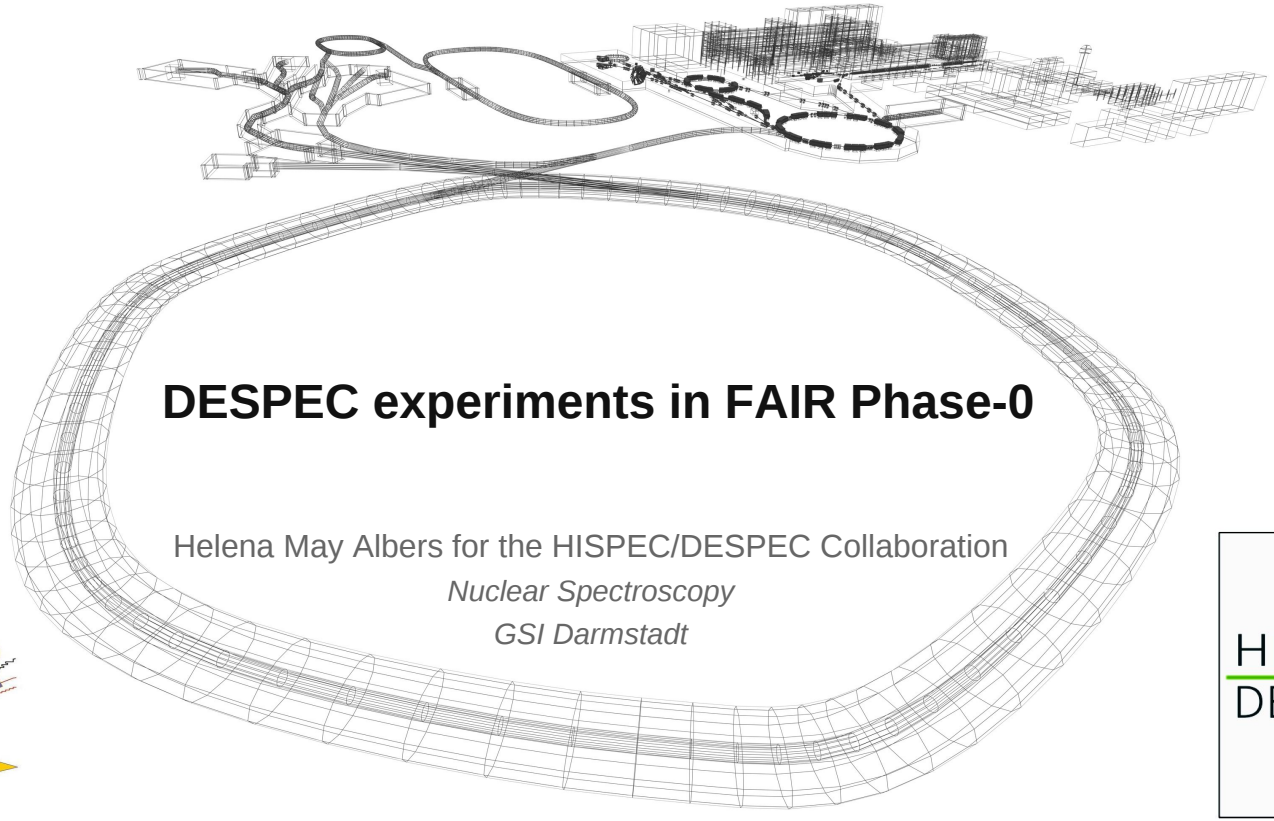
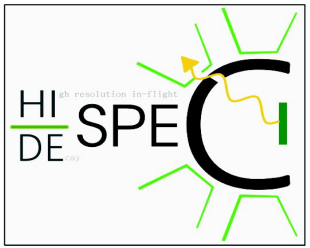


# DESPEC experiments in FAIR Phase-0

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

# Outline

- Introduction to DESPEC and FAIR
- Experimental setups
- Select physics highlights
- Summary and upcoming plans



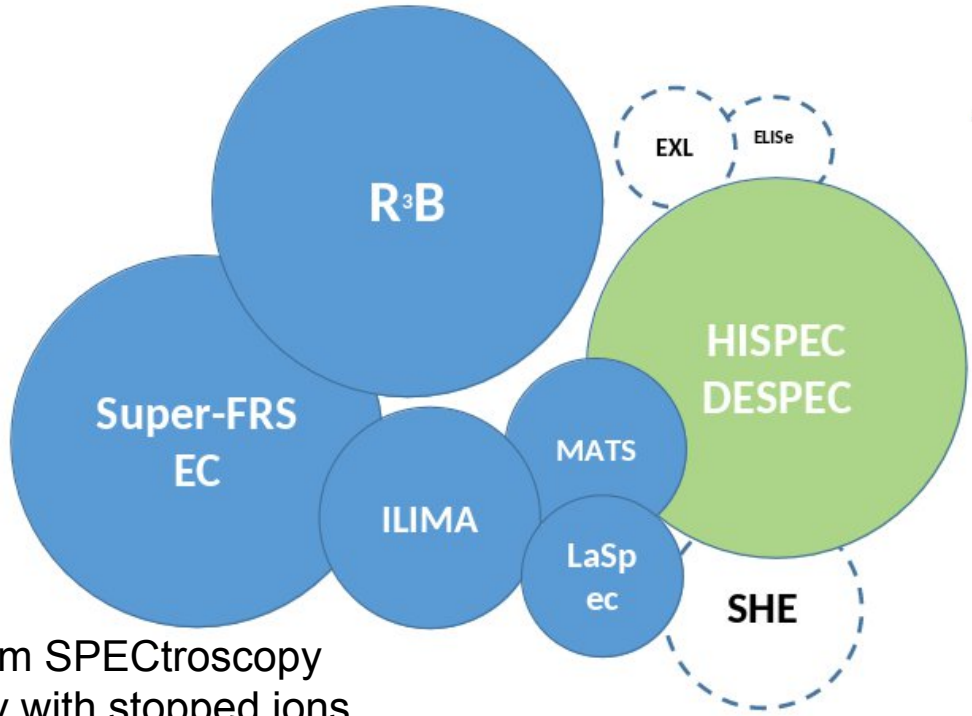

FAIR Phase 0 Research Program

# HISPEC/DESPEC Collaboration

HISPEC/DESPEC is part of the **NUSTAR** pillar, which has

**>700 members**

(incl. students, engineers)



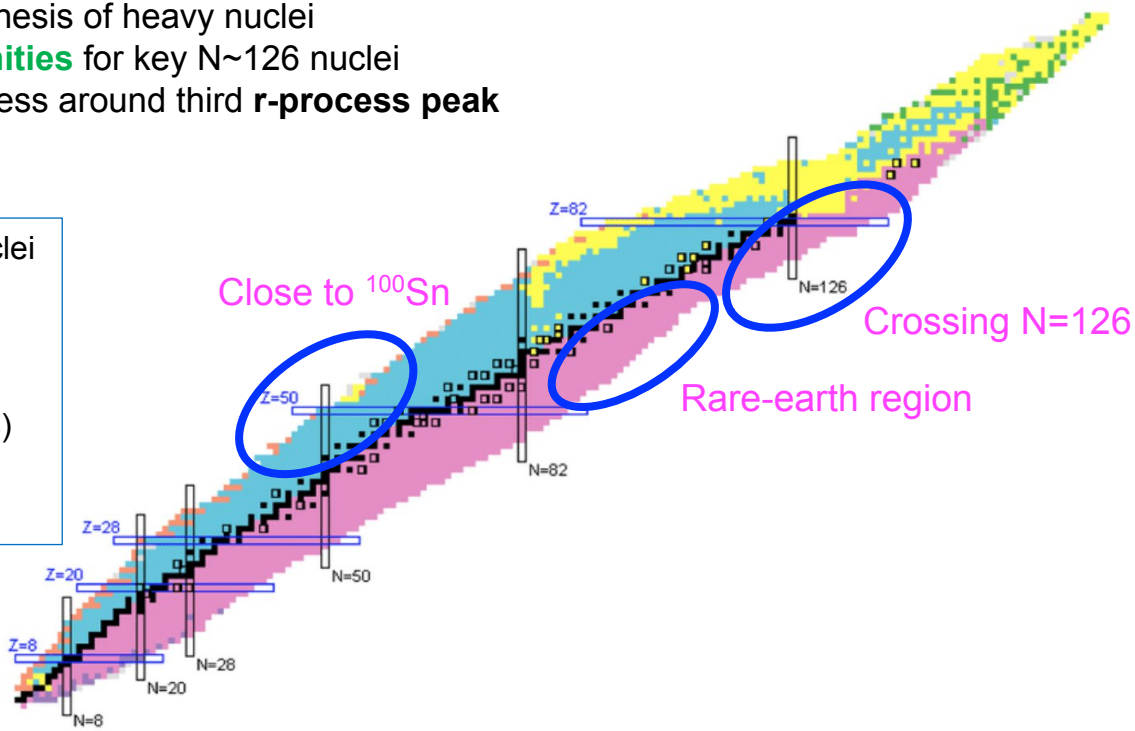

**HISPEC**: High-resolution In-beam SPECtroscopy
**DESPEC**: DEcay SPECtroscopy with stopped ions

Figure courtesy of A. Herlert

# DESPEC Physics goals

- 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)**

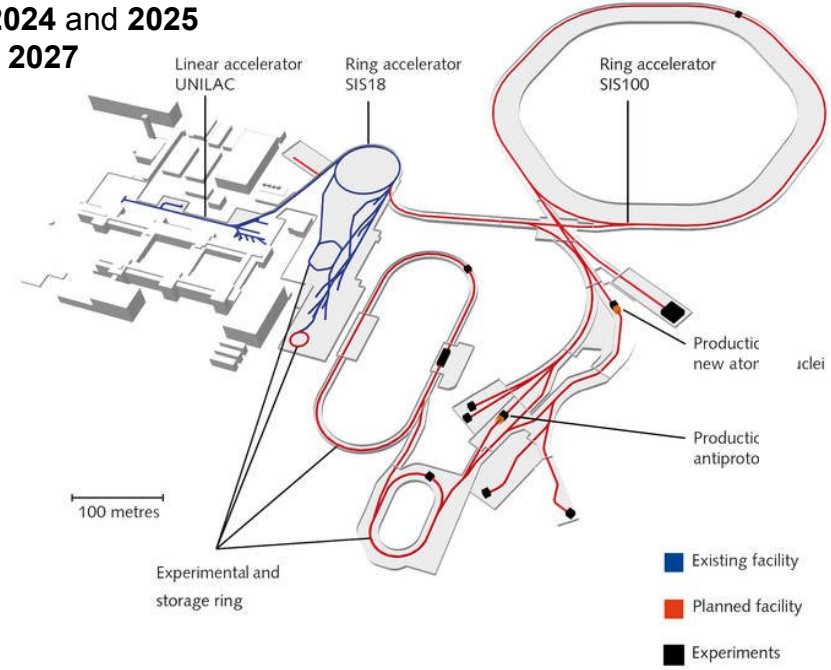
- Comprehensive decay information from key nuclei at secondary beam yields as low as
  ✓ ***one ion per hour***
- Sensitive to nuclear lifetimes spanning
  ✓ ***13 orders of magnitude*** (10ps-100s)
- Measurement of
  ✓ ***any mode of nuclear decay***



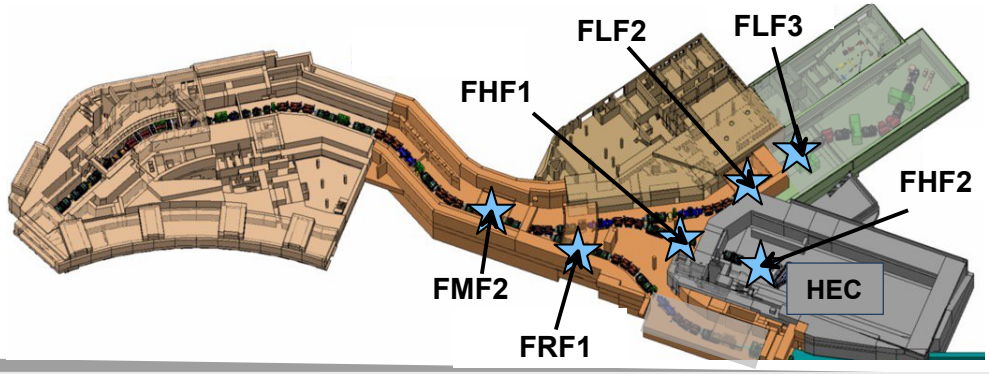
# DESPEC in FAIR Phase-0

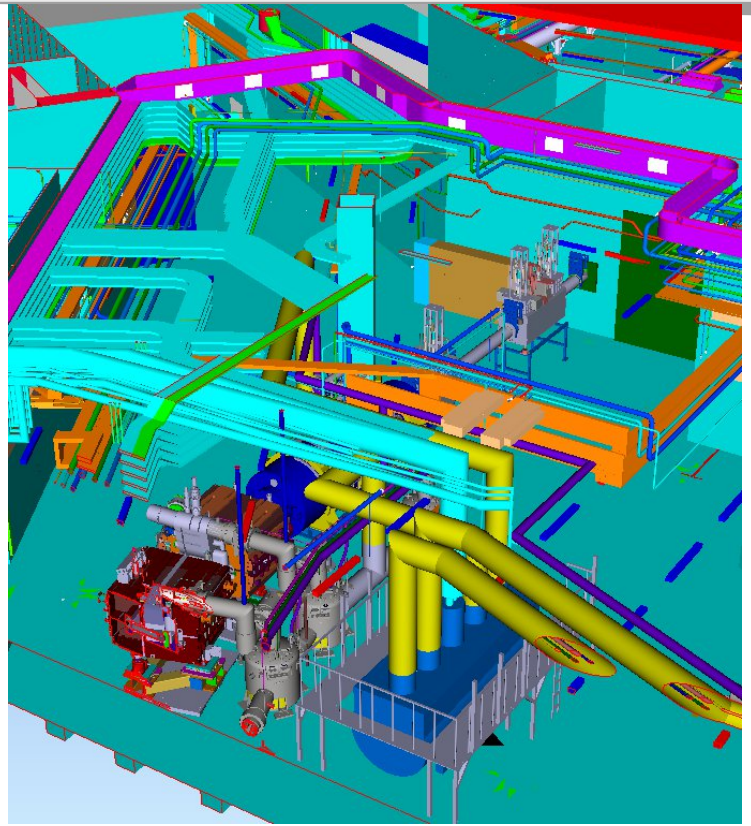
- FAIR Phase-0 operation began in 2019
- FAIR instrumentation and setups at GSI facilities
- DESPEC (physics) commissioning carried out in early **2020**
- Experimental campaigns in **2021** and **2022**, with more planned for **2024** and **2025**
- Future experiments at new S-FRS facility starting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

©D. Fehrenz, GSI/FAIR

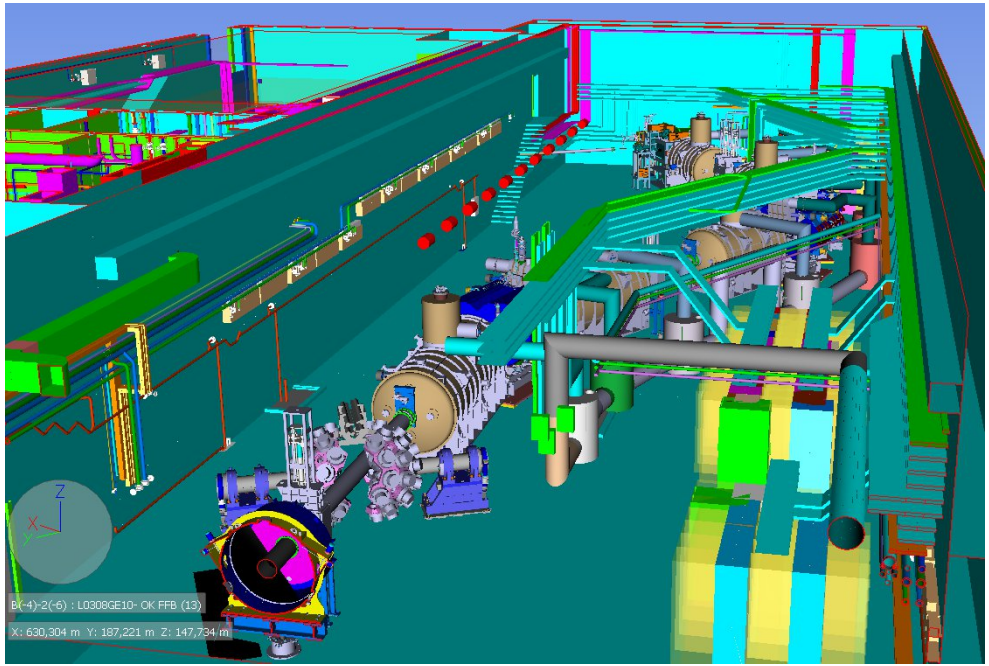


# FAIR Construction Status (FHF1)



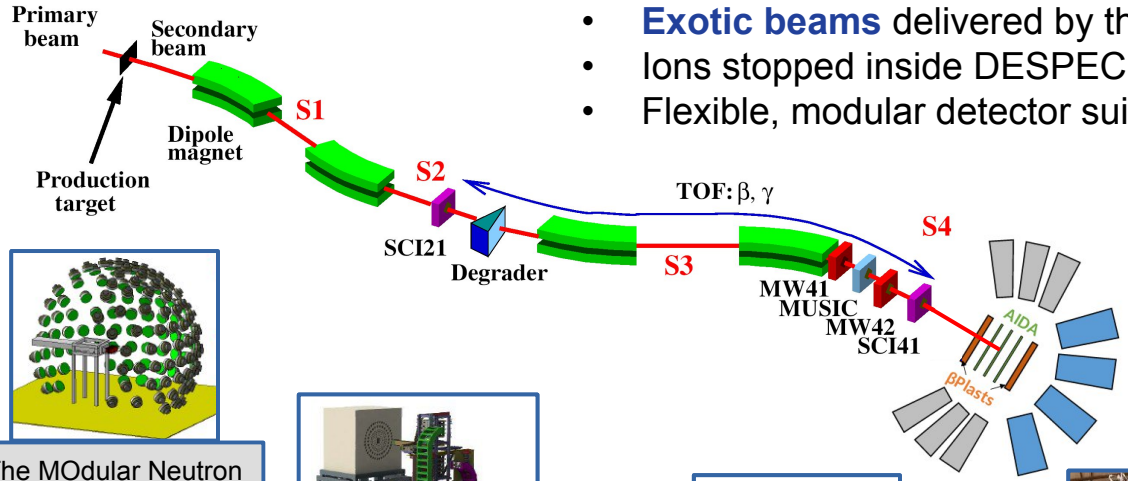



# FAIR Construction Status (LEC)




**NUSTAR Low-Energy Cave**

# DESPEC Setup Overview



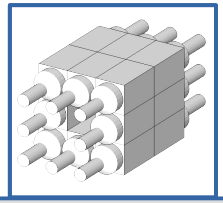

- **Exotic beams** delivered by the FRagment Separator (FRS)
- Ions stopped inside DESPEC setup
- Flexible, modular detector suite **tailored to physics goals**

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

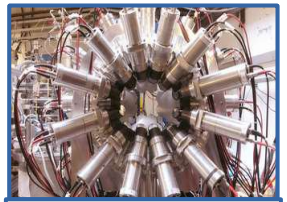


The MOdular Neutron SpectromeTER **(MONSTER)**

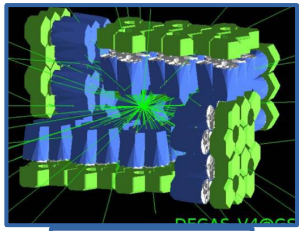
BEta-deLayEd Neutron detector **(BELEN)**
48 3He cylindrical counters



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



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



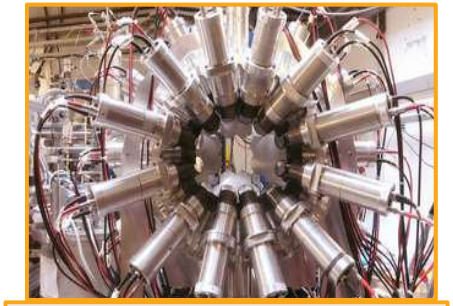
DESPEC Ge Array Spectrometer **(DEGAS)**

# Experimental campaigns 2020-2021

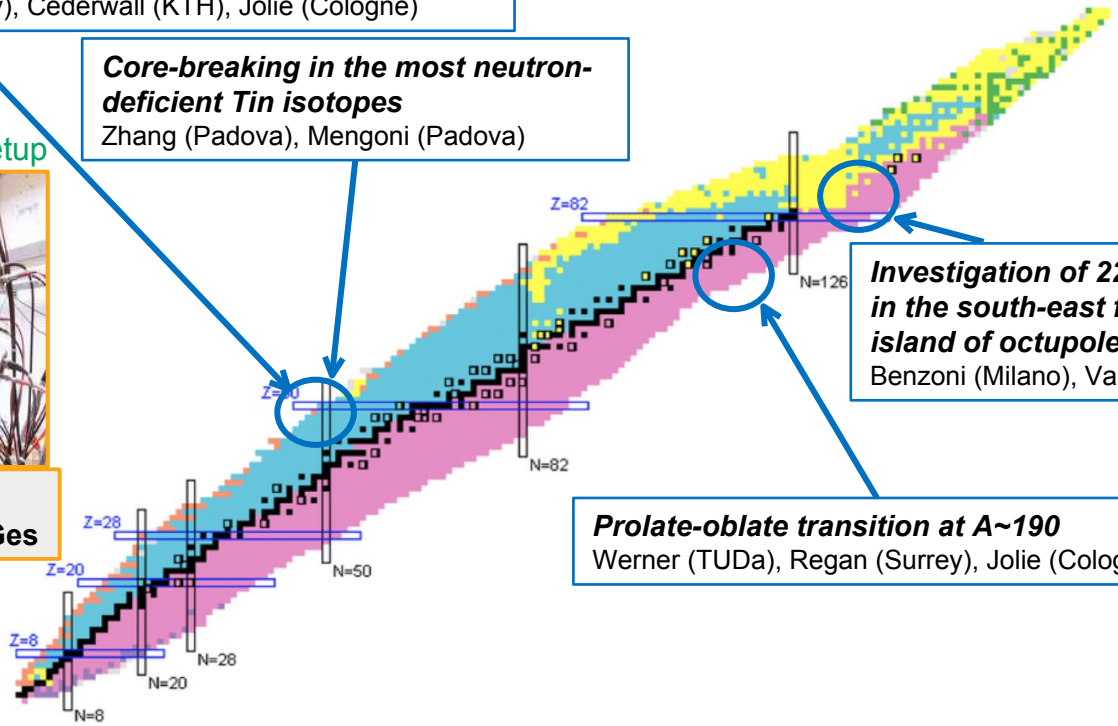
***Seniority transitions and EM transition rates in $^{94}$Pd***
Górska (GSI), Regan (Surrey), Cederwall (KTH), Jolie (Cologne)

***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**

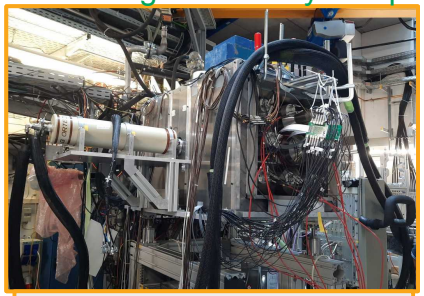



***Investigation of 220<A<230 Po-Fr nuclei lying in the south-east frontier of the A~225 island of octupole deformation***
Benzoni (Milano), Valiente Dobon (Legnaro)

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

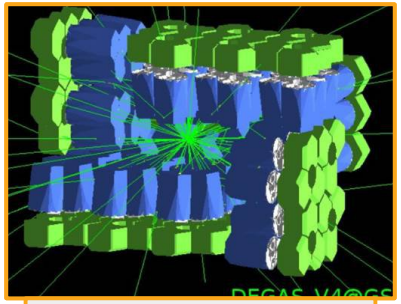
# Experimental campaign 2022

**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)

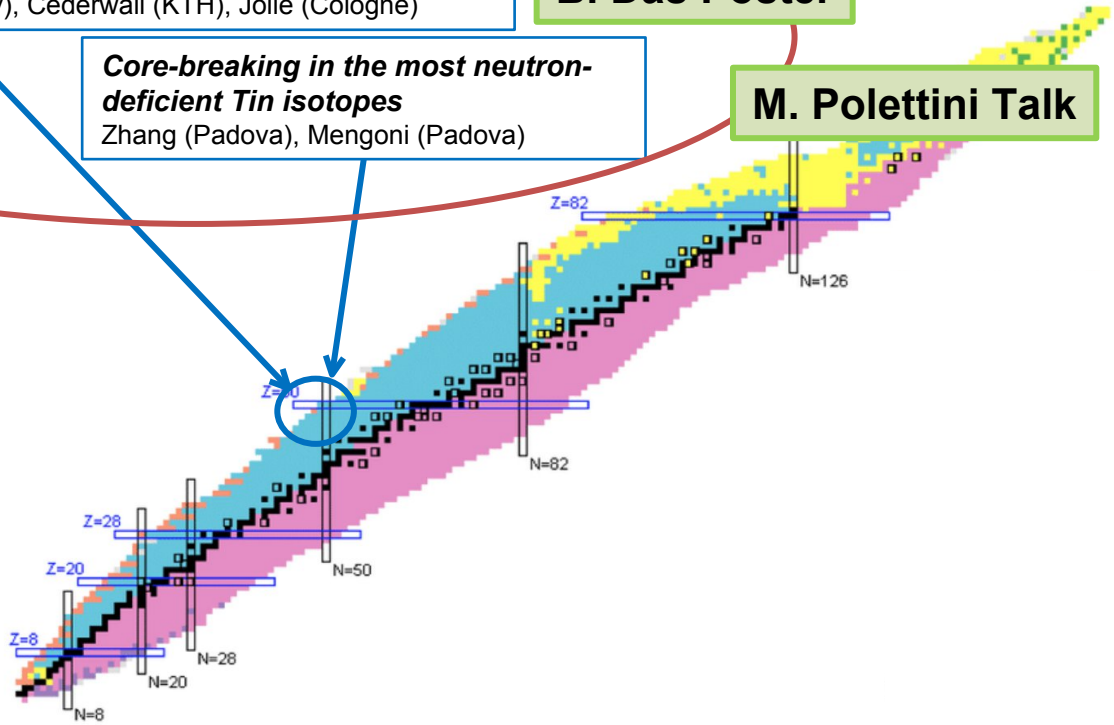
# Structure studies close to doubly-magic $^{100}$Sn

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

**B. Das Poster**

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

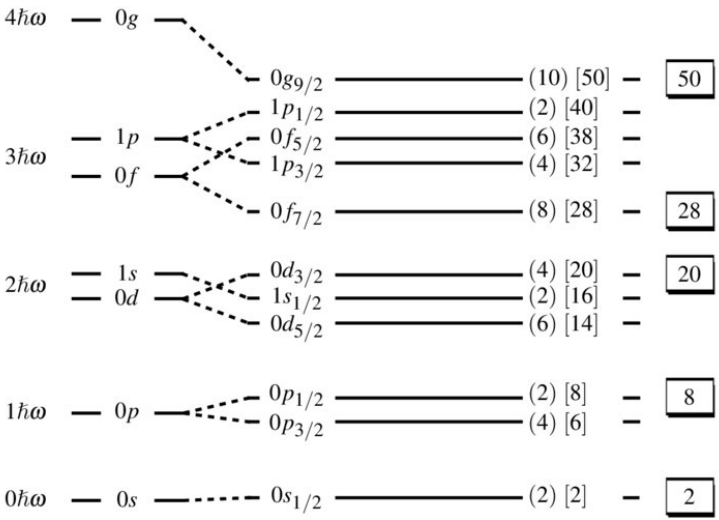
**M. Polettini Talk**

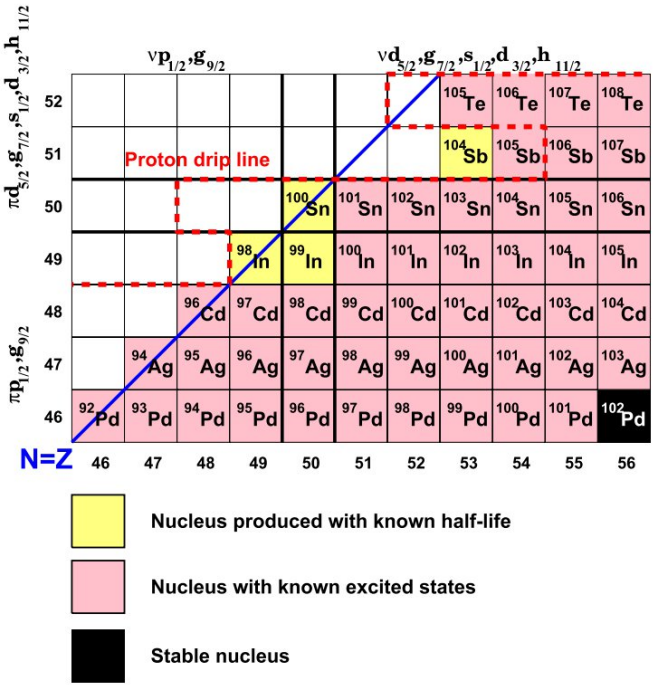


# Seniority transitions and EM transition rates in $^{94}$Pd

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

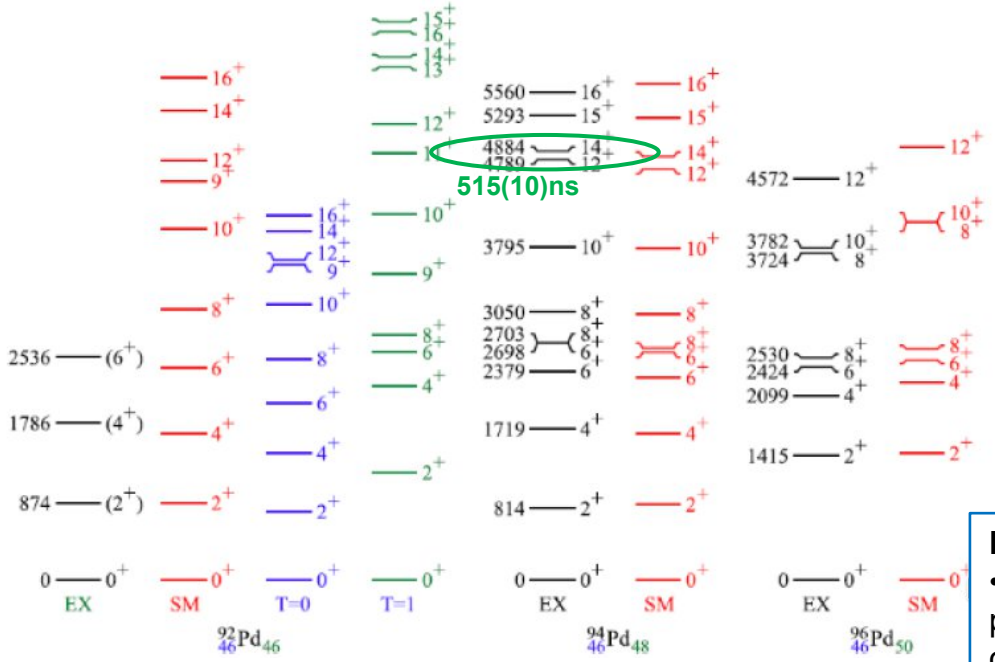



T.Faestermann, M.Górska, H.Grawe, Prog. Part. Nucl. Phys. 69, 85 (2013)

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

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



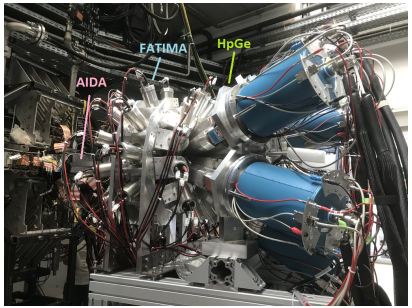

T.Faestermann, M.Górska, H.Grawe, Prog.Part.Nucl.Phys. 69, 85 (2013)
**SM:** R.Gross and A.Frenkel, Nucl. Phys. A 267, 85 (1976)
**Isomer $T_{1/2}$:** Häfner *et al.*, Phys. Rev. C 100, 024302 (2019)
(SM: GF interaction in the $\pi\nu(p_{1/2}g_{9/2})$ model space)

**Main Goals:**

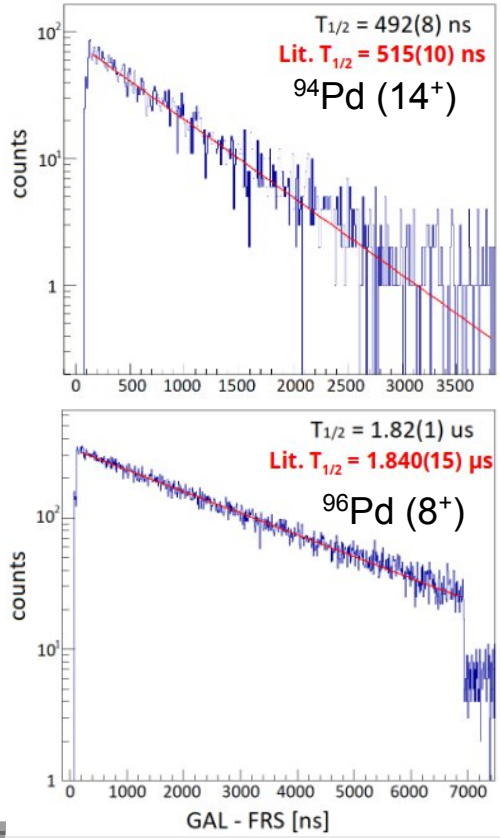
. $^{96}$Pd – seniority-type level scheme, $^{92}$Pd nearly constant energy spacing:
.***$^{94}$Pd intermediate nucleus***
. Competition between isoscalar (T = 0) and isovector (T = 1) components of pn interaction
. Importance of cross shell (N,Z = 50) excitations
. B(E2) values of **$8^+$ and $6^+$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

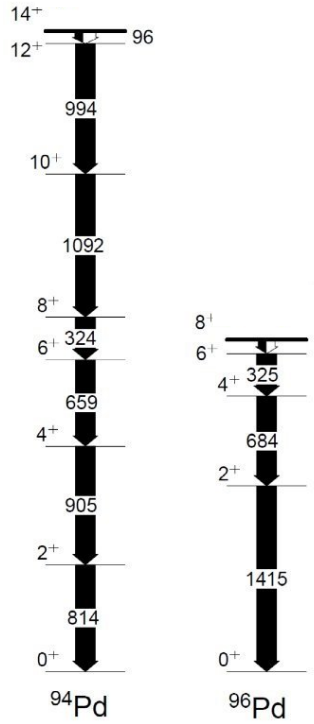
**Experiment:**

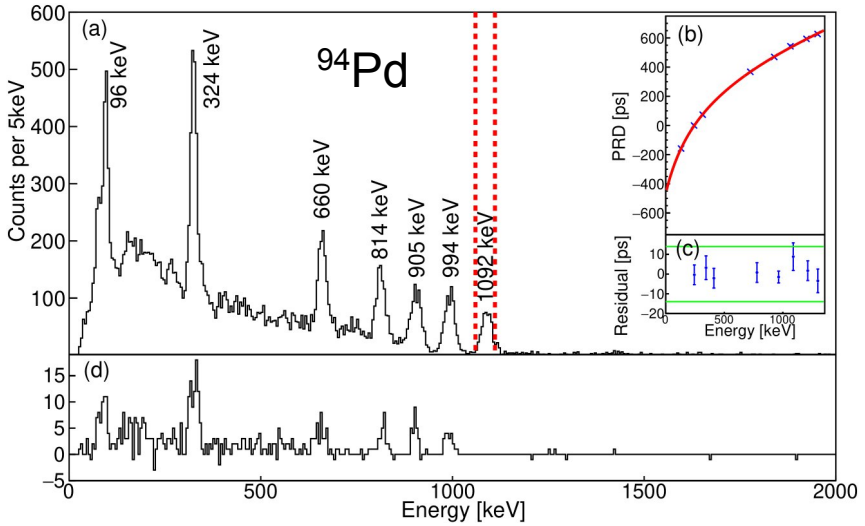
- Fragmentation of $^{124}$Xe primary beam (982 MeV/u) on a $^{9}$Be target
- DESPEC 'fast-timing' setup
- Hybrid array of HPGe (GALILEO) and $LaBr_3$ (FATIMA)



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



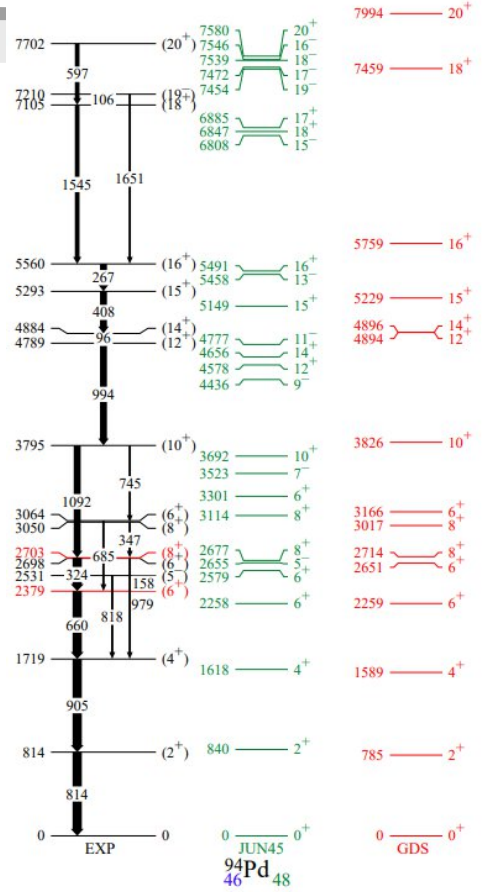




- $^{96}$Pd confirmed validity of measurement (S. Jazrawi *et al.*, Radiation Physics and Chemistry 200, 112234 (2022))
- For shorter (ps) lifetimes, Generalized Centroid Shift Method (GCSM) was employed

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



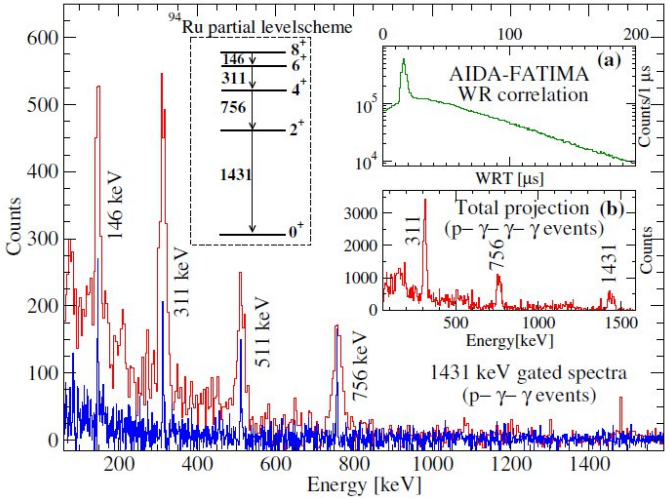

- Excellent reproduction of experimental data by LSSM (GDS) calculation -> importance of core excitations in the structure of $^{94}$Pd
- Importance of T = 0 pn interaction component in nuclear structure evolution from $^{96}$Pd to $^{92}$Pd

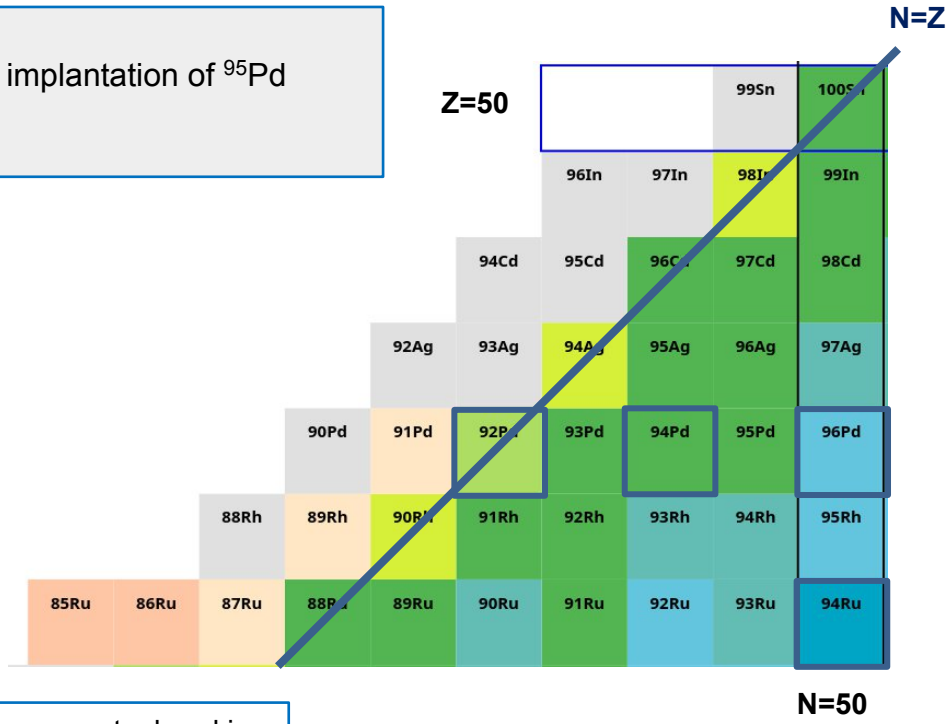
| Quantity [ns/$e^2fm^4$] | $I_i^\pi - I_f^\pi$ | | |
|---|---|---|---|
| | $14^+ \rightarrow 12^+$ | $8^+ \rightarrow 6^+$ | $6^+ \rightarrow 4^+$ |
| $T_{1/2}$ | 515(1) | 0.755(106) | ≤0.05 |
| $B_{exp}(E2)$ | 52.1(1) | $205^{+34}_{-25}$ | ≥90 |
| $B_{JUN45}(E2)$ | 113 | 277 | 496 |
| $B_{GDS}(E2)$ | 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

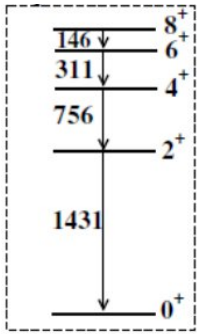
- Lifetimes of **states in $^{94}$Ru**
- Measured after **β-delayed proton emission** following implantation of $^{95}$Pd ($21/2^+$ isomer)
- Feeding $8^+$ isomer in $^{94}$Ru (~70 μs)




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



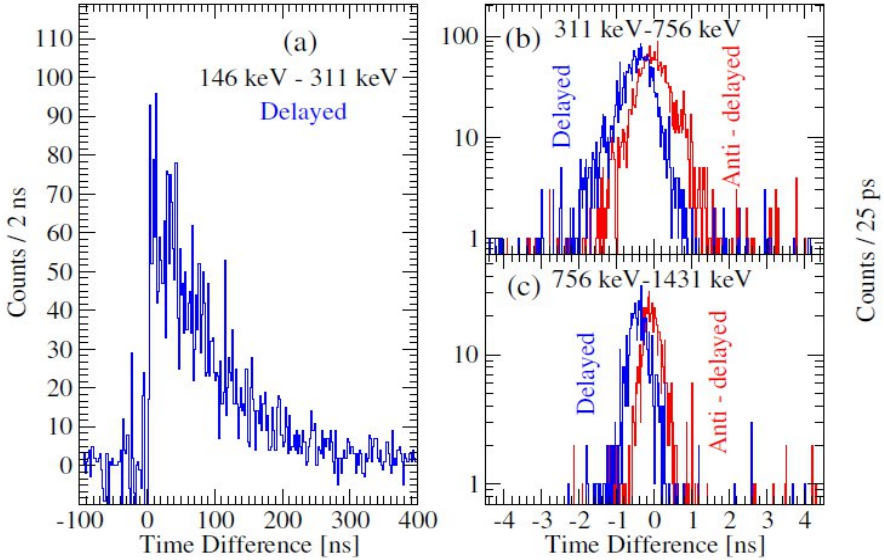




TABLE I. Experimental mean lifetimes and B(E2) strengths in $^{94}$Ru in comparison with various shell model predictions. Experimental data except for $8^+ \rightarrow 6^+$ [41, 45] are from the present work.

| $I_i^\pi \rightarrow I_f^\pi$ | $\tau$ [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 |
| $2^+ \rightarrow 0^+$ | $\leq 15$ | $\geq 10$ | 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

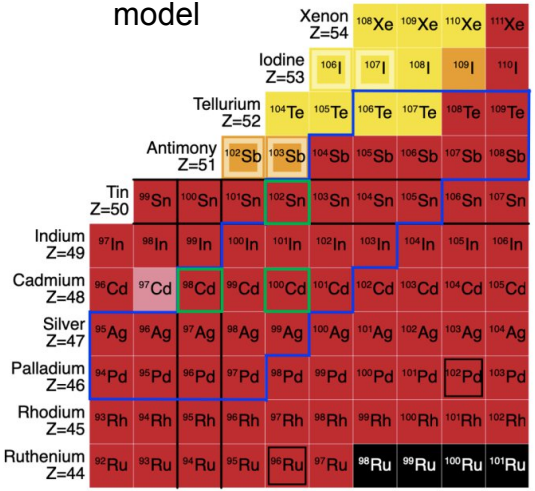
B. Das, B. Cederwall *et al.*, Nature of seniority symmetry breaking in the semimagic nucleus $^{94}$Ru, PRC Letters 105, L031304 (2022)

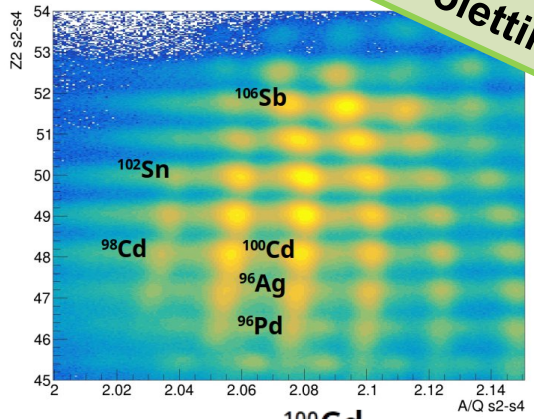
# Core breaking in the most neutron-deficient Sn isotopes

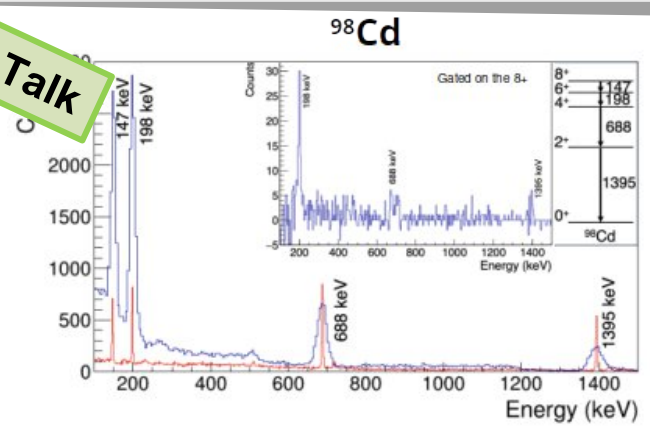
Mengoni (Padova), Zhang (Padova)

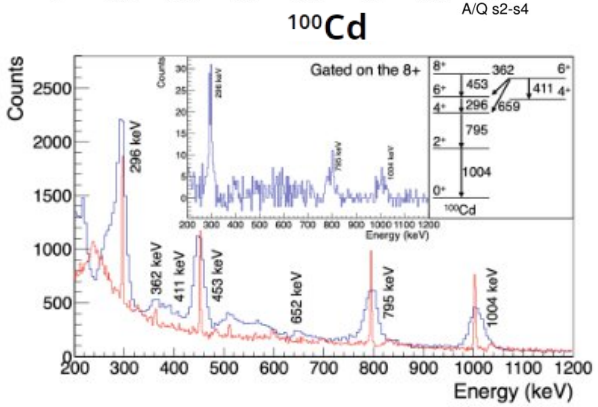
M. Polettini Talk

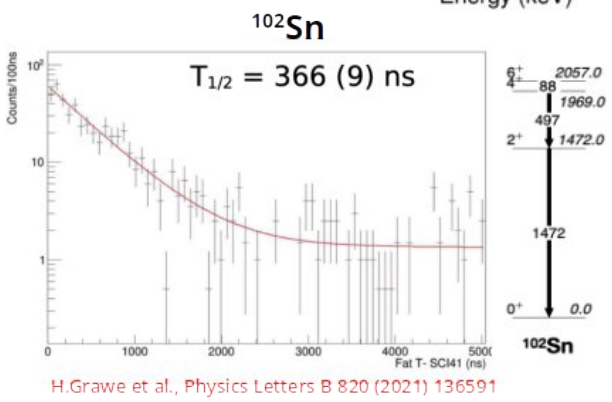
- Experimental study of the $^{100}$Sn region to assess:
  - the robustness of the **double shell closure**
  - **core-breaking** effects
  - the role of **p-n pairing** and **quadrupole** terms in shell model



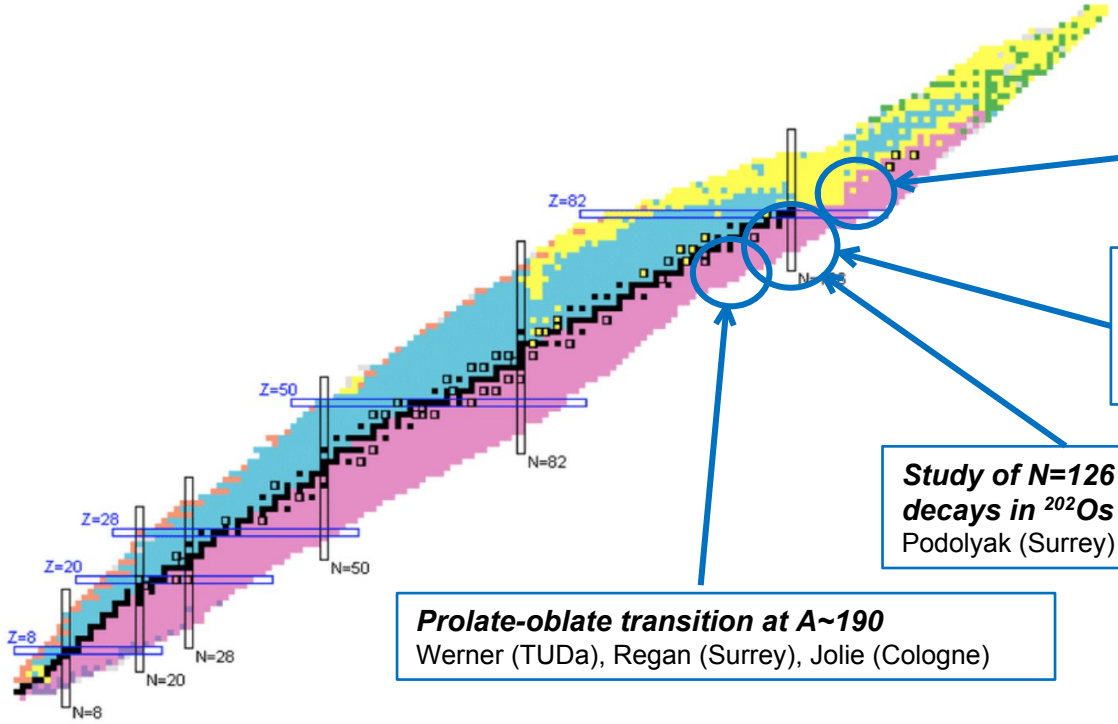




H.Grawe et al., Physics Letters B 820 (2021) 136591

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)

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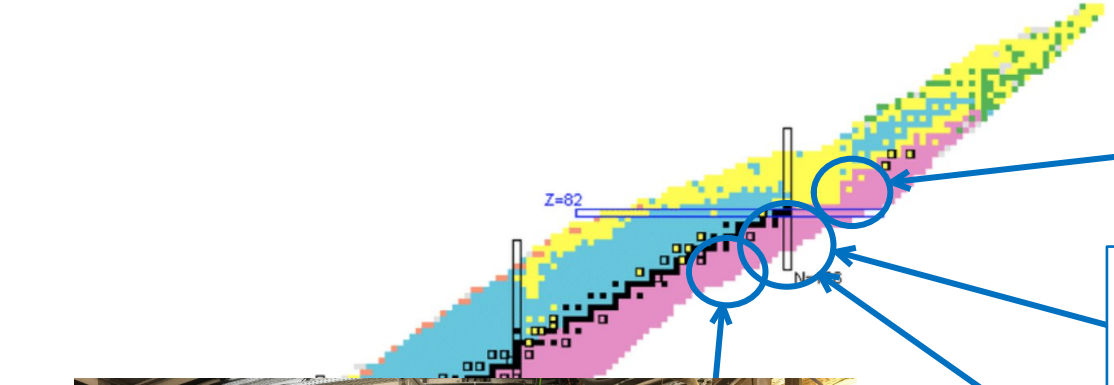


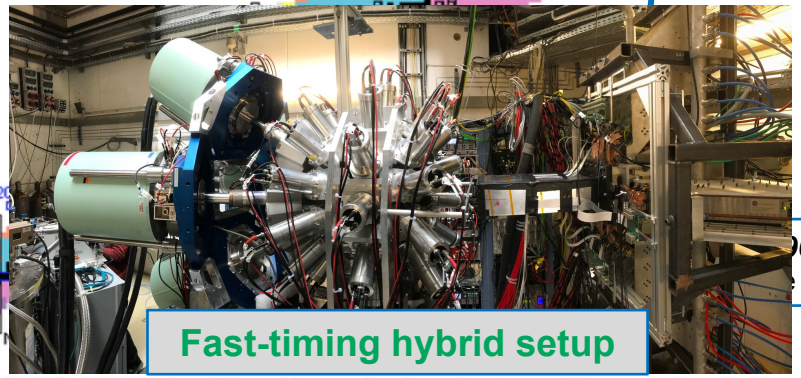

Fast-timing hybrid setup

***Investiga***
***in the so***
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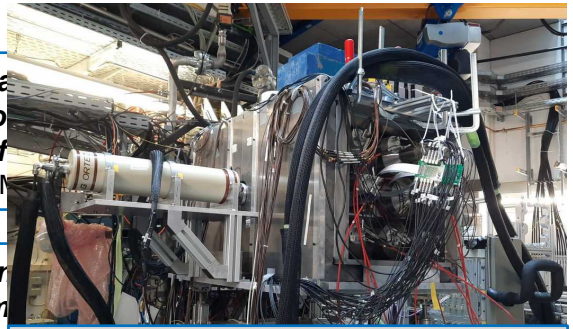
Benzoni (I

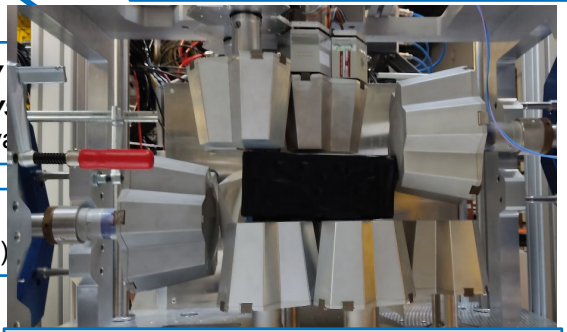


High-efficiency DTAS setup

***Investigation***
***and the form***
***abundance p***
Tain, Morales,

***Study***
***decay***
Podolya

***00***
(Cologne)

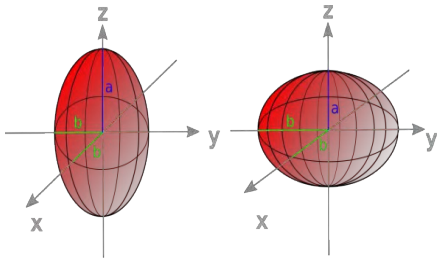


High-precision DEGAS setup

# Prolate-oblate transition at A~190

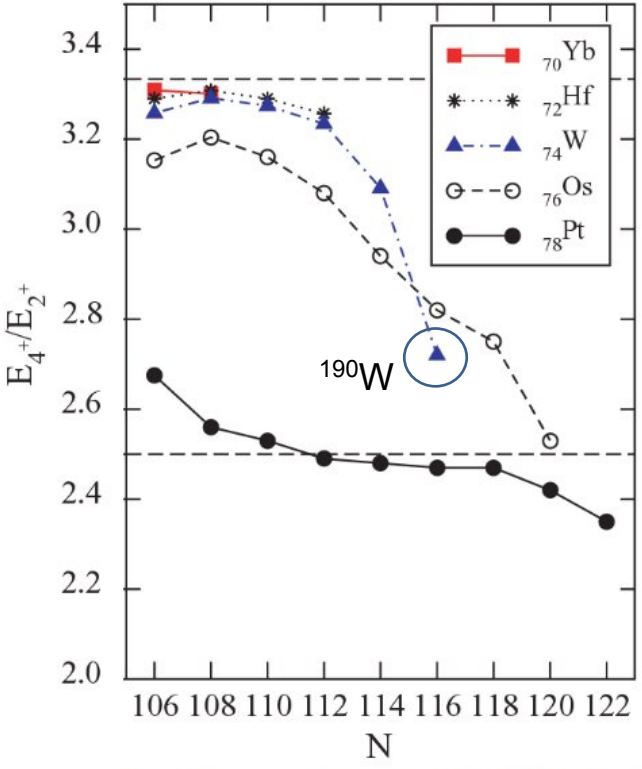
Werner (TU Darmstadt), Regan (Surrey), Jolie (Cologne)

- **Fast-timing measurements, isomer decays, spectroscopy**
- n-rich Ta, Re, Hf, W isotopes ($^{188,189}$Ta, $^{190}$W,...)
- Fragmentation of $^{208}$Pb on $^{9}$Be
- DESPEC ‘fast-timing’ hybrid setup
- Detailed spectroscopy and B(E2;$2^+_1 \rightarrow 0^+_1$)s




## Main Goals:

- Lifetime of $2_1^+$ state in $^{190}$W
- Drop in the B(E2) values expected in case of a prolate-oblate shape transition
- Isomerism and nuclear structure in $^{188,189}$Ta



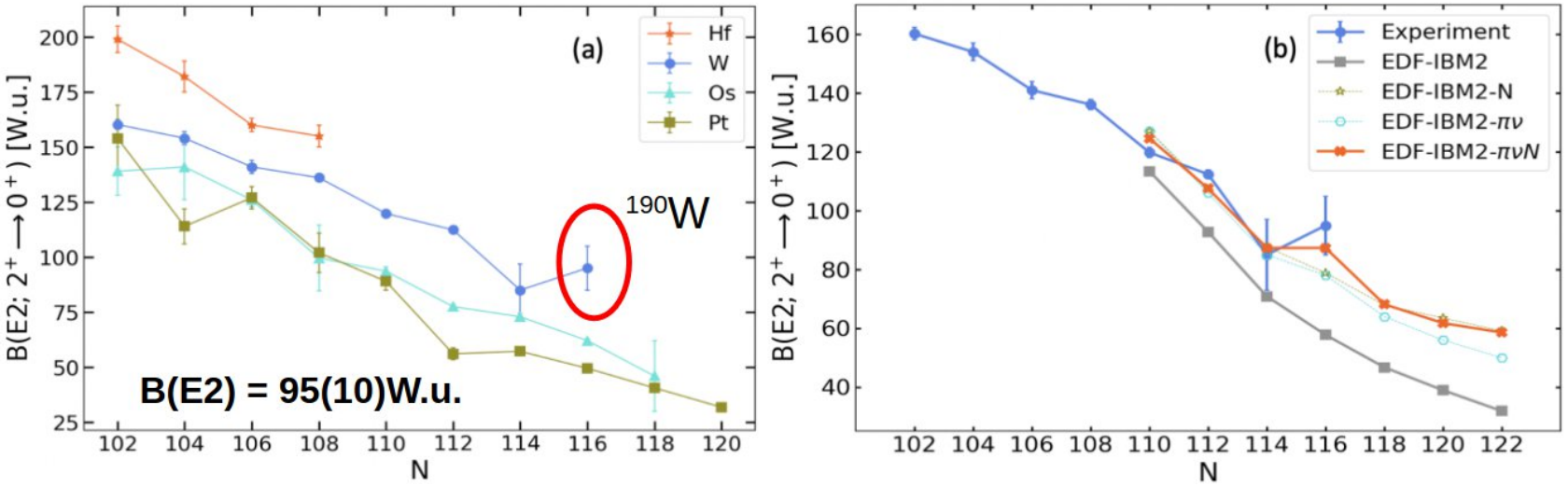

P. Sarriguren et al., Phys. Rev. C 77, 064322 (2008)

PhD work of E. Sahin (TUDa) and S. Alhomaidhi (TUDa)

# Prolate-oblate transition at A~190

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

**Results for $^{190}$W**




- Combined approach of scaling effective boson charge $e_B$ and differing values of $e_\pi$ and $e_\nu$ 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)

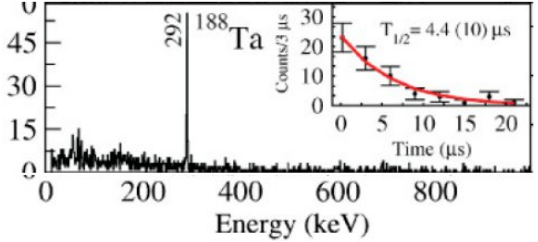
| | |
|---|---|
| EDF-IBM2: | the effective charges ( p = n = 0.13 eb) |
| EDF-IBM2-πνN: | the effective charges ( p = 0.145 eb and n = 0.2175 eb) |

E. Sahin *et al.*, in preparation

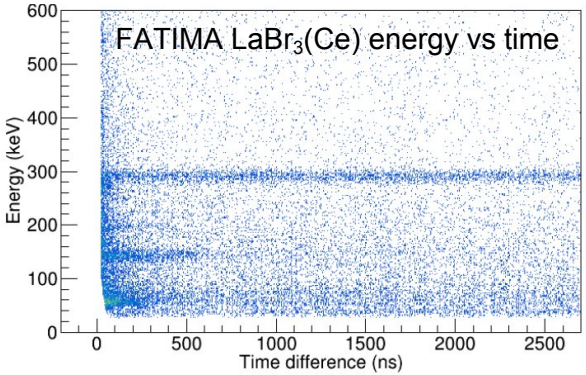
# Prolate-oblate transition at A~190

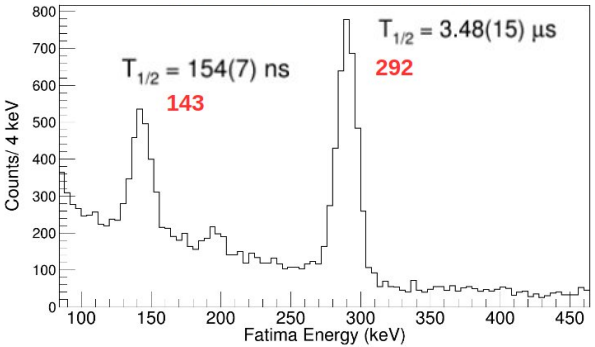
Werner (TU Darmstadt), Regan (Surrey), Jolie (Cologne)

**PRELIMINARY results for $^{188}$Ta**

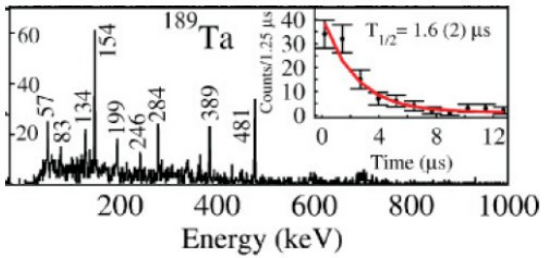



N. Alkhomashi *et al.*, Phys. Rev. C 80, 064308 (2009)

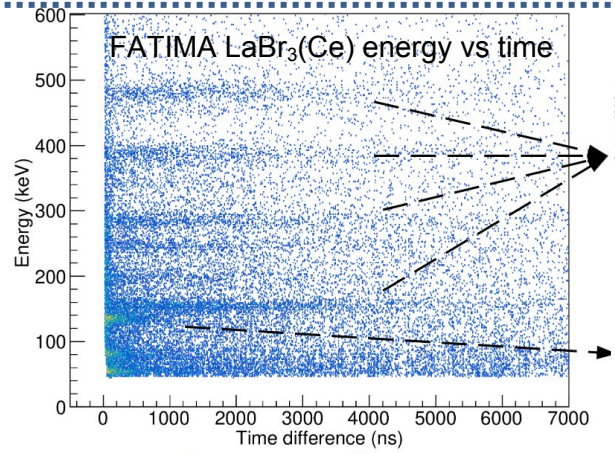


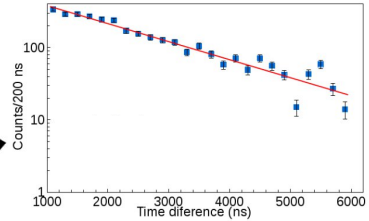




**PRELIMINARY results for $^{189}$Ta**

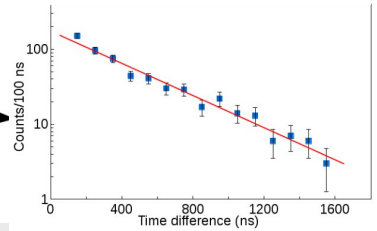



N. Alkhomashi *et al.*, Phys. Rev. C 80, 064308 (2009)




Isomer “1”
**$T_{1/2}$ = 1180(40)ns**




Isomer “2”
**$T_{1/2}$ = 230(10)ns**

# Upcoming experiments

***Structure of neutron-rich, rare-earth nuclei far from stability***

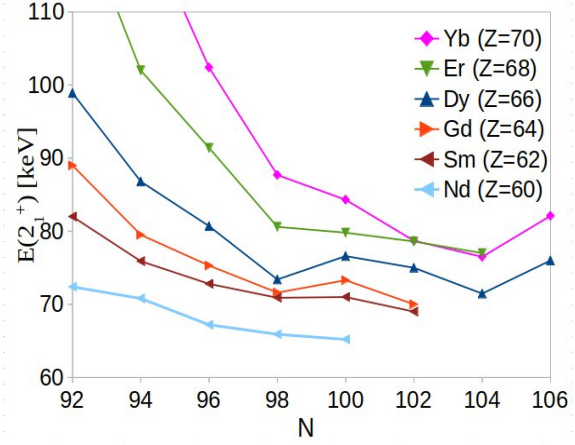
H.M.A (GSI), T. Grahn (JYFL), C.M. Petrache (Paris-Saclay), V. Werner (TUDa)

**Motivation:**

- 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
- $2^+$ (and $4^+$) **lifetimes** 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

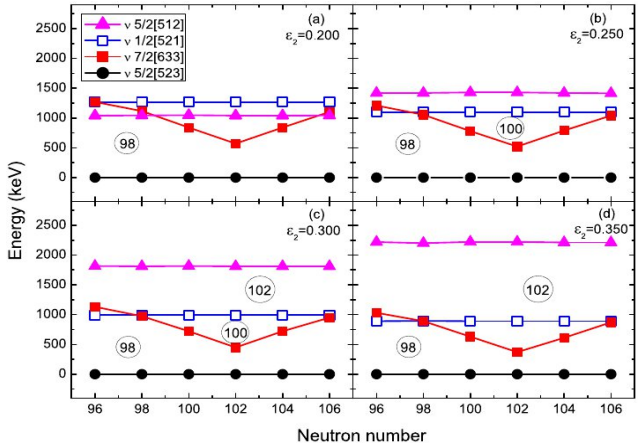
**Open questions:**

Are there deformed subshell closures?
Where are they located and what is their nature?
What is the underlying physics at play?
Where is the highest deformation, and why?




Energy systematics of $2_1^+$ states in even-even nuclei

- Conflicting interpretations from (e.g.) isomer decay spectroscopy, masses, β-decay halflives, decay properties,...
- Recent PSM calculations indicate location and size of subshell gaps **highly-dependent** on **deformation** and **neutron number N**
- **Fragmentation of $^{170}$Er**




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

# Upcoming experiments

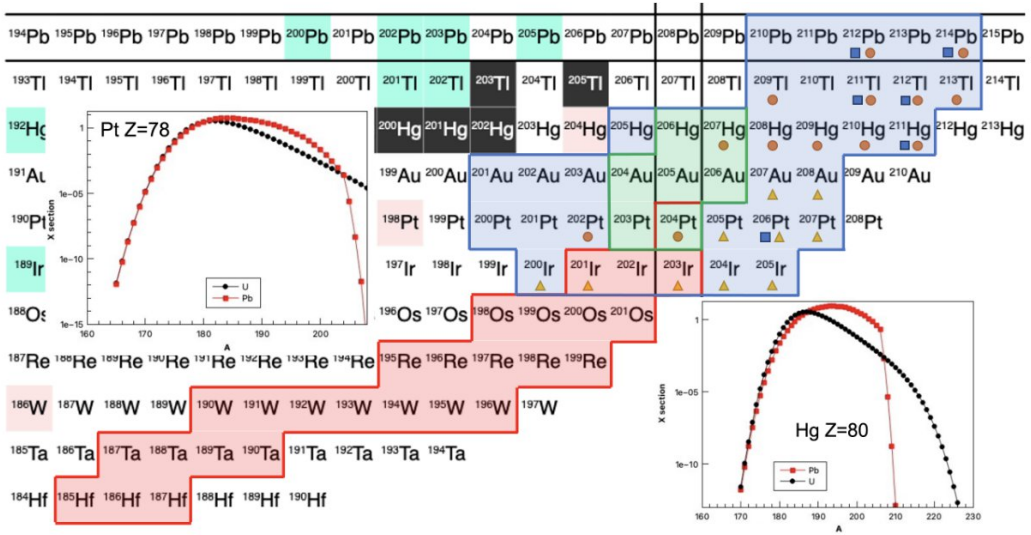
***Extending the quest towards the N=126 r-process waiting point***

Reiter (Cologne), Benzoni (Milano), Morales (Valencia), Polettini (Padova)

**Motivation:**

- Probing nuclear structure crossing N=126: a waiting point in r-process nucleosynthesis
- Testing ground for nuclear models: presence of large j neutron orbitals in an isolated space above the $^{208}$Pb core
- Role of first-forbidden (FF) transitions
- Accessing new isomeric states, nuclear lifetimes, level structure, beta-decay half-lives

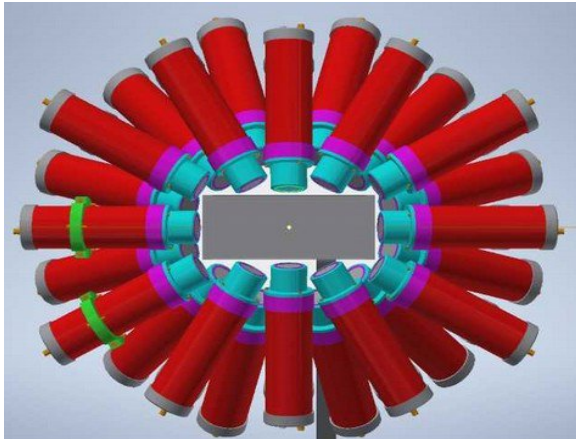
Primary beam of $^{238}$U @ 1 GeV/u on a $^{9}$Be target



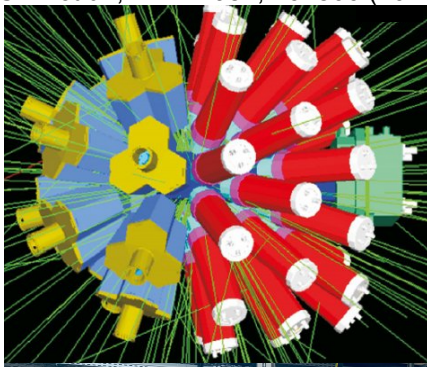

Red and green squares: regions studies in previous DESPEC experiments
Blue: region of interest for upcoming experiment

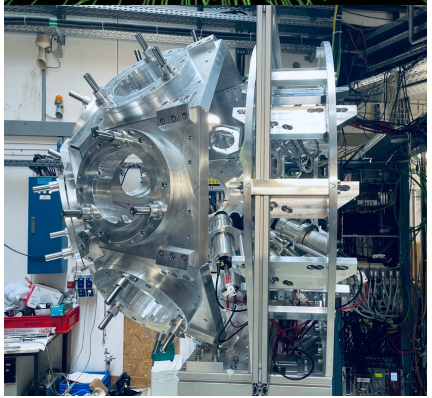
# Improved fast-timing array

- **12 DEGAS triple clusters** plus **36 FATIMA modules**
- 'Wide' 24x8 cm$^2$ **AIDA** + **βPlast**



G.S. Li *et al.*, NIM A 987, 164806 (2021)

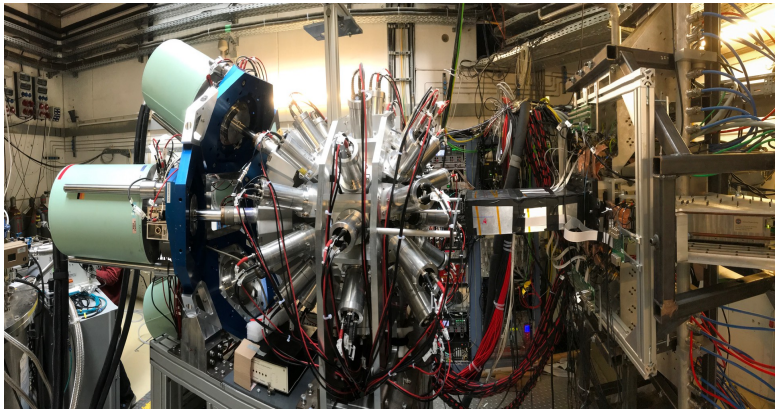


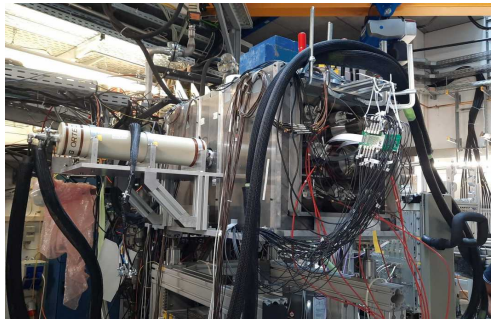


Local team:
G. Aggez, B. Bles, J. Bormans, C. Chatel, B. Das, J. Gerl, M. Górska, P. Herrmann, N. Hubbard, H. Huang, I. Kojouharov, J.E.L. Larsson, M. Mikołajczuk, H. Schaffner

# Summary

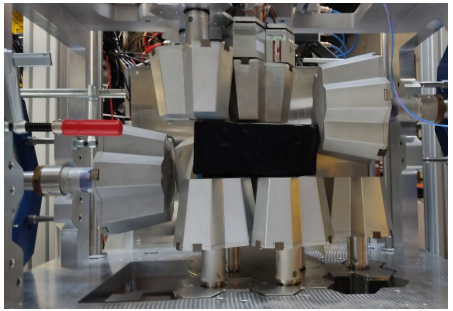
- DESPEC successfully commissioned in 2020
- Several campaigns in FAIR Phase-0 framework
- Suite of state-of-the-art detector systems tailored to experimental goals
- Physics highlights close to doubly-magic $^{100}$Sn and in heavy, n-rich nuclei





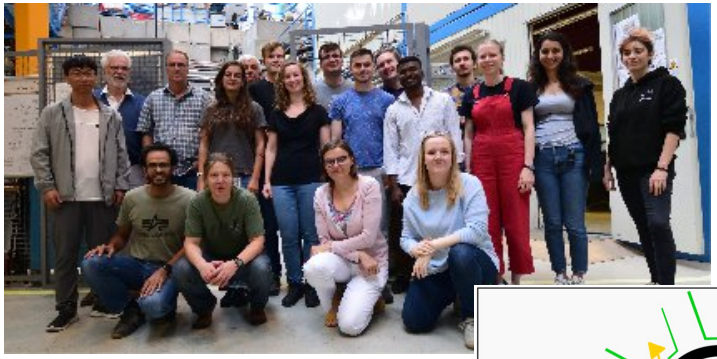
**Coming Soon:**

- Many more publications!
- New experiments in 2024 and 2025
- (soon-ish) NUSTAR (including DESPEC) prioritised for first experiments at FAIR



# With thanks to

G. Aggez, S. Alhomaidhi, T. Arici, M. Armstrong, A. Banerjee, G. Bartram, G. Benzoni, B. Das, T. Davinson, J. Gerl, M. Górska, T. Grahn, O. Hall, H. Heggen, P. Herrmann, N. Hubbard, S. Jazwari, C. Jones, I. Kojouharov, P. Koseoglou, G. Kosir, N. Kurz, G.-s. Li, M. Mikolajczuk, A.K. Mistry, A. Montalbano, A. Morales, C.M. Petrache, N. Pietralla, Zs. Podolyak, M. Polettini, P. Regan, M. Rudigier, D. Rodriguez, E. Sahin, H. Schaffner, A. Sharma, J-L. Tain, J. Vesic, V. Werner, M. Wiebusch, K. Wimmer, A. Yaneva, G. Zhang…



...and many more from the **HISPEC/DESPEC Collaboration**, the S480, S452, S460, S496, S450, S505, S100 and S181 collaborations, and the **FRS and EE Groups**