Shape Coexistence at $N = Z$: In-beam γ-ray spectroscopy of ^{70}Kr at the RIBF

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6 July 2018

東京大学 THE UNIVERSITY OF TOKYO

Outline

1 Introduction and motivation

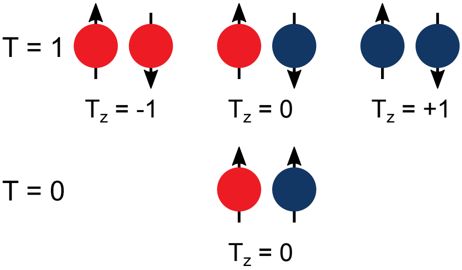
2 Spectroscopy of ^{70}Kr

3 Coulomb excitation of ^{72}Kr and ^{70}Kr

4 Perspectives for γ-ray spectroscopy at RIBF

Isospin symmetry

- neutron and proton: two representations of the nucleon with isospin $t_z = \pm 1/2$
- led to the concept of quarks as constituents



- two nucleon system in $T = 0$ and 1 channel: explains deuteron $J^{\pi} = 1^{+}$
- strong interaction independent of isospin or charge $V_{\mathrm{np}} = (V_{\mathrm{pp}} + V_{\mathrm{nn}})/2$
- symmetric under exchange of protons and neutrons $V_{\mathrm{pp}} = V_{\mathrm{nn}}$

- isospin symmetry:
  $\rightarrow$ spectra of mirror nuclei identical
- Coulomb interaction leads to differences
- $\rightarrow$ test isospin (in)dependence of the nuclear interaction

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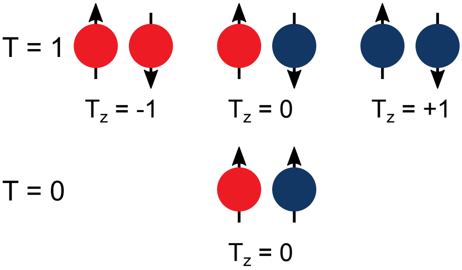

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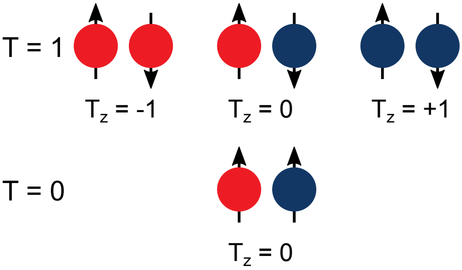

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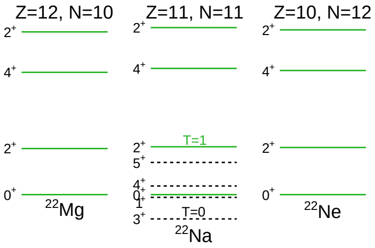
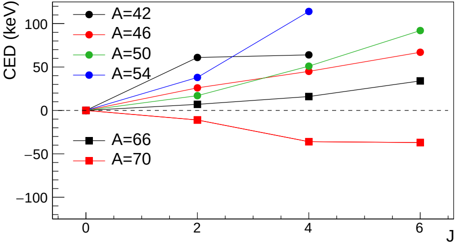


Isospin symmetry: anomaly at $A = 70$

- probing the charge symmetry and independence of the nuclear force
- Coulomb energy differences between $T = 1$ states:

$$\text{CED}(J^\pi) = E(J^\pi, T_z = 0) - E(J^\pi, T_z = 1)$$



G. de Angelis et al., Eur. Phys. Jour. A **12** (2001) 51,
B. S. Nara Singh et al., Phys. Rev. C **75** (2007) 061301

- CED rise as a function of spin in the *sd* and *fp* shell
- $A = 70$ isobars show anomalous Coulomb energy differences
- weakly bound: reduction of Coulomb repulsion due to spatial extension of proton wave function

- however, negative CED only occur in $A = 70$ isotones
- may be explained by a shape change between ^{70}Se and ^{70}Br
- $\rightarrow$ further lowering of yrast states for $T_z = -1$ nucleus ^{70}Kr expected

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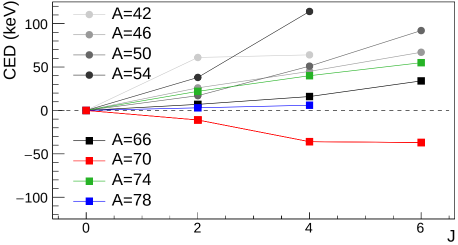

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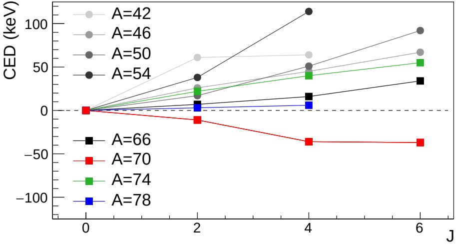

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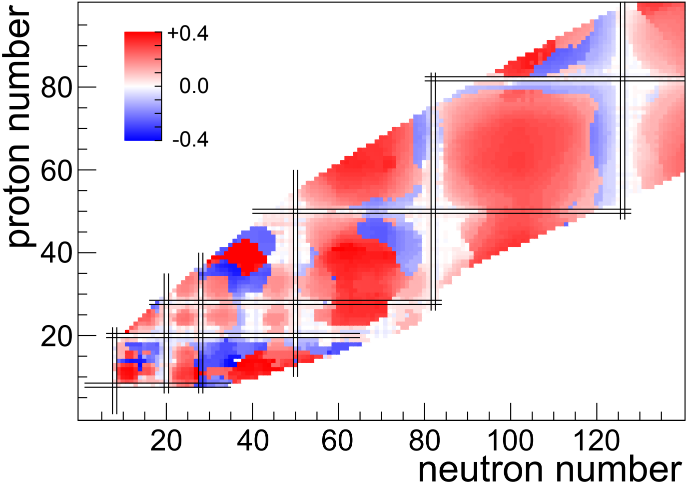
Predicted shapes of nuclei

- predicted deformation parameters using finite-range droplet macroscopic model



P. Möller et al., ADNDT **109** (2016) 1

- dramatic shape change around $N = Z$, $A \sim 70 - 80$

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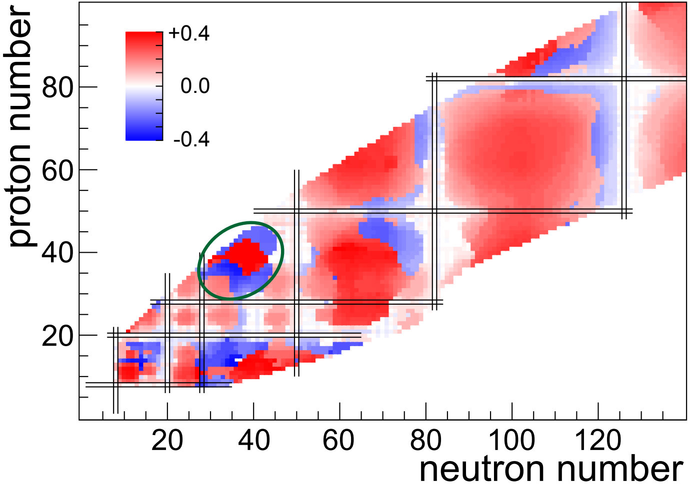

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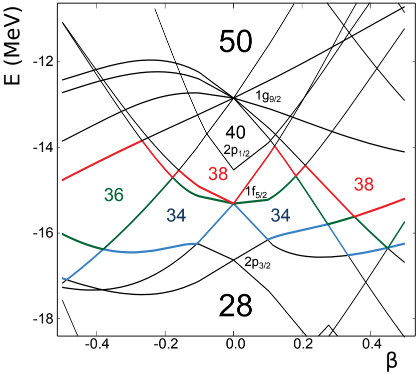
Shape coexistence at $A \sim 70$

Nilson plot:

- evolution of the gaps between $2p_{3/2}$, $1f_{5/2}$, $2p_{1/2}$, and $1g_{9/2}$ orbitals
- oblate (34, 36) and prolate (34, 38) minima along the Fermi surface
- variety of shapes can coexist at low excitation energy
- shape coexistence and shape transitions



experimental evidence from lifetime and low-energy Coulomb excitation experiments:

- krypton isotopes: prolate ground states up to ^{76}Kr, strongly mixed ^{74}Kr ($Z = 36, N = 38$)

A. Görgen et al., Eur. Phys. Jour. A **26** (2005) 153, E. Clément et al. Phys. Rev. C **75** (2007) 054313

- the ground state of ^{70}Se ($Z = 34, N = 36$) is oblate deformed

A. M. Hurst et al., Phys. Rev. Lett. **98** (2007) 072501, J. Ljungvall et al., Phys. Rev. Lett. **100** (2008) 102502

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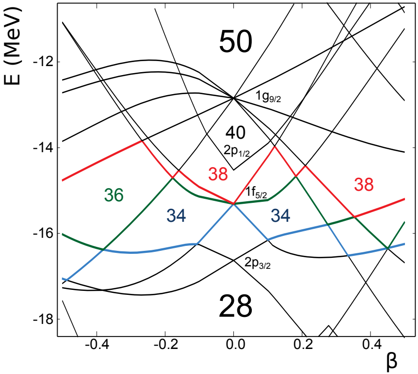

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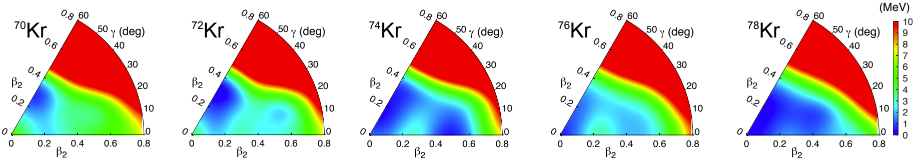
Shape coexistence in Kr isotopes

- proton-rich Kr isotopes show a variety of shapes
- self-consistent beyond mean-field calculations of potential energy surface



T. R. Rodríguez, Phys. Rev. C **90** (2014) 034306

- spherical for ^{78,80}Kr, prolate coexisting minimum appears in ^{76}Kr
- strong prolate - oblate shape mixing in ^{74}Kr

A. Görgen et al., Eur. Phys. Jour. A **26** (2005) 153, E. Clément et al. Phys. Rev. C **75** (2007) 054313

- Coulomb excitation and lifetime measurements in ^{72}Kr:
  oblate ground state and rapid oblate - prolate transition with increasing spin

A. Gade et al., Phys. Rev. Lett. **95** (2005) 022502, H. Iwasaki et al., Phys. Rev. Lett. **112** (2014) 142502

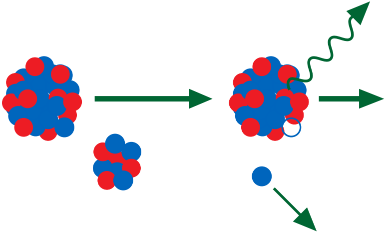
- excited 0^+ state in ^{72}Kr with large $\rho(E0)$: large difference in deformation

E. Bouchez et al., Phys. Rev. Lett. **90** (2003) 082502

- prediction for ^{70}Kr: oblate deformed, but γ-soft
  $\rightarrow$ spectroscopy and Coulomb excitation of ^{70}Kr

Experimental method

- study ^{70}Kr by knockout reactions and Coulomb excitation at RIBF
- peripheral collision probe the surface of the nucleus



- remove one nucleon in the collision with a light target
- single-particle properties

- excitation in the electro-magnetic field of a high Z target
- collective properties

- γ-ray emission from excited states detected in DALI2
- ZeroDegree spectrometer for the ejectile identification

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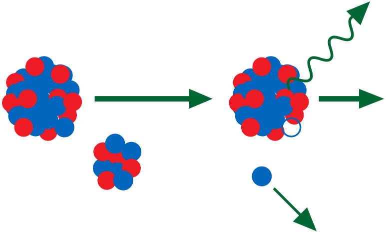

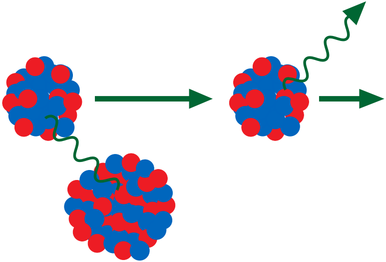

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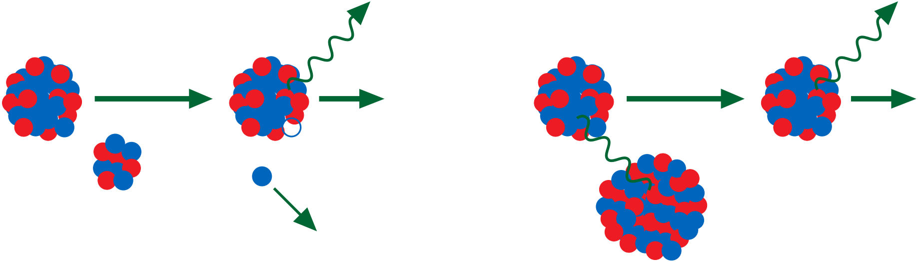

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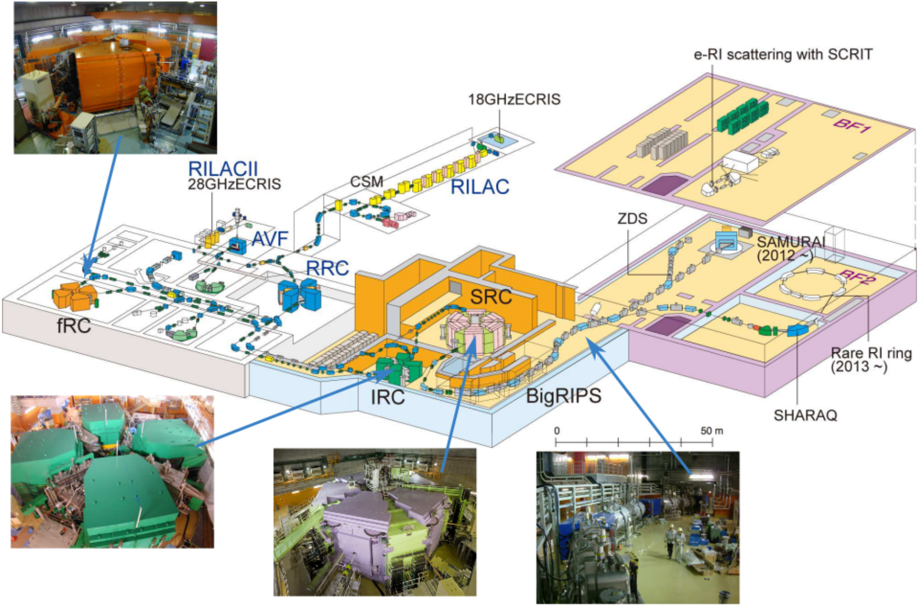
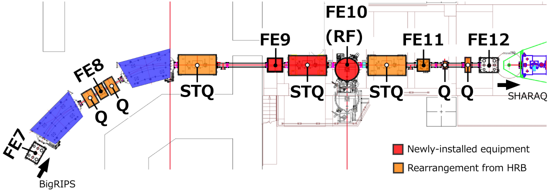
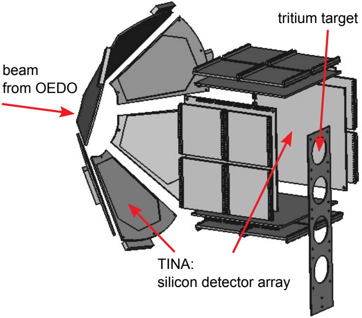
The Radioactive Isotope Beam Factory



OEDO and transfer reactions

- Optimized Energy Degrading Optics: monochromatic energy degrader and RF deflector for refocusing
- beam energies 10 - 50 MeV/u





TINA:
A Si/CsI Setup for Light Recoiling Particles from Transfer (and other) Reactions

P. Schrock, K. Wimmer, D. Suzuki, N. Imai et al.

- used in two experiments, Kyushu Tandem and at OEDO
- development of a tritium target

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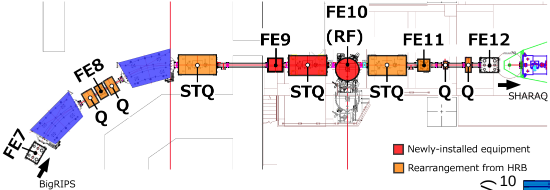

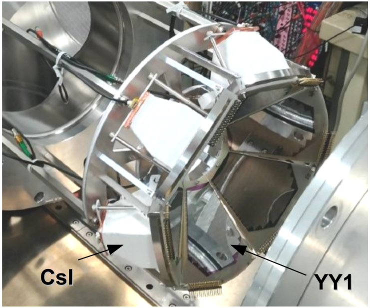

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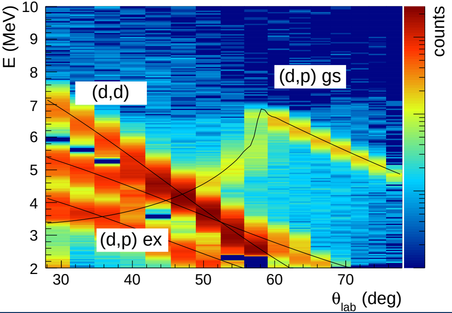
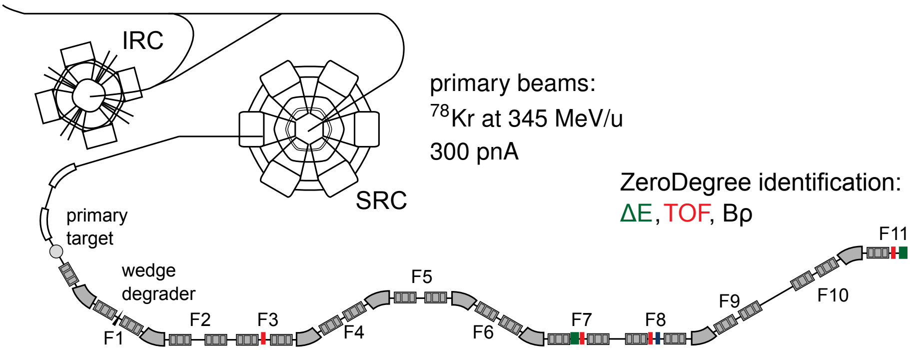


Experimental setup



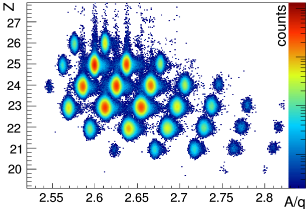
primary beams:
^{78}Kr at 345 MeV/u
300 pnA

ZeroDegree identification:
ΔE, TOF, Bρ

BigRIPS identification by:
ΔE, TOF, Bρ

secondary target
surrounded by DALI2

- fragmentation of ^{78}Kr primary beam
- two beam settings, centered on ^{72}Kr and ^{70,71}Kr
- DALI2 NaI array for γ-ray detection
- PPACs for scattering angle reconstruction



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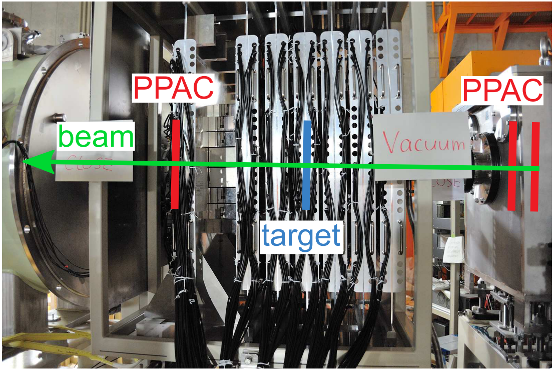
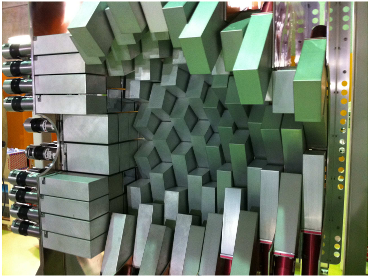
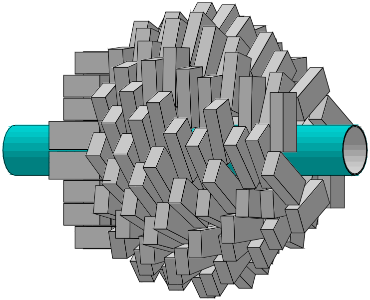




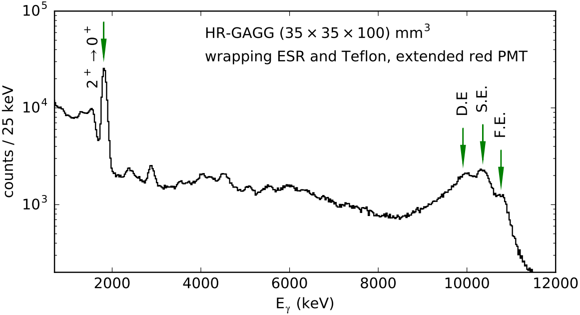


- 186 NaI(Tl) detectors
- intrinsic resolution 7 % at 1 MeV
- low in-beam resolution ∼ 10 %
- high efficiency ∼ 25 % at 1 MeV
- suitable for spectroscopy at the limits

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

Future γ-ray spectroscopy at RIBF

- new scintillator material GAGG
  $Ce:Gd_3Ga_3Al_2O_{12}$
  Gadolinium-Aluminum-Gallium-Garnet
- density $\rho = 6.63$ g/cm^3
- non hygroscopic, easy to handle, no dead material (except for ESR foil)
- first large volume detectors,
  $35 \times 35 \times 100$ mm^3 HR-GAGG



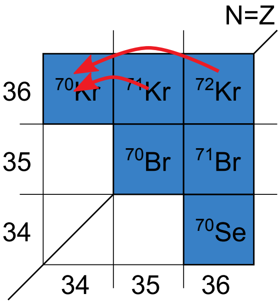
- detector test at RIKEN Pelletron laboratory (June 2018)
- $^{27}Al(p,\gamma)$ reaction excites 12.5 MeV state in ^{28}Si
- collaboration U Tokyo and RIKEN

T. Amano, N. Ogawa, R. Yamada, T. Ikeda, T. Koiwai, M. Niikura, H. Sakurai, K.Wimmer, University of Tokyo

Spectroscopy and Coulomb excitation of ^{70}Kr

Spectroscopy of ^{70}Kr

- inelastic scattering of ^{70}Kr on Be target
- one-neutron removal reaction from ^{71}Kr
- two-neutron removal from ^{72}Kr
- analogue reactions to ^{70}Se
- comparison of spectra and exclusive cross sections
- particle identification for ^{70,71}Kr on Be target



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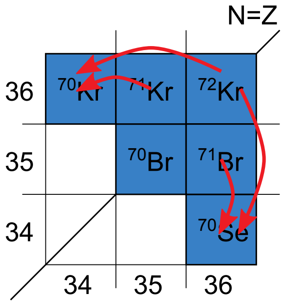

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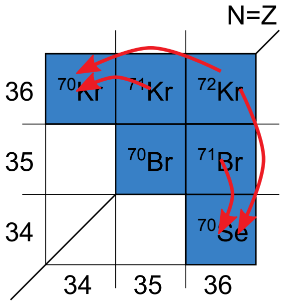

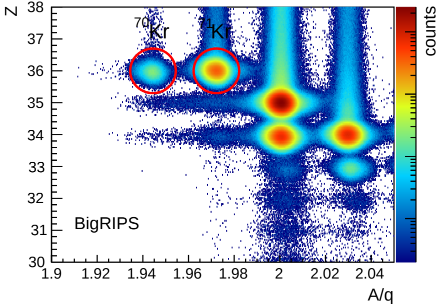

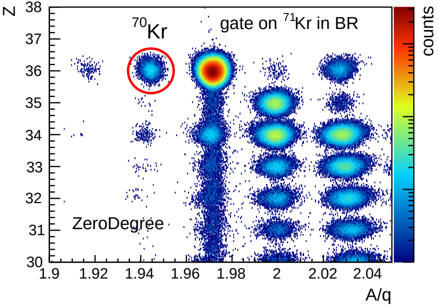

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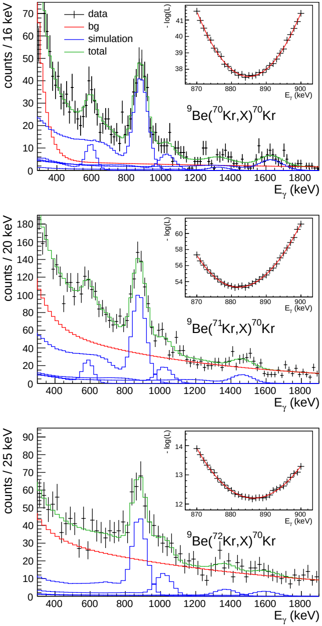
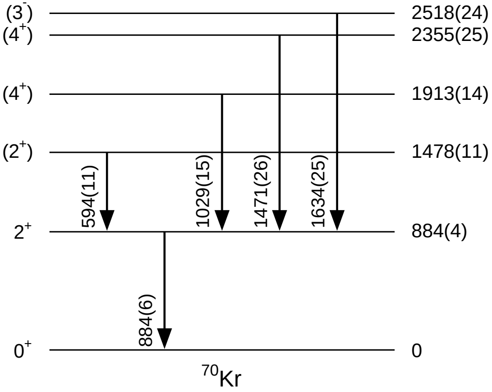
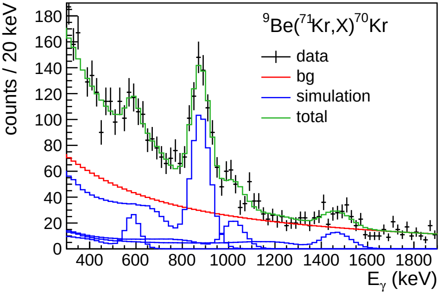


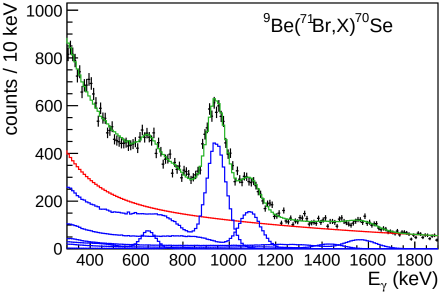
- inelastic scattering of ^{70}Kr on Be target
- one-neutron removal reaction from ^{71}Kr
- two-neutron removal from ^{72}Kr
- likely-hood fit to obtain γ-ray transitions energies



K. Wimmer et al., Phys. Lett B (2018) accepted

Comparison of analogue reactions

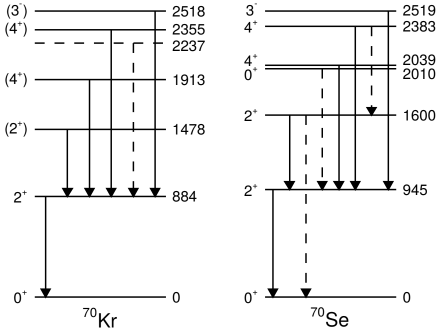




- population of the known 2^+_1, 2^+_2, 4^+_1, and (3^-_1) states in ^{70}Se with similar intensity
- assignment of (2^+_2) and (4^+_1)
- $\gamma - \gamma$ coincidences
- (3^-) state populated in inelastic scattering in all $A = 70$ nuclei

first spectroscopy of ^{70}Kr

K. Wimmer et al., Phys. Lett B (2018) accepted



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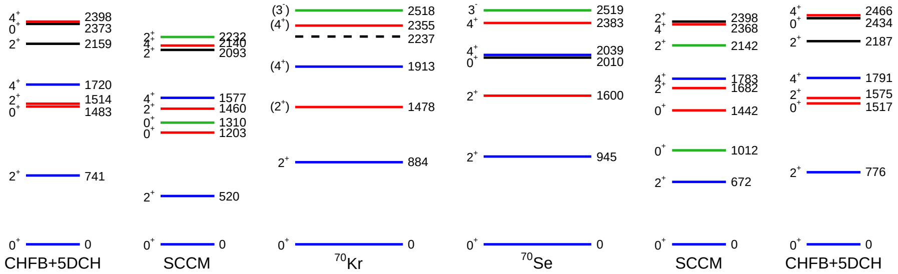
Shape coexistence in ^{70}Kr



- beyond mean-field Hartree-Fock-Bogoliubov calculations mapped on a five-dimensional collective Hamiltonian (CHFB-5DCH)

J. P. Delaroche, et al., Phys. Rev. C **81** (2010) 014303

- symmetry-conserving configuration-mixing calculations based on Gogny D1S: axial - oblate yrast band, but prolate - triaxial excited band

T. R. Rodríguez, Phys. Rev. C **90** (2014) 034306

- experimentally, there is no constraint on the shape from the present data
- in-beam spectroscopy is the only way to study this nucleus
- measurements of quadrupole moments are beyond the reach of even the next generation radioactive beam facilities

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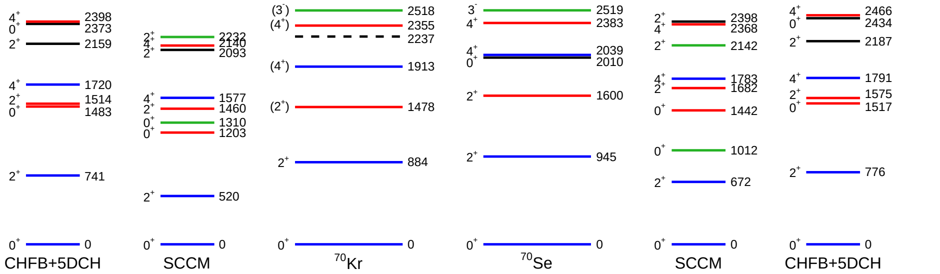
Shape coexistence in ^{70}Kr



- beyond mean-field Hartree-Fock-Bogoliubov calculations mapped on a five-dimensional collective Hamiltonian (CHFB-5DCH)

J. P. Delaroche, et al., Phys. Rev. C **81** (2010) 014303

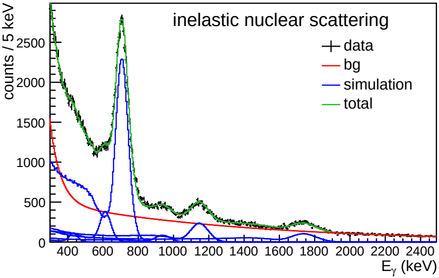
- symmetry-conserving configuration-mixing calculations based on Gogny D1S: axial - oblate yrast band, but prolate - triaxial excited band

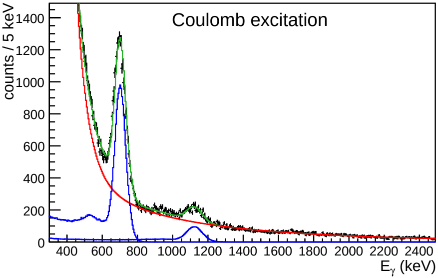
T. R. Rodríguez, Phys. Rev. C **90** (2014) 034306

- experimentally, there is no constraint on the shape from the present data
- in-beam spectroscopy is the only way to study this nucleus
- measurements of quadrupole moments are beyond the reach of even the next generation radioactive beam facilities

Collective properties

- nuclear inelastic scattering and Coulomb excitation of ^{70}Kr
- high statistics run for ^{72}Kr to test the analysis
- high-spin ^{72}Kr level scheme well known from fusion evaporation reactions
  N. S. Kelsall et al., Phys. Rev. C **64** (2001) 024309, S. M. Fisher et al., Phys. Rev. C **67** (2003) 064318
- excited states in ^{72}Kr populated in inelastic scattering off Be and Au targets

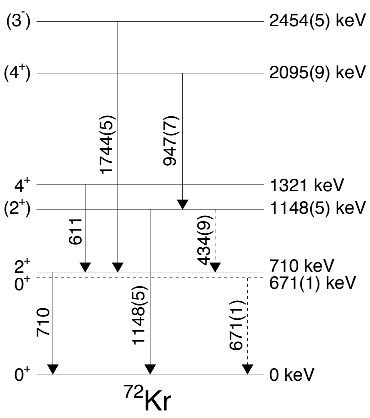


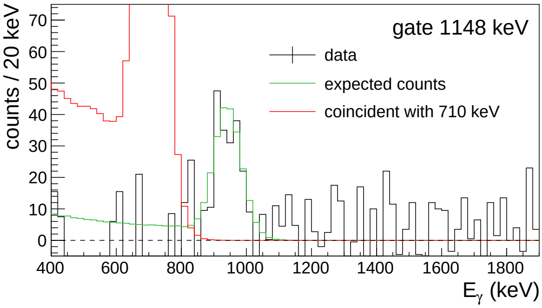


- populated known 2^+ and 4^+ states
- four new transitions in the nuclear scattering
- 1148(5) keV transition also in Coulomb excitation $\rightarrow$ 2^+ state

Extended spectroscopy of ^{72}Kr

- placing new transition into the level scheme
- coincidence analysis, comparison with the expected number of counts





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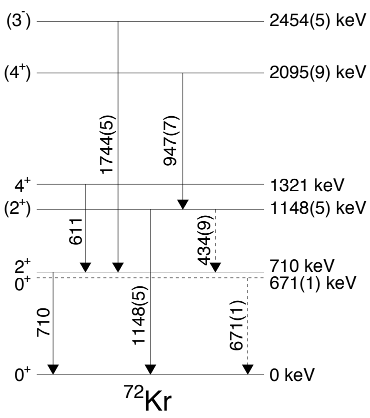

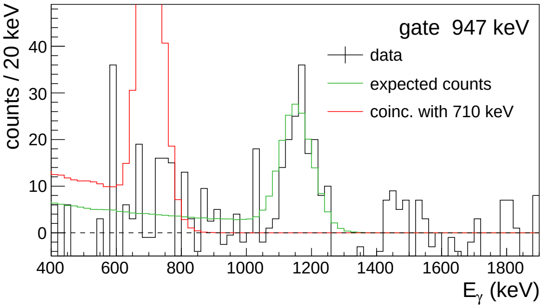

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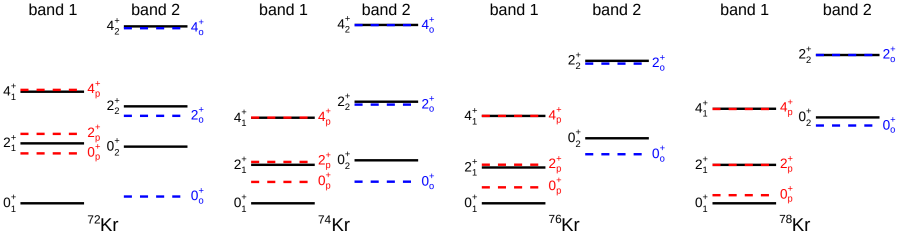
Band mixing model

- mixing of prolate and oblate bands
- obtain unperturbed energies from Harris extrapolation assuming a smooth evolution of the moment of inertia

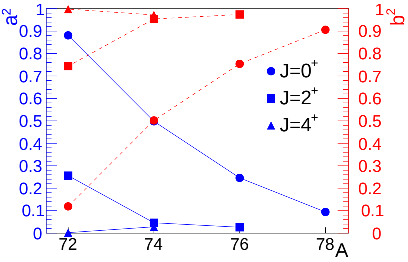


- transition from prolate to oblate 0^+_{gs}

F. Becker et al, Eur. Phys. Jour. A **4** 103,
E. Bouchez et al., Phys. Rev. Lett. **90** (2003) 082502

- rapid transition towards more prolate shapes with increasing spin
- consistent with $B(E2; 4^+_1 \rightarrow 2^+_1)$

H. Iwasaki et al., Phys. Rev. Lett. **112** (2014) 142502



shape change along the yrast band

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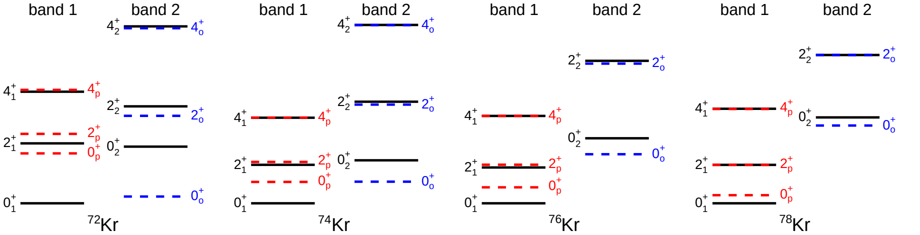

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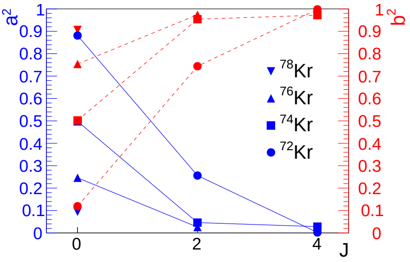
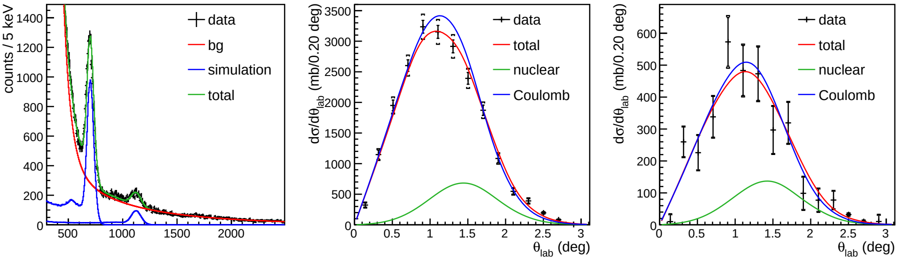


shape change along the yrast band

Coulomb excitation of ^{72}Kr



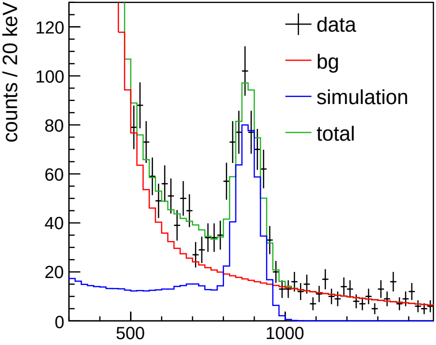
- second 2^+ state observed in Be and Au target inelastic scattering
- nuclear deformation length and *E*2 matrix elements obtained from comparison with FRESCO (DWCC) calculations
- angular distribution well reproduced

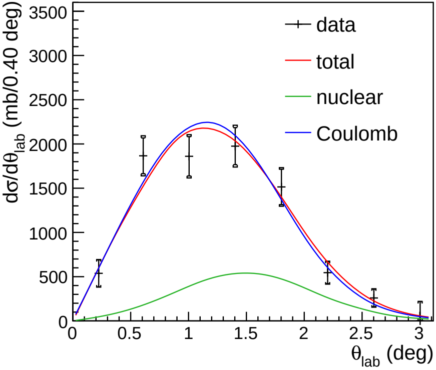
state	β_n	β_C	$B(E2\uparrow)$ (e^2fm^4) this	$B(E2\uparrow)$ (e^2fm^4) prev.
2_1^+	0.30(1)	0.30(1)	$4000(250)_{stat.}$	4997(647)
				4050(750)
2_2^+	0.10(1)	0.11(1)	$555(65)_{stat.}$	-

A. Gade et al., Phys. Rev. Lett. **95** (2005) 022502, H. Iwasaki et al., Phys. Rev. Lett. **112** (2014) 142502

- agreement with previous experiments, validation of the analysis (also for ^{68}Se)

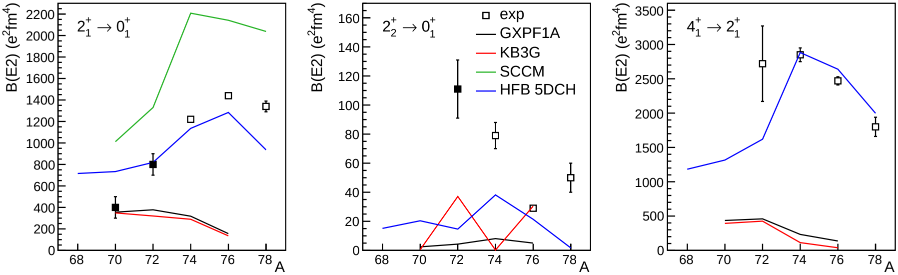
Coulomb excitation of ^{70}Kr





- nuclear deformation length from Be target data $\beta_n = 0.20(2)$
- $E2$ matrix elements obtained from comparison with FRESCO (DWCC) calculations
- feeding corrections estimated from ^{72}Kr and ^{68}Se
- preliminary result: $B(\mathrm{E2}\uparrow) = 2000(250)_{\mathrm{stat.}}$ e^{2}fm^4 or $\beta_C = 0.21(1)$

Evolution along the Kr isotopes



- comparison to several theoretical models for the proton-rich Kr isotopes

H. Iwasaki et al., Phys. Rev. Lett. **112** (2014) 142502,
E. Clement et al., Phys. Rev. C **75** (2007) 054313, F. Becker et al., Nucl. Phys. A **770** (2006) 107

- HFB calculations with the Gogny D1S interaction reproduce the trend and magnitude of $B(E2;\ 2_1^+ \to 0_1^+)$ and $B(E2;\ 4_1^+ \to 2_1^+)$ values

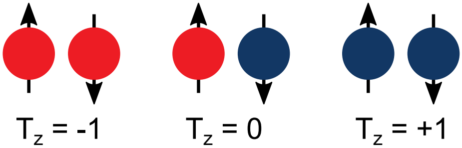
J. P. Delaroche et al., Phys. Rev. C **81** (2010) 014303

- symmetry-conserving configuration mixing (SCCM) method over-estimate $B(E2;\ 2_1^+ \to 0_1^+)$

T. R. Rodríguez, Phys. Rev. C **90** (2014) 034306

- shell model calculations predict too low collectivity

Isospin symmetry



alternative way to test isospin symmetry:

- determine multipole matrix elements from measured $B(\mathrm{E2})$ values

$$B(\mathrm{E2};\, J_\mathrm{i} \rightarrow J_\mathrm{f}) = \frac{e^2 M_\mathrm{p}^2}{2J_\mathrm{i}+1}$$

- in isospin representation:

$$M_{\mathrm{n/p}} = \frac{1}{2}\left(M_0(T_z) \pm M_1(T_z)\right)$$

- in $T = 1$ triplets the proton multipole matrix elements test isospin symmetry

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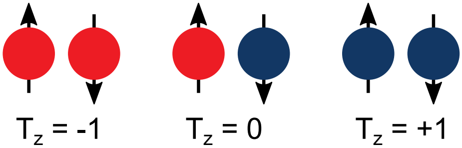

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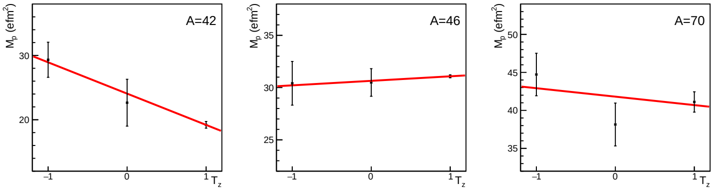
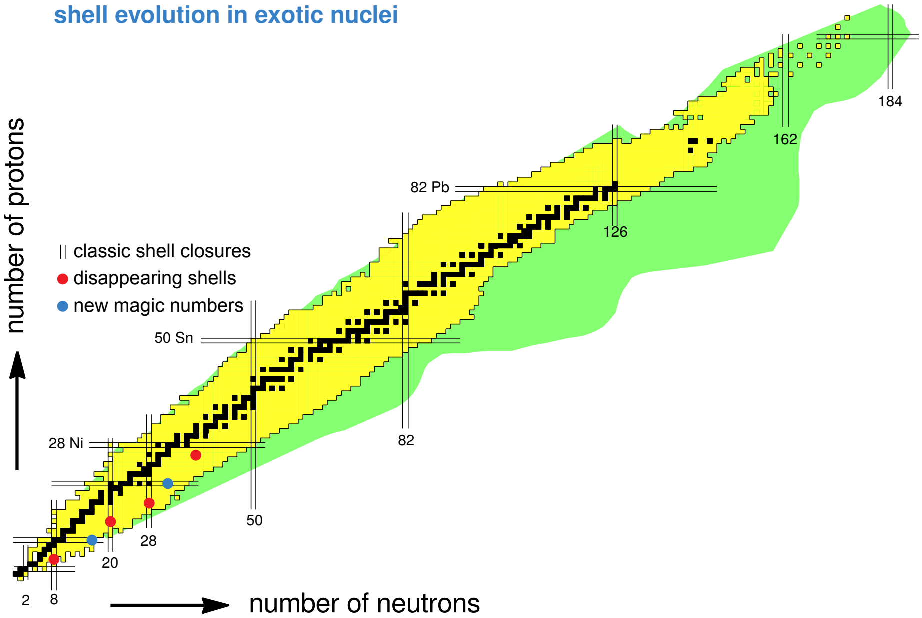


- systematic uncertainties from different measurements using different techniques
- new experiment approved to study $A = 62$ and 66

Outlook

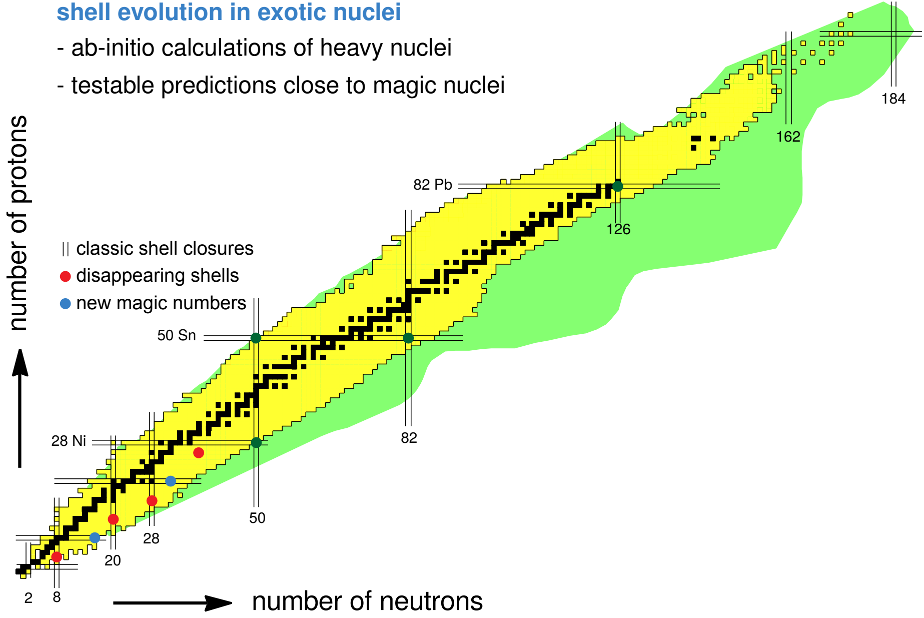
shell evolution in exotic nuclei



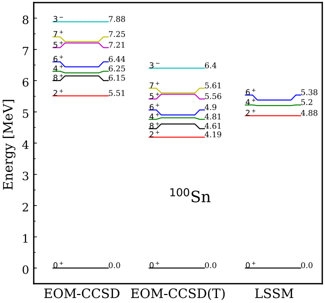
Outlook

shell evolution in exotic nuclei

- ab-initio calculations of heavy nuclei
- testable predictions close to magic nuclei



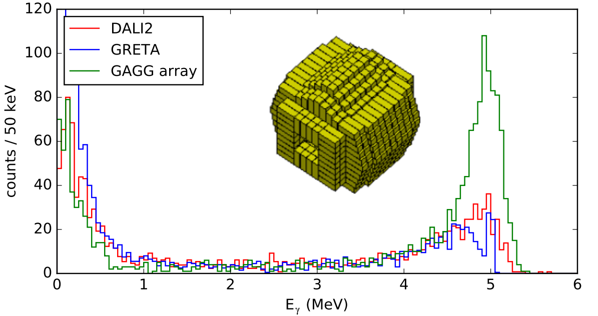
Spectroscopy of ^{100}Sn



- ^{100}Sn heaviest self-conjugate nucleus
- $N = Z = 50$ predicted doubly magic
- prediction of the 2^+ excitation energy

T. D. Morris et al., Phys. Rev. Lett. **120** (2018) 152503

- only possible at the RIBF
- simulations for existing γ-ray spectrometers



- GAGG offers highest peak-to-total and resolving power

new detectors required for the spectroscopy of exotic nuclei

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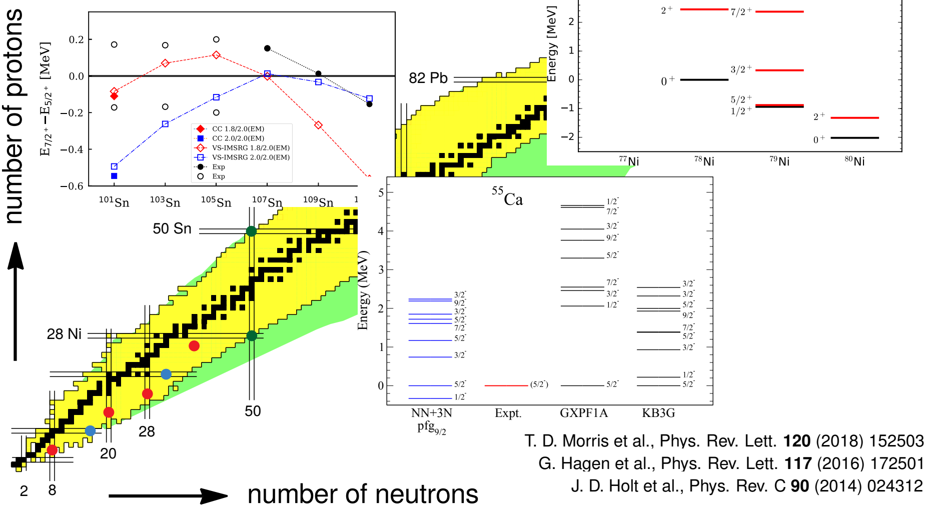

T. D. Morris et al., Phys. Rev. Lett. **120** (2018) 152503
G. Hagen et al., Phys. Rev. Lett. **117** (2016) 172501
J. D. Holt et al., Phys. Rev. C **90** (2014) 024312

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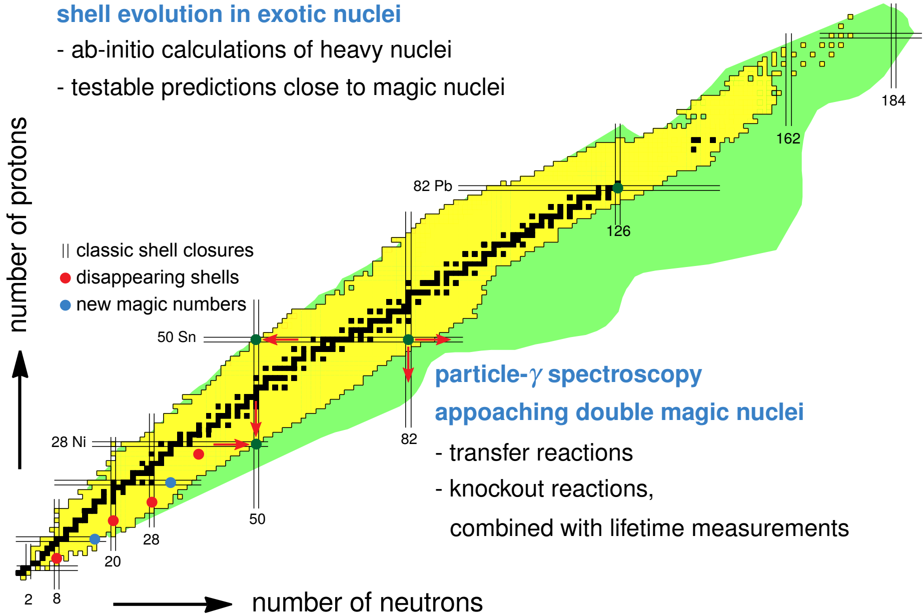

particle-γ spectroscopy

appoaching double magic nuclei

- transfer reactions
- knockout reactions,

  combined with lifetime measurements

Spectroscopy of odd nuclei

- require good energy resolution
- GAGG array in the forward wall configuration
- coupling to high-resolution Ge arrays (GRAPE, CAGRA, AGATA, GRETA)
- and multiple active diamond target for lifetime measurements

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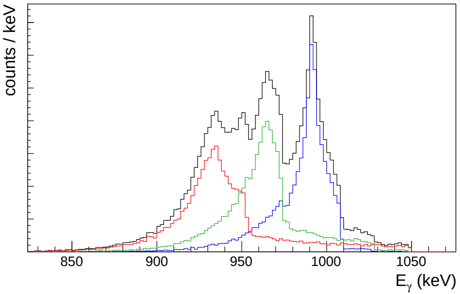

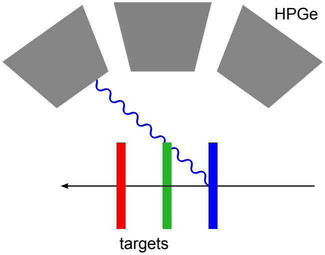

- reactions in different targets overlap
- knowing which target induced the reaction allows for multiplying the statistics
- measurement at different beam energies simultaneously
- sensitive to a large range of lifetimes

Summary

- very high beam intensities at RIBF allow for studies at the driplines
- investigate isospin symmetry and shape transitions around ^{70}Kr
- extended spectroscopy of ^{72}Kr:
  $\rightarrow$ rapid transition to prolate deformation in the ground state band
- first unambiguous spectroscopy of ^{70}Kr:
  second structure identified, 2_2^+ and 4_2^+
  $\rightarrow$ no evidence for shape change between Se and Kr
- Coulomb excitation of ^{72}Kr: second, less deformed (prolate) 2^+
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- HFB-5DCH calculations predict energies and $B(E2)$ values well
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Collaboration

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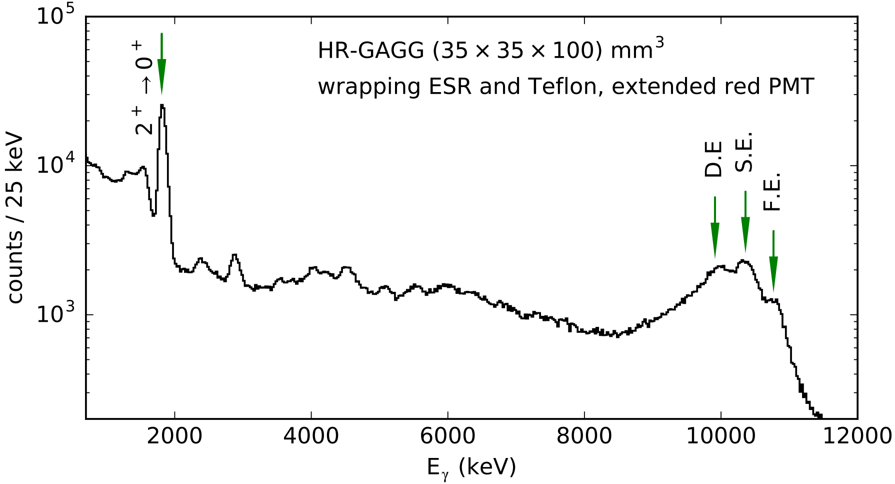
U Tokyo, RIKEN, CEA Saclay, GSI, U Giessen, CCEN, U Valencia, U Bordeaux, INFN Padova, U York, INFN Legnaro, GANIL, TU München, U Olso

Thank you for your attention

Backup

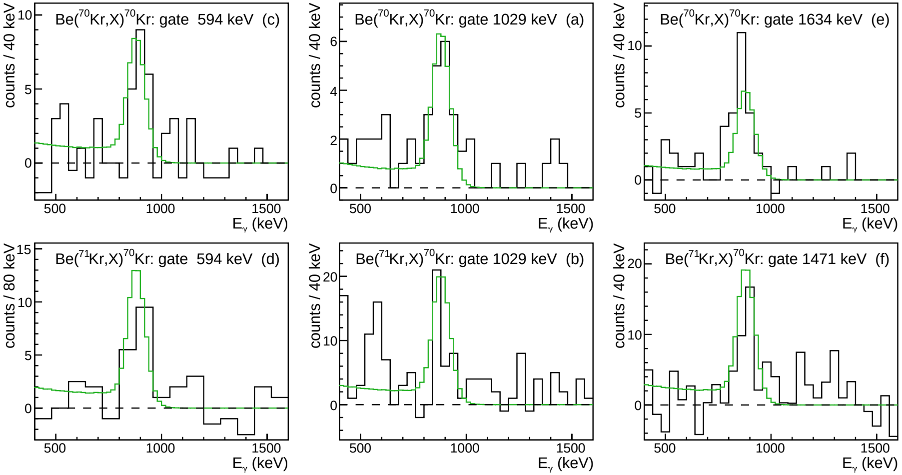
High energy response of GAGG

- $^{27}Al(p,\gamma)$ reaction excites 12.5 MeV state in ^{28}Si
- detector test at RIKEN Pelletron laboratory (June 2018)
- large volume HR-GAGG, wrapping ESR and Teflon, extended red PMT



T. Amano, N. Ogawa, R. Yamada, T. Ikeda, T. Koiwai, M. Niikura, H. Sakurai, K.Wimmer, University of Tokyo

Coincidence spectroscopy of ^{70}Kr



- all transitions built on the 2^+ state

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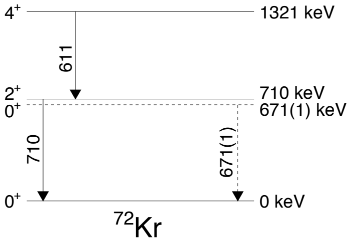

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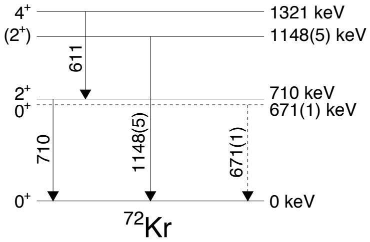

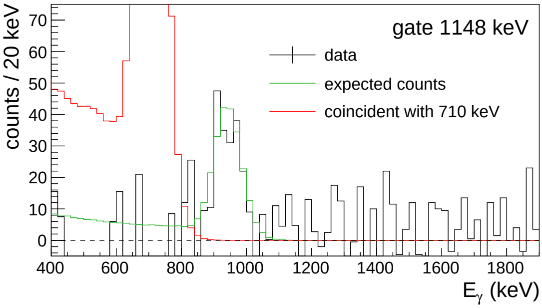

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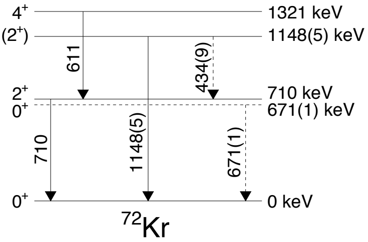

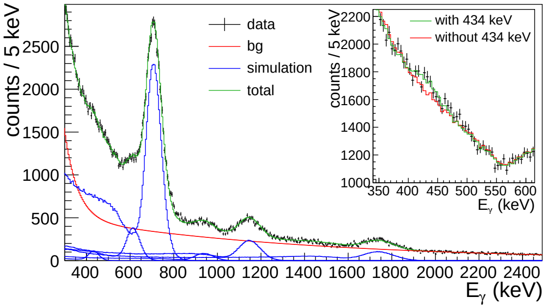

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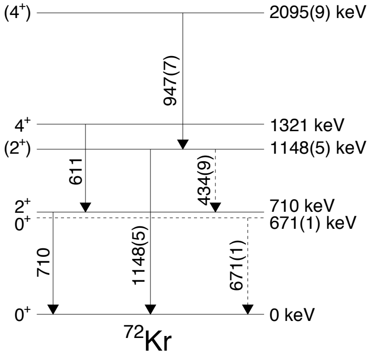

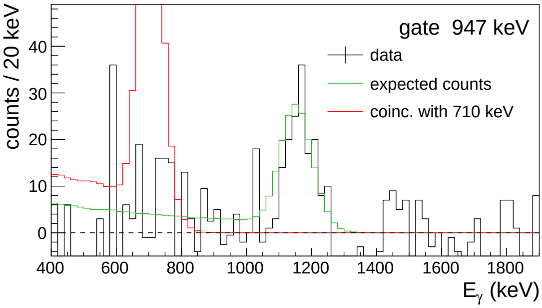

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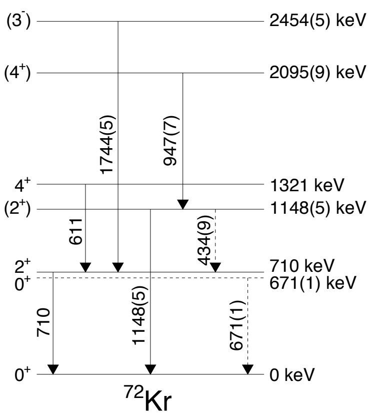

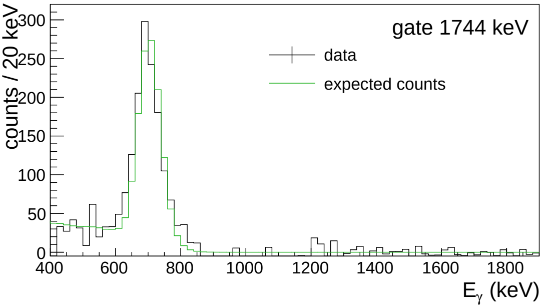

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Future plans:

Lifetime measurements for excited states in exotic nuclei

Lifetime measurements

- Coulomb excitation of exotic (and stable) nuclei has uncertainties and model dependence ($\sigma \leftrightarrow \delta/\beta \leftrightarrow B(E2)$)
- with fast and intermediate beam energies access only to (yrast) 2^+ states
- low-energy (safe) Coulomb excitation needs large beam intensities

$\rightarrow$ lifetime measurements

- no model dependence, access to all states
- rely difference in Doppler-correction as position and velocity at emission point are different from the reaction point

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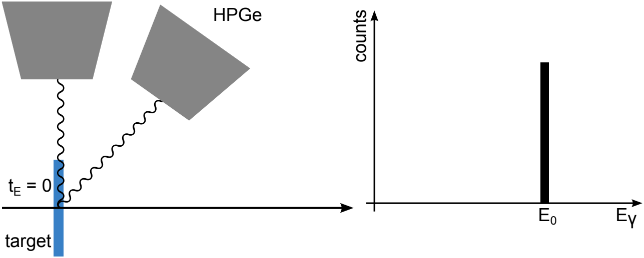

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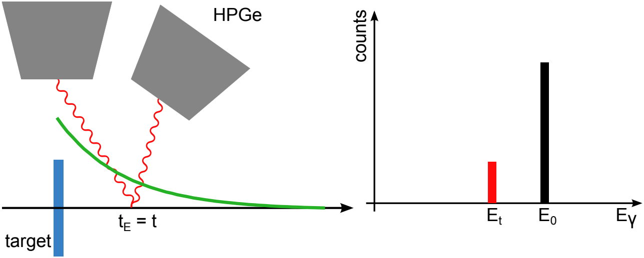
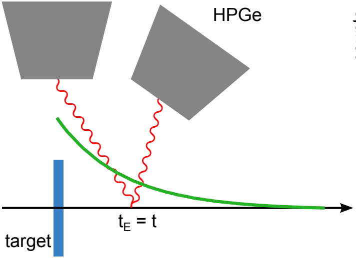


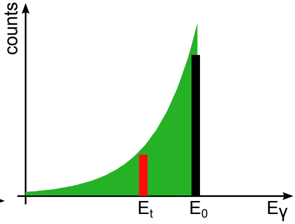
Lifetime measurements

- Coulomb excitation of exotic (and stable) nuclei has uncertainties and model dependence ($\sigma \leftrightarrow \delta/\beta \leftrightarrow B(E2)$)
- with fast and intermediate beam energies access only to (yrast) 2^+ states
- low-energy (safe) Coulomb excitation needs large beam intensities

$\rightarrow$ lifetime measurements

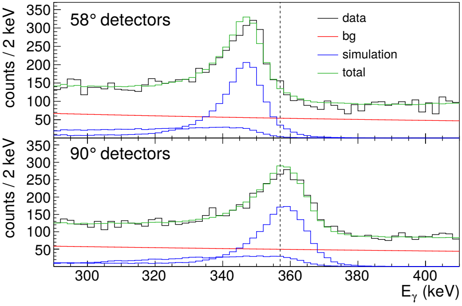
- no model dependence, access to all states
- rely difference in Doppler-correction as position and velocity at emission point are different from the reaction point



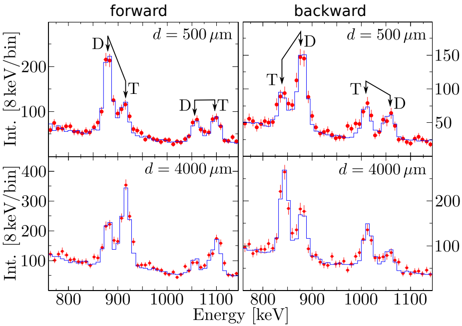


Lifetime measurements

- lineshape method: decay in flight after the target
  $\rightarrow$ shift in peak position (short lifetimes) and shape (long lifetimes)
- plunger method: add a degrader to change the ejectile velocity
  $\rightarrow$ two peaks intensity varies with distance



K. Wimmer et al., NSCL experiment

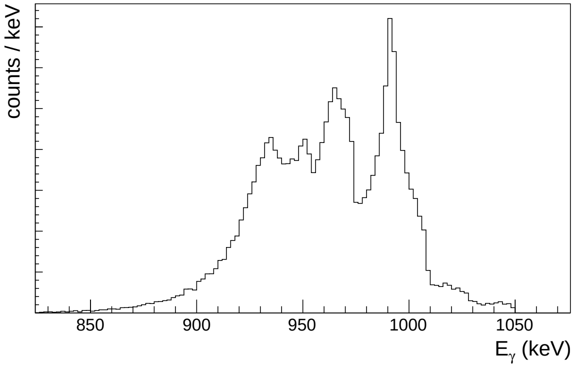


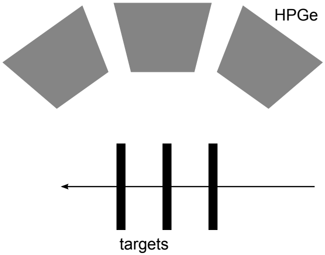
T. Braunroth et al., Phys. Rev. C **92** (2015) 034306

- plunger method very precise, but systematic uncertainties related to reactions in the degrader
- thin targets $\rightarrow$ high beam intensity

Improving the method

- multiple target to increase the luminosity
- 200 MeV/u, ^{128}Pd, 1 MeV, 50 ps, 3 $\times$ 100 mg/cm^2 C targets, distance 10 mm
- Doppler correction assuming β and z of first target





- reactions in different targets overlap
- knowing which target induced the reaction allows for multiplying the statistics
- measurement at different beam energies simultaneously

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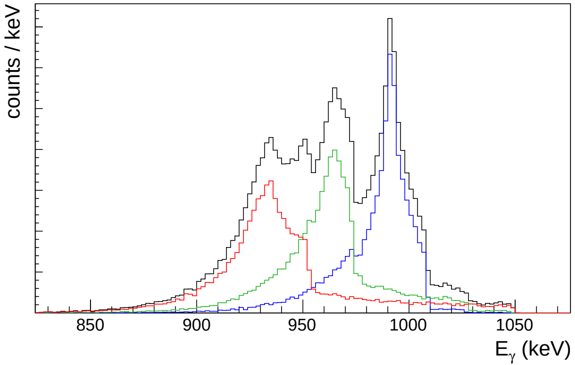

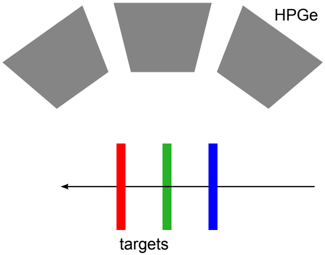

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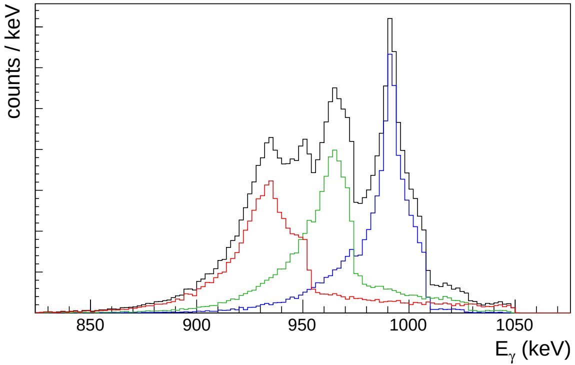

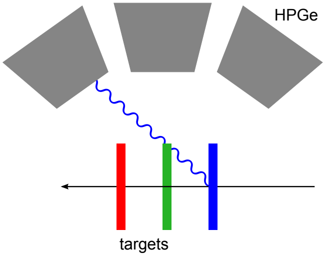

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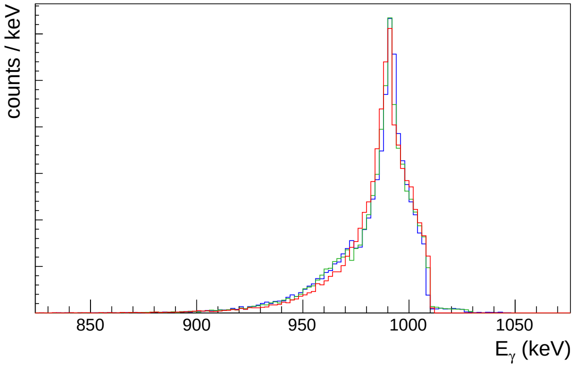

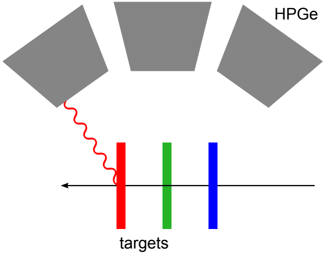

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Multiple targets, Doppler correction

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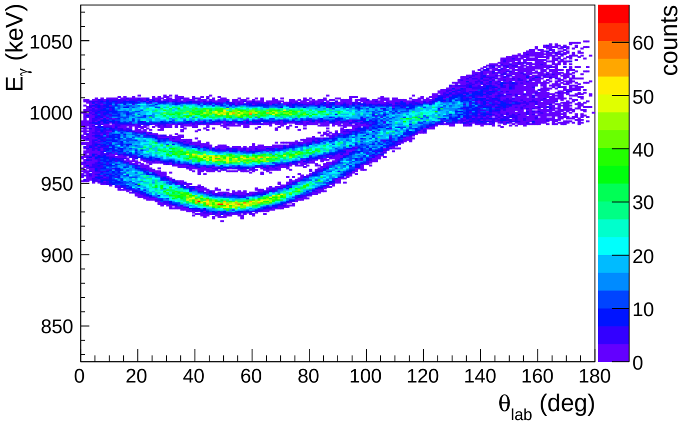
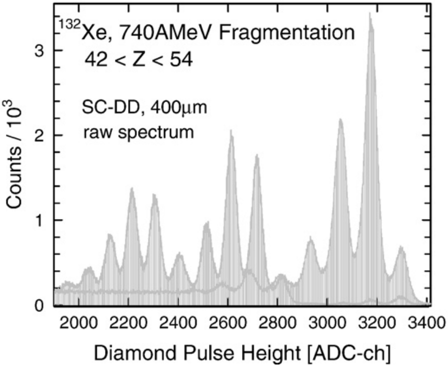
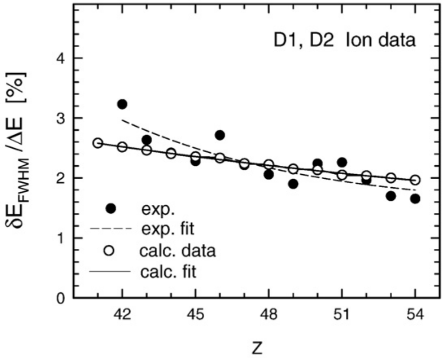


Active targets

- proton knockout, change in $Z \rightarrow$ different energy loss
- measure energy loss in each target $\rightarrow$ reaction position
- required resolution $\sim$ %



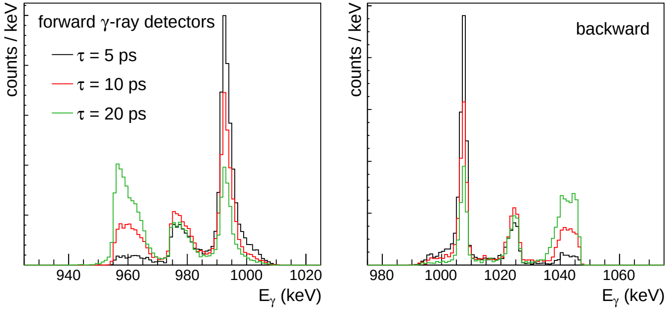


E. Berdermann et al., Diamond and Related Materials **17** (2008) 1159

$\rightarrow$ seems possible

Plunger mode

- Differential recoil distance method
- 200 MeV/u, ^{128}Pd, 1 MeV, 3 $\times$ 100 mg/cm^2 C targets, distance 1 mm
- Doppler correction assuming β and z of first target



- ratio of counts in target and degrader gives lifetime without changing distances

P. Bednarczyk et al., Acta. Phys. Pol. B. **41** (2010) 505,
H. Iwasaki et al., Nucl. Instr. Meth. **806** (2016) 123

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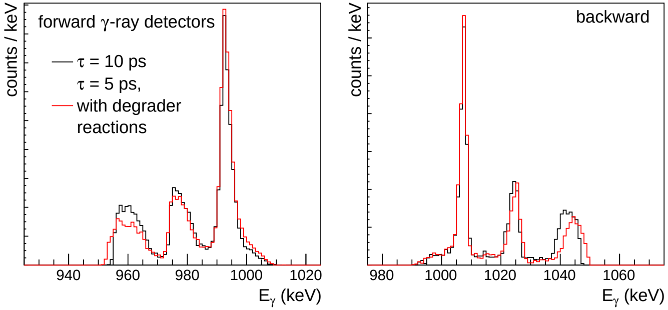

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