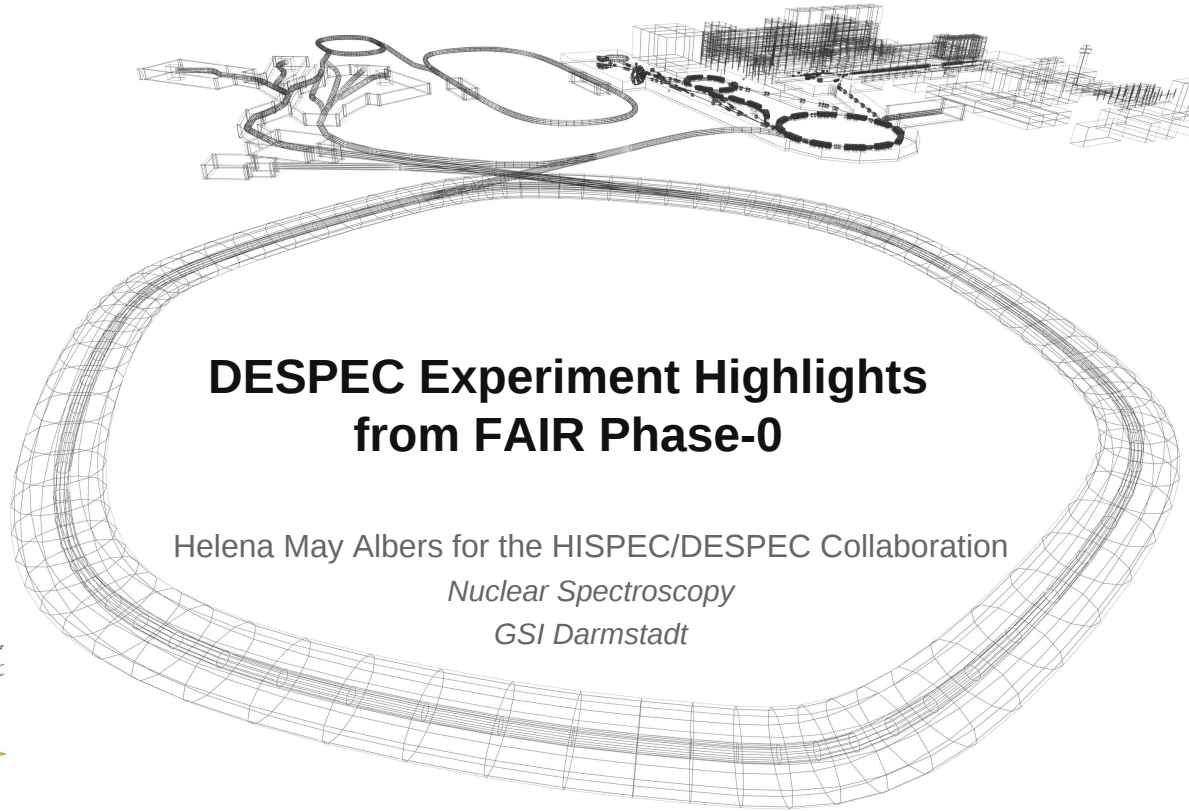
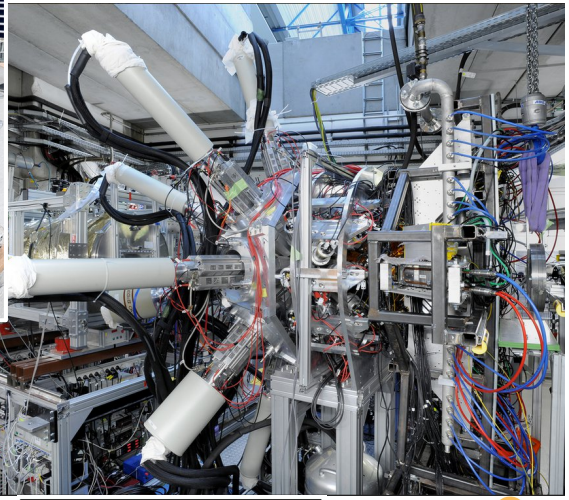


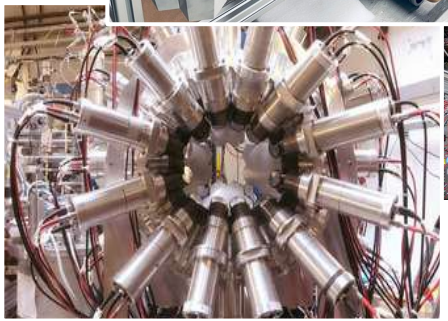
DESPEC Experiment Highlights from FAIR Phase-0

Helena May Albers for the HISPEC/DESPEC Collaboration
Nuclear Spectroscopy
GSI Darmstadt

Outline

- Introduction to DESPEC and FAIR
- Experimental setups
- Physics highlights
- Upcoming plans





Outline

- **Introduction to DESPEC and FAIR**
- Experimental setups
- Physics highlights
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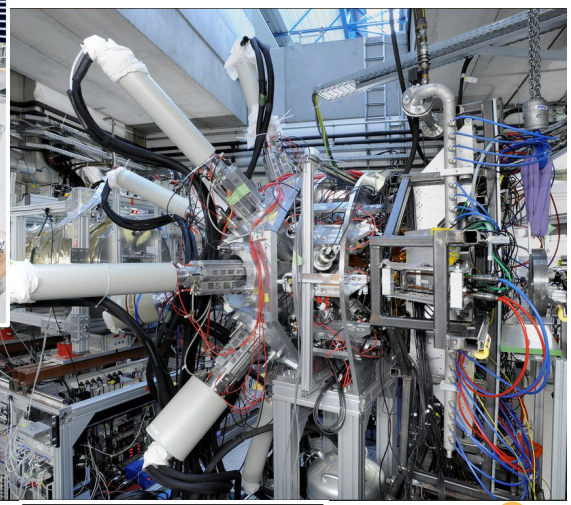
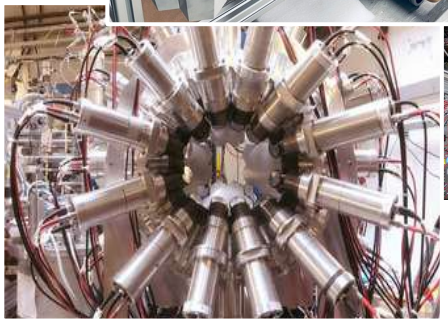


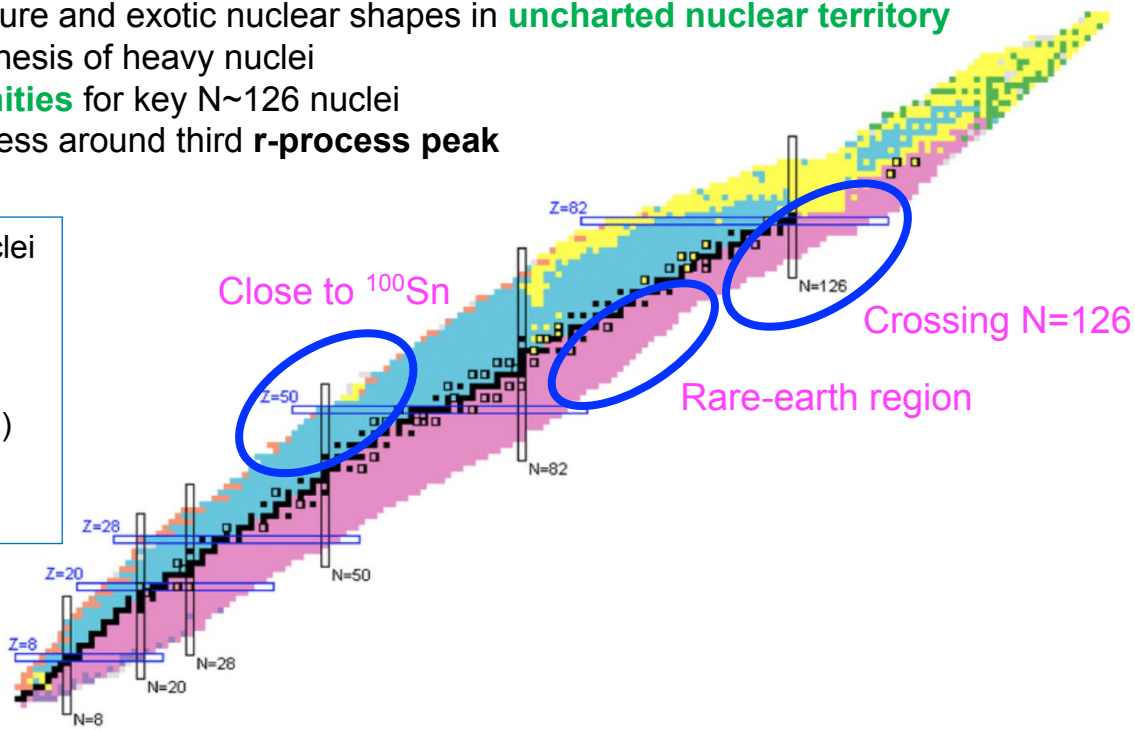


Phase 0
Research Program

DESPEC Physics goals

- **DESPEC** (DEcay SPECtroscopy) is part of the **HISPEC/DESPEC** collaboration at **GSI/FAIR** within the **NUSTAR** pillar
- Shedding light on the evolution of shell structure and exotic nuclear shapes in **uncharted nuclear territory**
- Spectroscopic information for the nucleosynthesis of heavy nuclei
  - GSI/FAIR provides **unique opportunities** for key N~126 nuclei
- Towards a full picture of the beta-decay process around third **r-process peak**
- Nuclear structure around **^{100}Sn (and ^{132}Sn)**

- Comprehensive decay information from key nuclei at secondary beam yields as low as
  ✓ ***one ion per hour***
- Sensitive to nuclear lifetimes spanning
  ✓ ***13 orders of magnitude*** (10ps-100s)
- Measurement of
  ✓ ***any mode of nuclear decay***

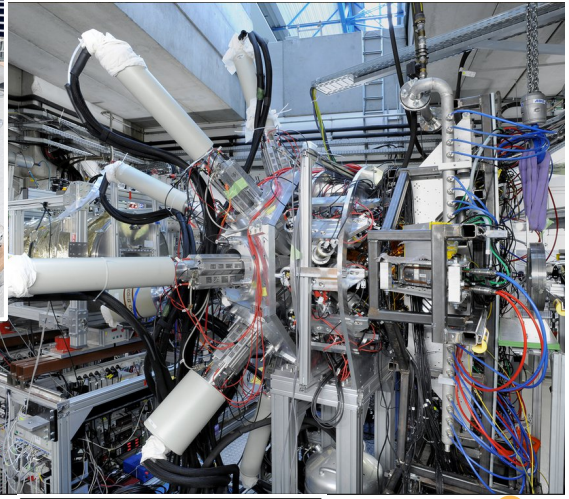


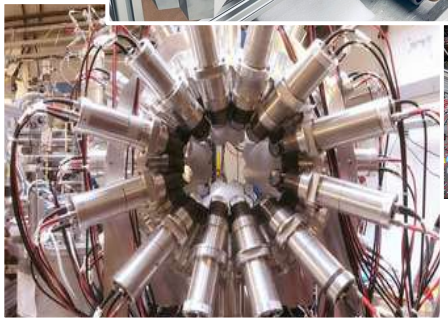
DESPEC in FAIR Phase-0

FAIR Phase-0 operation began in 2019
FAIR instrumentation and setups at GSI facilities
DESPEC (physics) commissioning carried out in early *2020*
Experimental campaigns in *2021*, *2022*, and *2024*, planned for *2025*
Future experiments at new Super-FRS facility starting (Early Science) in *2027*

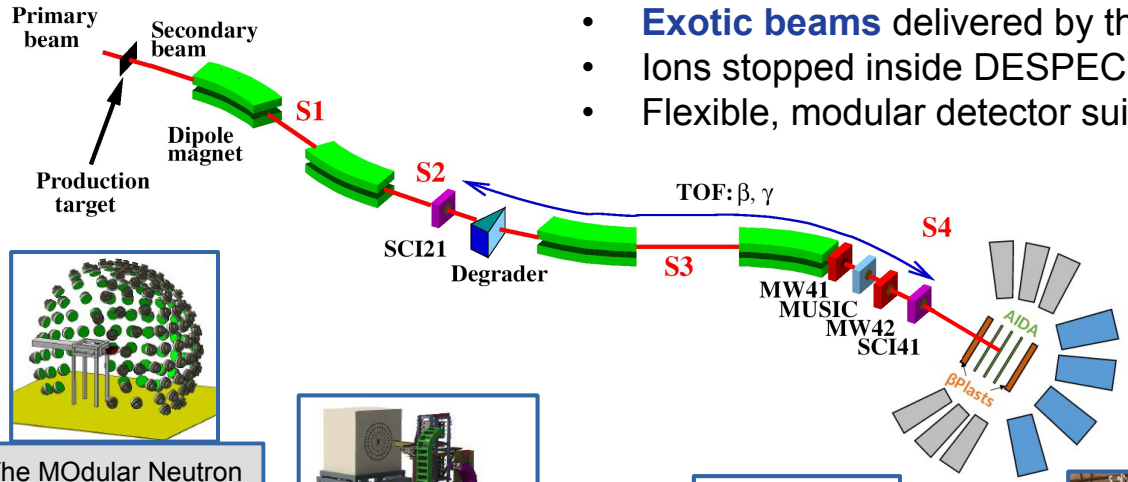
Outline

- Introduction to DESPEC and FAIR
- **Experimental setups**
- Physics highlights
- Upcoming plans





DESPEC Setup Overview

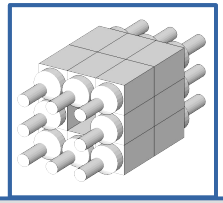


- **Exotic beams** delivered by the FRagment Separator (FRS)
- Ions stopped inside DESPEC setup
- Flexible, modular detector suite **tailored to physics goals**

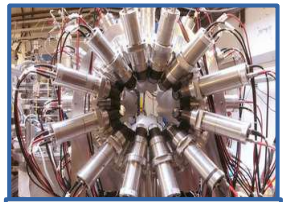
A.K. Mistry *et al.*, The DESPEC setup for GSI and FAIR, NIM A, 166662 (2022)

The MOdular Neutron SpectromeTER **(MONSTER)**

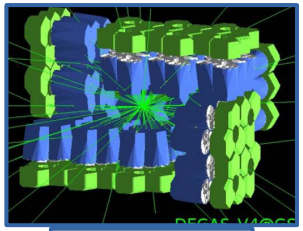
BEta-deLayEd Neutron detector **(BELEN)**
48 3He cylindrical counters



Decay Total Absorption γ-ray Spectrometer **(DTAS)**
NaI(Tl) modules



FAst TIMing Array $LaBr_3(Ce)$ modules **(FATIMA)**



DESPEC Ge Array Spectrometer **(DEGAS)**

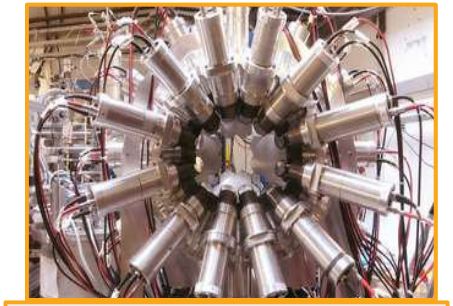
Experiments 2020-2021

Seniority transitions and EM transition rates in ^{94}Pd
Górska (GSI), Regan (Surrey), Cederwall (KTH), Jolie (Cologne)

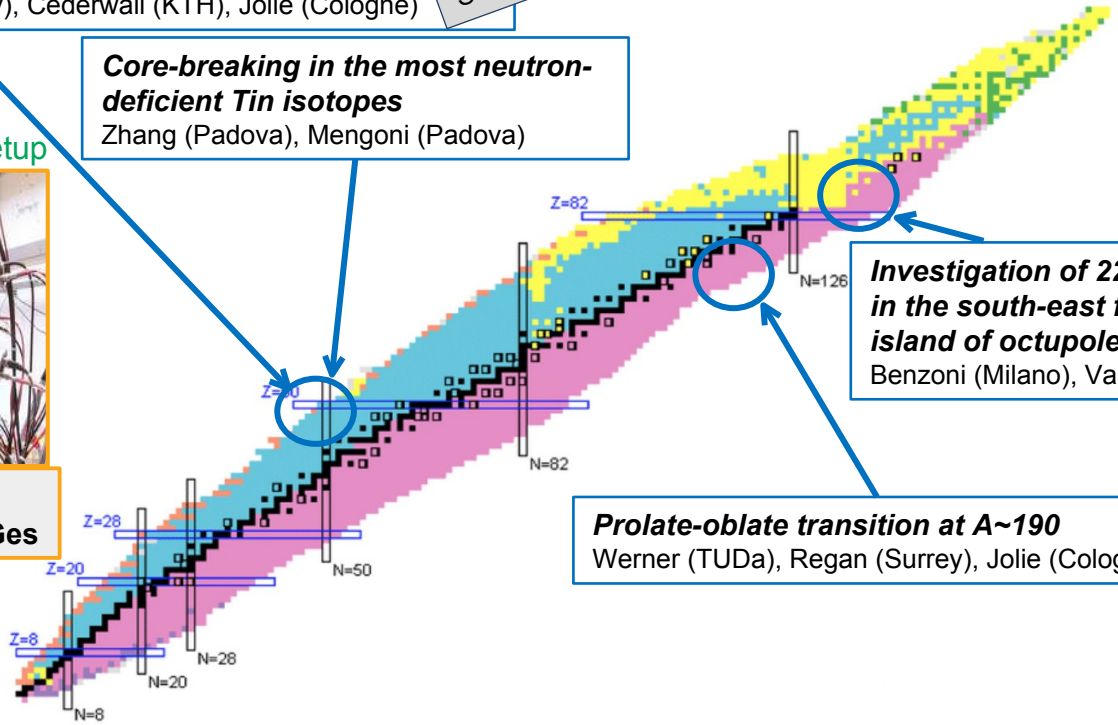
See poster of **B. Das**

Core-breaking in the most neutron-deficient Tin isotopes
Zhang (Padova), Mengoni (Padova)

2020-2021: Fast-timing setup



FAst TIMing Array
$LaBr_3(Ce)$ **(FATIMA) + HPGes**

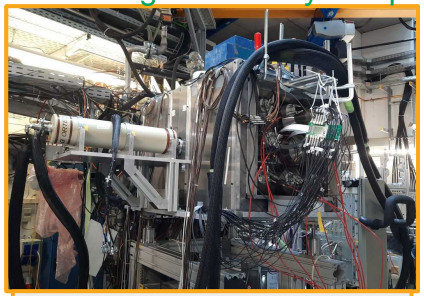


Investigation of 220<A<230 Po-Fr nuclei lying in the south-east frontier of the A~225 island of octupole deformation
Benzoni (Milano), Valiente Dobon (Legnaro)

Prolate-oblate transition at A~190
Werner (TUDa), Regan (Surrey), Jolie (Cologne)

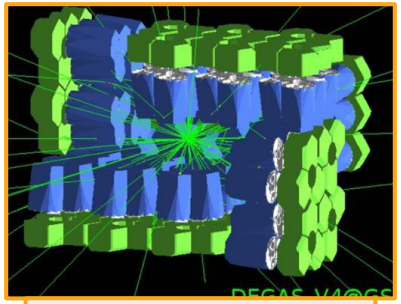
Experiments 2022

2022: High-efficiency setup



Decay Total Absorption γ-ray Spectrometer **(DTAS)**

2022: High-precision setup



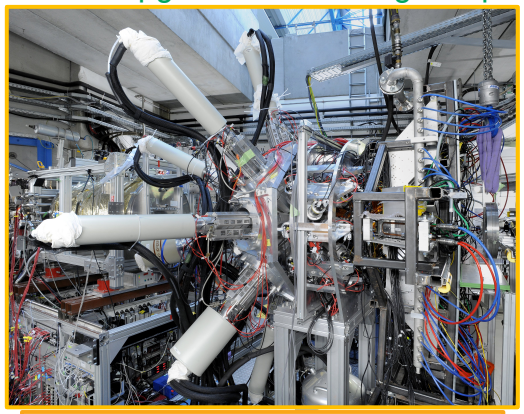
DESPEC Ge Array Spectrometer **(DEGAS)**

Investigation of the beta-strength crossing N=126 and the formation of the 3rd r-process abundance peak
Tain, Morales, Nacher (Valencia)

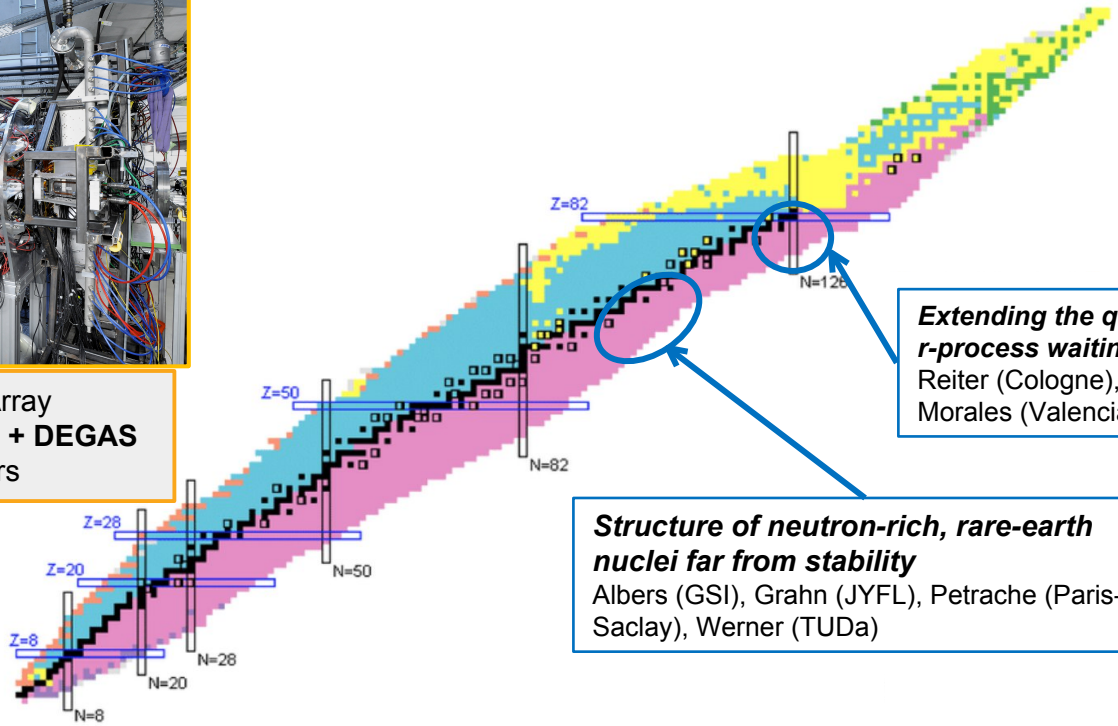
Study of N=126 nuclei: isomeric and beta decays in ^{202}Os and ^{203}Ir
Podolyak (Surrey)

Experiments 2024

2024: Upgraded fast-timing setup



FAst TIMing Array
$LaBr_3(Ce)$ **(FATIMA) + DEGAS**
triple clusters



Extending the quest towards the N=126 r-process waiting point
Reiter (Cologne), Benzoni (Milano), Morales (Valencia), Polettini (Padova)

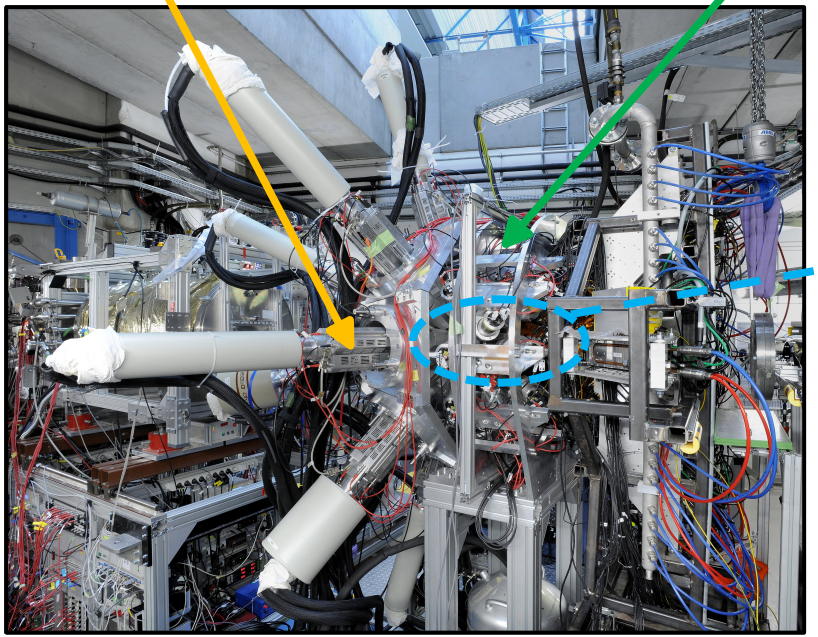
Structure of neutron-rich, rare-earth nuclei far from stability
Albers (GSI), Grahn (JYFL), Petrache (Paris-Saclay), Werner (TUDa)

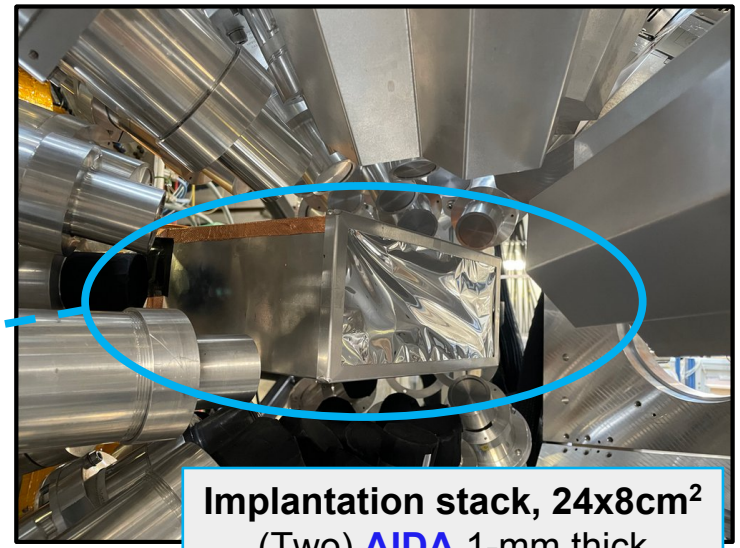
Upgraded Fast-Timing Hybrid Array

Hybrid configuration for simultaneous **high-precision spectroscopy** and **fast-timing measurements**

12 DEGAS triple-cluster HPGe detectors

***36 FA**st **TIM**ing **A**rray (**FATIMA**)* $LaBr_3(Ce)$ detector modules



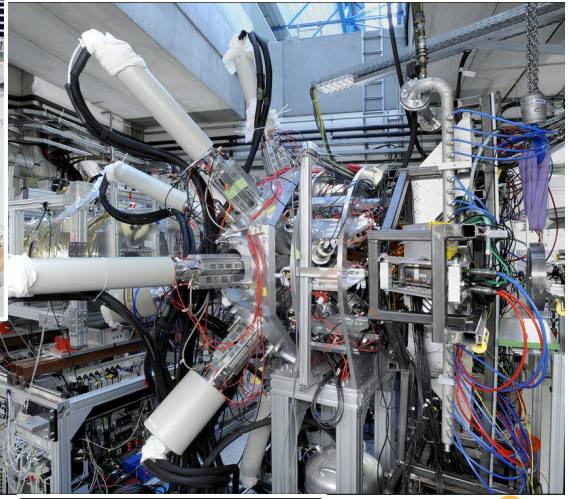


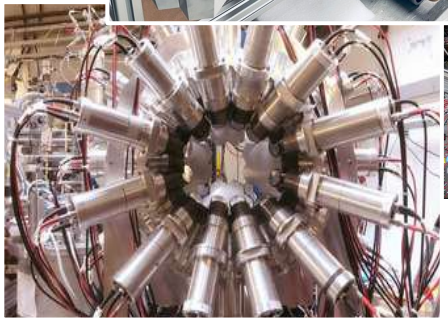
Implantation stack, 24x8cm²
(Two) **AIDA** 1-mm thick double-sided Si strip detectors

(Two) **βPlast** detectors: 3-mm thick fast plastic scintillators

Outline

- Introduction to DESPEC and FAIR
- Experimental setups
- **Physics highlights**
- Upcoming plans

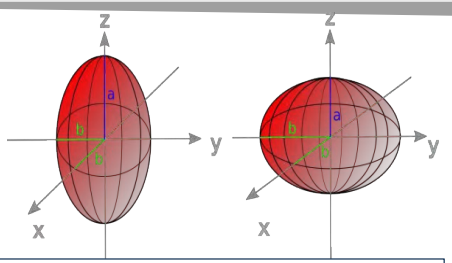


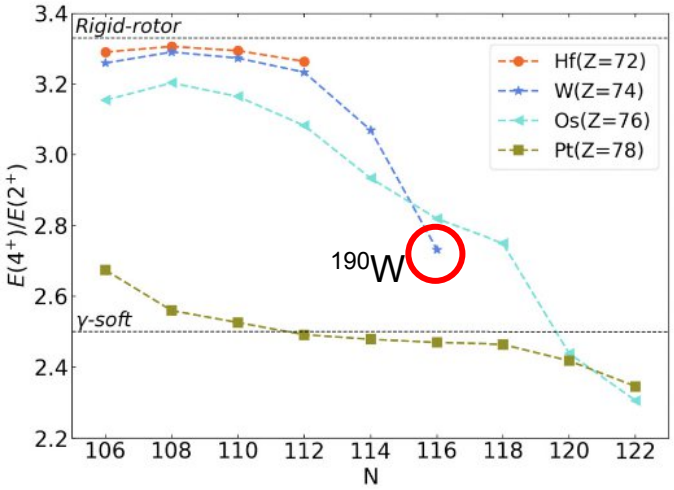


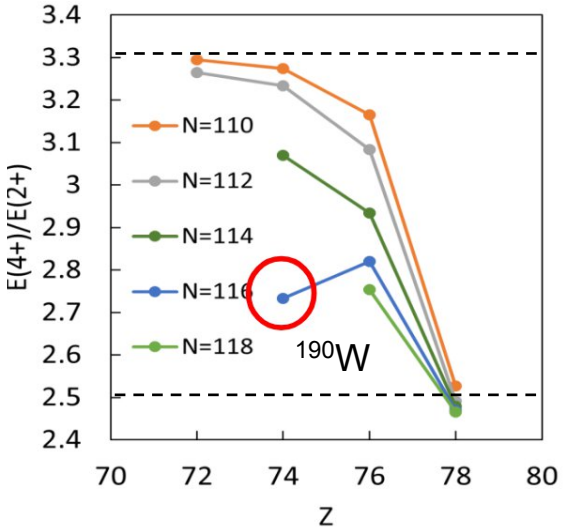
Prolate-oblate shape transition at ^{190}W

Werner (TU Darmstadt), Regan (Surrey), Jolie (Cologne)

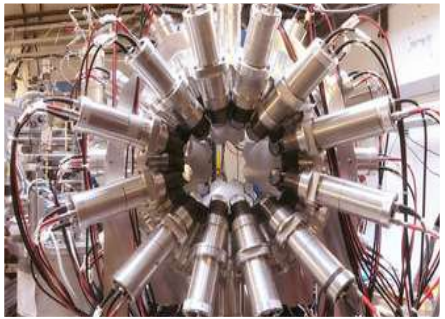
- Ground states of neutron-rich nuclei with A~190 exhibit **evolution from prolate to oblate** deformation
- Steep decrease in $R_{4/2} = E(4^+_1)/E(2^+_1)$ indicates **shape change** at ^{190}W (Z = 74, N = 116)
- Information on **reduced (quadrupole) transition strength $B(E2; 2^+_1 \rightarrow 0^+_1)$** required to characterise nature of transition







- Fragmentation of ^{208}Pb @ 1GeV/u on ^{9}Be target
- Nuclei of interest transmitted and identified by FRS and stopped inside DESPEC Fast-Timing Hybrid Array

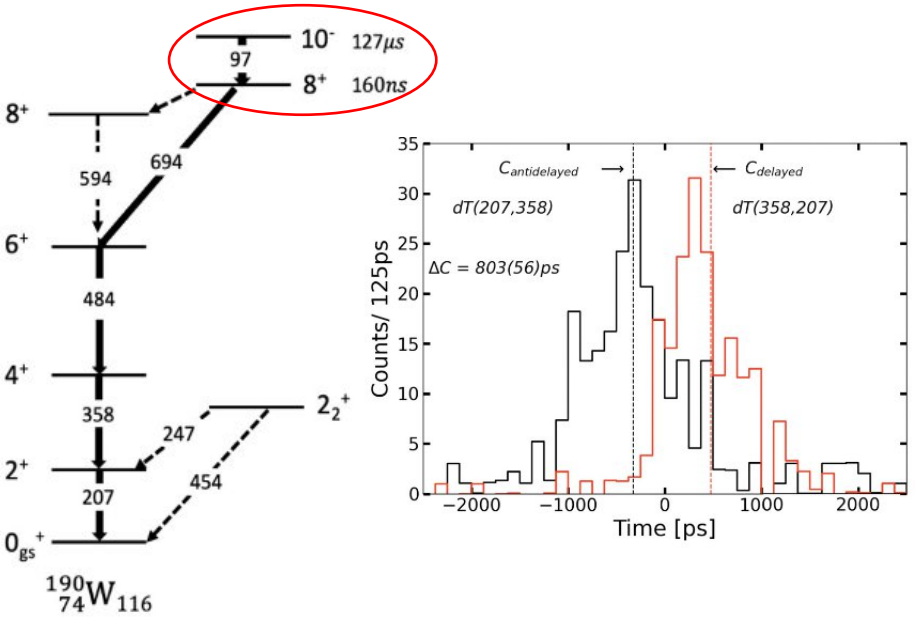


E. Şahin, V. Werner *et al.*, Phys. Lett. B 857, 138976 (2024)

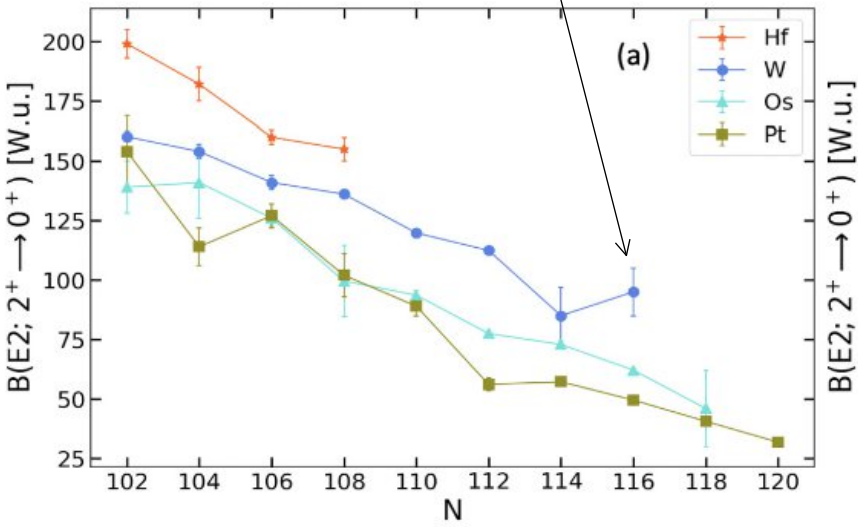
Prolate-oblate shape transition at ^{190}W

Werner (TU Darmstadt), Regan (Surrey), Jolie (Cologne)

- ^{190}W produced in 10^- isomeric state (neutron $K^\pi = 10^-$, $9/2^-[505]11/2^+[615]$ configuration)
- Lifetime of 2^+_1 state extracted using Generalised Centroid Difference (GCD) Method



$B(E2; 2^+_1 \rightarrow 0^+_1) = 95(10)$ W.u.



E. Şahin, V. Werner *et al.*, Phys. Lett. B 857, 138976 (2024)

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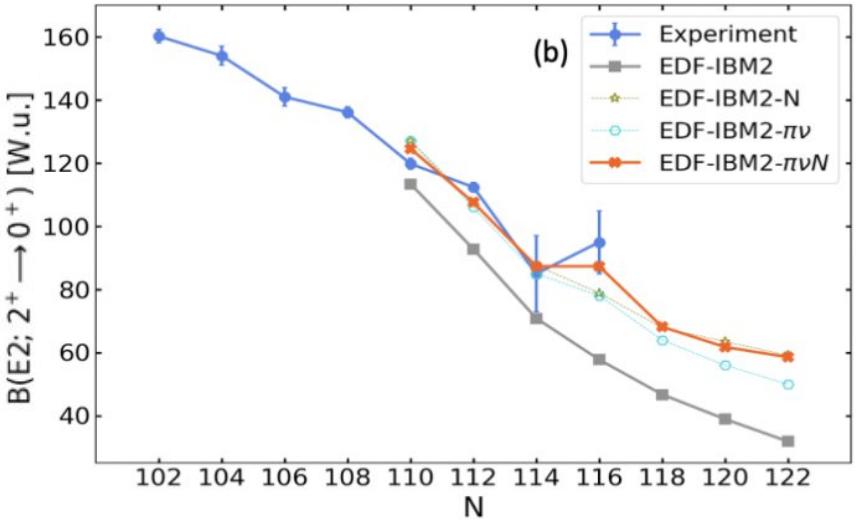
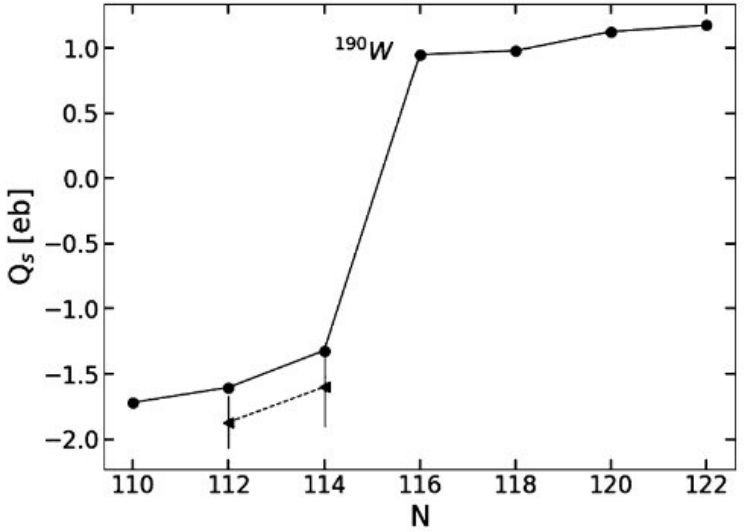




- Combined approach of scaling effective boson charge e_B and differing values of e_π and e_ν best reproduces data
- Continued decrease of B(E2) values beyond N=116 not in line with expectations of shape transition
  -> due to approach to N=126 closure (i.e. decreased number of bosons in IBM2)

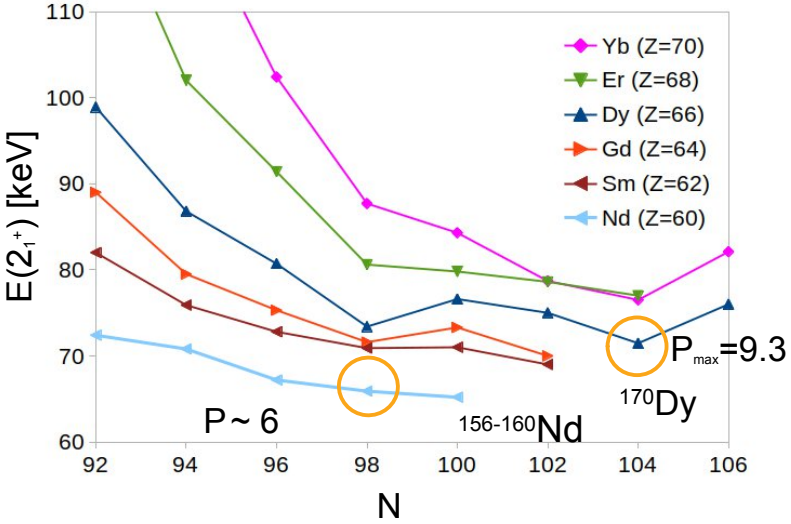
EDF-IBM2:	the effective charges (p = n = 0.13 eb)
EDF-IBM2-πνN:	the effective charges (p = 0.145 eb and n = 0.2175 eb)

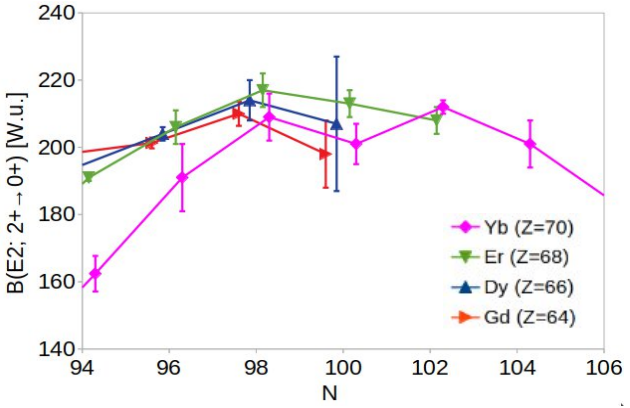
E. Şahin, V. Werner *et al.*, Phys. Lett. B 857, 138976 (2024)

Neutron-rich, rare-earth nuclei approaching N=104

Albers (GSI), Grahn (JYFL), Petrache (Paris-Saclay), Werner (TUDa)

- Rare-earth nuclei mid-way between Z=50,82 and N=82,126 are **highly collective**
- ^{170}Dy (N=104), doubly-midshell, **highest $N_\pi N_\nu$** of any nucleus with A<208
- P = $N_\pi N_\nu/(N_\pi+N_\nu)$ highest at ^{170}Dy; very low 2^+_1 values of Nd chain interpreted as **deformed shell closure** at Z=60 (e.g. Hartley *et al.*, Phys. Rev. C 105 (2022) 014301)





- **Discontinuities** in E(2_1^+) and B(E2; $2^+_1 \rightarrow 0^+_1$) approaching mid-shell with increasing $N_\pi N_\nu$ can indicate deformed shell closure(s)

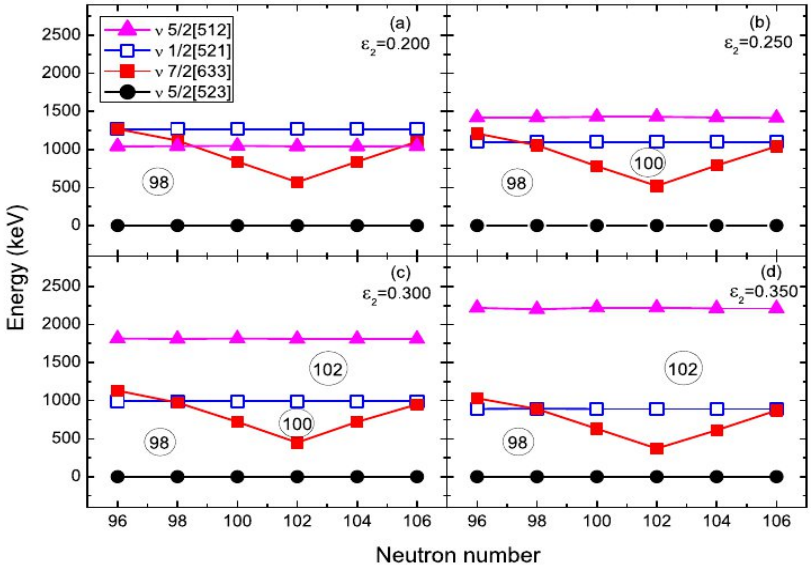
Neutron-rich, rare-earth nuclei approaching N=104

Albers (GSI), Grahn (JYFL), Petrache (Paris-Saclay), Werner (TUDa)

- Conclusions on presence (and location) of possible deformed shell gaps from various experimental methods (e.g.) isomer decay spectroscopy [2], masses [3], β-decay halflives [4], decay properties [5],...
- PSM calculations location and size of subshell gaps **highly-dependent** on **deformation** and **neutron number** [1]
- Additional spectroscopic data for this region **sorely needed**

- DESPEC experiment using upgraded fast-timing hybrid array
- Neutron-rich nuclei produced via fragmentation of **newly-developed, high-energy (~1 GeV/u) ^{170}Er beam**

- **Main Experimental Goals:**
  - Lifetimes of 2^+_1 (and other) states in even-even neutron-rich Dy, Gd and Sm isotopes
  - Level structures of poorly-known nuclei after beta decay
  - New data on isomeric decays, search for new isomers



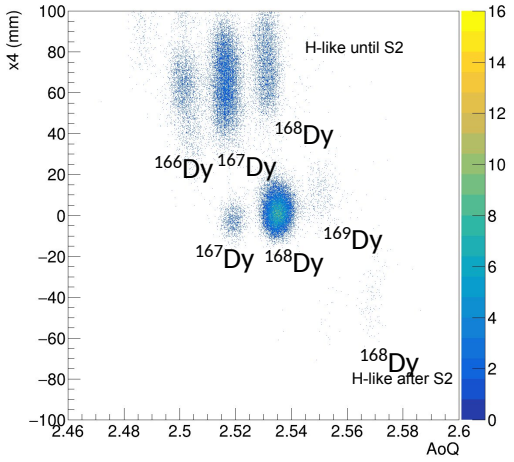
[1] Y.X. Liu *et al.*, J. Phys. G: Nucl. Part. Phys. 47, 055108 (2020)
[2] Z. Patel *et al.*, PRL **113**, 262502 (2014)
[3] M. Vilen *et al.*, PRL **120**, 262701 (2018)
[4] J. Wu *et al.*, PRL **118**, 072701 (2017)
[5] D.J. Hartley *et al.*, PRL **120**, 182502 (2018)

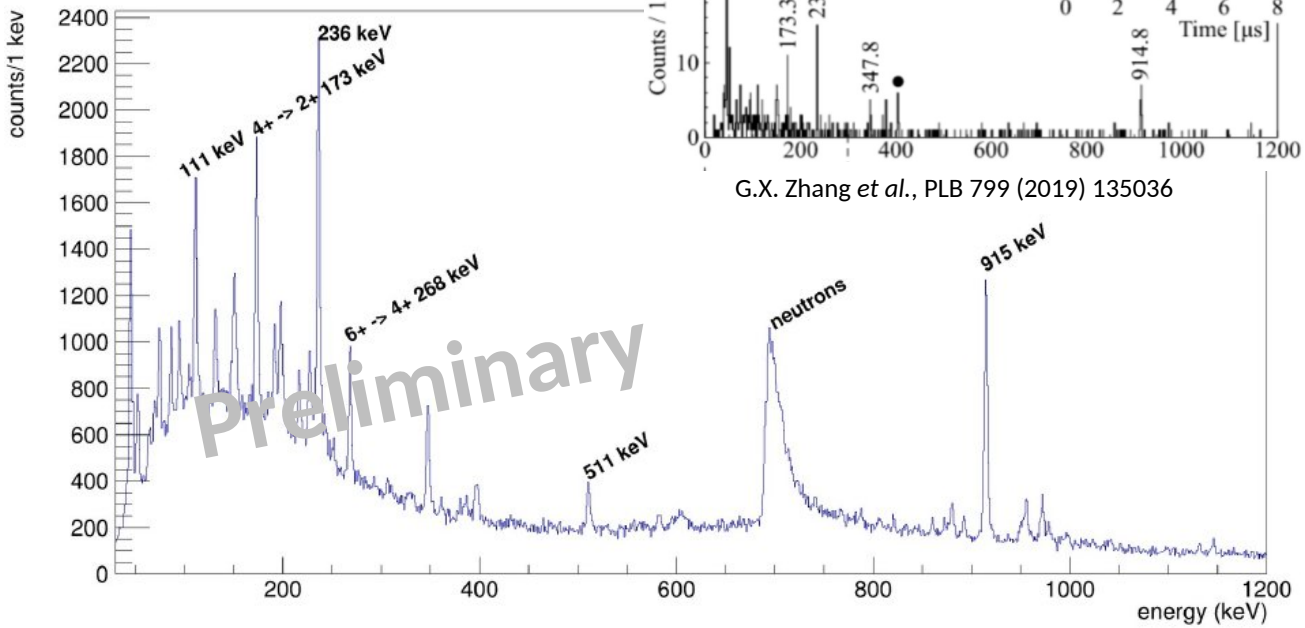
Neutron-rich, rare-earth nuclei approaching N=104

Albers (GSI), Grahn (JYFL), Petrache (Paris-Saclay), Werner (TUDa)

DEGAS HPGe spectrum gated on ^{168}Dy, 0-2.5 us after implantation

Very clean particle identification achieved:
Example isotope separation for Z=66 nuclei





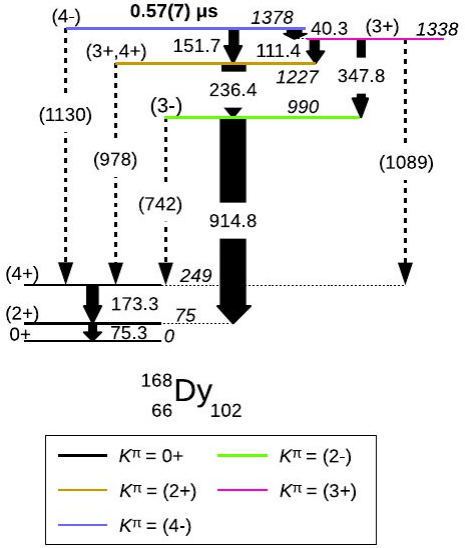
G.X. Zhang *et al.*, PLB 799 (2019) 135036

Spectra courtesy of Johan Emil Linnestad Larsson and Jeroen Bormans (PhD students, TUDa and GSI)

Neutron-rich, rare-earth nuclei approaching N=104

Albers (GSI), Grahn (JYFL), Petrache (Paris-Saclay), Werner (TUDa)

- $K^{\pi} = 4^-$, 0.57-μs isomer in ^{168}Dy observed at RIKEN using U beam [1]
- $K^{\pi} = 4^-$ and 6^- isomers have been observed in N=102 isotones
- No such 6^- isomer previously observed (expected ~1.6 MeV)



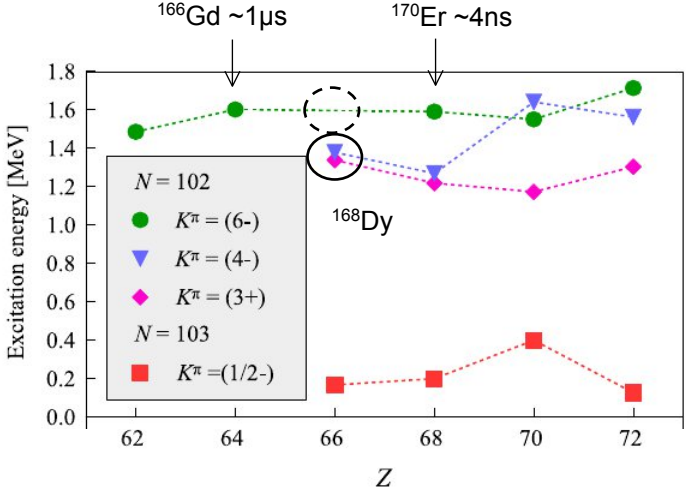


Figure modified from [1]

- **Many new transitions** observed in new data, including $6^+ \rightarrow 4^+$, 248-keV transition
- Evidence of **new isomeric state(s)**
- Ongoing work to develop level schemes and measure **lifetimes** with FATIMA

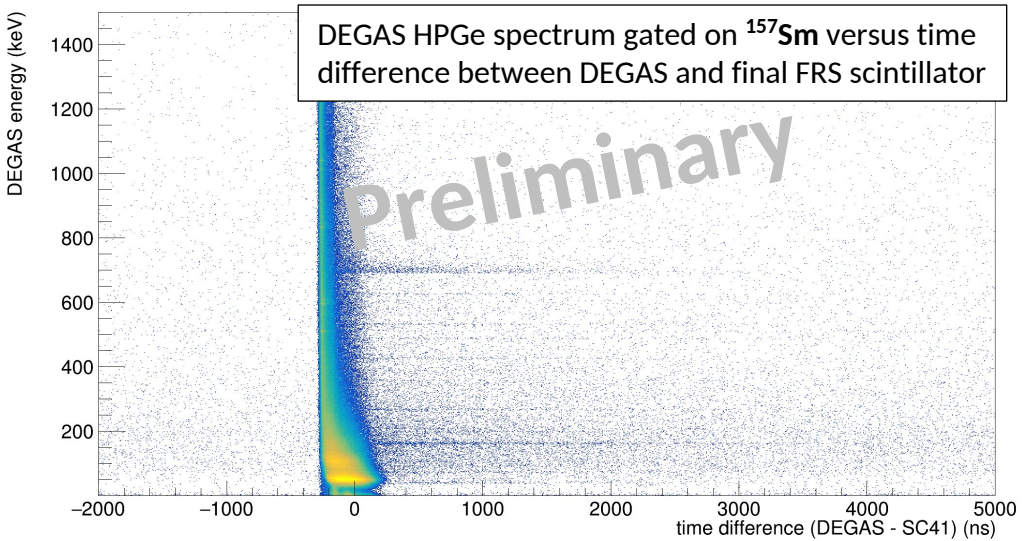
[1] G.X. Zhang *et al.*, PLB 799 (2019) 135036

Neutron-rich, rare-earth nuclei approaching N=104

Albers (GSI), Grahn (JYFL), Petrache (Paris-Saclay), Werner (TUDa)

- Level scheme of ^{157}Sm recently greatly expanded via β decay of ^{157}Pm (D.J. Hartley *et al.*, Phys. Rev. C 110 (2024) 044319)
- **New transitions** observed and indication of **new ~µs isomer** in ^{157}Sm in DESPEC data
- $K^{\pi}=15/2^{+}$ and $17/2^{-}$ isomers already observed in heavier Sm isotopes ^{159,161}Sm, respectively (Z. Patel *et al.*, Phys. Rev. C (2017) 034305)

DEGAS HPGe spectrum gated on **^{157}Sm** versus time difference between DEGAS and final FRS scintillator



Spectra courtesy of Johan Emil Linnestad Larsson and Jeroen Bormans (PhD students, TUDa and GSI)

^{159}Sm (N=97)
$K^{\pi} = 15/2^{+}$
ν: $5/2^{-}[523]$
π: $5/2^{-}[532]$,$5/2^{+}[413]$

^{161}Sm (N=99)
$K^{\pi} = 17/2^{-}$
ν: $7/2^{+}[633]$
π: $5/2^{-}[532]$,5/2+[413]

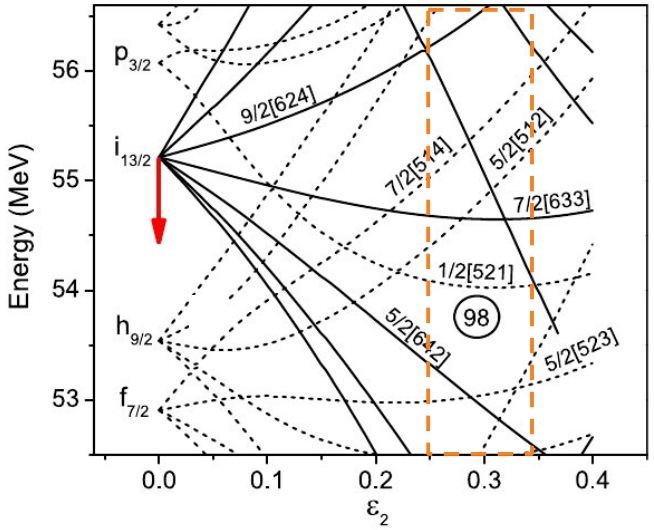
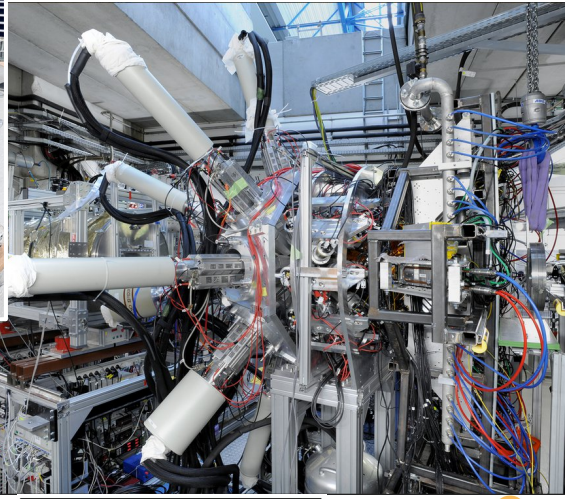
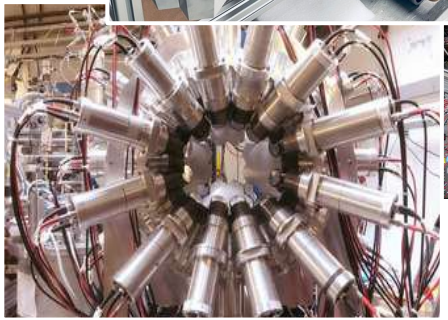


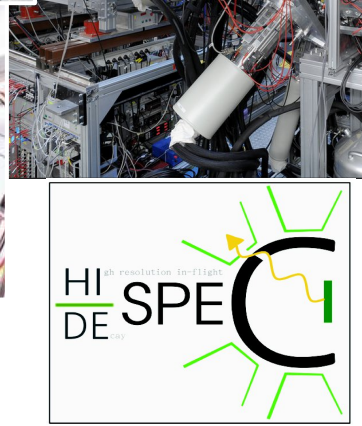
Figure Liu *et al.*, J. Phys. G: Nucl. Part. Phys. 47, 055108 (2020)

Outline

- Introduction to DESPEC and FAIR
- Experimental setups
- Physics highlights
- **Upcoming plans**



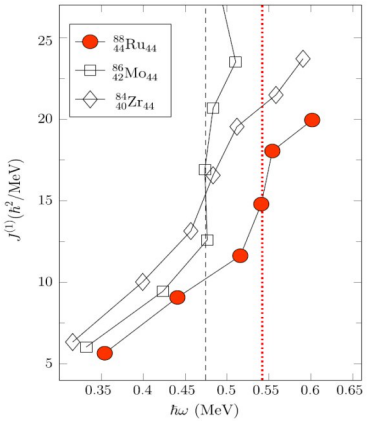


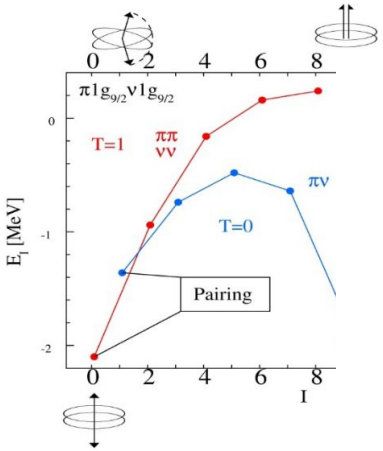


Interplay of collectivity and single particle properties below ^{100}Sn

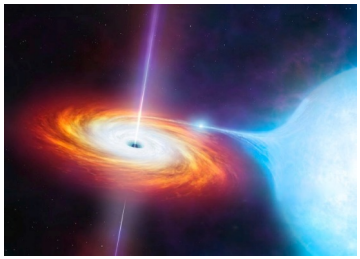
Cederwall (KTH Sweden), Algora (Valencia), Górska (GSI), Regan (Surrey), Ruotsalainen (JYFL)

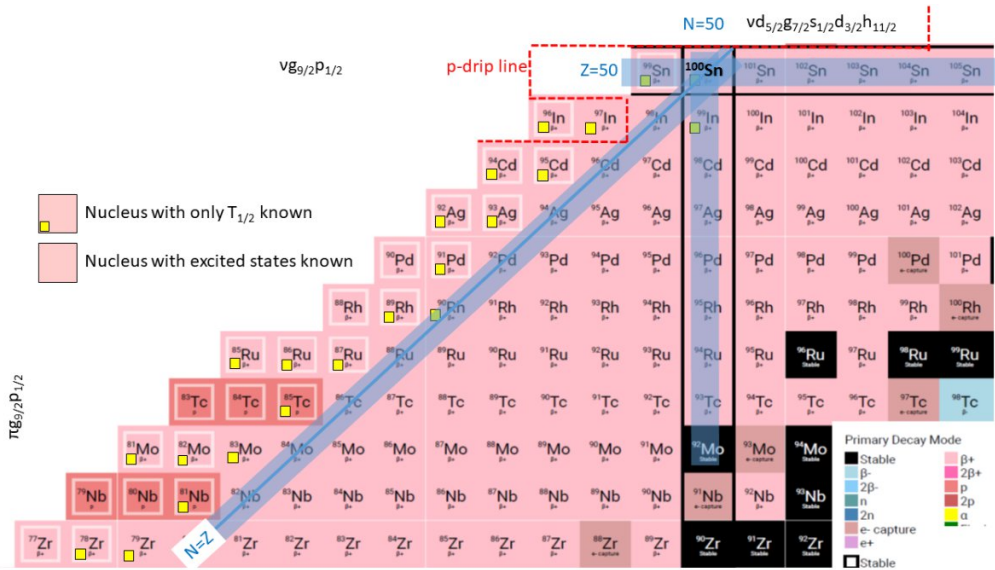
- Region of interest between closed neutron shell at N=50 and N=Z line
- Rotational band in ^{88}Ru similar to known states in self-conjugate ^{84}Mo
- 'Missing' 16^+ spin-trap isomer in ^{84}Mo not yet observed
- Ground-state lifetimes affect rp-process flow and determine directly the amount of nuclei produced in X-ray bursts





- Experiment planned in February 2025, fragmentation of ^{107}Ag
- Full DEGAS Setup in close configuration

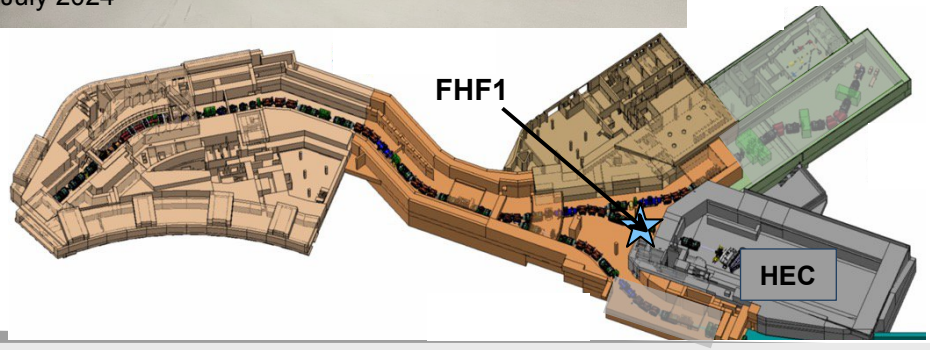


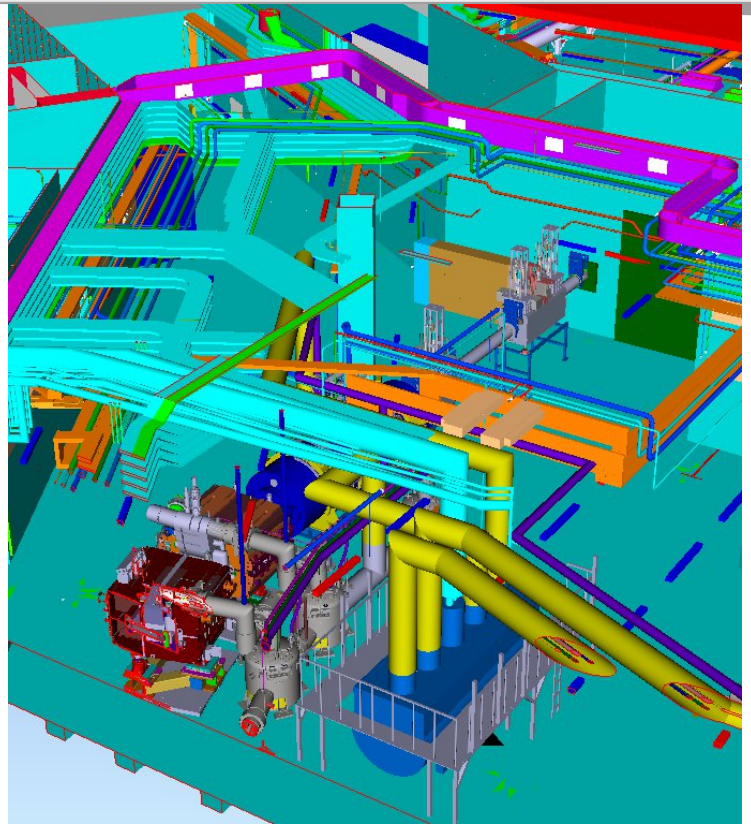


B. Cederwall *et al.*, PRL 124 (2020) 062501
B. S. Nara Singh, *et al.*, PRL 107 (2011) 172502

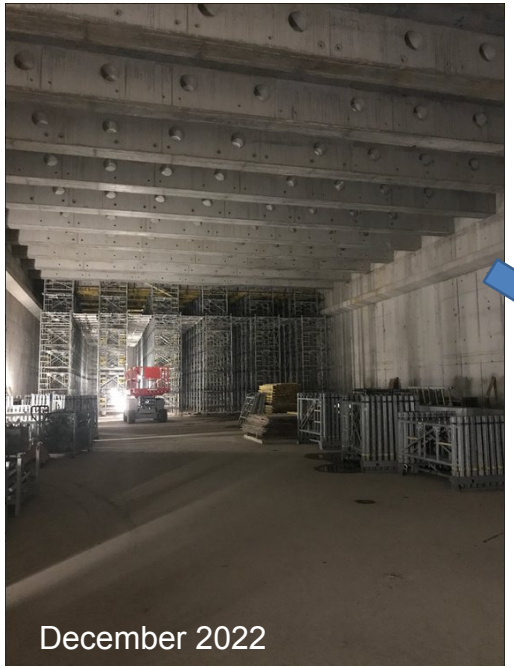
Courtesy of M. Górska

Construction update, FHF1



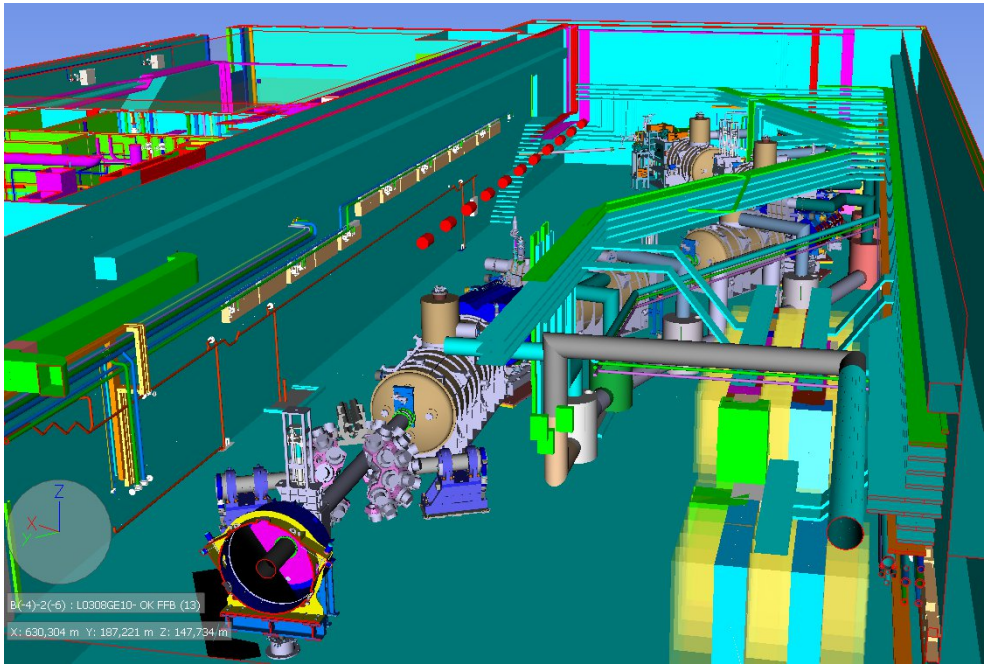


Construction update, Low-Energy Cave



NUSTAR Low-Energy Cave

Low-Energy Cave Visualisation



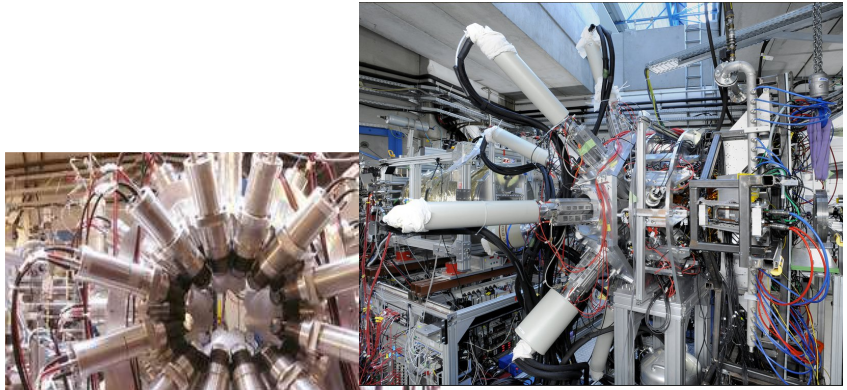
NUSTAR Low-Energy Cave

Summary

- DESPEC campaigns at GSI/FAIR in 2020-2022 and 2024
- Suite of state-of-the-art detector systems tailored to experimental goals
- **Physics highlights in 2024:**

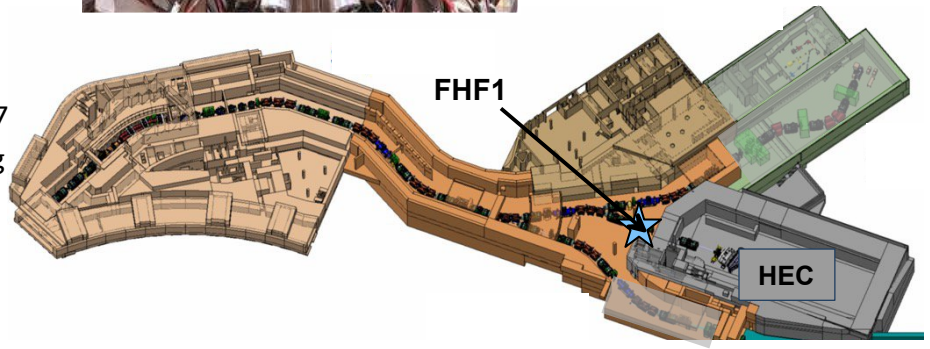
  ✓ *2^+_1 lifetime of prolate-oblate transitional nucleus ^{190}W published*

  ✓ Rich spectroscopic data collected via fragmentation of ^{170}Er beam on a number of neutron-rich rare earth isotope *data analysis ongoing…*



Upcoming…

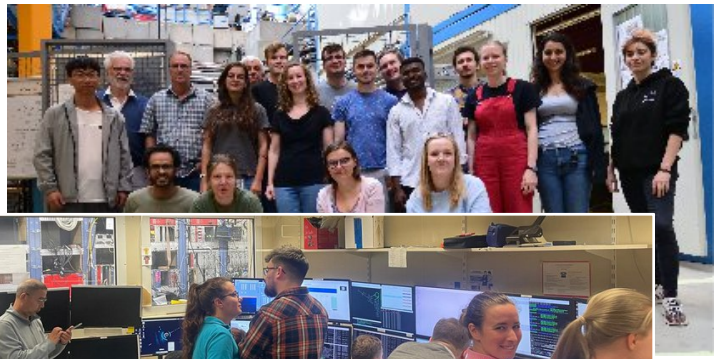
- Construction of **FAIR progresses well**; new Super-FRS to be operational in 2027 with SIS-100 synchrotron commissioning in 2028
- Current **open PAC Call** for experiments in 2026-2027

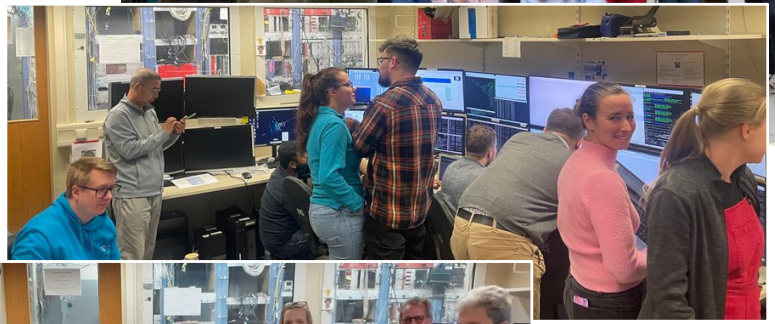


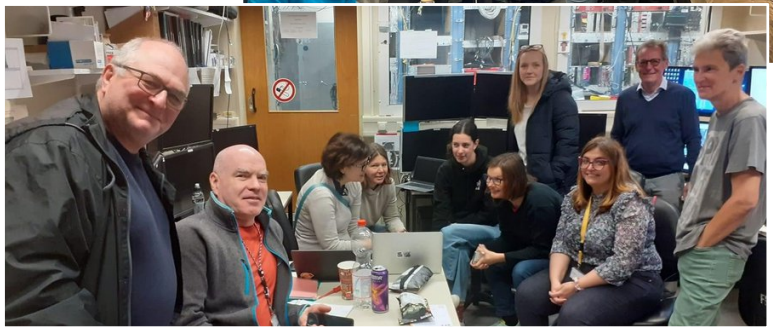
With thanks to:

A. Algora, G. Benzoni, B. Bles, J. Bormans, B. Das, D. Das, B. Cederwall, C. Chatel, Z. Chen, T. Davinson, F. Drent, E. Gandolfo, J. Gerl, M. Górska, T. Grahn, H. Heggen, P. Herrmann, N. Hubbard, C. Jones, A. Jungclaus, I. Kojouharov, G. Kosir, N. Kurz, J.E.L. Larsson, G.-s. Li, M. Mikolajczuk, A. Morales, C.M. Petrache, N. Pietralla, Zs. Podolyak, W. Poklepa, M. Polettini, M. Reece, P. Regan, D. Rodriguez, E. Sahin, H. Schaffner, J-L. Tain, J. Vesic, V. Werner, M. Wiebusch, K. Wimmer, A. Yaneva, G. Zhang…

…and many more from the **HISPEC/DESPEC Collaboration**, and the **FRS and EE Groups**







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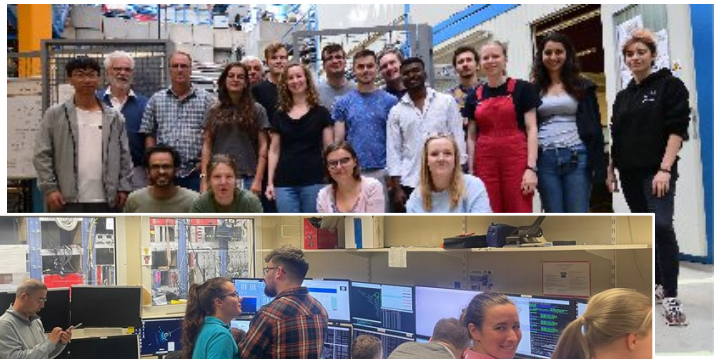
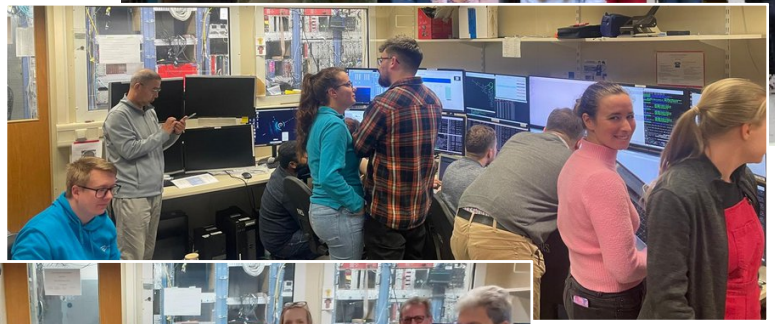


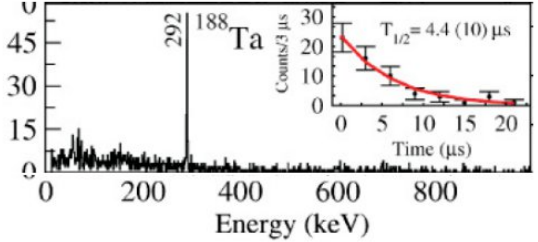


Thank you

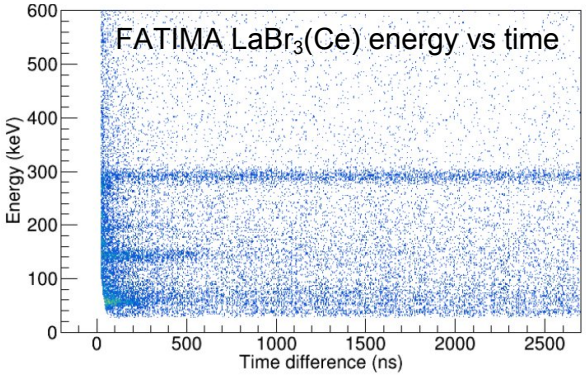
Isomeric states in ^{188,189}Ta

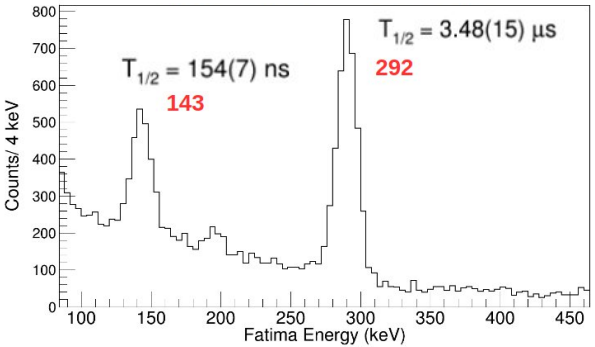
Werner (TU Darmstadt), Regan (Surrey), Jolie (Cologne)

PRELIMINARY results for ^{188}Ta

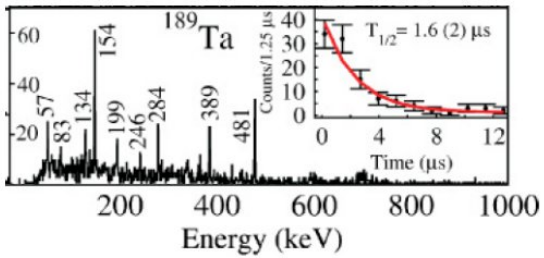


N. Alkhomashi *et al.*, Phys. Rev. C 80, 064308 (2009)

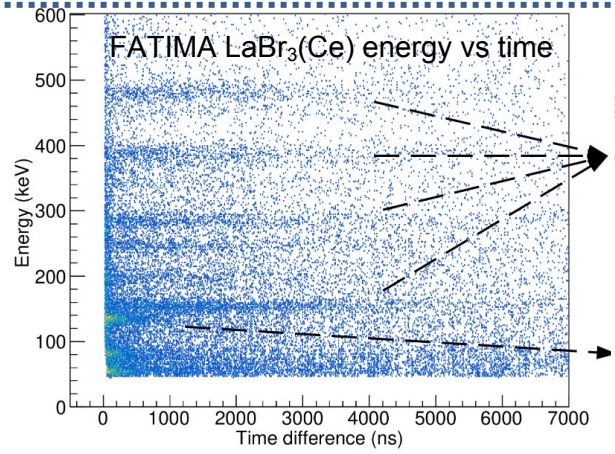


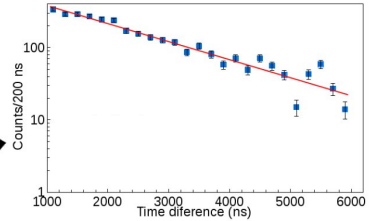


PRELIMINARY results for ^{189}Ta

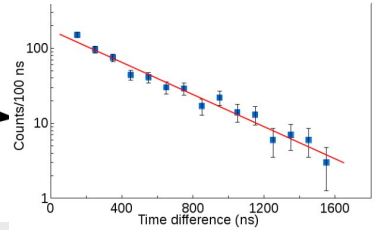


N. Alkhomashi *et al.*, Phys. Rev. C 80, 064308 (2009)





Isomer “1”
$T_{1/2}$ = 1180(40)ns



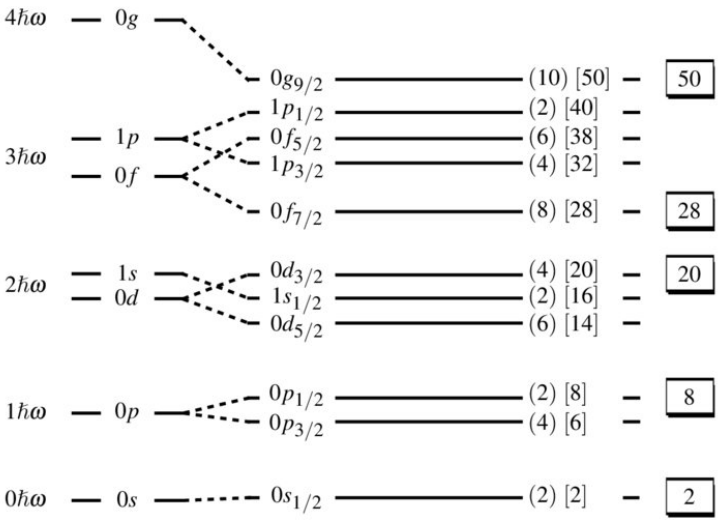
Isomer “2”
$T_{1/2}$ = 230(10)ns

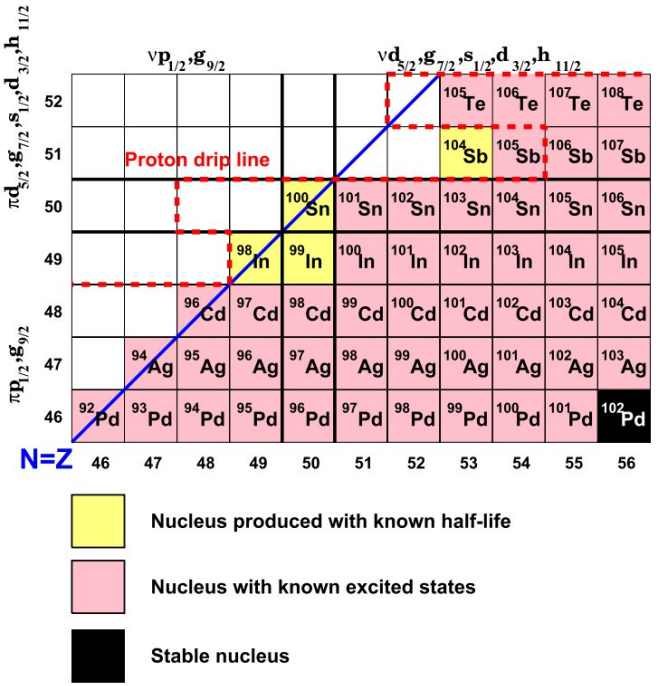
PhD work of S. Alhomaidhi (TUDa/GSI)

Seniority transitions and EM transition rates in ^{94}Pd

Górska (GSI), Regan (Surrey), Cederwall (KTH), Jolie (Cologne)

- ^{100}Sn region and the N=Z line
- Hole states - dominated by $0g_{9/2}$ intruder orbit
- Unique structural features - seniority and parity-changing isomerism, pn pairing and seniority-induced symmetries

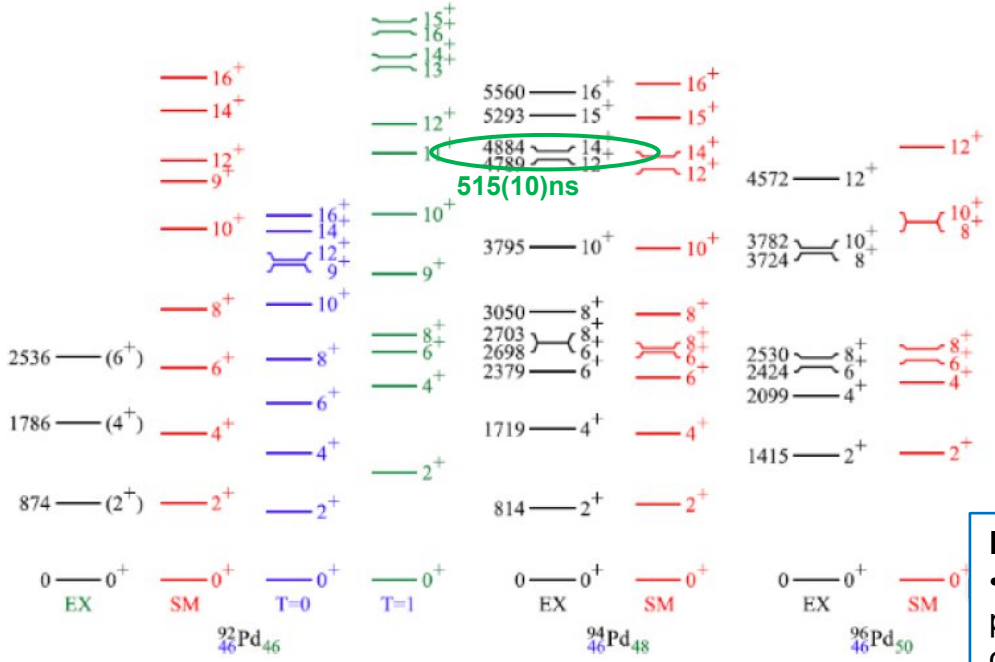




T.Faestermann, M.Górska, H.Grawe, Prog. Part. Nucl. Phys. 69, 85 (2013)

Seniority transitions and EM transition rates in ^{94}Pd

Students: A. Yaneva (Cologne), S. Jazrawi (Surrey), M. Mikołajczuk (Warsaw)



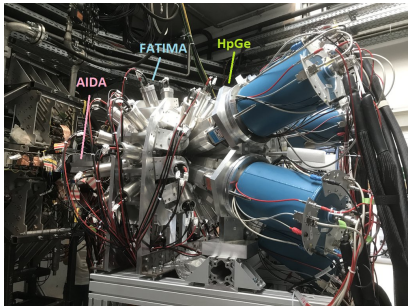
T.Faestermann, M.Górska, H.Grawe, Prog.Part.Nucl.Phys. 69, 85 (2013)
SM: R.Gross and A.Frenkel, Nucl. Phys. A 267, 85 (1976)
Isomer $T_{1/2}$: Häfner *et al.*, Phys. Rev. C 100, 024302 (2019)
(SM: GF interaction in the $\pi\nu(p_{1/2}g_{9/2})$ model space)

Main Goals:

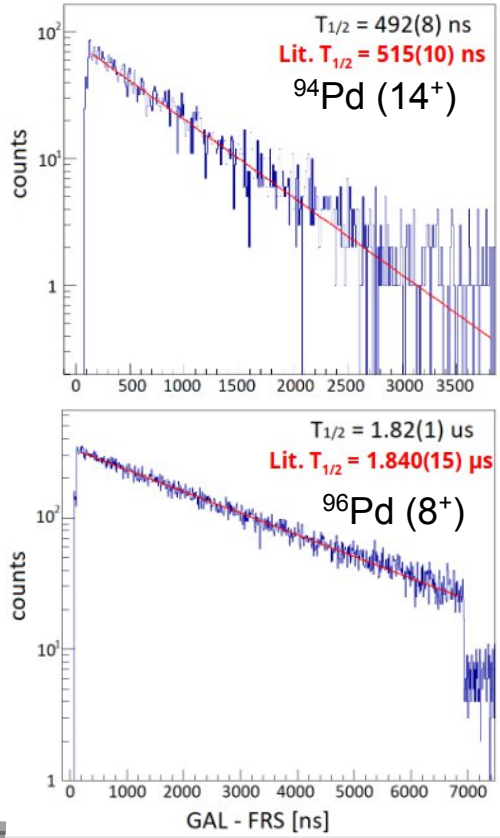
. ^{96}Pd – seniority-type level scheme, ^{92}Pd nearly constant energy spacing:
.***^{94}Pd intermediate nucleus***
. Competition between isoscalar (T = 0) and isovector (T = 1) components of pn interaction
. Importance of cross shell (N,Z = 50) excitations
. B(E2) values of **8^+ and 6^+ states** below 14^+ isomer
. Stringent test for various models and model spaces

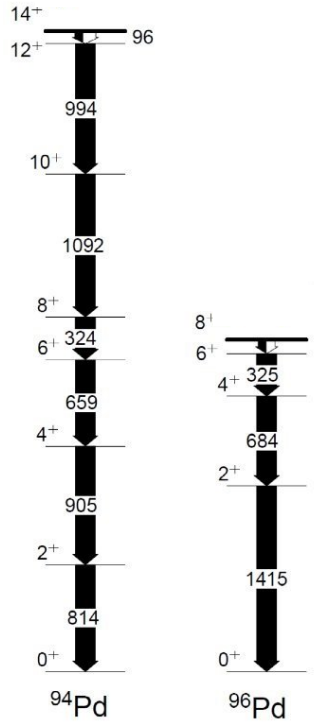
Experiment:

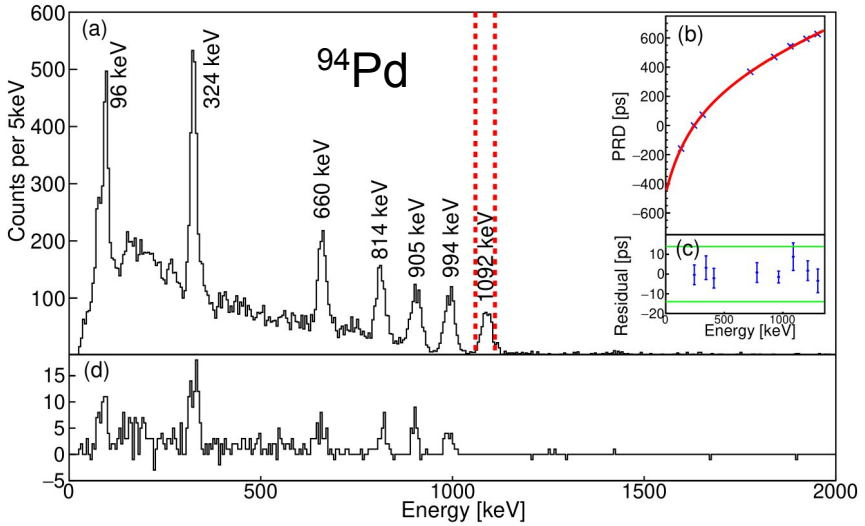
- Fragmentation of ^{124}Xe primary beam (982 MeV/u) on a ^{9}Be target
- DESPEC 'fast-timing' setup
- Hybrid array of HPGe (GALILEO) and $LaBr_3$ (FATIMA)



Seniority transitions and EM transition rates in ^{94}Pd





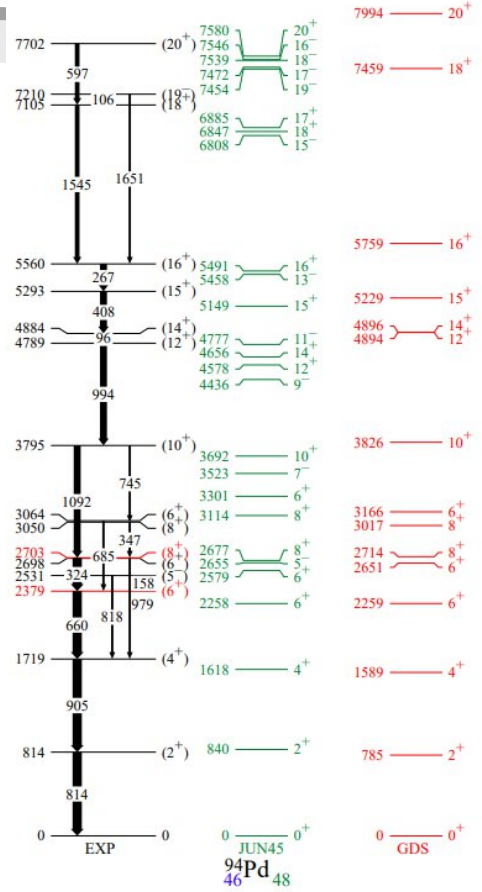


- ^{96}Pd confirmed validity of measurement (S. Jazrawi *et al.*, Radiation Physics and Chemistry 200, 112234 (2022))
- For shorter (ps) lifetimes, Generalized Centroid Shift Method (GCSM) was employed

Lit. isomer half-life values taken from:
Häfner *et al.*, Phys.Rev. C 100, 024302 (2019)

A. Yaneva , S. Jazrawi *et al.*, manuscript submitted

Seniority transitions and EM transition rates in ^{94}Pd



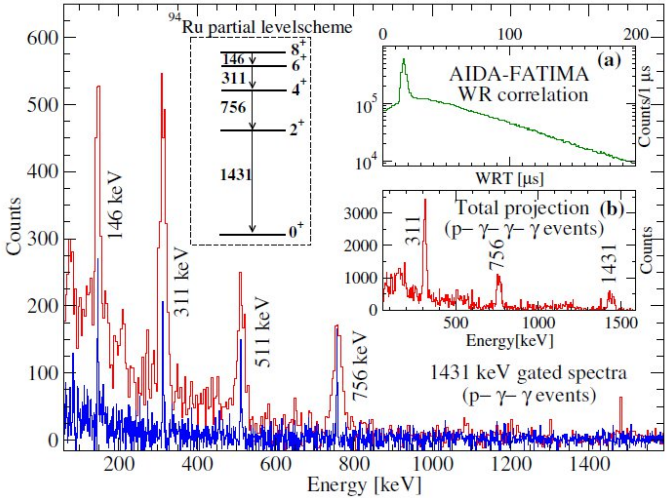
- Excellent reproduction of experimental data by LSSM (GDS) calculation -> importance of core excitations in the structure of ^{94}Pd
- Importance of T = 0 pn interaction component in nuclear structure evolution from ^{96}Pd to ^{92}Pd

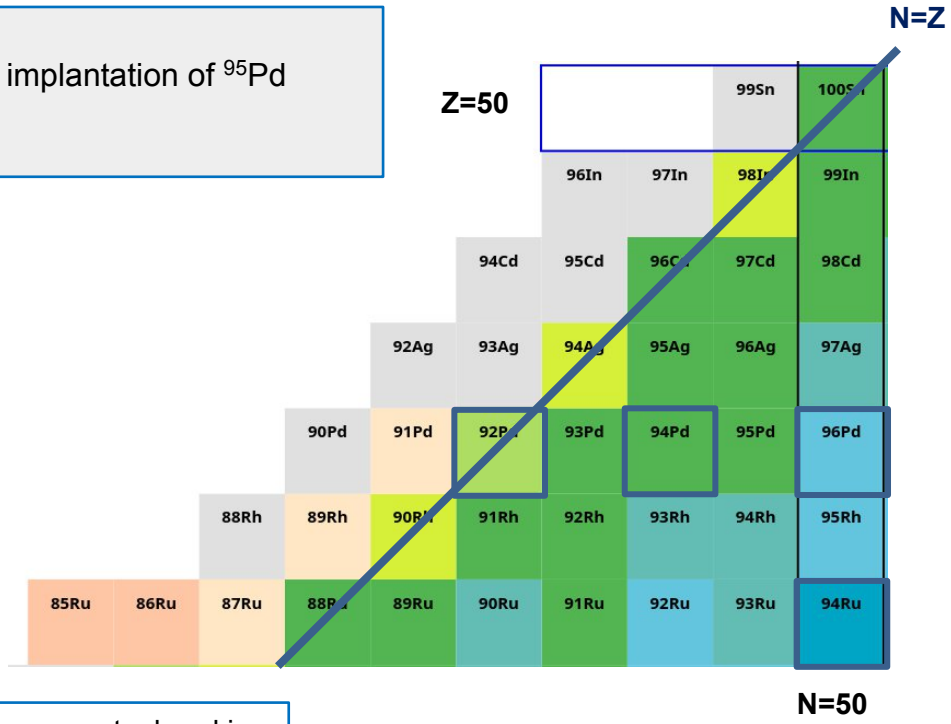
Quantity [ns/e^2fm^4]	$I_i^\pi - I_f^\pi$		
	$14^+ \rightarrow 12^+$	$8^+ \rightarrow 6^+$	$6^+ \rightarrow 4^+$
$T_{1/2}$	515(1)	0.755(106)	≤0.05
$B_{exp}(E2)$	52.1(1)	205^{+34}_{-25}	≥90
$B_{JUN45}(E2)$	113	277	496
$B_{GDS}(E2)$	49	192	548
$B_{g_{9/2}}(E2)$	85	115	307
$B_{g_{9/2}T=0(pn)}(E2)$	63	152	308
$B_{g_{9/2}T=1(pn)}(E2)$	3	12	8
$B_{EXVAM}(E2)$[21]	56	165	336

A. Yaneva, S. Jazrawi *et al.*, manuscript submitted

Seniority symmetry-breaking in ^{94}Ru

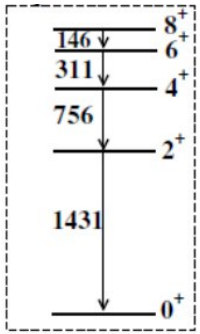
- Lifetimes of **states in ^{94}Ru**
- Measured after **β-delayed proton emission** following implantation of ^{95}Pd ($21/2^+$ isomer)
- Feeding 8^+ isomer in ^{94}Ru (~70 μs)





B. Das, B. Cederwall *et al.*, Nature of seniority symmetry breaking in the semimagic nucleus ^{94}Ru, PRC Letters 105, L031304 (2022)

Seniority symmetry-breaking in ^{94}Ru



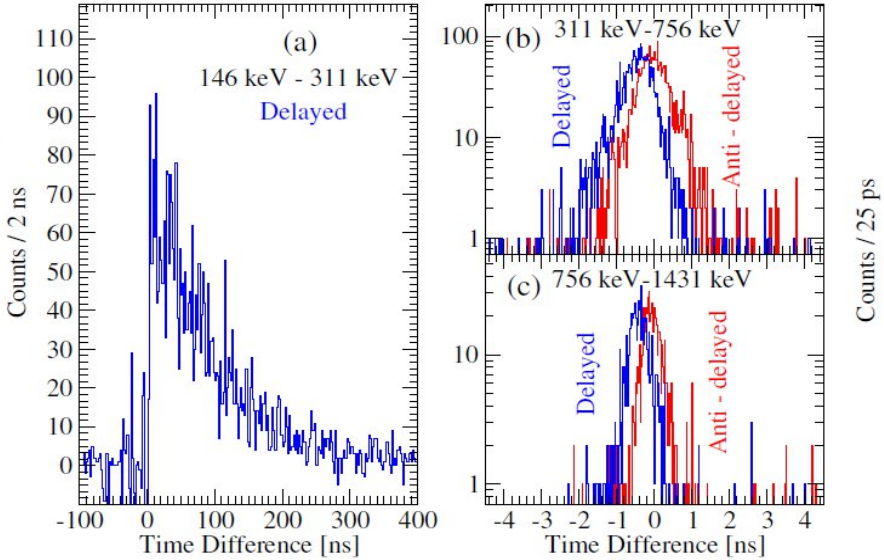


TABLE I. Experimental mean lifetimes and B(E2) strengths in ^{94}Ru in comparison with various shell model predictions. Experimental data except for $8^+ \rightarrow 6^+$ [41, 45] are from the present work.

$I_i^\pi \rightarrow I_f^\pi$	τ [ps]	$B_{EX}(E2)$ $[e^2fm^4]$	$B_{SMLB}(E2)$ $[e^2fm^4]$	$B_{SDGN}(E2)$ $[e^2fm^2]$
$8^+ \rightarrow 6^+$	$102(4) \times 10^6$	0.09(1)	2.0	0.77
$6^+ \rightarrow 4^+$	$91(3) \times 10^3$	3.0(2)	6.1	17.3
$4^+ \rightarrow 2^+$	32(11)	103(24)	6.8	85.2
$2^+ \rightarrow 0^+$	≤ 15	≥ 10	225	295

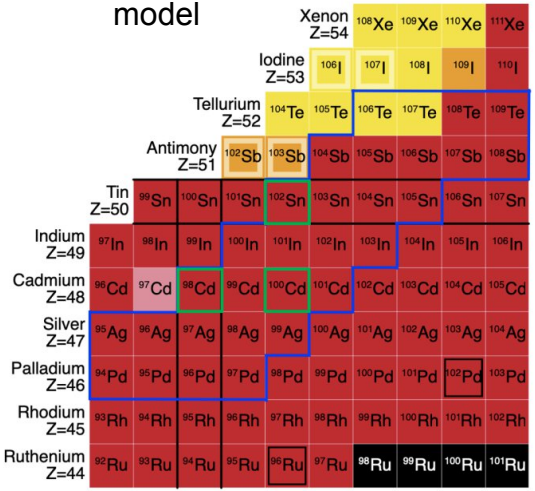
- v=2 to v=2 transitions should be strongly suppressed if seniority conserved
- **$4^+ \rightarrow 2^+$ transition strength greatly enhanced!**
- Interpreted as constructive interference between v=2 and v=4 configurations of same spin

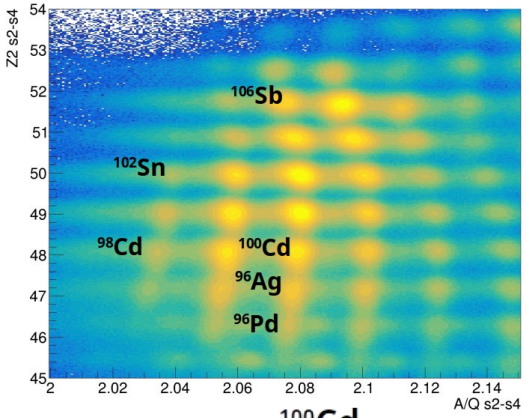
B. Das, B. Cederwall *et al.*, Nature of seniority symmetry breaking in the semimagic nucleus ^{94}Ru, PRC Letters 105, L031304 (2022)

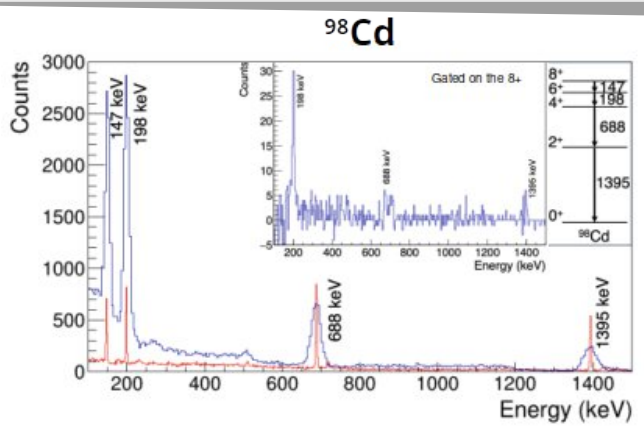
Core breaking in the most neutron-deficient Sn isotopes

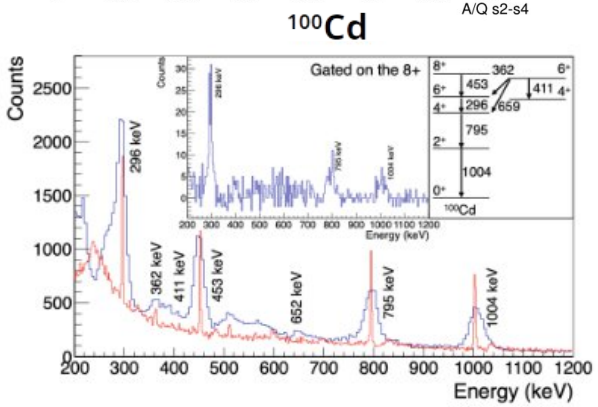
Mengoni (Padova), Zhang (Padova)

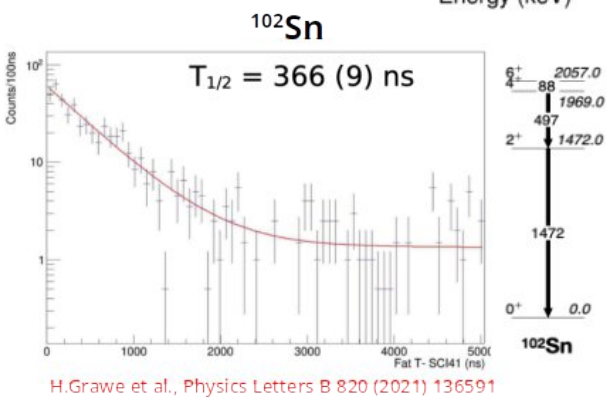
- Experimental study of the ^{100}Sn region to assess:
  - the robustness of the **double shell closure**
  - **core-breaking** effects
  - the role of **p-n pairing** and **quadrupole** terms in shell model







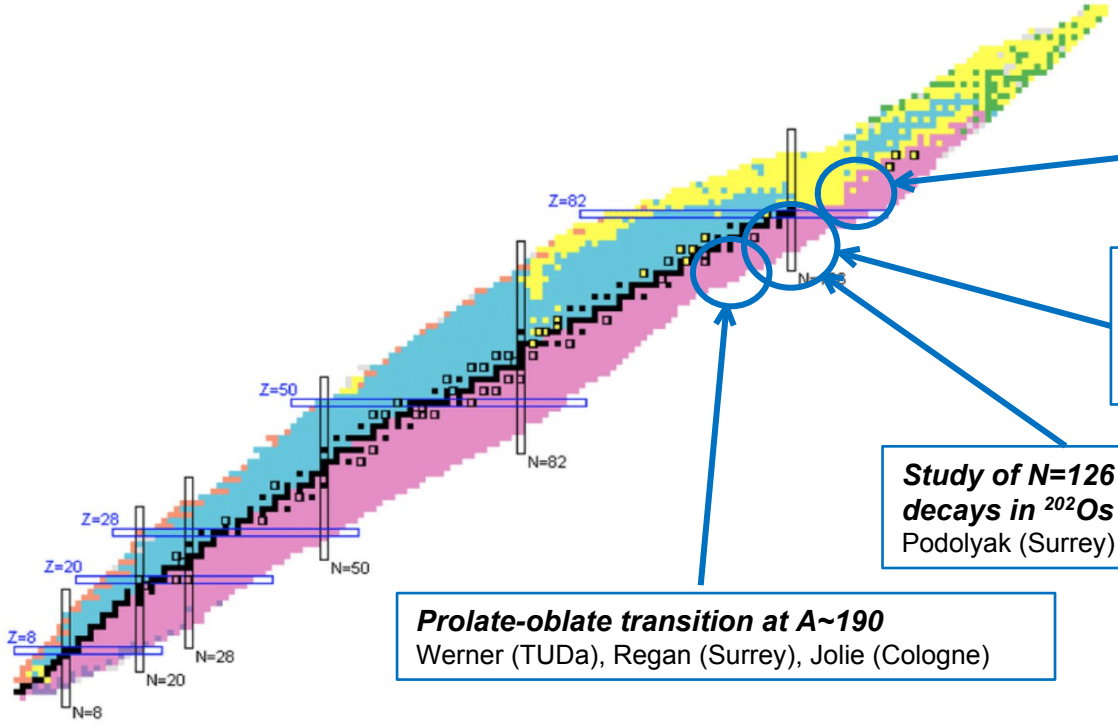




H.Grawe et al., Physics Letters B 820 (2021) 136591

Material: Zhang, Polettini

Complementary studies approaching, at and beyond the N=126 closure



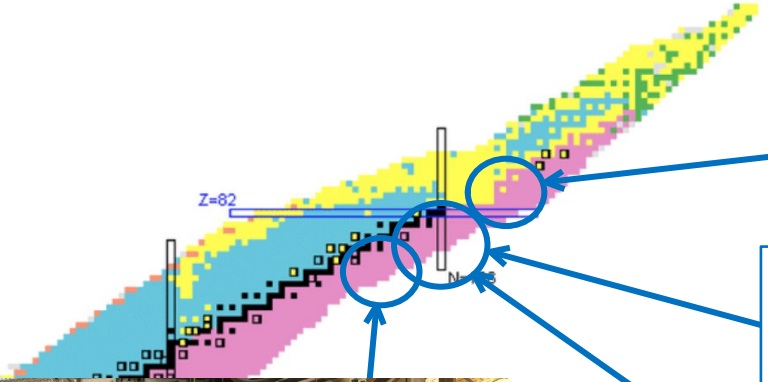
Investigation of 220<A<230 Po-Fr nuclei lying in the south-east frontier of the A~225 island of octupole deformation
Benzoni (Milano), Valiente Dobon (Legnaro)

Investigation of the beta-strength crossing N=126 and the formation of the 3rd r-process abundance peak
Tain, Morales, Nacher (Valencia)

Study of N=126 nuclei: isomeric and beta decays in ^{202}Os and ^{203}Ir
Podolyak (Surrey)

Prolate-oblate transition at A~190
Werner (TUDa), Regan (Surrey), Jolie (Cologne)

Complementary studies approaching, at and beyond the N=126 closure



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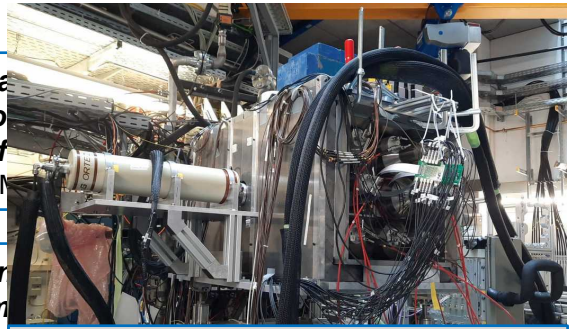

Investigation
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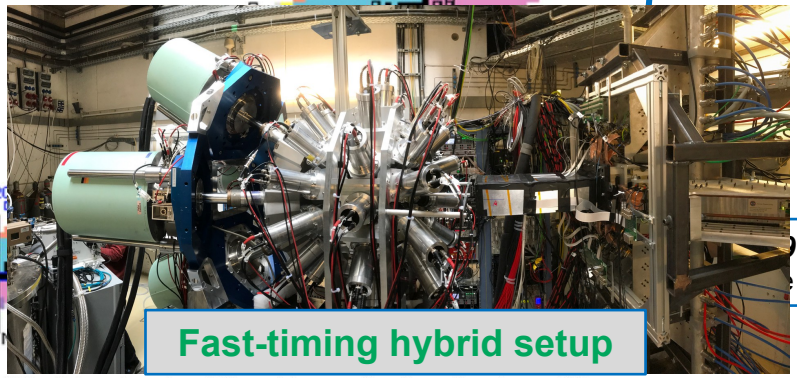
Tain, Morales,

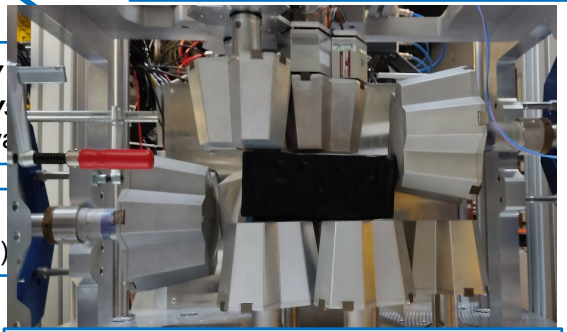
High-efficiency DTAS setup



Fast-timing hybrid setup

Study
decay
Podolya

00
(Cologne)



High-precision DEGAS setup