Towards high-resolution in-beam γ-ray spectroscopy at the RIBF

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ウィマー　カトリン

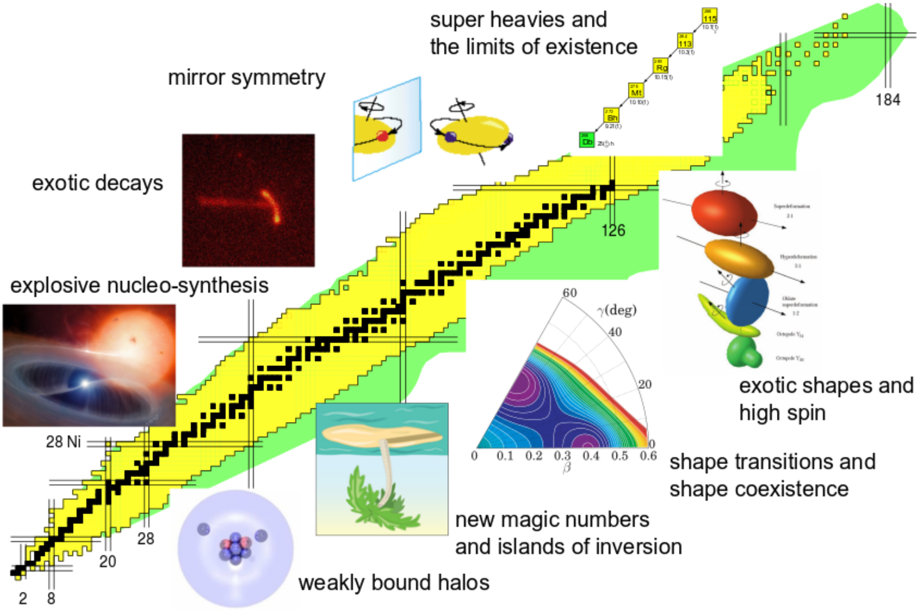
The University of Tokyo

14 May 2019

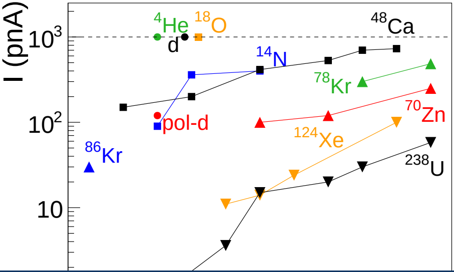
Outline

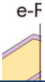
1. In-beam γ-ray spectroscopy at the RIBF
2. Selected recent results
3. High-resolution spectroscopy
4. Summary

Many interesting features

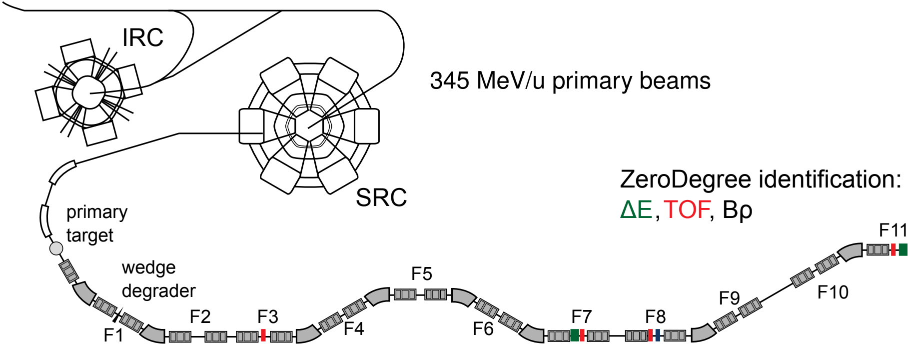


The Radioactive Isotope Beam Factory


I (pnA)
10^3
10^2
10
4He
d
18O
48Ca
14N
78Kr
70Zn
pol-d
124Xe
86Kr
238U


e-F

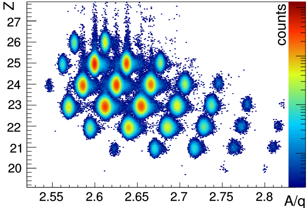
Beam production and identification



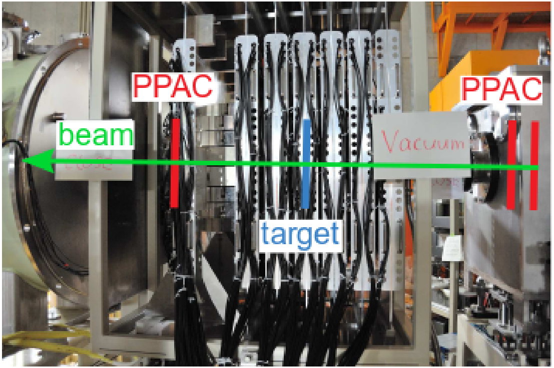
BigRIPS identification by:
ΔE, TOF, Bρ

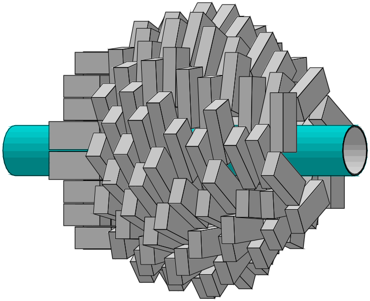
secondary target:
LH_2, Be, Au, ...

- fragmentation or fission of intense primary beam
- particle identification by $B\rho - \Delta E -$ TOF
- secondary reaction target at F8
- identification after target:
  ZeroDegree or SAMURAI spectrometer



DALI2





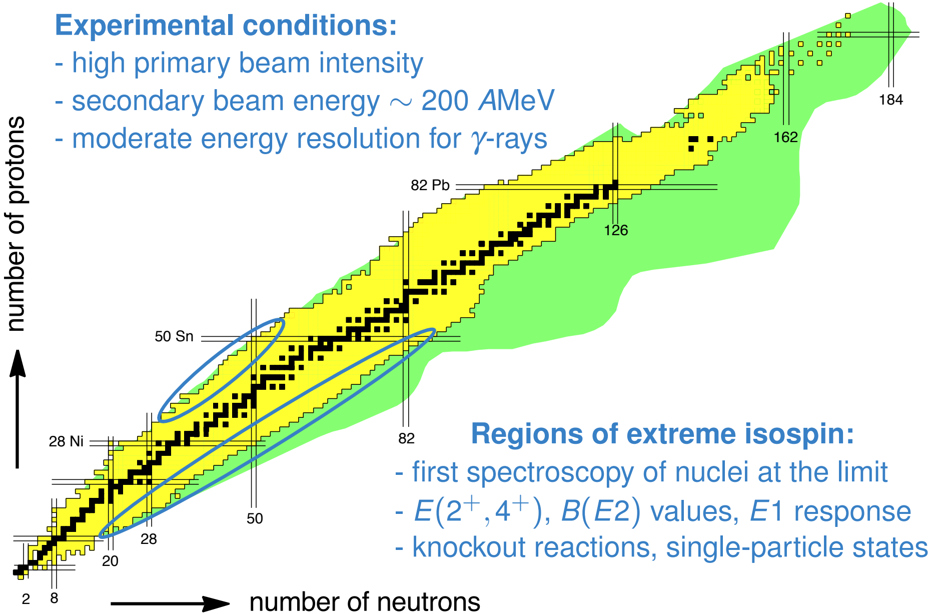
- 186 NaI(Tl) detectors (upgrade to 226)
- intrinsic resolution 7 % at 1 MeV
- in-beam resolution $\sim$ 10 % at 150 *A*MeV
- efficiency $\sim$ 20 % at 1 MeV (before add-back)
- beam tracking by PPACs

S. Takeuchi et al., Nucl. Instr. Meth. **A 763** (2014) 596.

In-beam γ-ray spectroscopy at the RIBF

Experimental conditions:

- high primary beam intensity
- secondary beam energy $\sim$ 200 *A*MeV
- moderate energy resolution for γ-rays



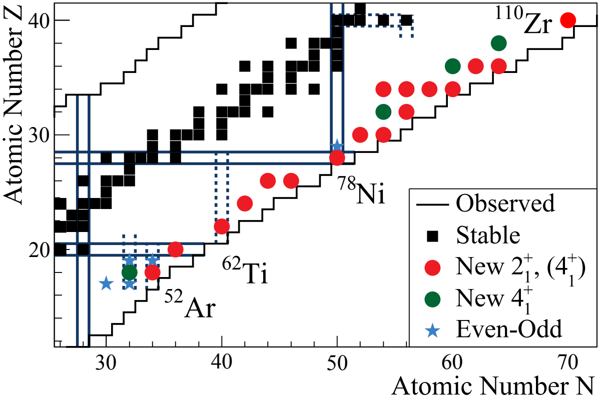
Regions of extreme isospin:

- first spectroscopy of nuclei at the limit
- $E(2^+, 4^+)$, $B(E2)$ values, $E1$ response
- knockout reactions, single-particle states

Selected recent results

SEASTAR

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



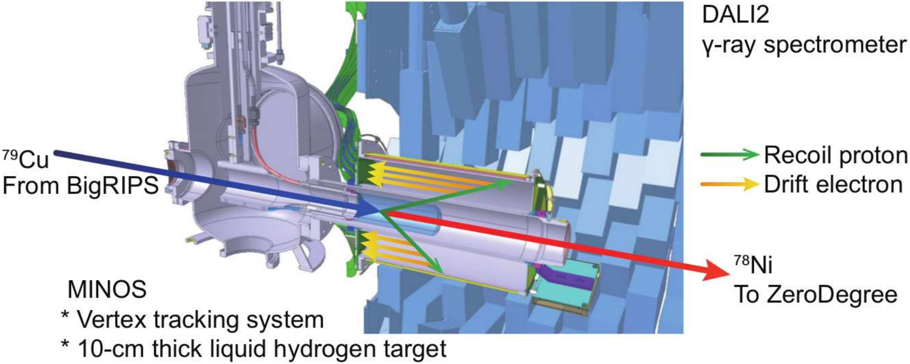
combining

- highest intensity secondary beams
- large acceptance spectrometer
- thick liquid hydrogen target MINOS
- DALI2 γ-ray detector
- few spectrometer settings

- first spectroscopy of neutron-rich nuclei
- many by-products and even-odd channels
- 27 days of beam time in 3 campaigns
- spokesperson: P. Doornenbal and A. Obertelli

MINOS

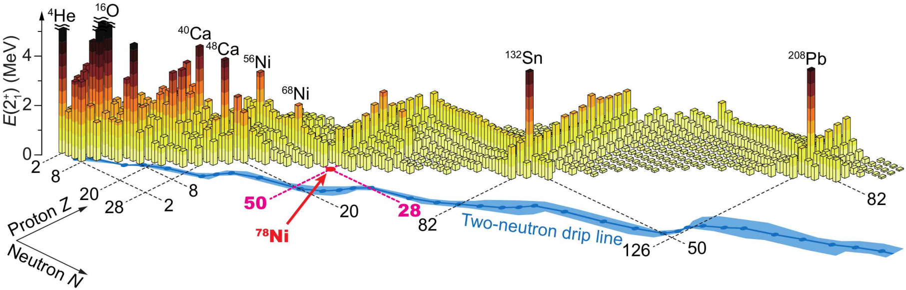
- maximize luminosity
- thick liquid hydrogen target ($\sim$ 1 g/cm^2, $\sim$ 10 cm)



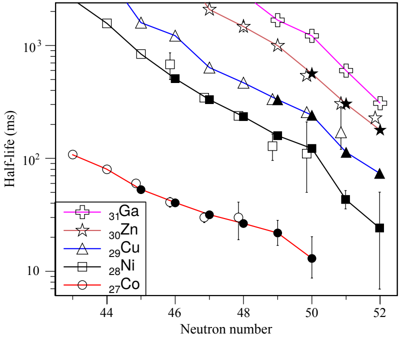
- event-by-event Doppler-correction needs β and θ
  $\rightarrow$ interaction vertex reconstruction
- target surrounded by time-projection-chamber
- vertex resolution 5 mm

A. Obertelli et al., Eur. Phys. Jour. A **50** (2014) 8, C. Santamaria et al., Nucl. Instr. Meth. B **905** (2018) 138.

Doubly-magic ^{78}Ni

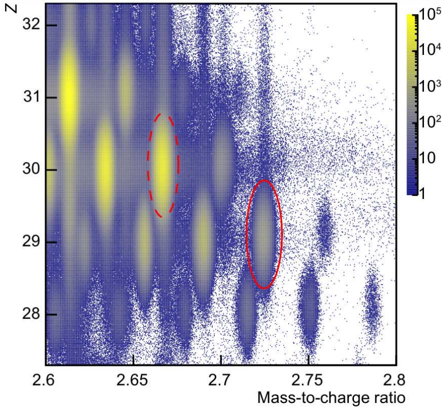


- ^{78}Ni is the only neutron-rich doubly-magic nucleus with unknown $E(2^+)$
- within the predicted neutron drip-line
  J. Erler et al., Nature **486** (2012) 509.
- magicity inferred from β-decay measurements
  P. T. Hosmer et al., Phys. Rev. Lett. **94** (2005) 112501,
  Z. Y. Xu et al., Phys. Rev. Lett. **113** (2014) 032501.
- prediction $E(2^+) = 2 - 4$ MeV

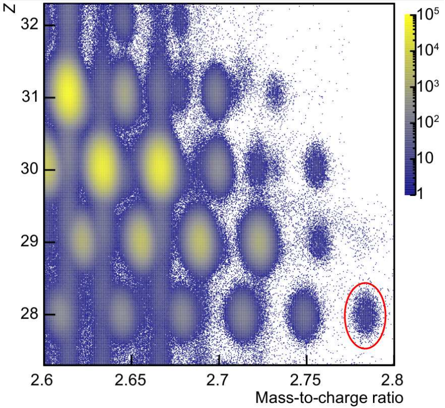


Particle identification

incoming beam, BigRIPS



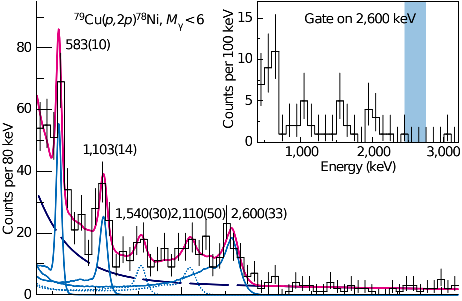
outgoing beam, ZeroDegree



- ^{238}U primary beam at 13 pnA for 6 days
- 5.2 pps ^{79}Cu and 290 pps ^{80}Zn identified in BigRIPS
- detected $\sim$ 1000 events for each (p,2p) and (p,3p) to ^{78}Ni in ZeroDegree

R. Taniuchi, PhD Thesis, The University of Tokyo, 2018

γ-ray spectra for ^{78}Ni



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

- inclusive cross section $\sigma = 1.7(4)$ mb
- highest intensity peak
  $\rightarrow E(2^+) = 2600(33)$ keV
- 583(10) keV transition:
  $4^+ \rightarrow 2^+$ candidate, $R_{4/2} = 1.22(2)$
  similar to other doubly magic nuclei

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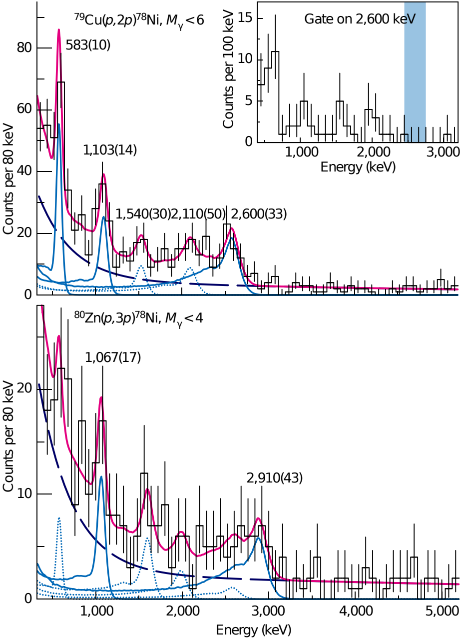

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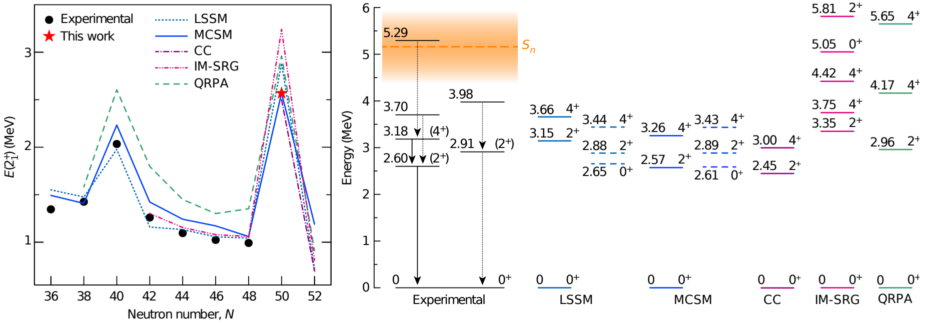
^{80}Zn$(p, 3p)^{78}$Ni

- inclusive cross section $\sigma = 0.016(6)$ mb
- $2_1^+ \rightarrow 0_1^+$ transition not observed
- 2910(43) keV transition: candidate for a 2_2^+

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

Theoretical calculations for ^{78}Ni



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

- high 2^+ energy: doubly-magic character
- large-scale and Monte-Carlo shell model calculations predict spherical ($\beta \sim 0$) ground and deformed intruder excited configurations
  $\rightarrow$ shape coexistence in ^{78}Ni
- lowering of the intruder band in ^{76}Fe and ^{74}Cr predicted: Island of Inversion
- mass measurements for ^{78}Ni and neighbors are crucial

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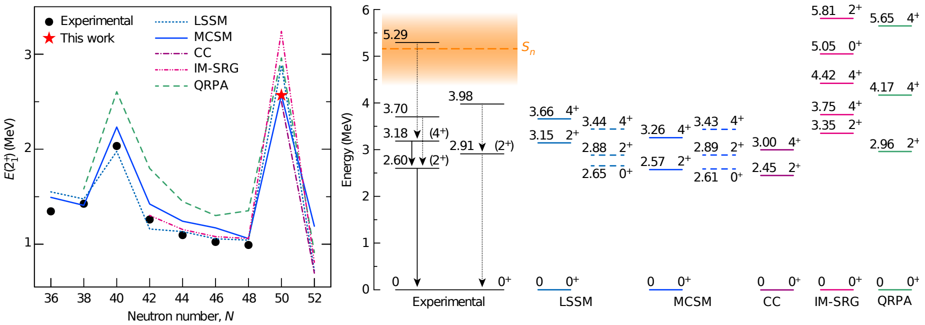

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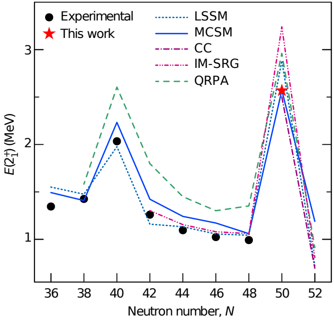

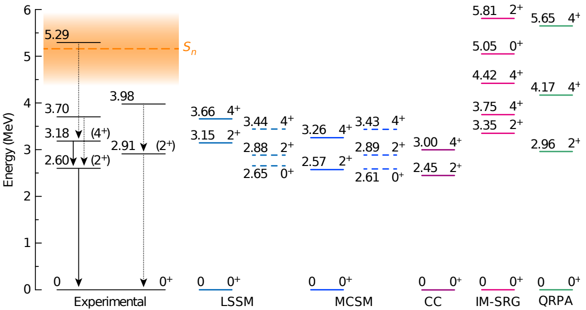

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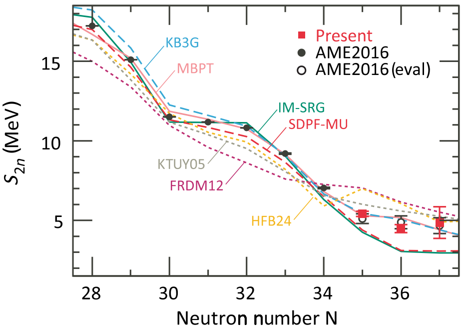
Ge based high resolution array will help to clarify the level scheme

Recent results on Ca isotopes



F. Wienholtz et al., Nature **498** (2013) 346,
S. Michimasa et al., Phys. Rev. Lett. **121** (2018) 022506.

- masses of $^{53-57}$Ca:
  gap between $\nu 2p_{3/2}$ and $2p_{1/2}$
  and $\nu 2p_{1/2}$ and $1f_{5/2}$
  $\rightarrow$ new magic numbers at $N = 32, 34$
- discovery of ^{60}Ca
- drip-line extends at least to ^{60}Ca

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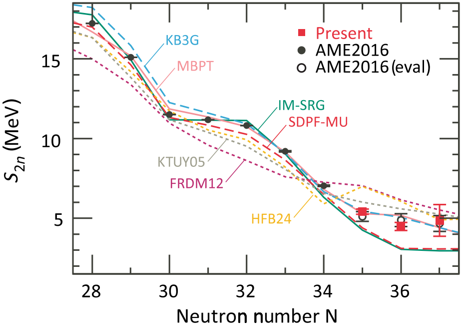

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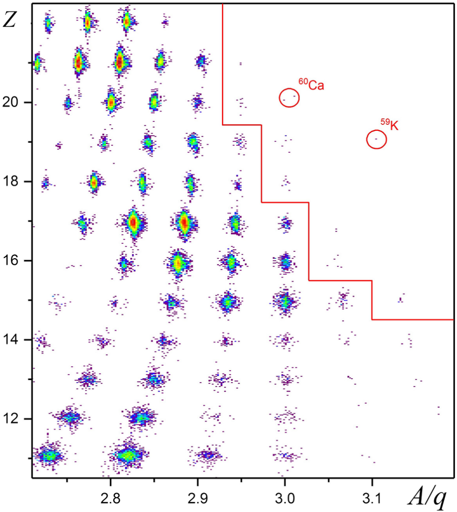

O. Tarasov et al., Phys. Rev. Lett. **121** (2018) 022501.

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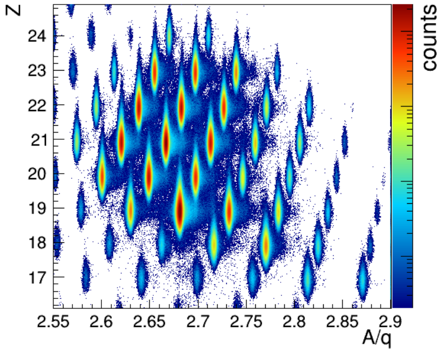
Particle identification

incoming beam, BigRIPS



- ^{70}Zn primary beam, 345 MeV/*u*, 250 pnA
- one single setting to cover neutron-rich beams from ^{64}V down to ^{49}Cl
- unique A/q and Z identification in BigRIPS and SAMURAI
- sufficient statistics for all main objectives

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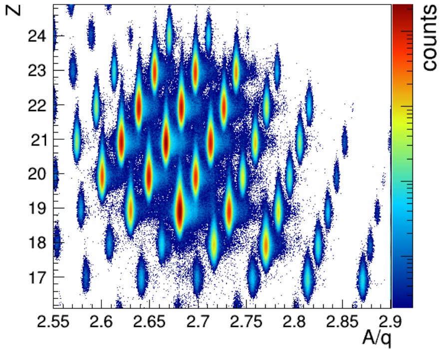

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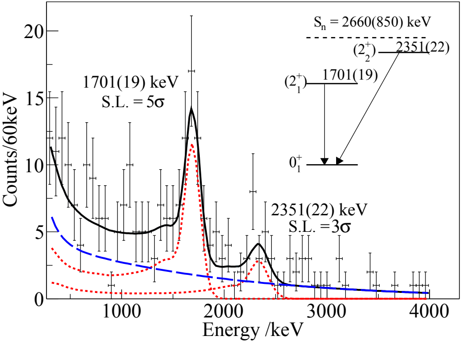
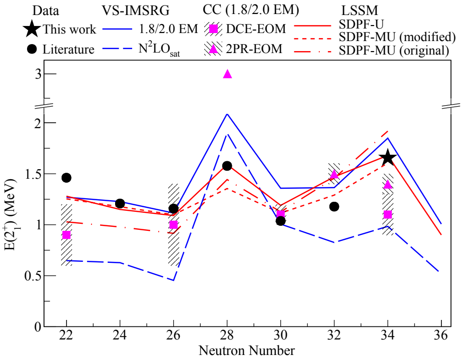
^{52}Ar: $N = 34$ gap below ^{54}Ca





- largest $E(2^+)$ in Ar isotopes beyond $N = 20$
- phenomenological interaction SDPF-MU predicts trend well
  Y. Utsuno et al., Phys. Rev. C **86** (2012) 051301(R), D. Steppenbeck et al., Phys. Rev. Lett. **114** (2015) 252501.
- *ab-initio* calculations using VS-IMSRG and
- coupled cluster calculations give different results
- $N = 34$ shell gap persists in ^{52}Ar

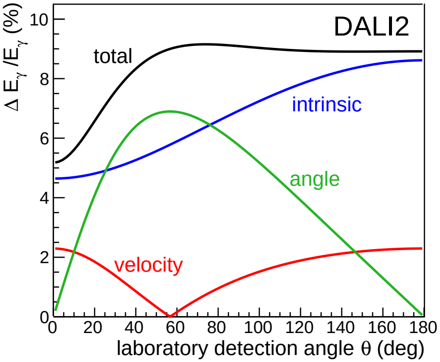
H. Liu et al., Phys. Rev. Lett. **122** (2019) 072502.

removed unpublished and preliminary results

High-resolution spectroscopy

Towards high resolution

- DALI2 limited by intrinsic and angular resolution



- resolution for segmented and tracking detectors at least factor 3 better
- Miniball array available 2019/20 due to CERN long shut down
- GRETA-type quad tracking detector at RCNP Osaka

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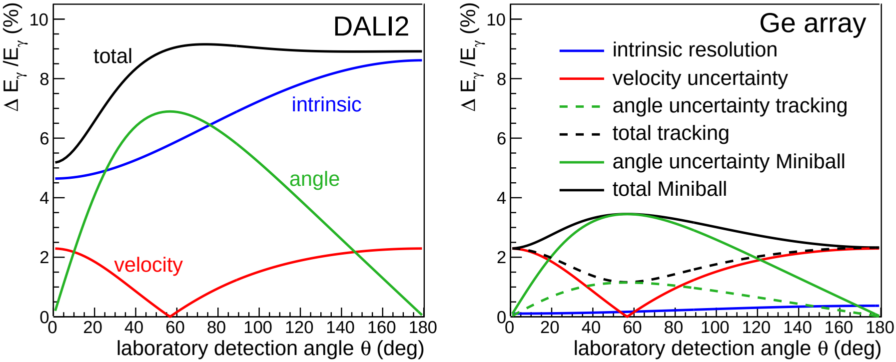

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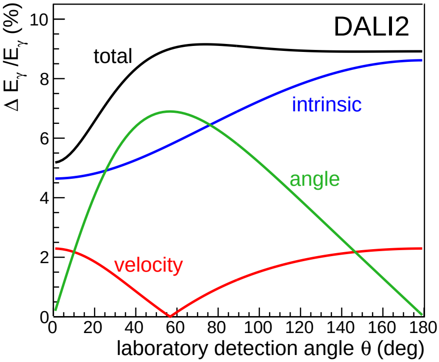

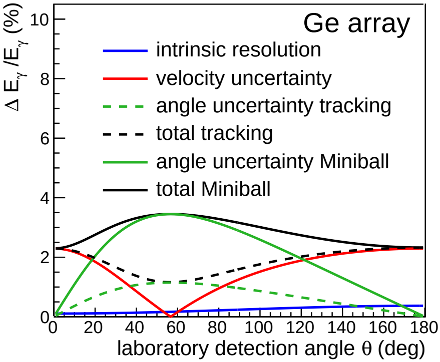

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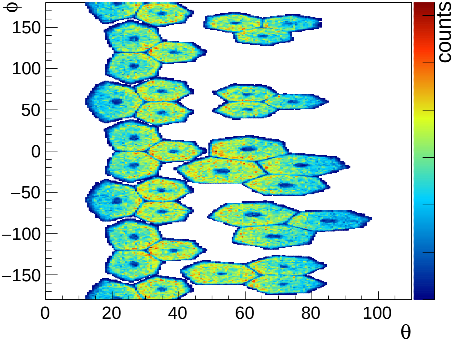
ideal combination with the unique beams at the RIBF

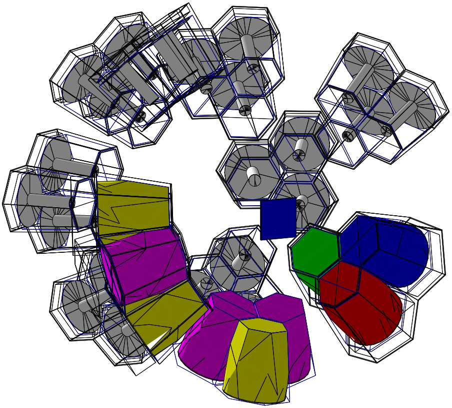
High-resolution γ-ray spectroscopy

proposal for a hybrid array based on

- 8 Miniball triple-cluster
- RCNP quad (GRETA type)
- LBNL triple (GRETA type)
- D-AGATA triple

for a total in-beam efficiency of 9.4 %





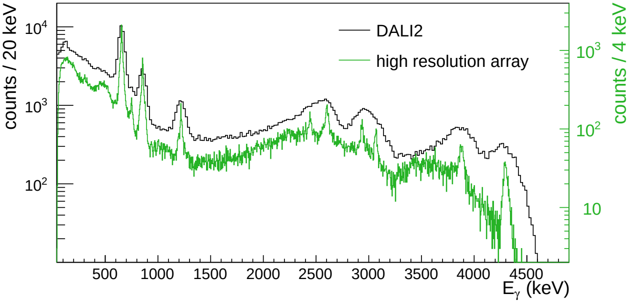
- LOI to Miniball community
- construction proposal to RIBF PAC
- supported by JSPS Kakenhi Kiban-A

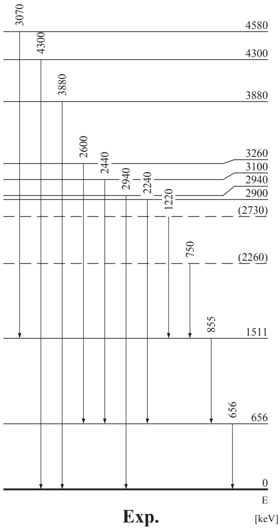
spokespeople:
P. Doornenbal and K. Wimmer

Expected performance

- GEANT4 simulation to optimize geometry
- realistic reaction modeling and resolutions

spectroscopy of ^{79}Cu:
knockout from ^{80}Zn at 200 *A*MeV on 7 mm Be target





- level scheme and relative intensities from experiment

L. Olivier et al. Phys. Rev. Lett. **119** (2017) 192501.

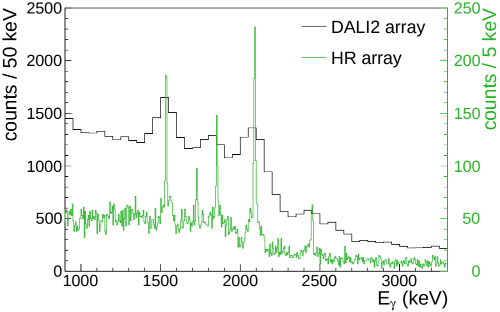
- significantly improved peak-to-total ratio
- clear peak identification possible

Expected performance

- first spectroscopy of ^{55}Sc
- knockout from ^{56}Ti at 180 *A*MeV

D. Steppenbeck et al.,
Phys. Rev. C **96** (2017) 064310.

- much better resolving power
- clear $\gamma - \gamma$ coincidences



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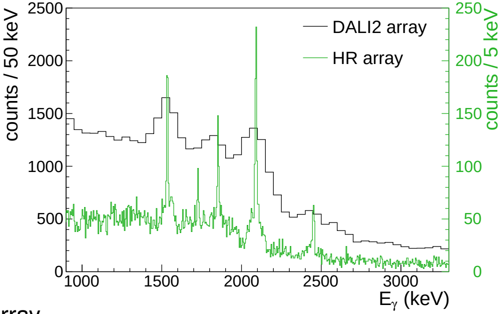
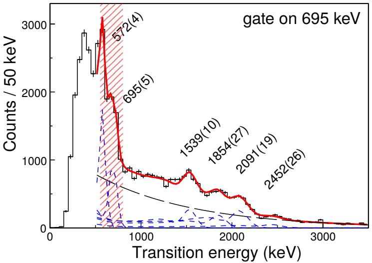
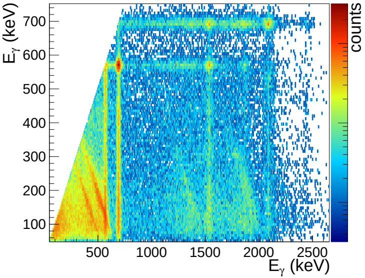
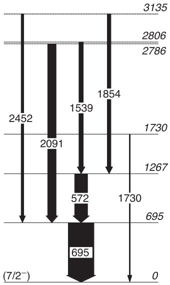


DALI2



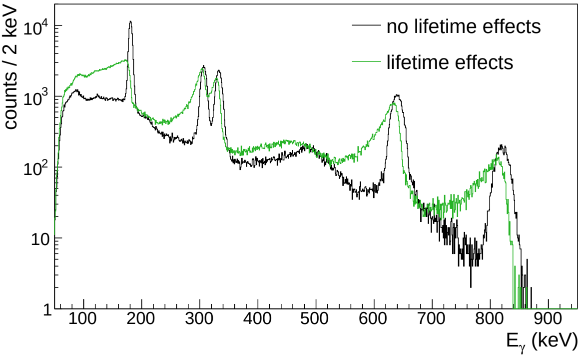
HR array

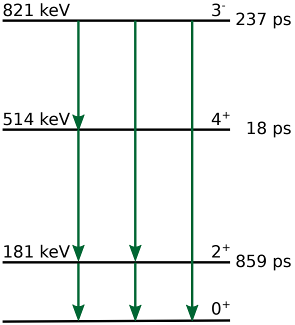




Lifetime effects

- finite lifetimes have an effect on the Doppler corrected energy
- lifetimes can be obtained from peak-shape
- example ^{146}Ba, decay of the 3^{-} state

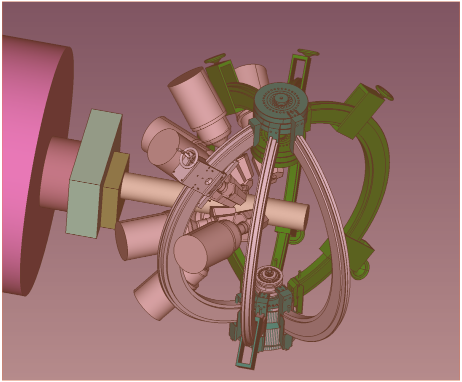




- sensitivity 10 - 100 ps
- shift of peak and tail towards lower energies
- alternative: plunger

The HR array at RIBF

- GRETA type digitizer for all detectors
- MINOS can be used as well (mechanical design ongoing)
- plunger device for lifetime measurements
- will be combined with MR-TOF system at F11



workshop April 10-12 in Darmstadt,
60 participants, 39 presentations
established working groups on

- mechanics (D. Suzuki, RNC)
- detectors and infrastructure (P. Doornenbal, RNC)
- electronics and DAQ (K. Wimmer, U Tokyo)
- MINOS (A. Corsi, CEA Saclay)
- plunger (RCNP, U Köln)

to be ready for spring 2020

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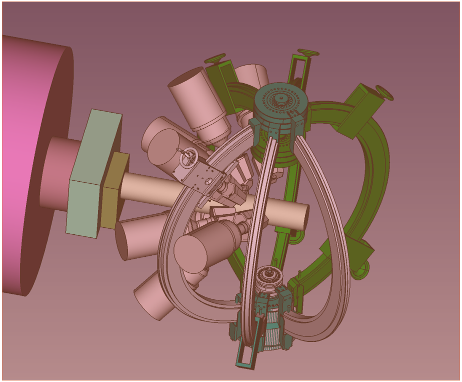

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call for pre-proposals which will be discussed August 26-28 in Osaka

Summary

- in-beam γ-ray spectroscopy at the RIBF, moderate resolution, but high efficiency
- γ-ray spectroscopy at extreme isospin with high intensity fast beams

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- first spectroscopy of the doubly-magic nucleus ^{78}Ni
- $\rightarrow$ robust shell closures at $Z = 28$ and $N = 50$
- second 2^+ state $\rightarrow$ shape coexistence

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- second 2^+ state $\rightarrow$ shape coexistence

- first spectroscopy towards ^{60}Ca
- $\rightarrow$ $N = 34$ persists in ^{52}Ar
- see talk by M. L. Cortés on Thursday

Summary

- in-beam γ-ray spectroscopy at the RIBF, moderate resolution, but high efficiency
- γ-ray spectroscopy at extreme isospin with high intensity fast beams

- first spectroscopy of the doubly-magic nucleus ^{78}Ni
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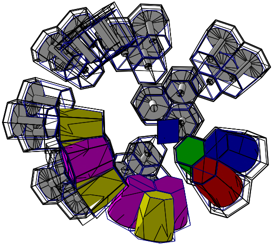

- high-resolution campaign at the RIBF approved
- PAC proposals due in October
- $\rightarrow$ unique opportunities with intense beams and high resolution
- $\rightarrow$ join the collaboration

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