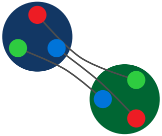
From magicity to deformation: neutron-rich nuclei between $N = 32$ and 40

Kathrin Wimmer

GSI Helmholtzzentrum für Schwerionenforschung

7. October 2022

Symmetry breaking and collectivity



- dual quantum liquid consisting of protons and neutrons which are interacting
- leads to the well-known shell structure of atomic nuclei
- strong nuclear interaction and its isospin dependence leads to changes along isotopic and isotonic chains
- shell evolution can change the spacing and ordering of the single-particle orbitals
  $\rightarrow$ degenerate levels in a nuclear Jahn-Teller effect
  $\rightarrow$ spontaneous symmetry breaking and quantum phase transitions
- excitations associated with collective quantum mechanical rotations or vibrations
- many nucleons are moving coherently in phase

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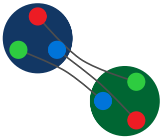

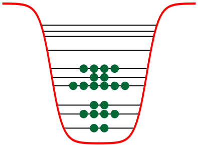

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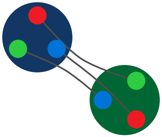

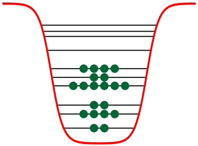

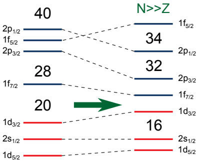

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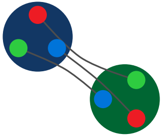

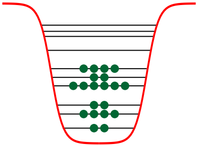

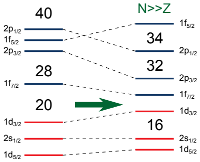

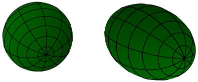

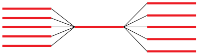

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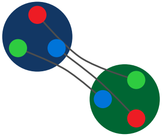

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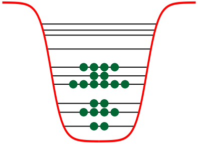

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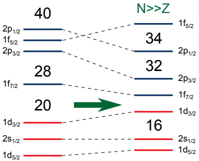

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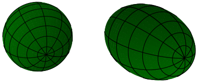
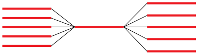
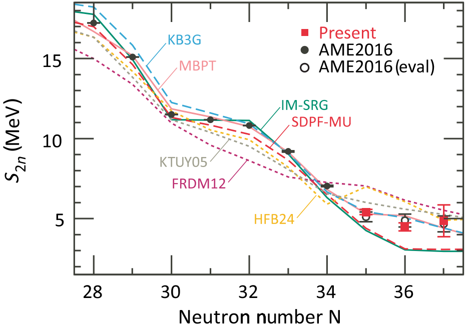


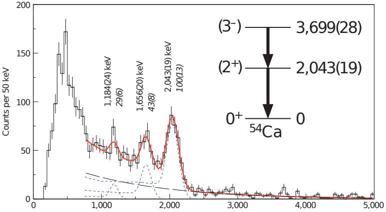
where and how does collective motion and deformation of nuclei emerge from the single-particle degrees of freedom of the protons and neutrons?

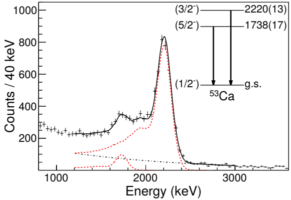


Magicity in the calcium isotopes



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



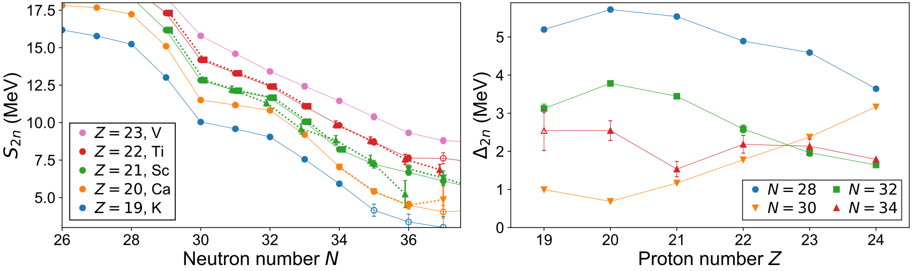


D. Steppenbeck et al., Nature **502** (2013) 207,
S. Chen et al., Phys. Rev. Lett. **123** (2019) 142501.

- masses of $^{53-57}$Ca: drops in S_{2n} after shell closure
- spectroscopy of ^{54}Ca: high excitation energy of 2^+ state
- nucleon removal reactions: fully occupied $\nu 1p_{3/2}$, $1p_{1/2}$ orbitals, $0f_{5/2}$ empty
- sizable gaps between $\nu 1p_{3/2}$, $1p_{1/2}$, and $0f_{5/2}$ orbitals
  $\rightarrow$ new magic numbers $N = 32$ and 34

Magicity in the calcium isotopes

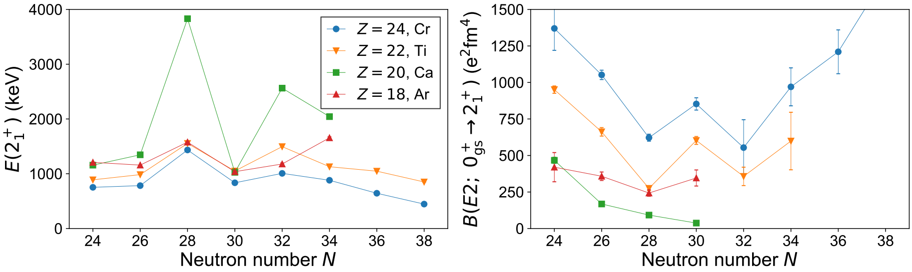
- is everything well understood?
- charge and matter radii increase (upcoming RIBF experiment Nov. 2022)



S. Michimasa et al., Phys. Rev. Lett. **125** (2020) 122501, E. Leistenschneider et al., Phys. Rev. Lett. **126** (2021) 042501, Z. Meisel et al., Phys. Rev. C **101** (2020) 052801.

- lots of activity on mass measurements in recent years
- empirical shell gap $\Delta_{2n}(Z,N) = S_{2n}(Z,N) - S_{2n}(Z,N+2)$
- at $N = 32$, increase from Cr to Ca
- no such increase observed for $N = 34$, spike at ^{54}Ca
- data below Ca not yet conclusive (AME20 extrapolation)

Transition from magicity to deformation



- clear rise in $E(2^+_1)$ at $N = 32$ also in Cr and Ti, smaller in Ar
- $N = 34$ shell gap persists in ^{52}Ar

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

- lots of developments in theory as well

J. D. Holt et al., Phys. Rev. C **90** (2014) 024312, G. Hagen et al., Phys. Rev. Lett. **109** (2012) 032502, V. Somà et al., Phys. Rev. C **89** (2014) 061301, J. Simonis et al., Phys. Rev. C **96** (2017) 014303, H. Hergert et al., Phys. Rev. C **90** (2014) 041302, S. R. Stroberg et al., Phys. Rev. Lett. **118** (2017) 032502, L. Coraggio et al., Phys. Rev. C **102** (2020) 054326 (2020), S. R. Stroberg et al., Phys. Rev. Lett. **126** (2021) 022501,

and probably more

- increasing collectivity toward $N = 40$
- theoretical calculations point out necessity of particle-hole excitations to the $\nu 0g_{9/2}$ and $1d_{5/2}$ orbitals

S. M. Lenzi et al., Phys. Rev. C **82** (2010) 054301.

- proposal of a new Island of Inversion

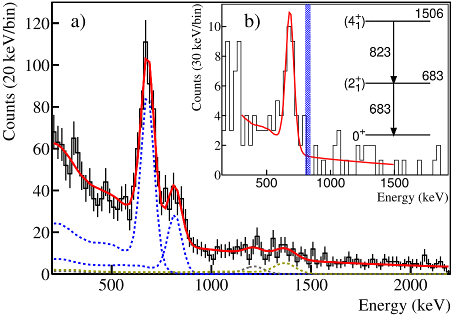
Transition from magicity to deformation

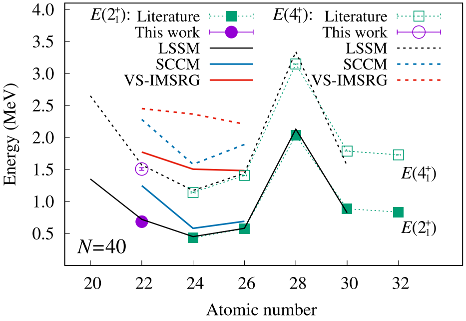
- discovery of $Z = 20, N = 40$ nucleus ^{60}Ca

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

- drip-line expected at $N = 50$
- intruder dominated isomers in Ti and Sc

K. Wimmer et al., Phys. Lett. B **792** (2019) 16, Phys. Rev. C **104** (2021) 014304.





- spectroscopy at $N = 40$ reaches ^{62}Ti

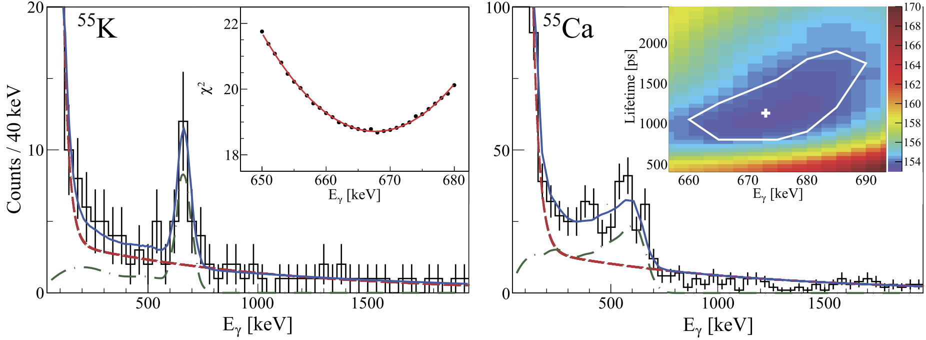
M. L. Cortés et al., Phys. Lett. B **800** (2020) 135071.

- despite the rise in energy toward $N = 40$ theoretical calculations show particle-hole dominated configurations

Single-particle structure of ^{56}Ca

- proton and neutron knockout from ^{56}Ca with the high-efficiency DALI2$^+$, MINOS, SAMURAI setup within the SEASTAR project

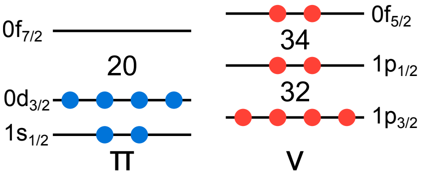
S. Takeuchi et al., Nucl. Instr. Meth. A **763** (2014) 596, A. Obertelli et al., Eur. Phys. J. A **50** (2014) 8, T. Kobayashi et al., Nucl. Instr. Meth. B **317** (2013) 294



T. Koiwai et al., Phys. Lett. B **827** (2022) 136953.

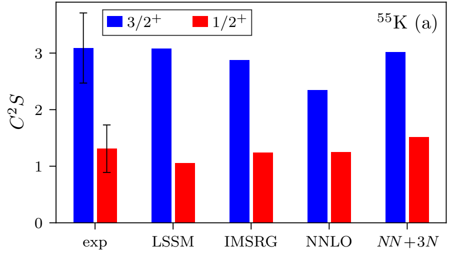
- long tail of 673(17) keV transition $\rightarrow$ long lifetime $\tau = 1130^{+520}_{-330}$ ps
- single-particle state with $B(E2;\,(1/2^-) \rightarrow (5/2^-)) = 5.2\ e^2\text{fm}^4$ or 0.4 W.u.

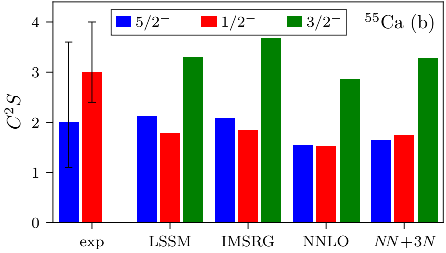
Single-particle structure of ^{56}Ca



- population of a single state in agreement with expectation
- simple structure of ^{56}Ca

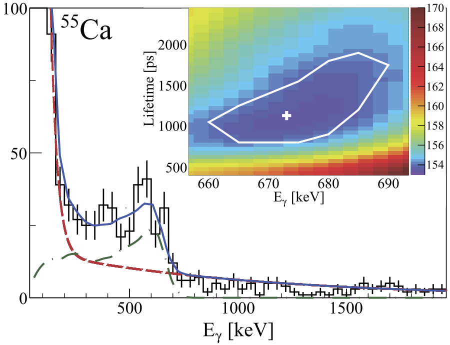
T. Koiwai et al., Phys. Lett. B **827** (2022) 136953.

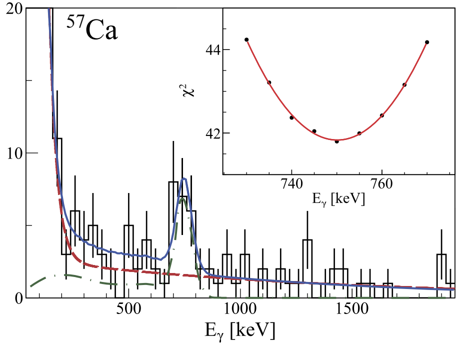




- cross sections (spectroscopic factors) in agreement with fully occupied $\pi 0d_{3/2}$ and $1s_{1/2}$ orbitals
- good agreement with various calculations, large-scale shell model and ab initio
- neutron removal reaction consistent with two neutrons in each $\nu 1p_{1/2}$ and $0f_{5/2}$

Increase in collectivity





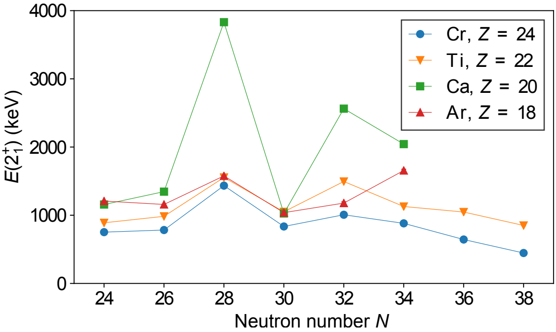
- first spectroscopy of ^{57}Ca, transition at 751(13) keV
- populated in proton removal from ^{58}Sc, which is predicted to be a member of the $N = 40$ Island of Inversion   K. Wimmer et al., Phys. Rev. C **104** (2021) 014304.
- assuming again $E2$ transition, $B(E2) > 55.2\ e^2\text{fm}^4$, ten times larger than for ^{56}Ca

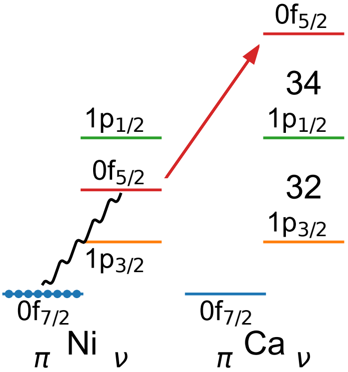
transition toward many particle-hole dominated configurations in the N $=$ 40 Island of Inversion

T. Koiwai et al., Phys. Lett. B **827** (2022) 136953.

Shells and shapes of neutron-rich Ca

- new magic numbers at $N = 32$ and 34 established in Ca, energy of 2_1^+ states, neutron separation energies, spectroscopic factors
- how do these evolve with proton number?
- how does the transition to collectivity proceed?





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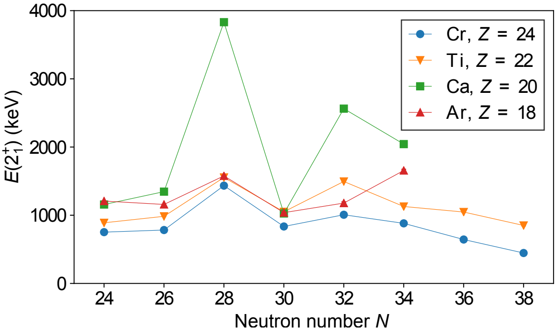

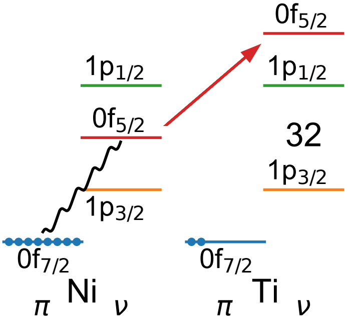

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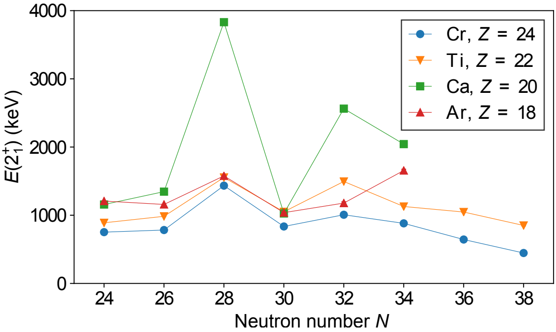
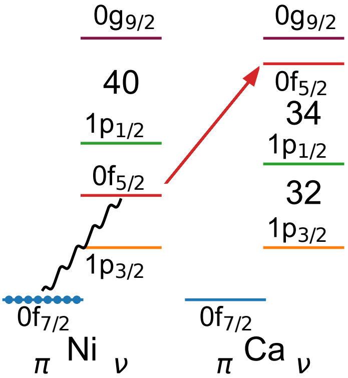
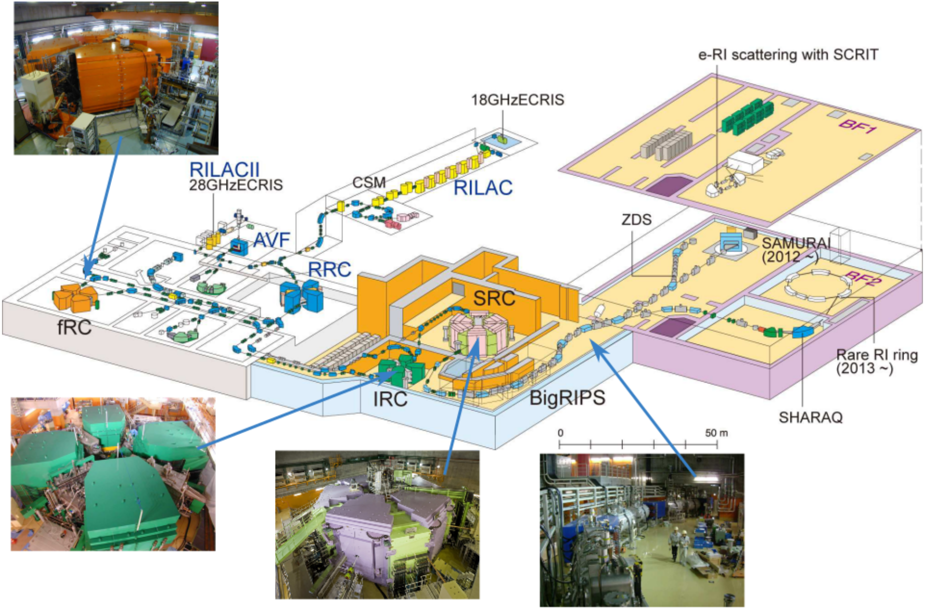


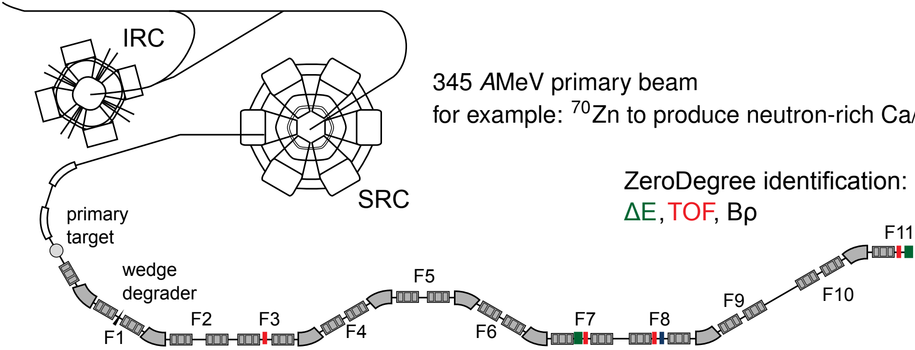


study single-particle and collective properties of Ti and Ca chains

The Radioactive Isotope Beam Factory



Beam production and identification



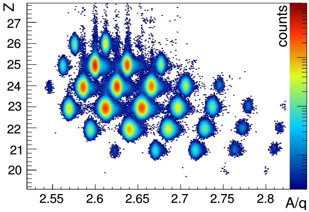
345 *A*MeV primary beam
for example: ^{70}Zn to produce neutron-rich Ca/Ti

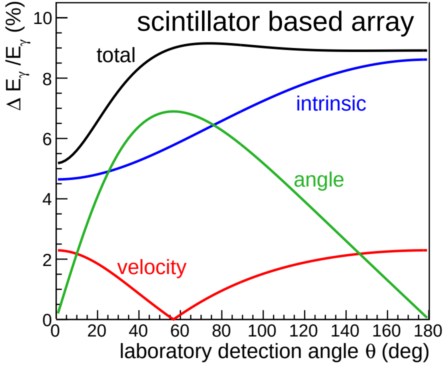
ZeroDegree identification:
ΔE, TOF, Bρ

BigRIPS identification by:
ΔE, TOF, Bρ

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

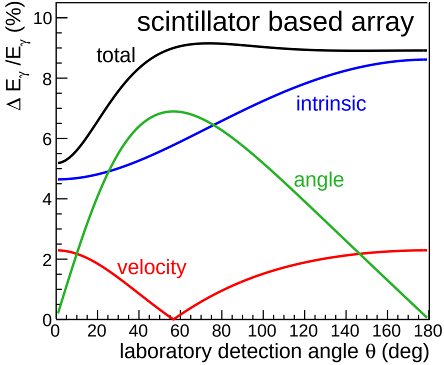
- fragmentation or fission of intense primary beam
- particle identification by $B\rho - \Delta E - \mathrm{TOF}$
- secondary reaction target at F8, surrounded by γ-ray detectors
- identification after target: ZeroDegree spectrometer

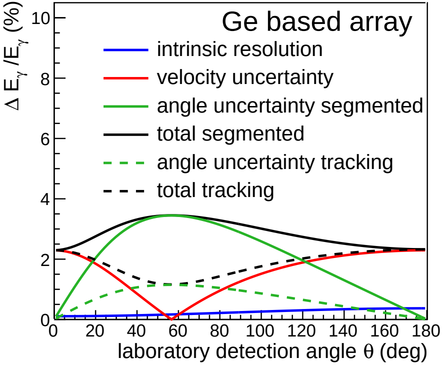




- intrinsic energy and position resolutions as well as velocity uncertainty
- limited to simple level schemes
- resolution for segmented and tracking detectors at least factor 3 better
- allow for higher level density, deformed nuclei, and lifetime measurements

SFB workshop 2018: in-beam resolution





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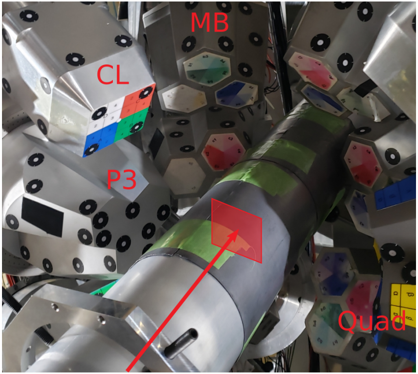
Ge based array: ideal combination with unique beams at the RIBF

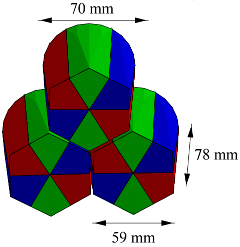
High-resolution Cluster Array at the RIBF

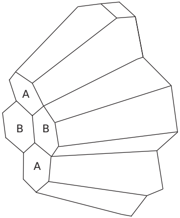
- hikari 光 means “light”
- Wako-shi (city where RIBF is) 和光市

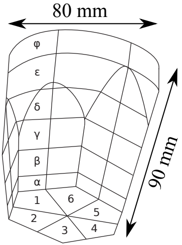
international effort:

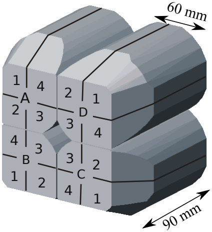
- 6 Miniball triple-cluster from Europe
- RCNP quad (GRETA-type, Japan)
- LBNL triple (GRETA-type, USA)
- 4 Super-Clovers from IBS (Korea)
- 4 Clovers from IMP Lanzhou (China)
- GRETA-type electronics and DAQ (RCNP, ANL, LBNL, U Tokyo)
- Miniball frame (U Köln, Germany)





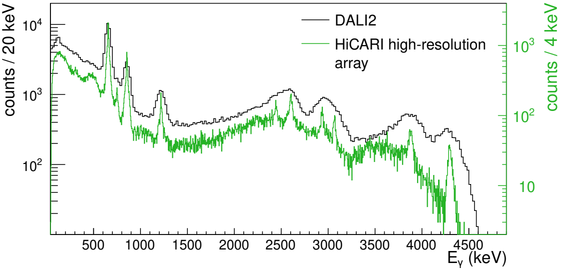






comparison to existing data $^{80}Zn(p,2p)^{79}Cu$

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



significantly improved resolving power

- state identification
- $\gamma - \gamma$ coincidences
- lifetime measurements

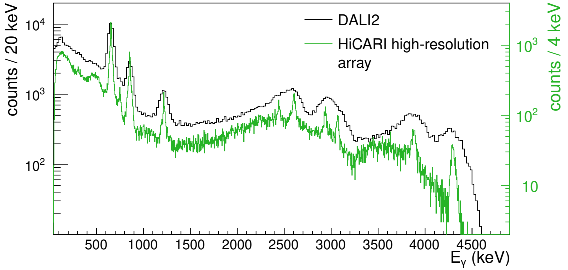
spokespersons: P. Doornenbal and K. Wimmer,

funding: JSPS KAKENHI 19H00679, RIKEN, RCNP

Expected performance

comparison to existing data $^{80}\mathrm{Zn}(p,2p)^{79}\mathrm{Cu}$

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



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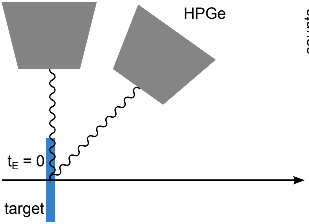
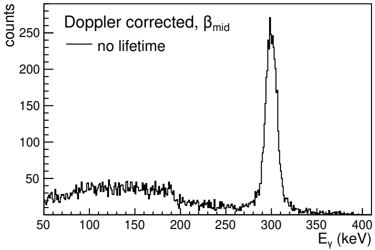


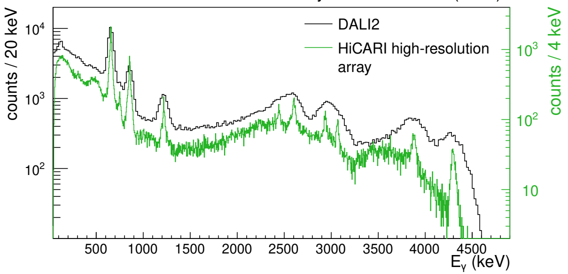


spokespersons: P. Doornenbal and K. Wimmer,
funding: JSPS KAKENHI 19H00679, RIKEN, RCNP

Expected performance

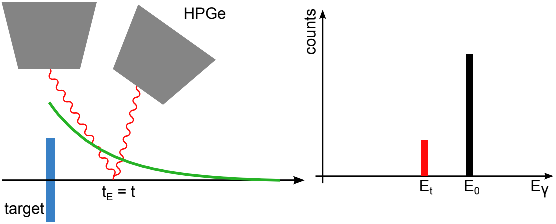
comparison to existing data $^{80}Zn(p,2p)^{79}Cu$

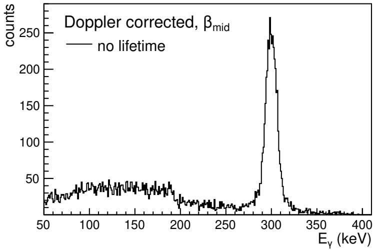
L. Olivier et al. Phys. Rev. Lett. **119** (2017) 192501.



significantly improved resolving power

- state identification
- $\gamma - \gamma$ coincidences
- lifetime measurements





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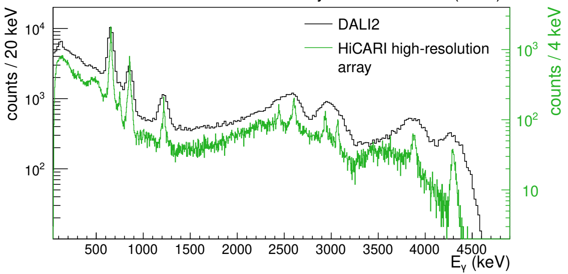

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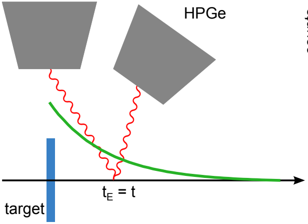

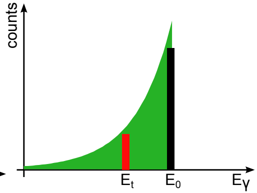

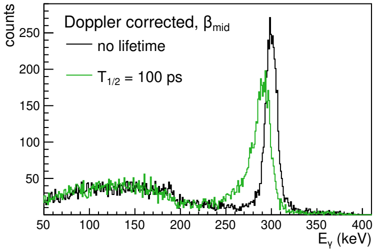

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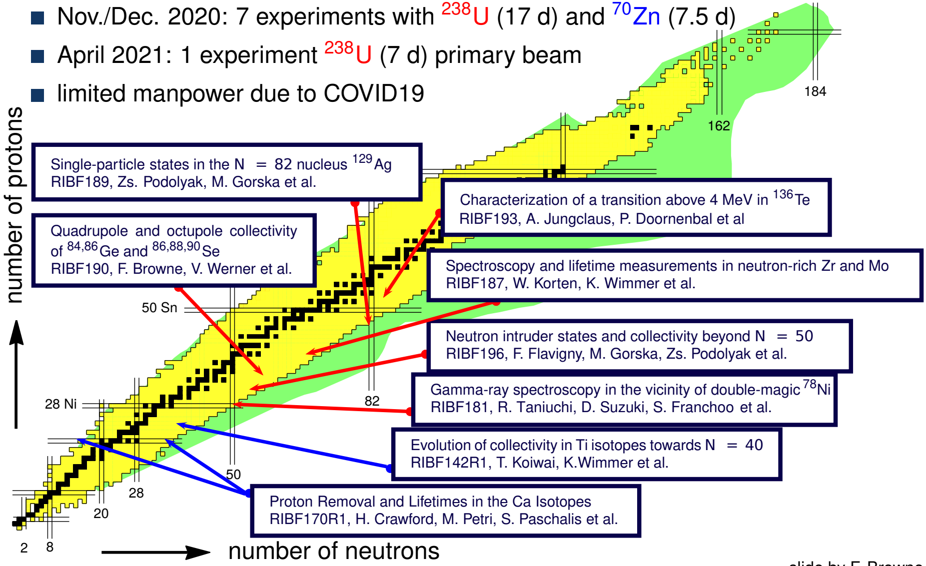
HiCARI campaign

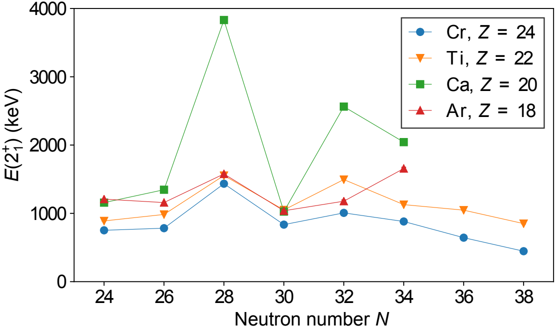
- initially planned for spring 2020, Japan declared state of emergency → postponed
- Nov./Dec. 2020: 7 experiments with ^{238}U (17 d) and ^{70}Zn (7.5 d)
- April 2021: 1 experiment ^{238}U (7 d) primary beam
- limited manpower due to COVID19

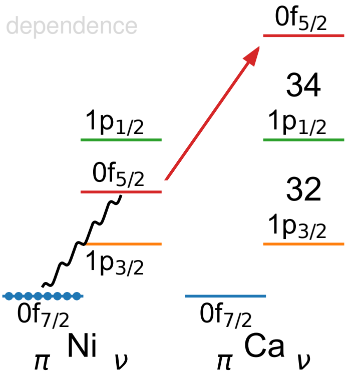


slide by F. Browne

Shell evolution beyond N = 34

- new magic numbers at $N = 32$ and 34 established in Ca
- ^{56}Ti: no signs of $N = 34$ sub-shell closure
- shell evolution due to tensor interaction, strong Z dependence





RIBF142, T. Koiwai (U Tokyo) et al.

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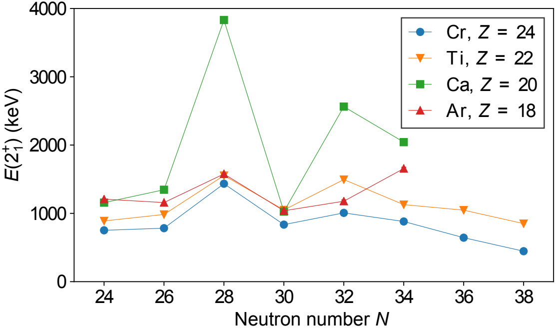

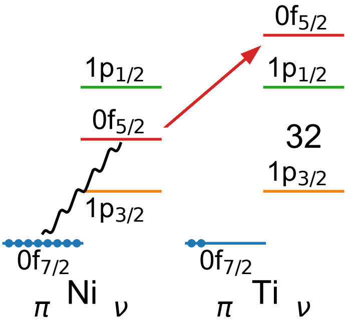

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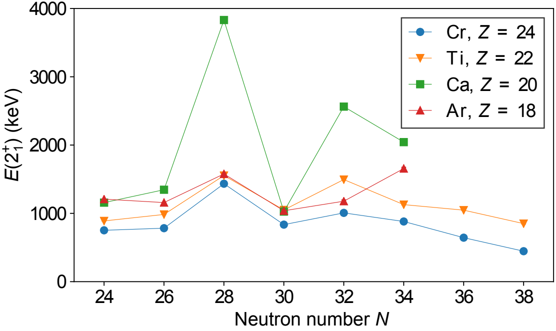
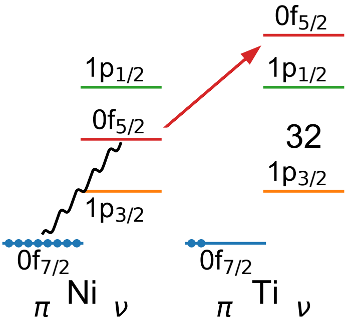


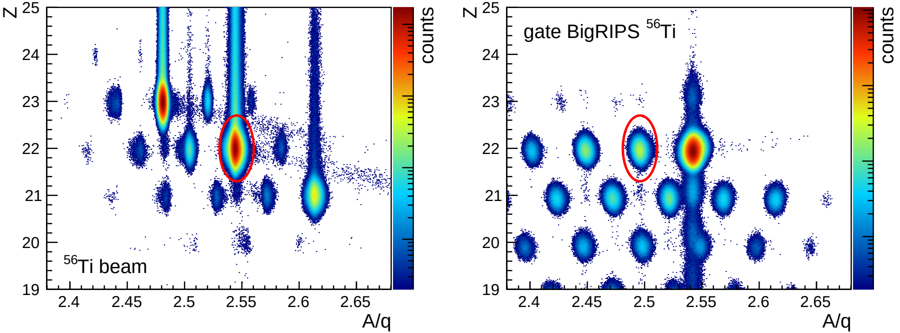


- detailed investigation of the neutron single-particle structure
- spectroscopy of odd Ti nuclei by one-neutron knockout reactions
- Coulomb excitation of even Ti isotopes

RIBF142, T. Koiwai (U Tokyo) et al.

First results for ^{55,57}Ti

neutron knockout reactions from ^{56,58}Ti at 190 *A*MeV on 3 mm thick Be target



inclusive one-neutron knockout cross sections:

- $\sigma_{\mathrm{inc}}(^{56}\mathrm{Ti}(^{9}\mathrm{Be,X})^{55}\mathrm{Ti}) = 81(2)$ mb (preliminary, statistical error only)
- agrees well with $83(12)$ mb measured at 500 *A*MeV

P. Maierbeck et al., Phys. Lett. B **675** (2009) 22.

- similar result for ^{58}Ti: $\sigma_{\mathrm{inc}} = 82(2)$ mb
- reduced $1p_{1/2}$ occupation at $N = 34, 36$?

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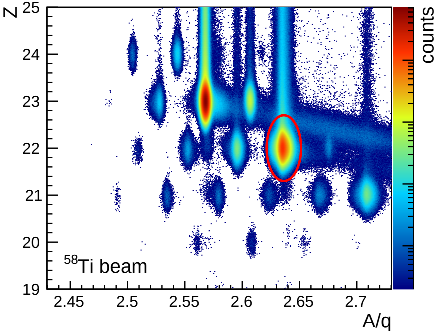

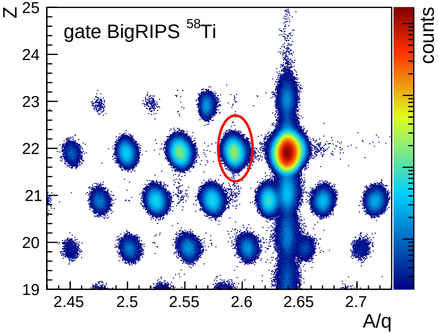

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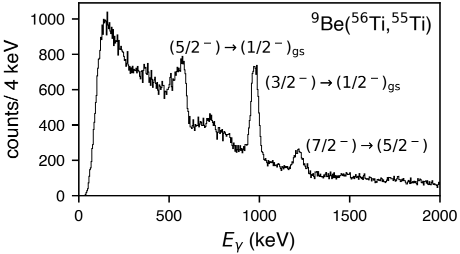

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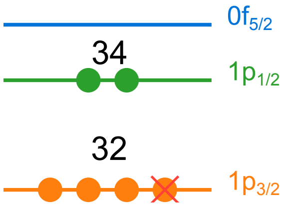
- also strong population of $(5/2^-)$ state with single-particle character (long lifetime) and $(7/2^-)$ state proposed as particle-hole excitation

- exclusive cross sections and momentum distributions of $1/2^-$ ground and $(5/2^-)$ states will give configuration of ^{56}Ti ground state at $N = 34$
- very different spectra for ^{57}Ti



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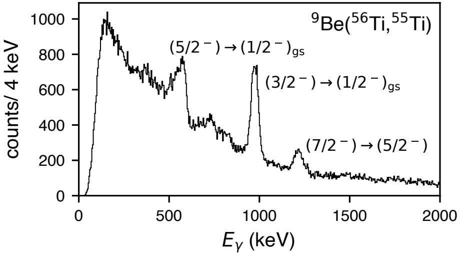

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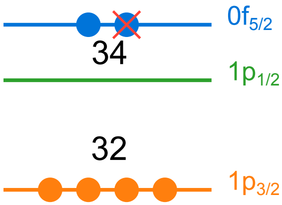

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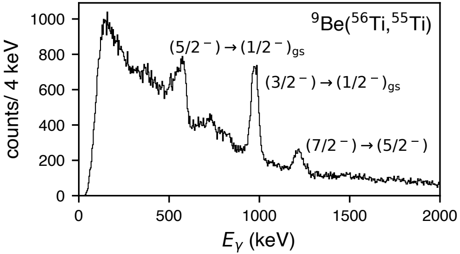

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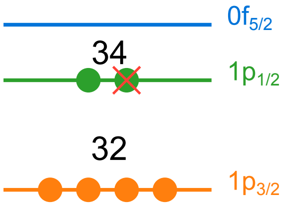

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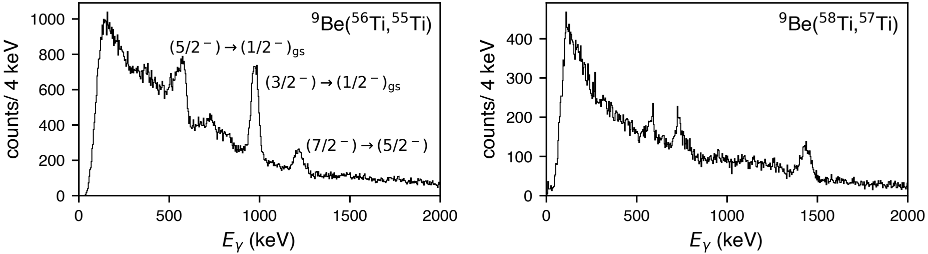

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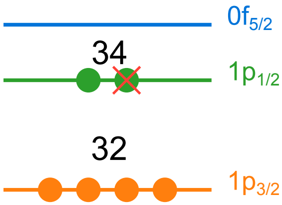
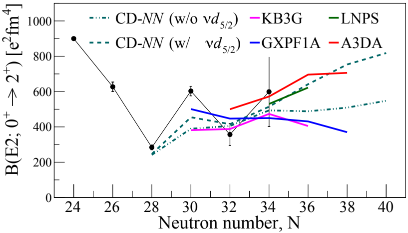
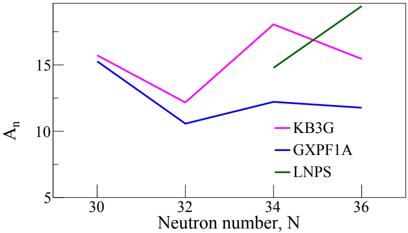


stay tuned for more results

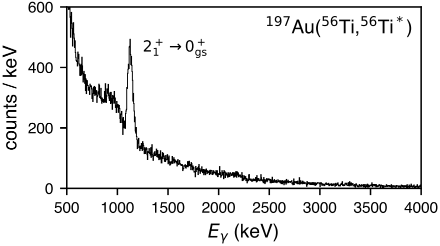
The N = 40 Island of Inversion

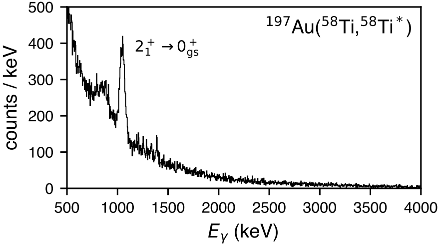
- increase in collectivity toward $N = 40$
- some shell-model calculations predict increase in neutron amplitudes for $N > 34$





Coulomb excitation of ^{56,58}Ti on Au target

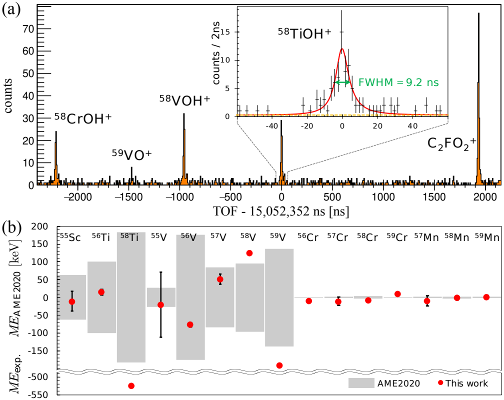


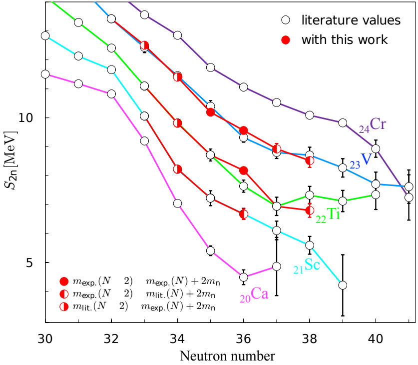


analysis by A. Kohda (U Osaka / RCNP)

Freebies

- ZeroDegree MR-TOF-MS was installed at the end of our beam-line
- mass measurements in parallel to all the HiCARI experiments





analysis by S. Iimura (U Osaka / RIKEN)

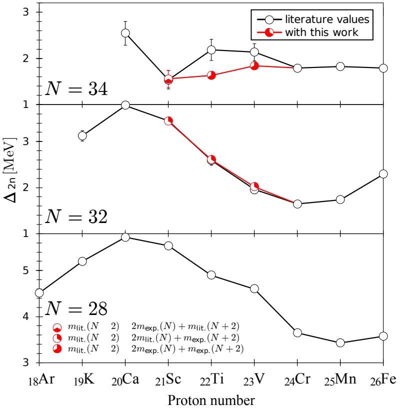
- new value for ^{58}Ti deviates from previous measurements
- implications for the $N = 34$ shell gap

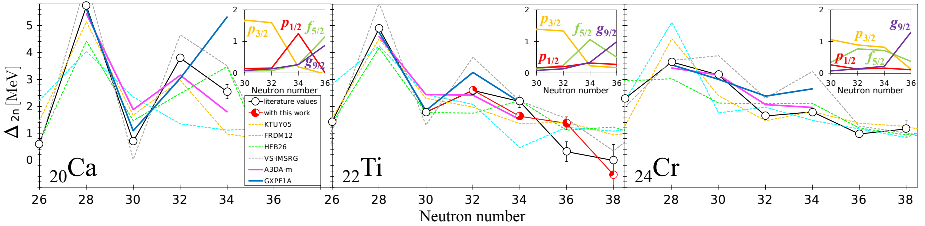
Freebies

- peculiar behavior of the empirical shell gap at Sc is resolved
- no $N = 34$ gap in Ti
- as function of neutron number: continuous reduction toward $N = 40$

  analysis by S. Iimura (U Osaka / RIKEN)

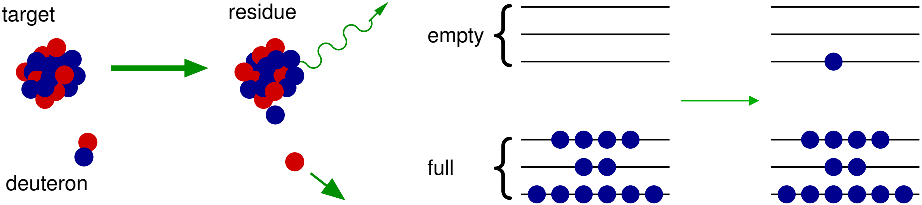
to be published soon!
provides additional motivation for the neutron knockout experiments





What is next?

- transfer reactions probe valence space
- impinge radioactive beam on deuteron target



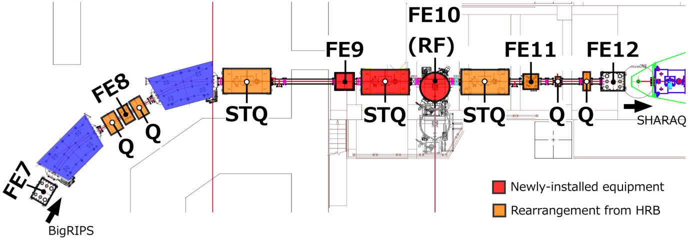
- proton energy and angle gives missing mass $\longrightarrow$ excitation energy
- proton angular distribution is determined by $\Delta L \longrightarrow J^{\pi}$ of state
- γ ray decay properties $\longrightarrow$ further information on level scheme

challenges:

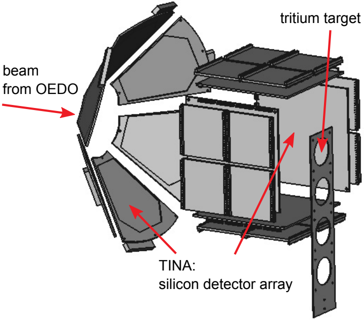
- beam energies around Coulomb barrier
- thin targets $\longrightarrow$ high beam intensity

The OEDO beam line

- Optimized Energy Degrading Optics:
  monochromatic energy degrader and RF deflector for refocusing



- beam energies 10 - 50 *A*MeV
- TINA:
  A Si/CsI Setup for Light Recoiling Particles from Transfer (and other) Reactions
- commissioned and used in experiments at Kyushu and RIBF
- developed by U Tokyo, CNS, RIKEN
- ejectile identification with SHARAQ



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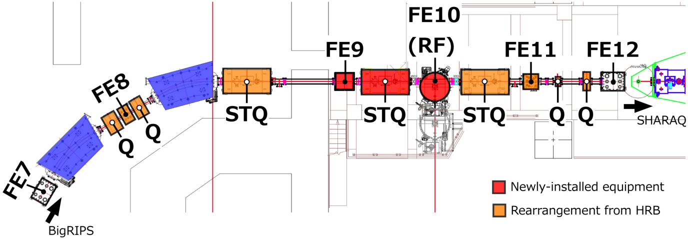

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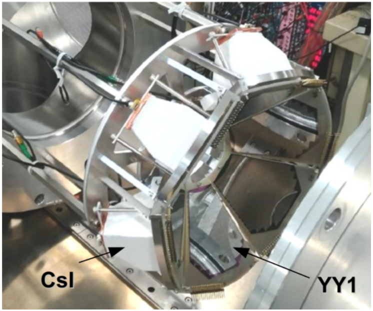
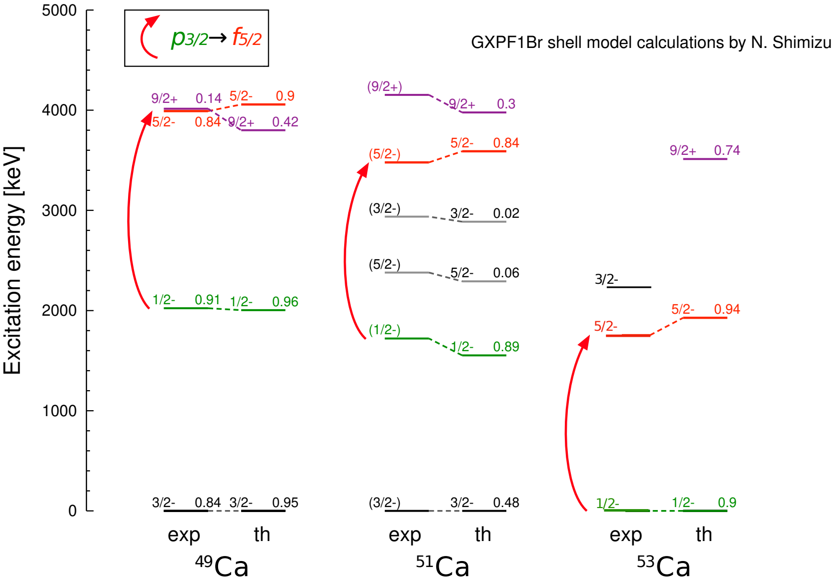


The SHARAQ12 experiment

- probe $N = 32, 34$, and 40 shell gaps simultaneously



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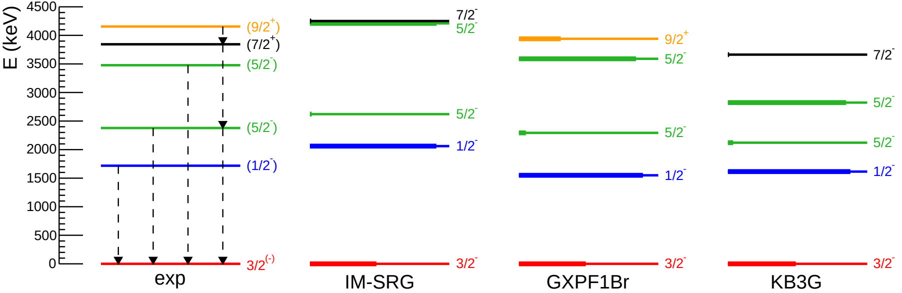

- realistic simulations using ADWA calculations for the (d, p) cross sections
- firm assignments of particle states
- excitation energies, angular distributions, and cross sections
- search for $0g_{9/2}$ strength
- complementary data to $^{52}\mathrm{Ca}(p, pn)^{51}\mathrm{Ca}$ $\rightarrow$ see talk by Madalina Enciu

scheduled this November at RIBF

start of a campaign $\rightarrow$ next $^{52}\mathrm{Ca}(\mathrm{d}, \mathrm{p})$

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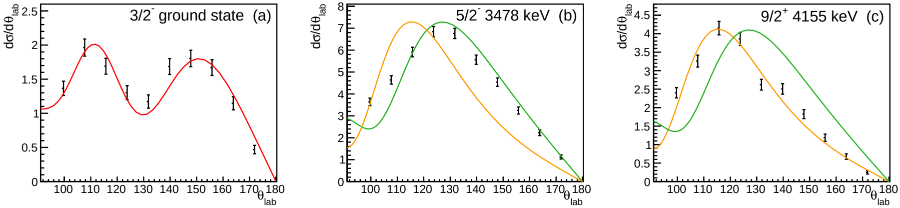

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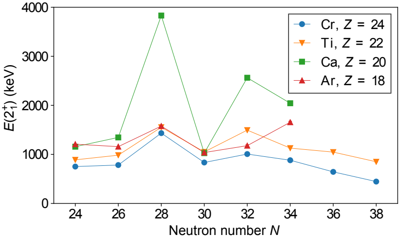
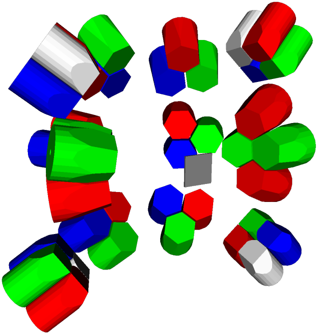
Summary

- many observables confim the new shell closures at $N = 32$ and 34
- transition to deformation at $N = 40$ is expected and observed

lots of new results expected soon





- HiCARI: high-resolution campaign at the RIBF
- unique opportunity to study complex level schemes and measure lifetimes
- 8 experiments with neutron-rich beams in 2020/21
- transfer reactions to probe the valence space

launch a campaign to probe N $= 32 - 40$ nuclei

https://web-docs.gsi.de/~kwimmer/

Thanks to

the HiCARI core team

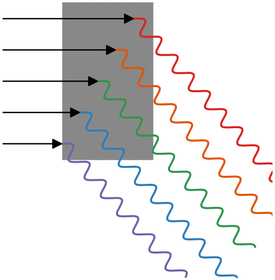
N. Aoi, H. Baba, F. Browne, C. Campbell, Z. Chen, H. Crawford, H. de Witte,
P. Doornenbal, C. Fransen, H. Hess, S. Iwazaki, J. Kim, A. Kohda, T. Koiwai, B. Mauss,
B. Moon, P. Reiter, D. Suzuki, N. Warr, K. Wimmer, Y. Yamamoto

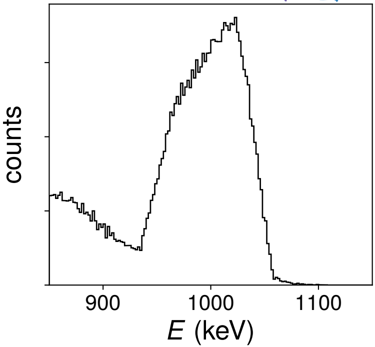
Funding by:
JSPS KAKENHI Grant Number JP19H00679
Ramón y Cajal RYC-2017-22007
ERC CoG 101001561-LISA

Thank you for your attention

Outlook: improving the resolution

- to access the most exotic nuclei thick targets have to be used (few mm or g/cm^2)
- reaction and emission at different velocities
- (angle dependent) spread in Doppler reconstructed spectrum
- different mean decay velocities and different depths in the target
- with an active target resolution can be greatly improved





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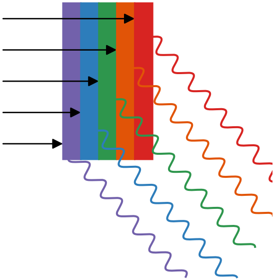

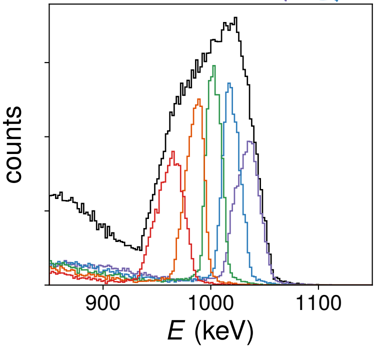

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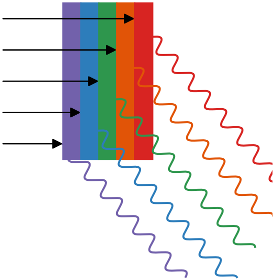

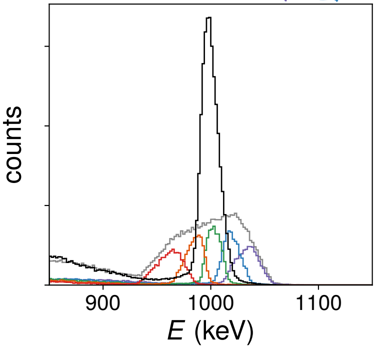

Outlook: improving the resolution

- to access the most exotic nuclei thick targets have to be used (few mm or g/cm^2)
- reaction and emission at different velocities
- (angle dependent) spread in Doppler reconstructed spectrum
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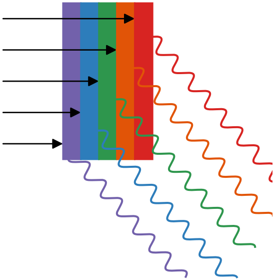
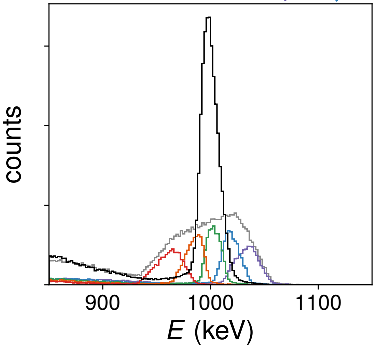


active targets have several advantages for in-beam spectroscopy:

- multiply statistics without sacrifice to resolution
- increased sensitivity for lifetime measurements



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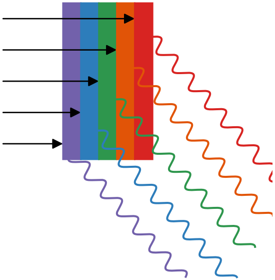

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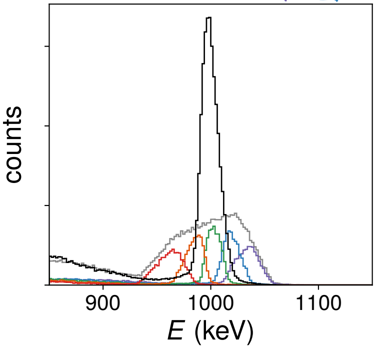
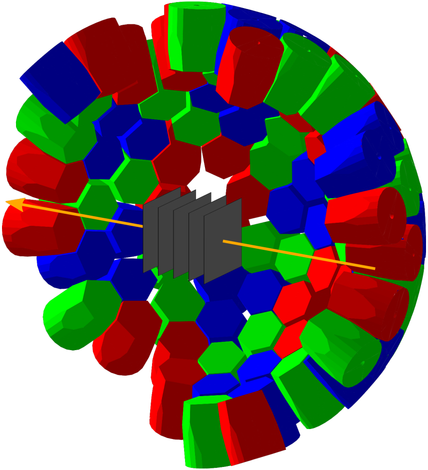


LIfetime measurements with Solid Active targets

Future of lifetime measurements: LISA

LIfetime measurements with Solid Active targets

- use active targets to determine reaction point and velocity
- improvement of in-beam resolution
- ideal for lifetime measurements



- combined with AGATA at FAIR
- lifetime range 1 - 1000 ps

LISA

looking for postdoc and PhD candidates

ERC CoG 101001561-LISA, k.wimmer@gsi.de
https://web-docs.gsi.de/~ kwimmer/

European Research Council
Established by the European Commission

Backup

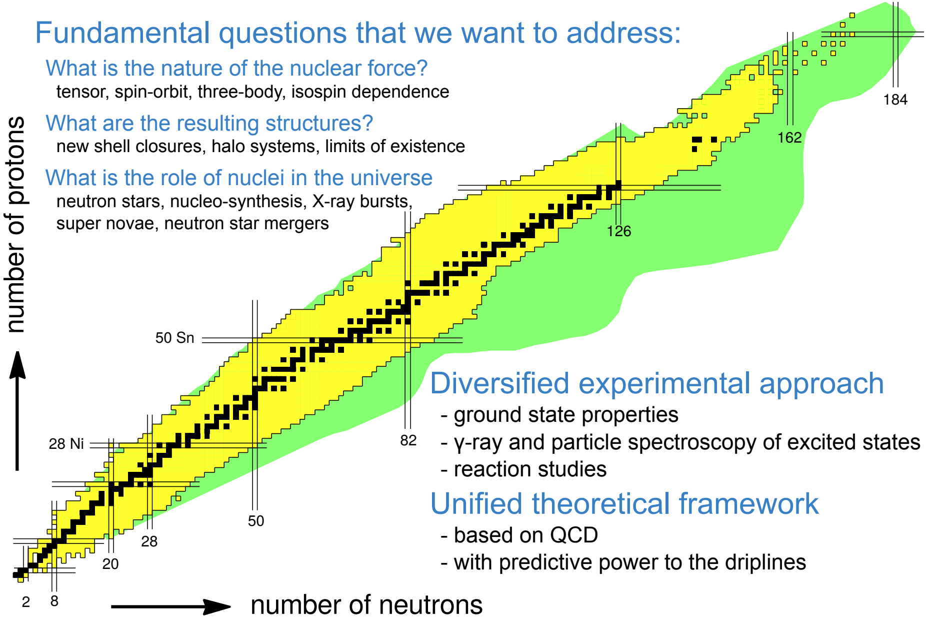
Nuclear structure at the extremes

Fundamental questions that we want to address:

What is the nature of the nuclear force?
tensor, spin-orbit, three-body, isospin dependence

What are the resulting structures?
new shell closures, halo systems, limits of existence

What is the role of nuclei in the universe
neutron stars, nucleo-synthesis, X-ray bursts, super novae, neutron star mergers



Diversified experimental approach
- ground state properties
- γ-ray and particle spectroscopy of excited states
- reaction studies

Unified theoretical framework
- based on QCD
- with predictive power to the driplines