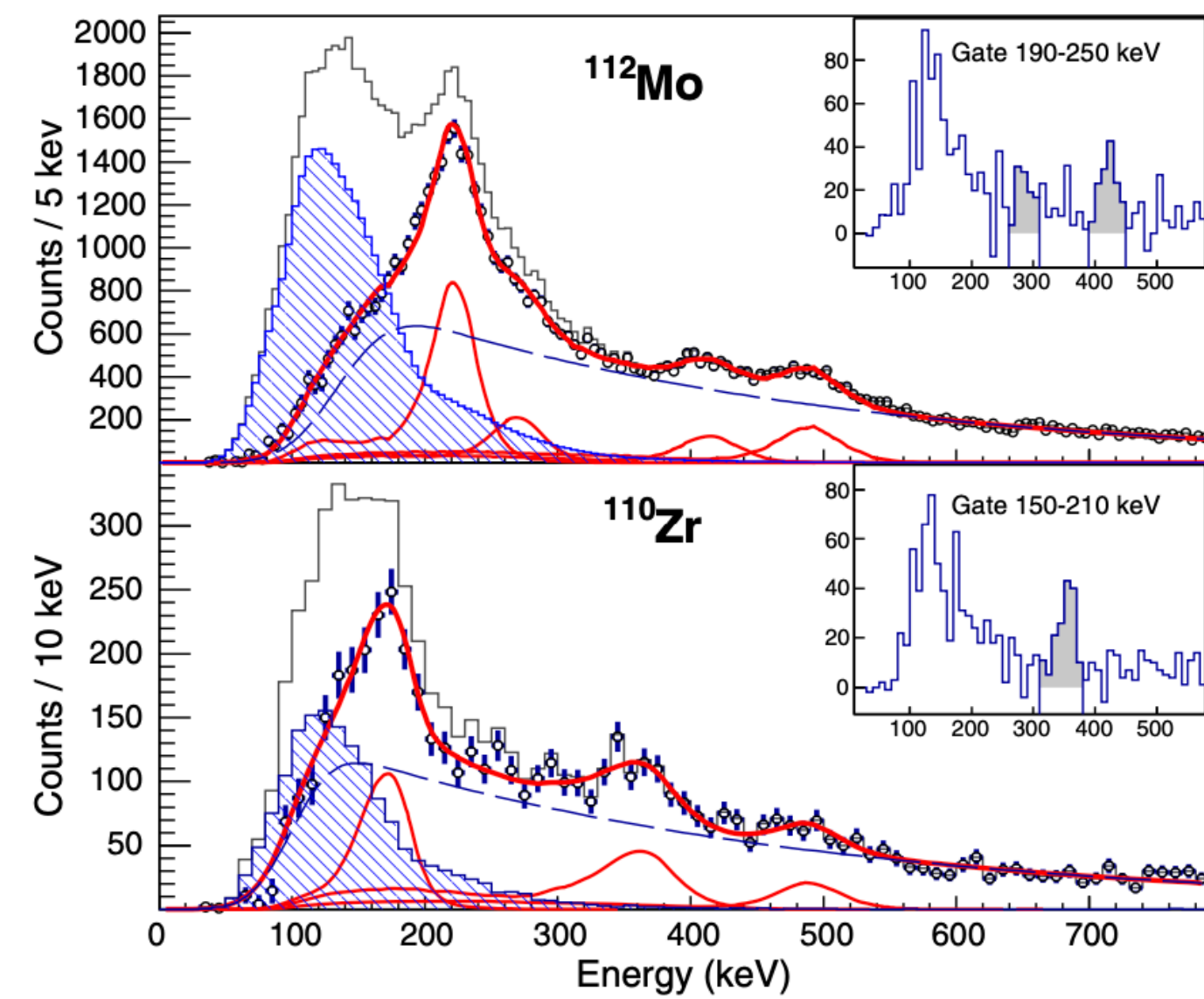
- Various physics campaigns focused on γ -ray spectroscopy have been conducted and are planned at RIBF.
- The high-resolution decay spectroscopy at RIBF, EURICA was carried out from 2012 to 2016.
- The high-resolution in-beam γ -ray spectroscopy at RIBF, HiCARI was conducted from 2020 to 2021.
- The world-largest fast-timing γ -ray spectrometer, IDATEN will be conducted at RIBF and the first commissioning experiment was successfully done in 2024.
- A high-resolution and high-efficiency in-beam and delayed γ -ray spectroscopy will be conducted at RIBF.



Backup slides

Introduction

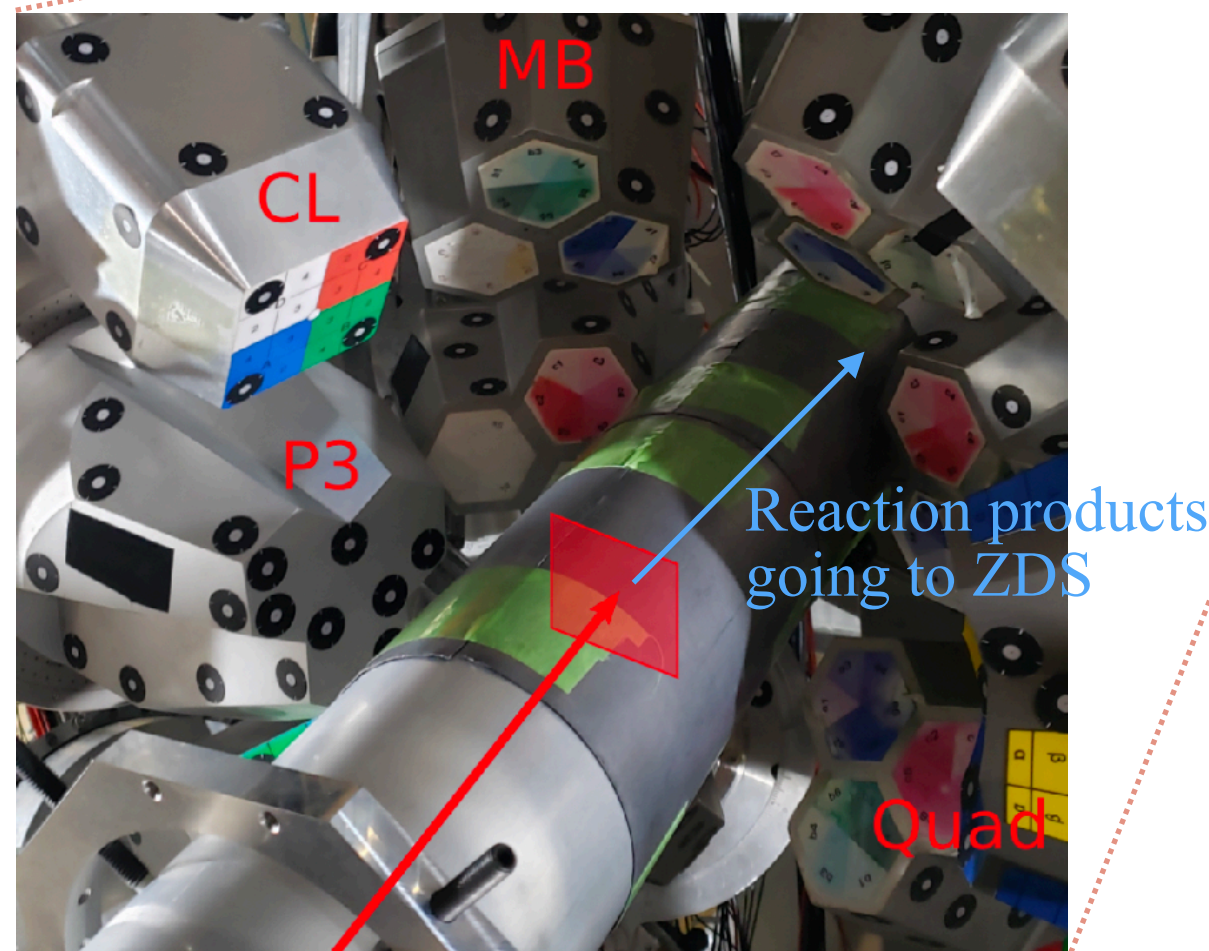
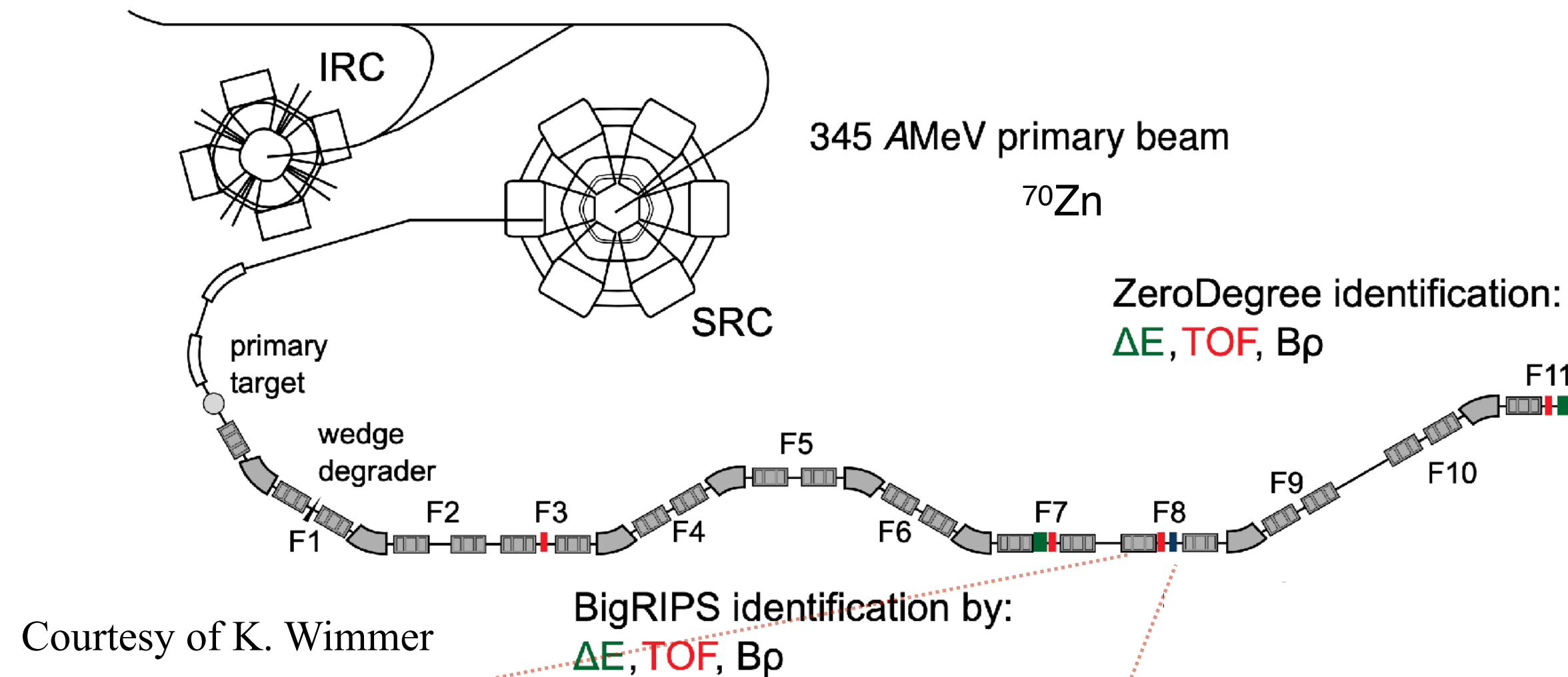
- New magic number $N = 70$?



N. Paul *et al.*, PRL **118**, 032501 (2017)

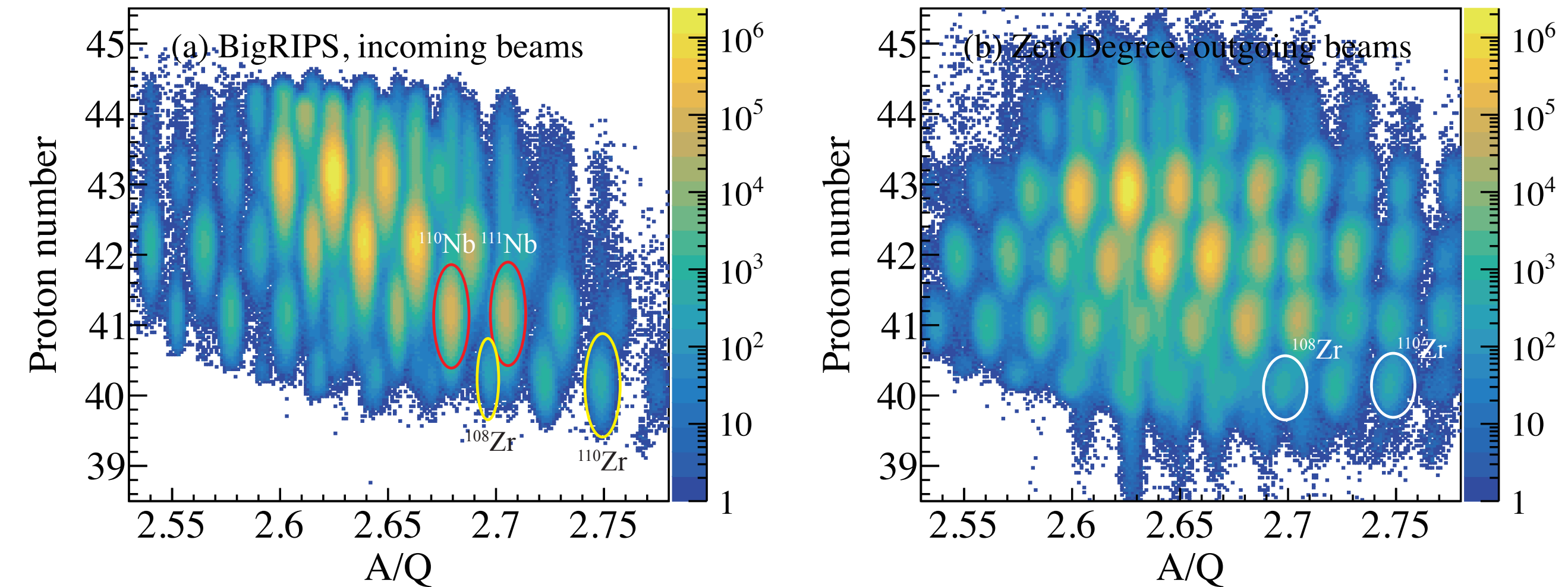
- Doubly harmonic oscillator magic numbers $Z = 40$ and $N = 70$?
- No magic character was observed in ^{110}Zr .
- The level scheme is well described by different theories.
- Then how about nuclear shape?

Experiment



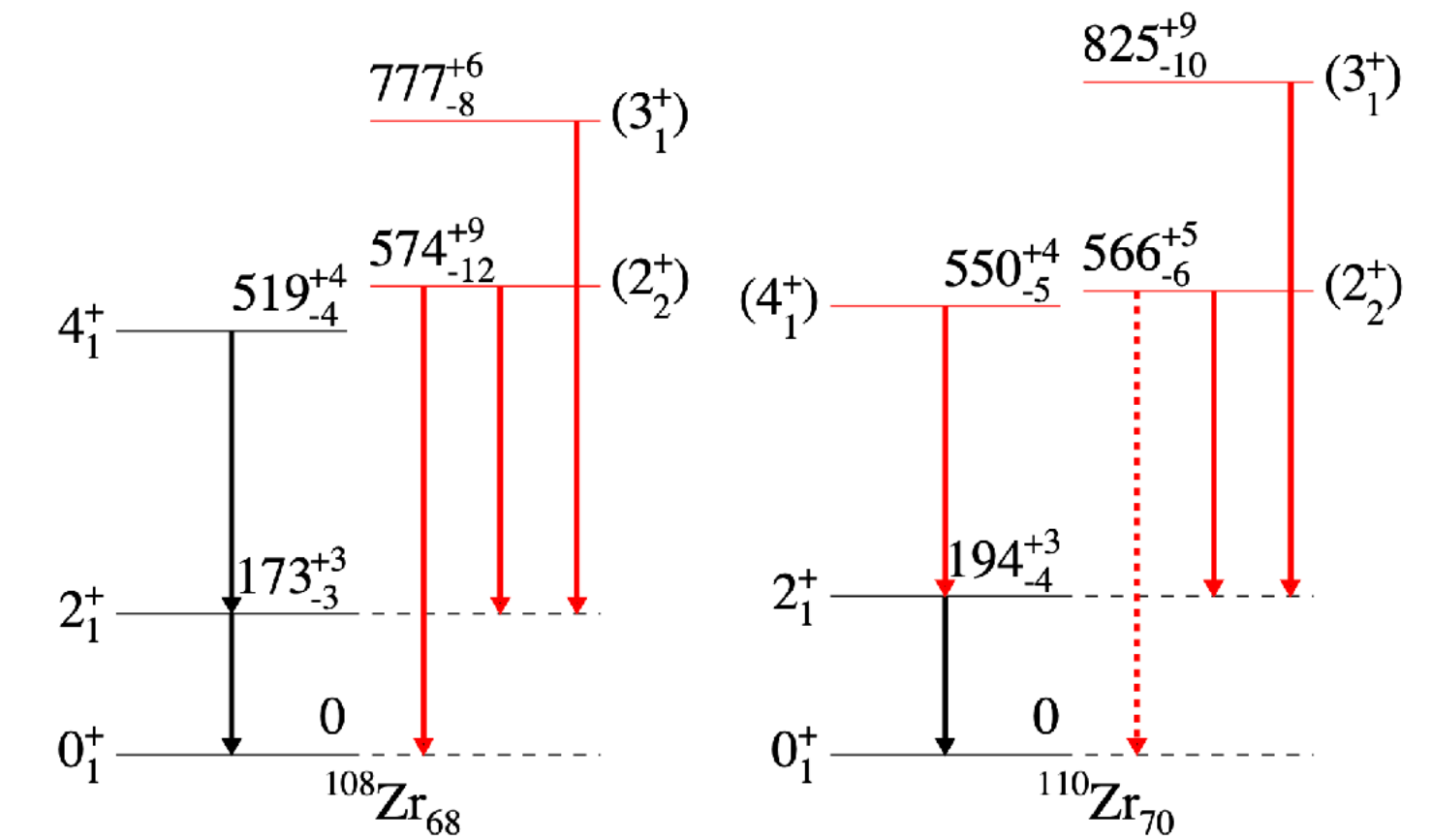
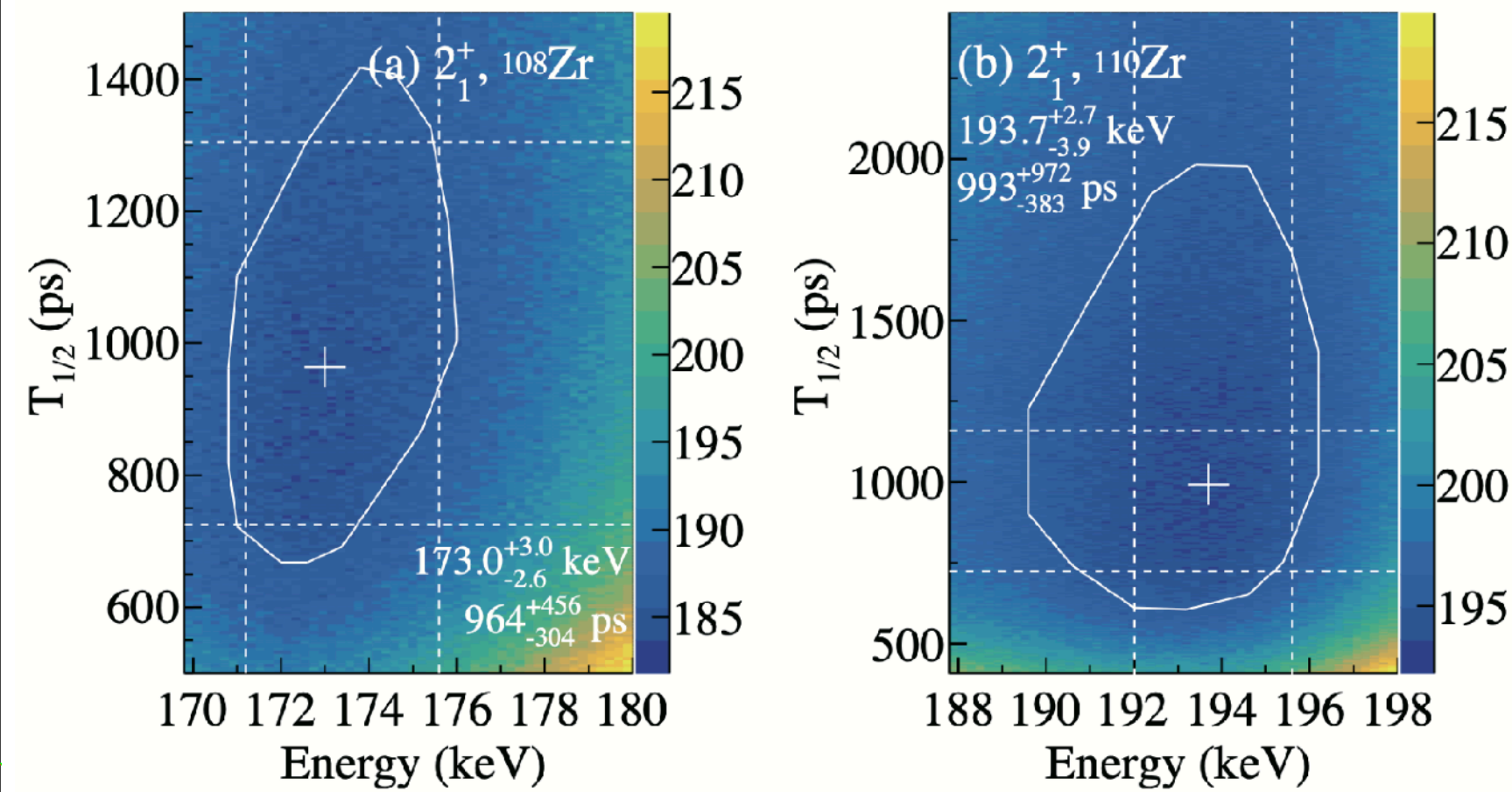
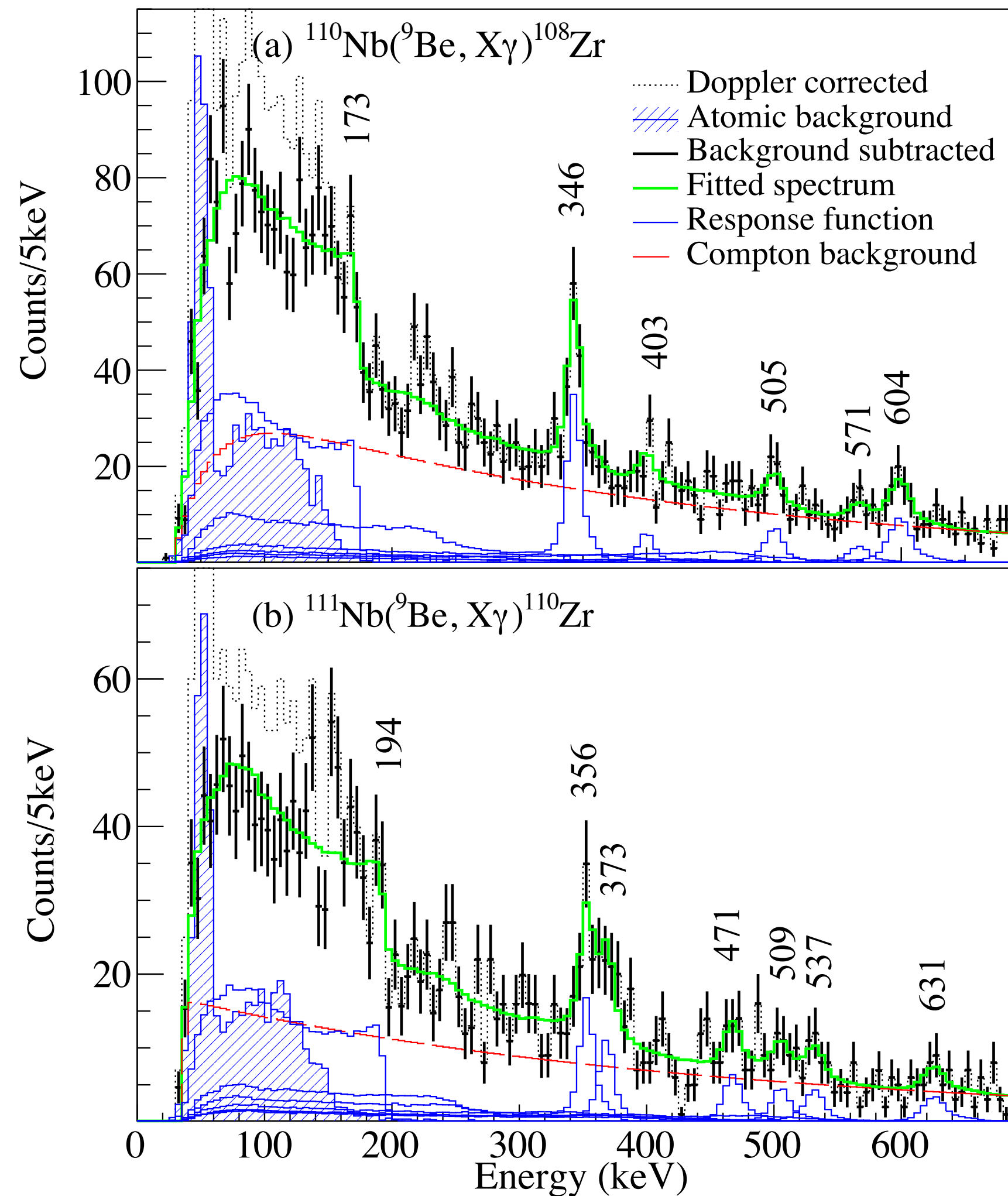
RI beams from BigRIPS

K. Wimmer et al., RIKEN Accel. Prog. Rep. 54 (2021) S27



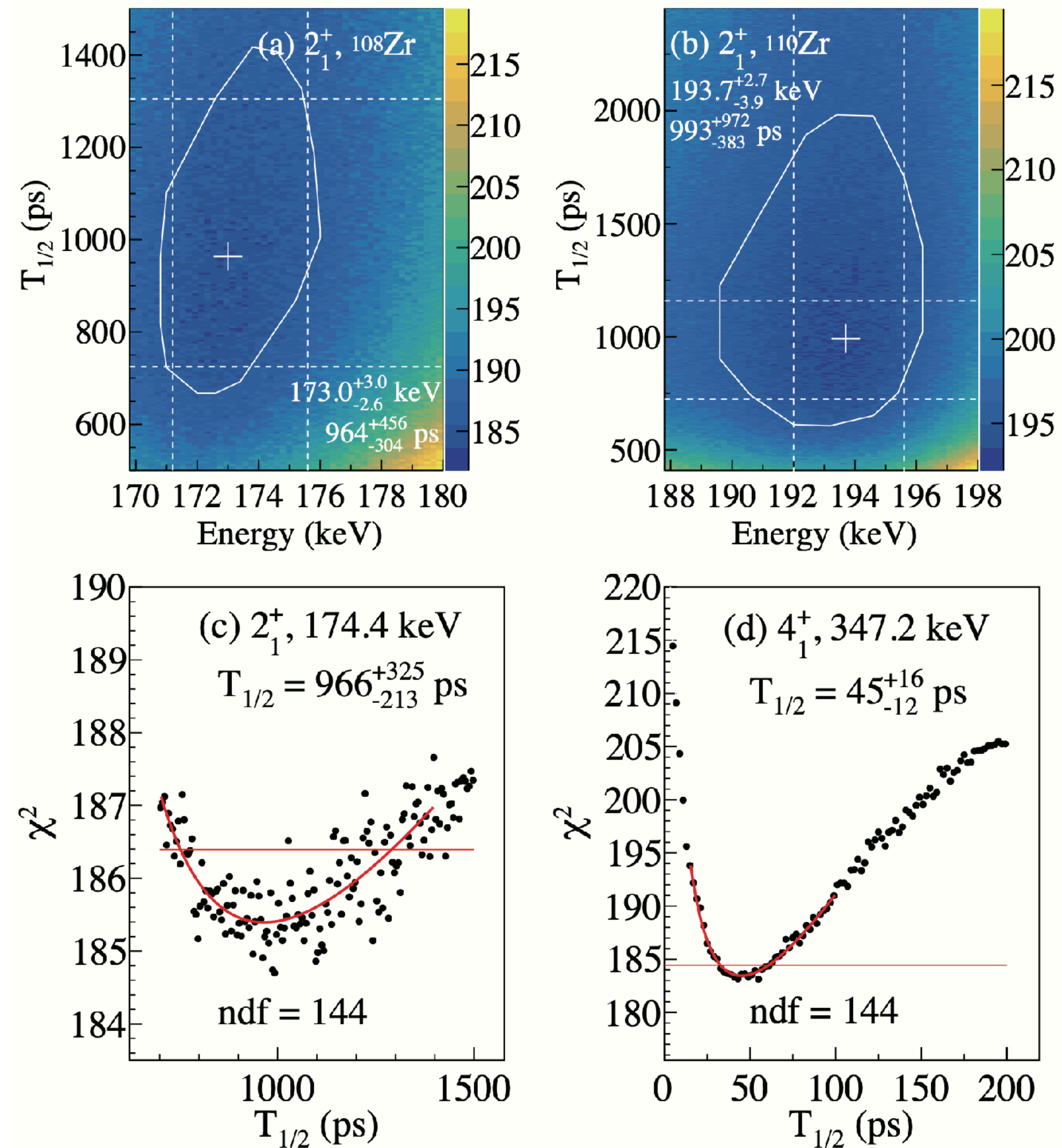
- Primary beams from SRC with an energy up to 345 MeV/u
- RI production and selection from the in-flight fission or fragmentation method
- F1-F7: BigRIPS / F8-F11: ZeroDegree Spectrometer / F8: HiCARI
- HiCARI (High-resolution Cluster Array at RIBF)
Hybrid HPGe detector array with 6 Miniball clusters, 4 segmented clover detectors from IMP, one P3-type tracking detector from LBNL, and one Quad-type tracking detector from RCNP
- The secondary target of ^9Be with 6-mm thickness was installed at 10 cm upstream with respect to the standard target position.

Triaxial deformation in $^{108}, ^{110}\text{Zr}$



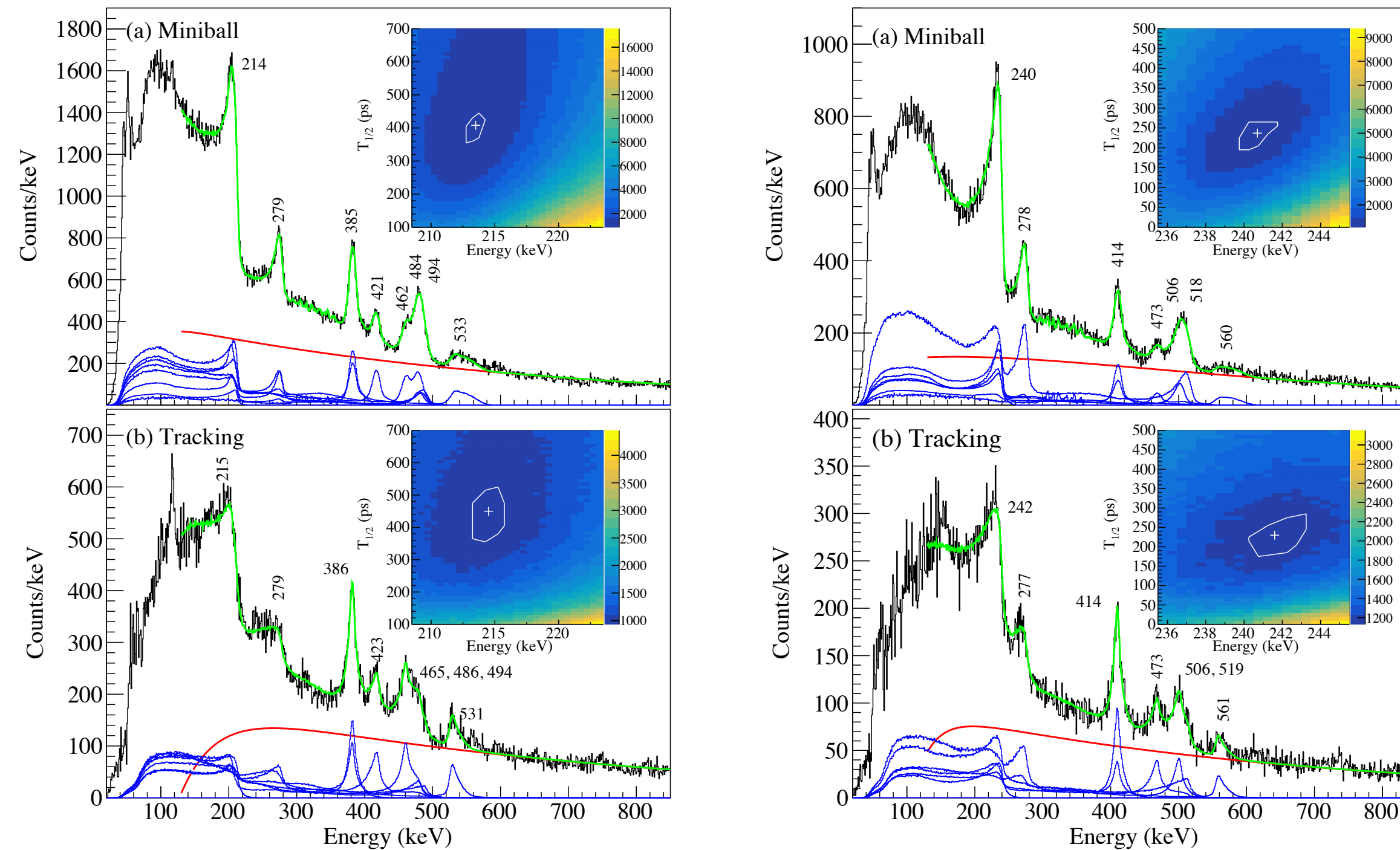
- Doppler corrected by the velocity after the target, only Miniball detectors used
- Lifetime measurement by using simulated response functions
- Obtain 2 dimensional χ^2 maps to simultaneously deduce the energies and half-lives with correlated errors
- New levels identified in ^{108}Zr and ^{110}Zr
- More precise and accurate $E(2^+)$ and $R_{4/2}$ values of ^{110}Zr could be achieved.

Lifetime measurement

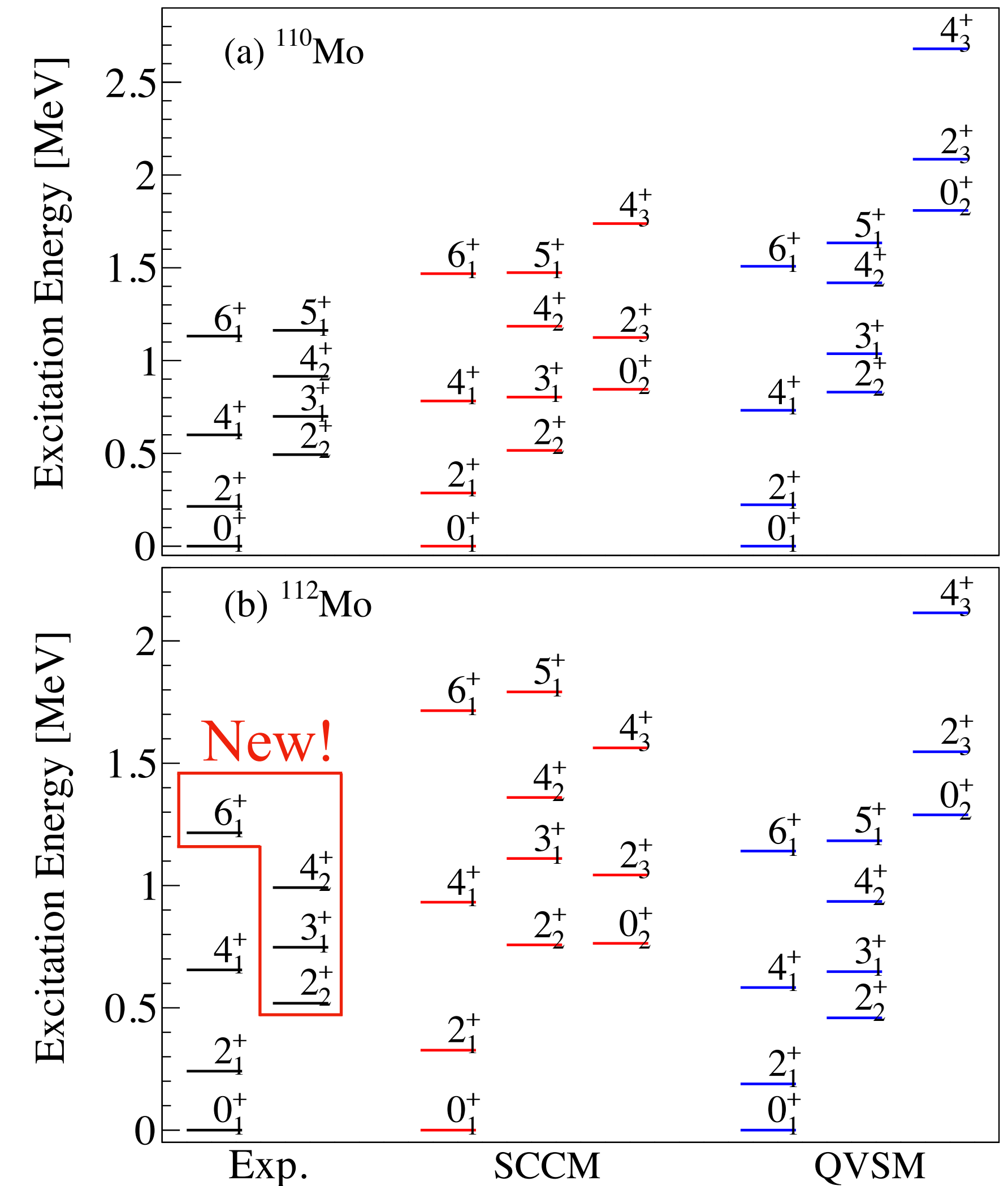


- Lifetime measurement by using simulated response functions
- Obtain 2 dimensional χ^2 maps to simultaneously deduce the energies and half-lives with correlated errors
- $\chi^2_{\min} + 2.4$ limits used for the 1σ errors in the 2D maps
- For the known transitions, fixed transition energies to reduce the uncertainties
- $\chi^2_{\min} + 1.0$ limits used for the 1σ errors in this case

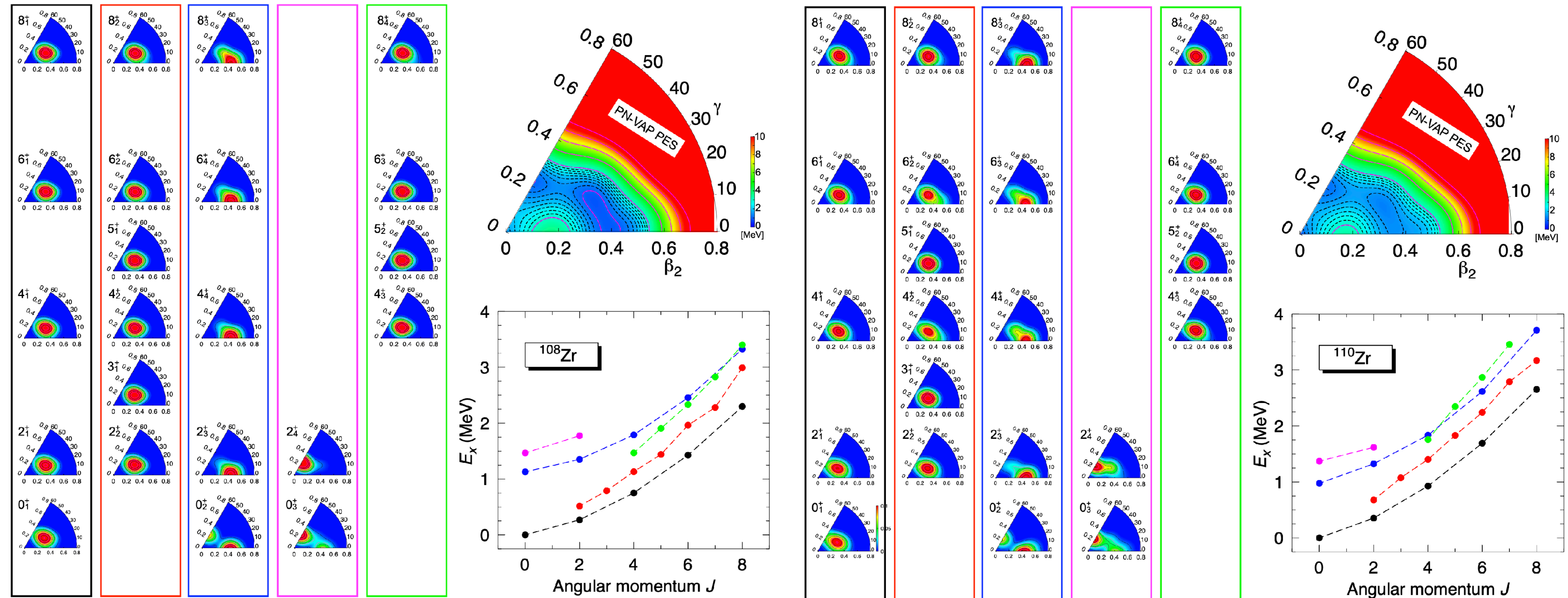
Triaxial deformation in $^{110,112}\text{Mo}$



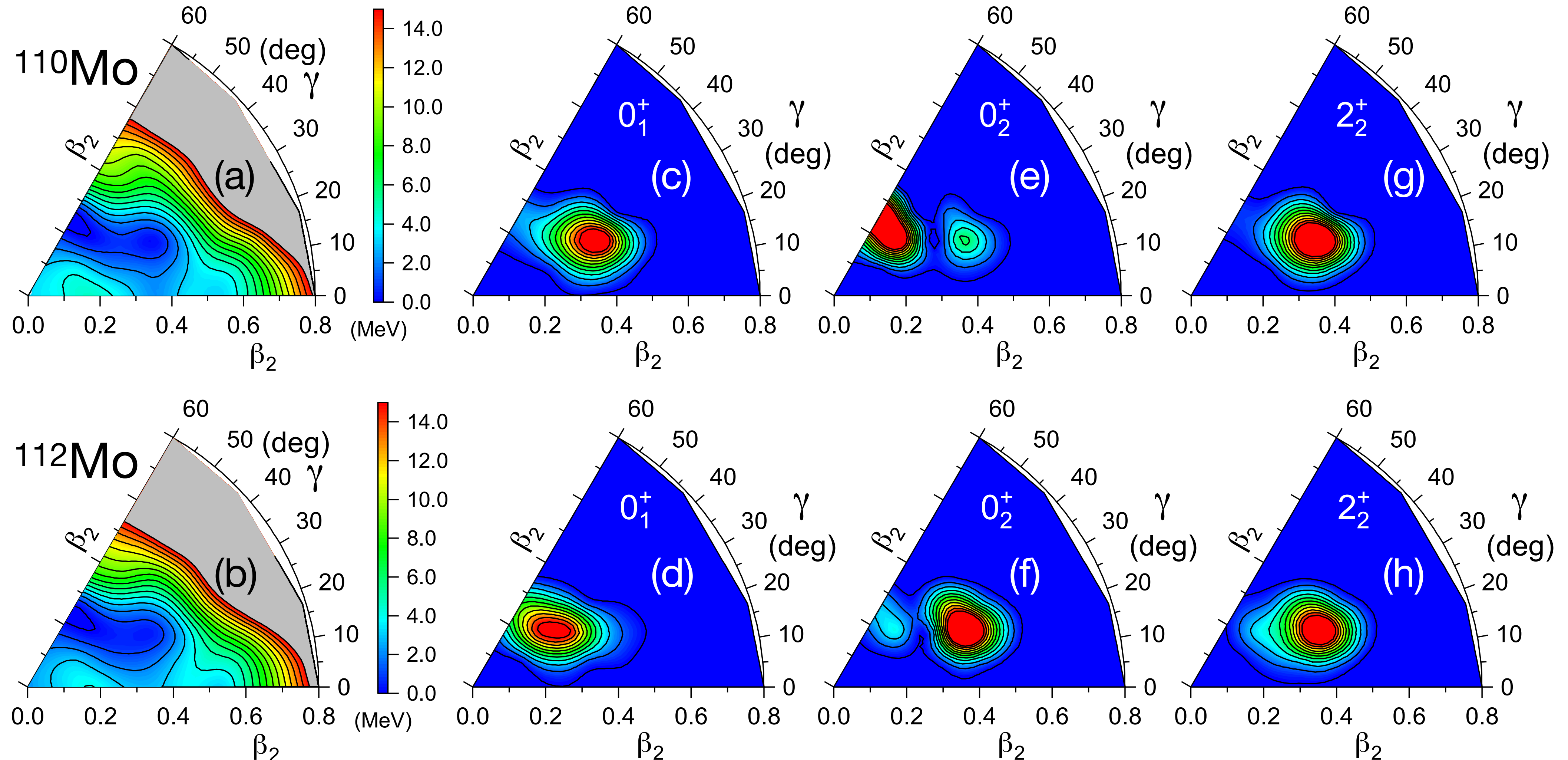
- Doppler corrected using the velocity after the target
- Applied cascading effects in the simulation based on the known level schemes
- First time to observe the γ -band structure in ^{112}Mo
- First time to measure the level lifetimes except the 2^+_{11} state in ^{110}Mo



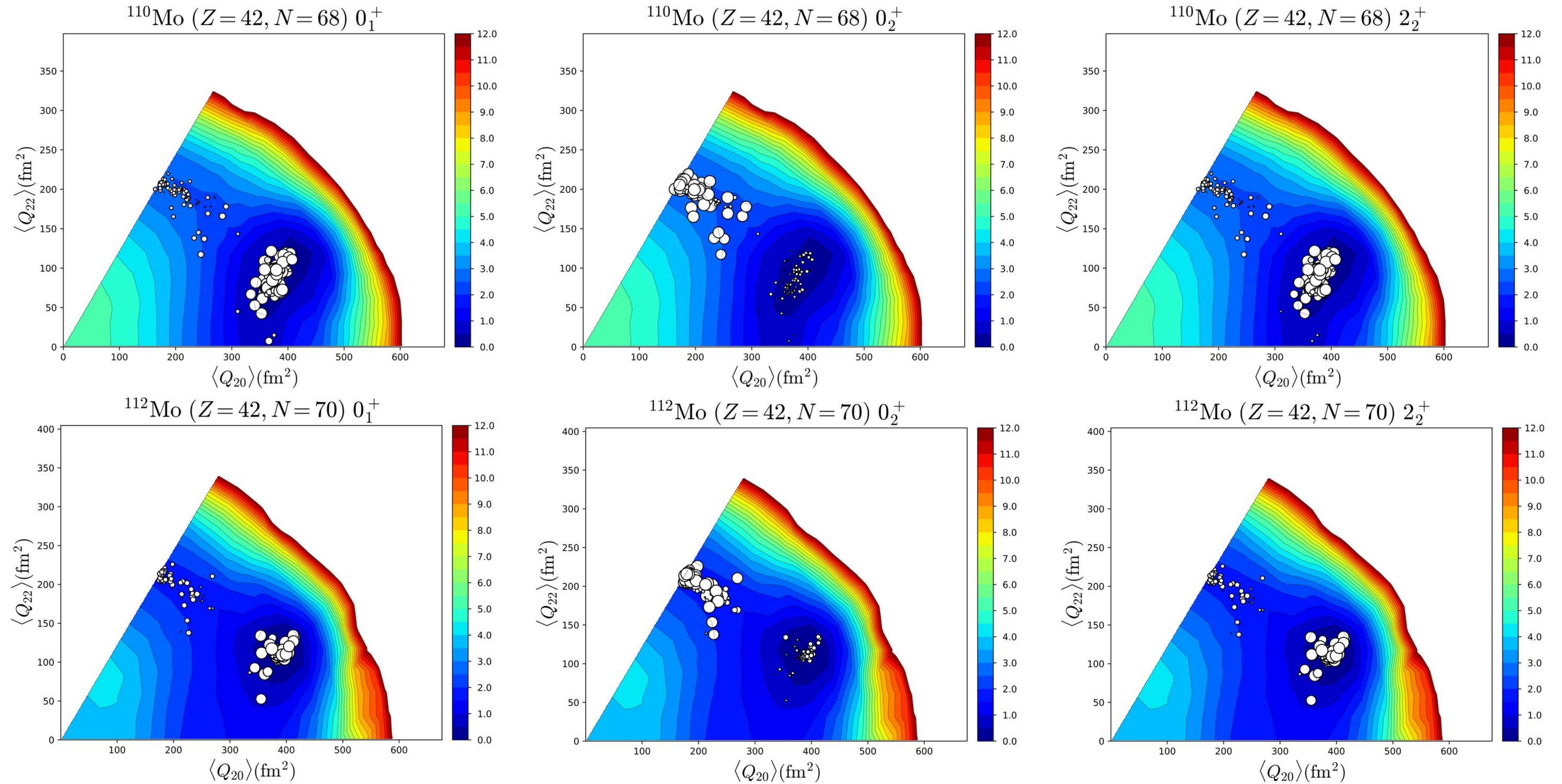
SCCM PES & collective wave functions



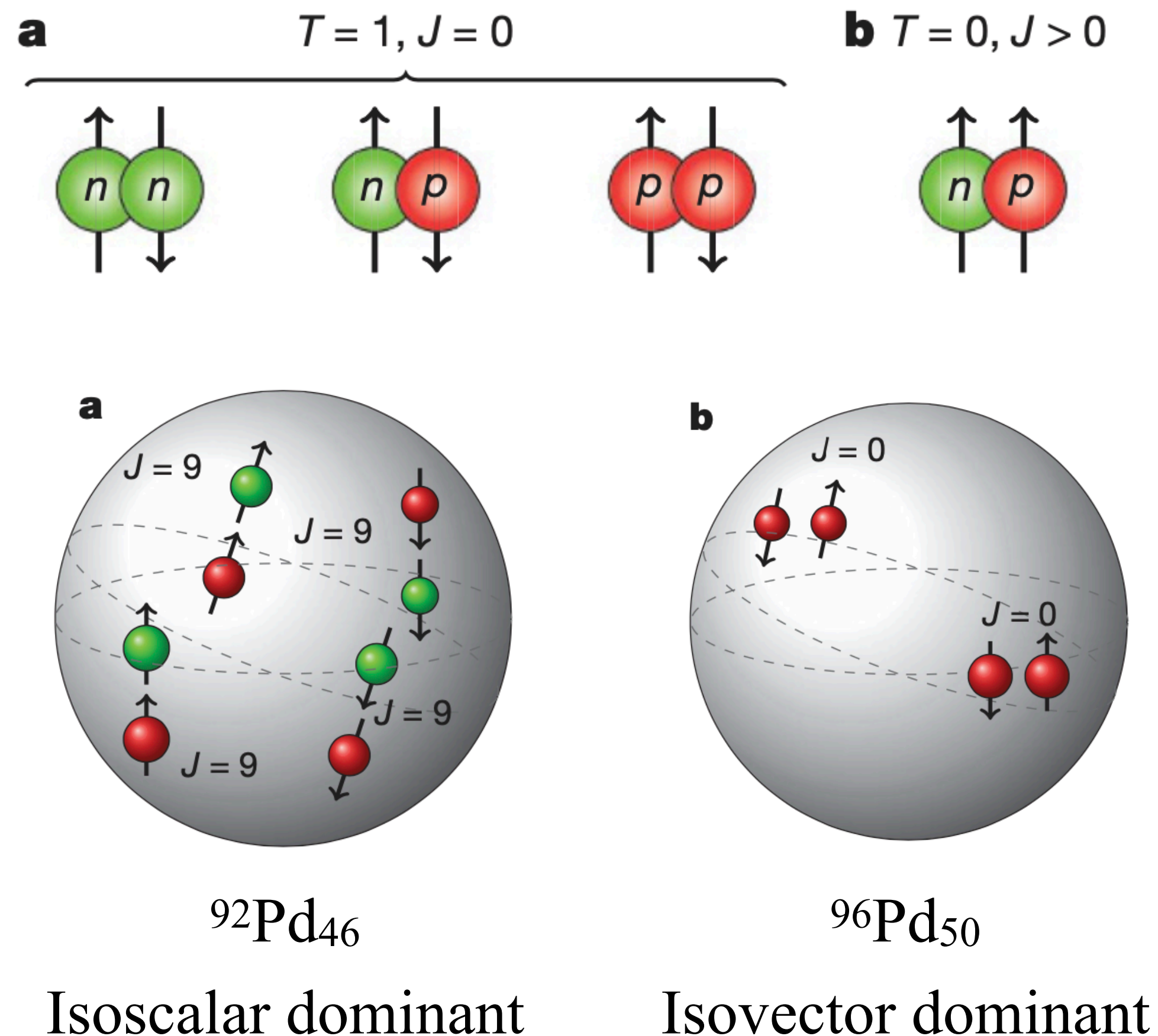
SCCM PES & collective wave functions



QVSM T-plots



Isoscalar and isovector in self-conjugate nuclei

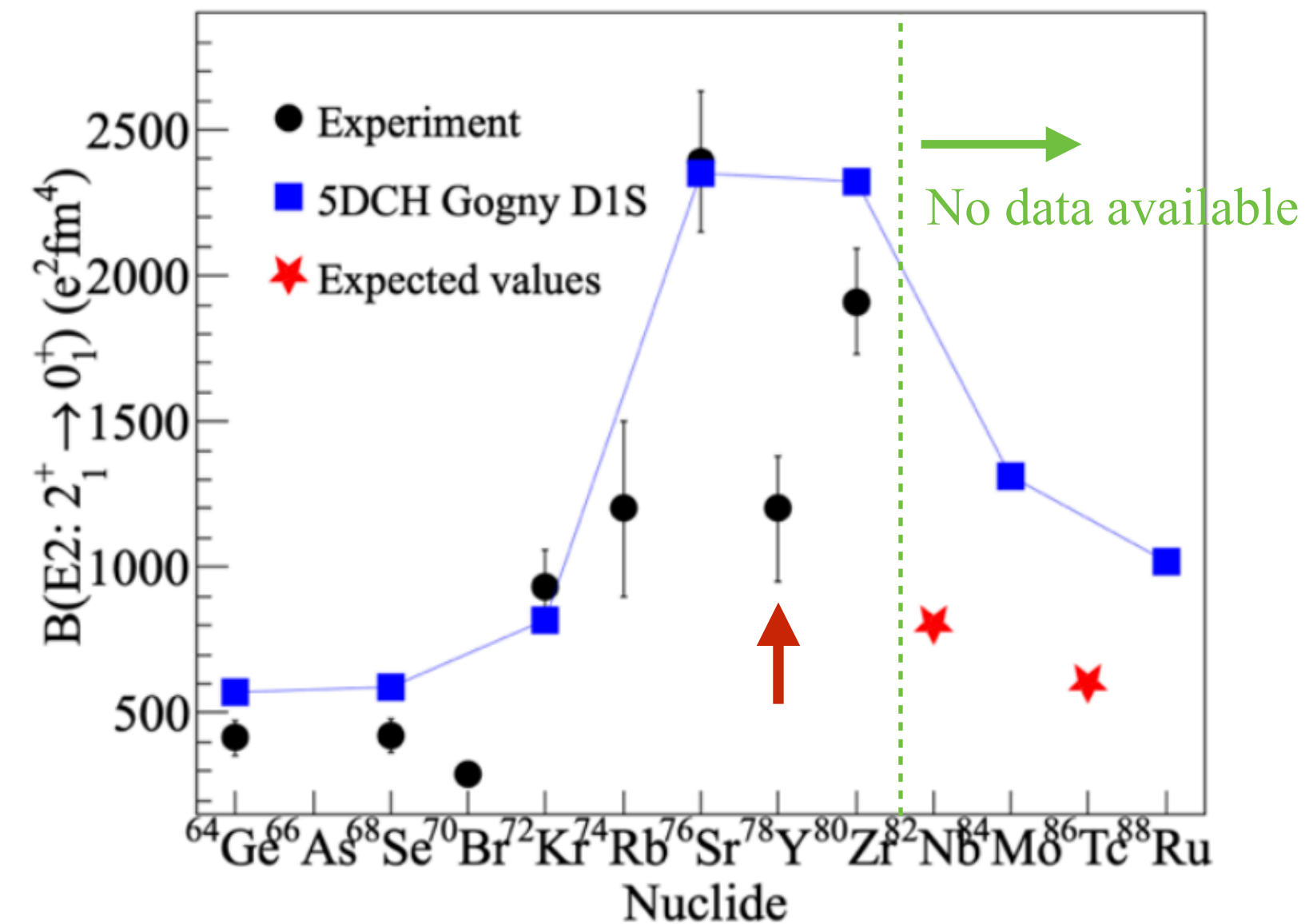
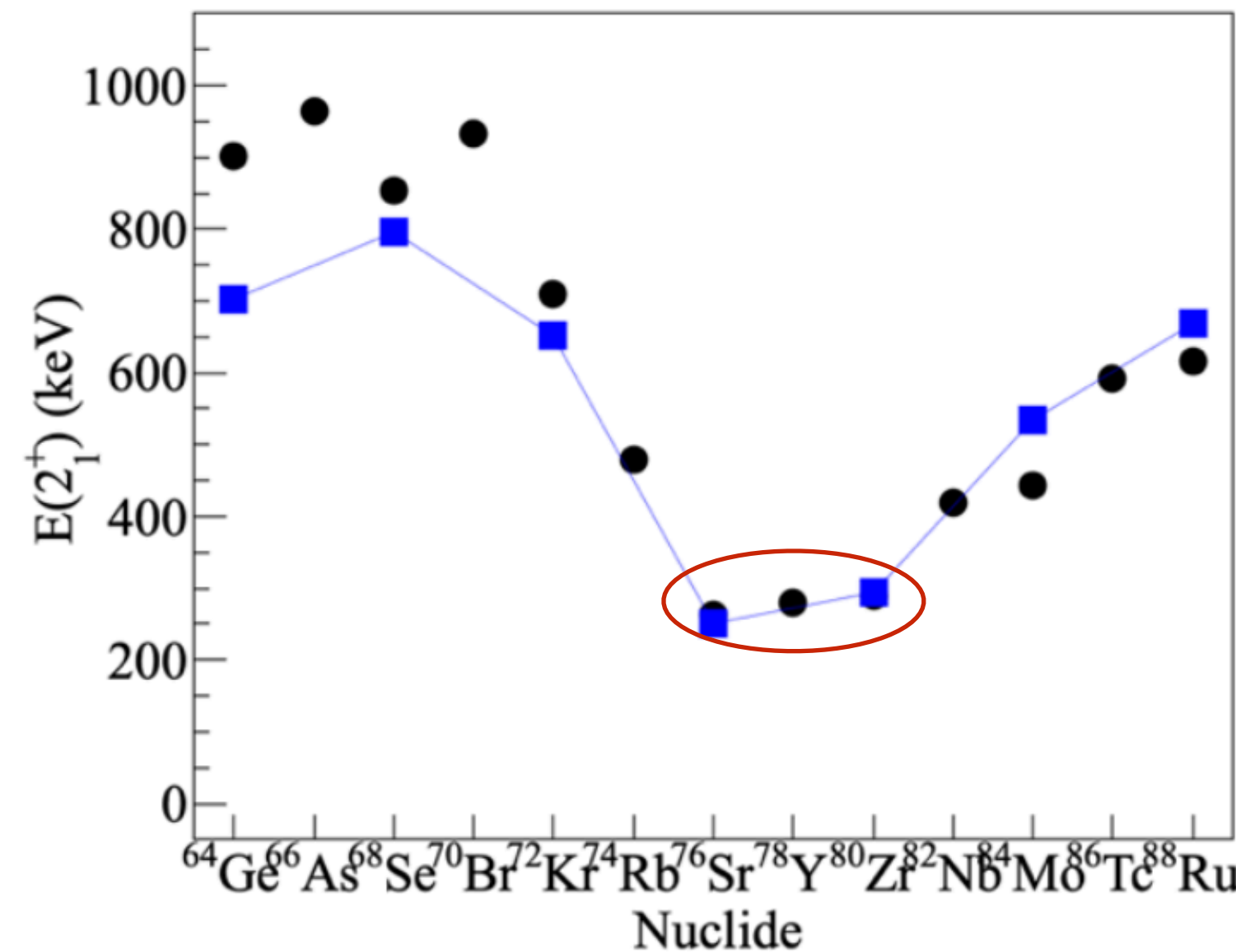


B. Cederwall et al., Nature 469, 68 (2011)

- Nuclei with $N = Z$ systems, unique microscopic laboratories for nucleon-nucleon interactions
- Two types of pairing modes:
 $T = 1$ (isovector) mode and $T = 0$ (isoscalar) mode
- In the medium-heavy mass region, np pairs with $T = 1$ dominate the ground-band structure.
- Recently, however, evidence of $T = 0$ dominance in the ground-band structure in ^{92}Pd was observed.
- This proposal aims to investigate in detail the effect of np pairing in the odd-odd $N = Z$ nuclei, ^{82}Nb and ^{86}Tc .

Collectivity in $N = Z$ ^{82}Nb and ^{86}Tc

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- Nuclei with $N = Z$ systems, unique microscopic laboratories for nucleon-nucleon interactions
- Evidence of $T = 0$ dominance in the ground-band structure in ^{92}Pd was observed. [Nature 469, 68 (2011)]
- An anomalously suppressed $B(E2; 2_1^+ \rightarrow 0_1^+)$ value in ^{78}Y was observed, suggested to have the effect of the $T = 0$ isoscalar pairing mode. [PRL 124, 152501 (2020)]
- It is also important to study the isospin symmetry breaking effect by comparing isospin partners, ^{82}Zr and ^{86}Mo ($T_z = 1$).