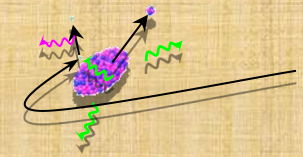


UNIVERSITÀ DEGLI STUDI DI MILANO

INFN Istituto Nazionale di Fisica Nucleare

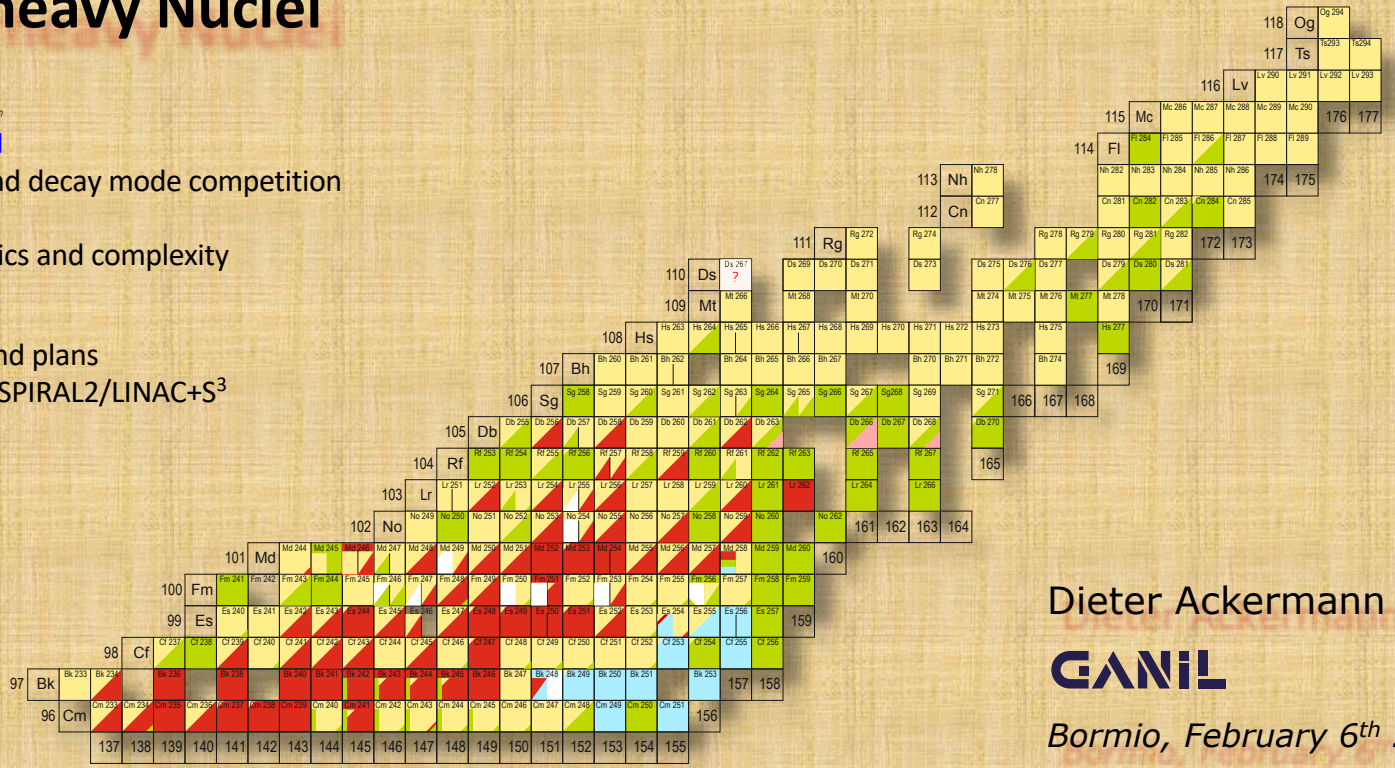
VIIth Topical Workshop on
Modern Aspects in Nuclear Structure

The Many Facets of Nuclear Structure

BORMIO 3-8 February 2025

Metastable States in Superheavy Nuclei

- **examples in SHN**
  - isomers and decay mode competition
  - *K*-isomers
  - low statistics and complexity
- **perspectives**
  - facilities and plans
    (for GANIL SPIRAL2/LINAC+S^3

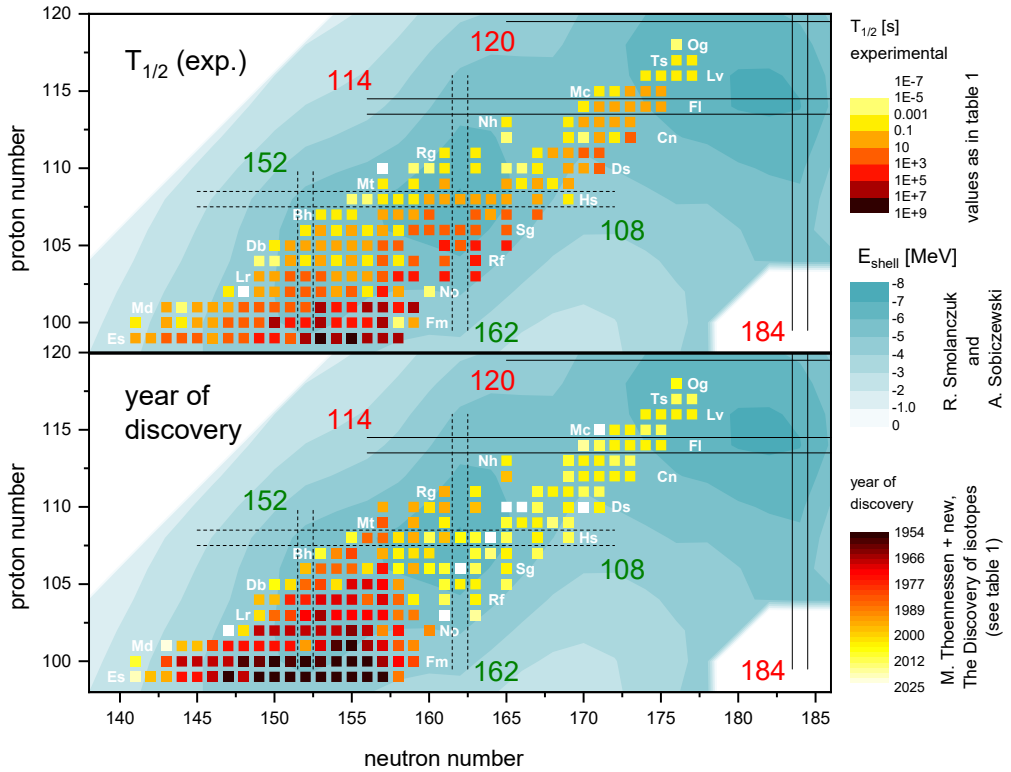


Dieter Ackermann

GANIL

Bormio, February 6th 2025

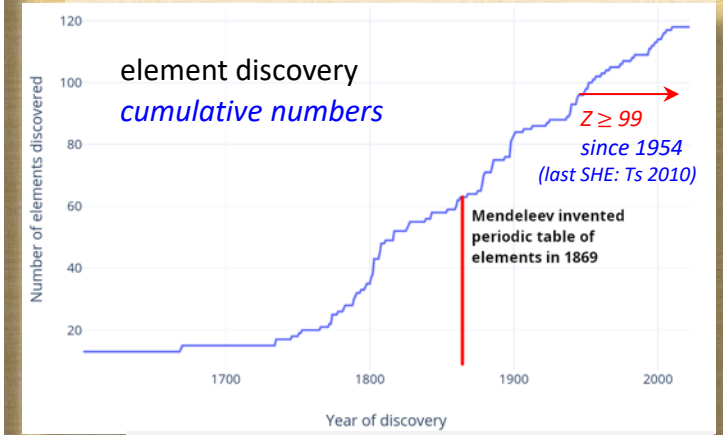
SHE/SHN – einsteinium to oganesson



D. Ackermann arXiv:2501.04053

198 isotopes (as of 2024)

$T_{1/2}$ **shortest:** ^{250}No: 4.2 μs **longest:** ^{252}Es: 472 days



See also Michael Thoenesssen "The discovery of Isotopes"
https://people.frib.msu.edu/~thoennes/isotopes/

Present SHE searches

Z= 119
- **RIKEN, Wako, Japan** ^{51}V+^{248}Cm
- **IMP, Lanzhou, China** ^{54}Cr+^{243}Am

Z= 120
- **FLNR/JINR, Dubna, Russia** ^{54}Cr+^{248}Cm
- **LBNL, Berkeley Cf, USA (?)** ^{50}Ti+^{249}Cf
- **(news on ^{50}Ti+^{244}Pu→^{290}Lv+4n)**

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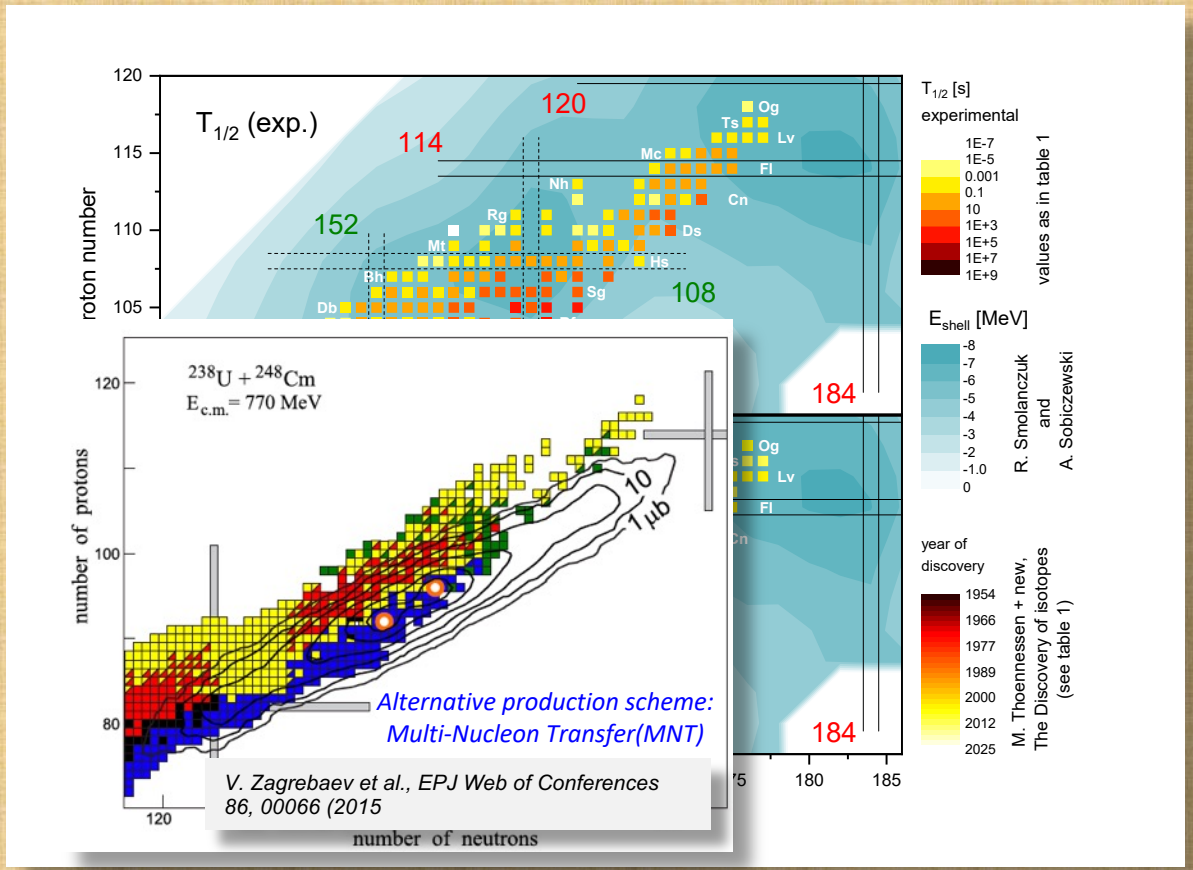

V. Zagrebaev et al., EPJ Web of Conferences 86, 00066 (2015

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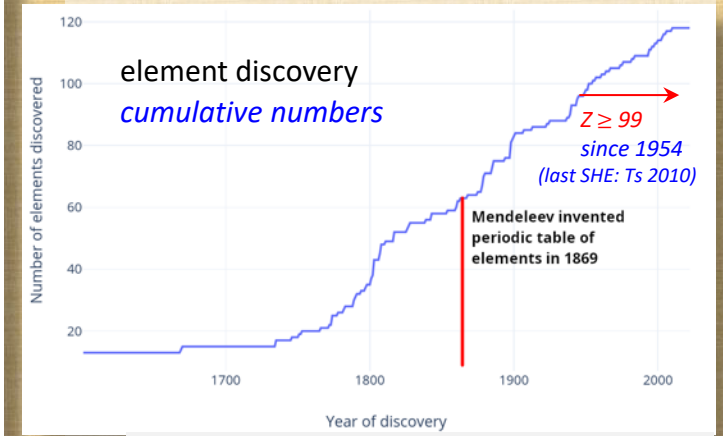

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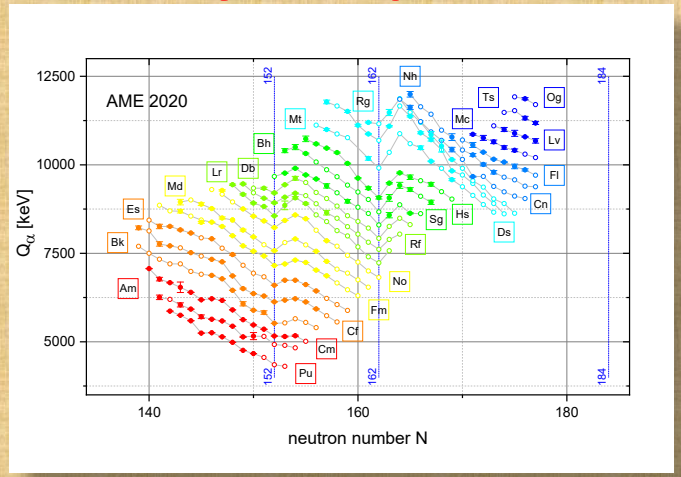
SHN nuclear structure: beyond the mere discovery –

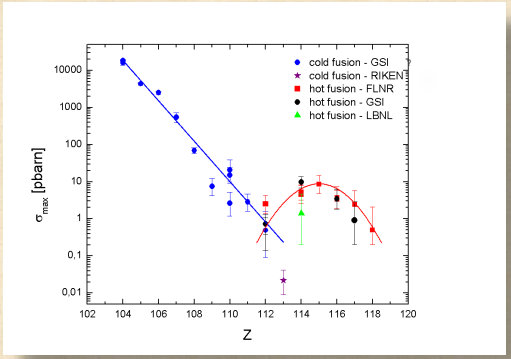
Decay modes, stability and quantum mechanics



SHE/SHN research

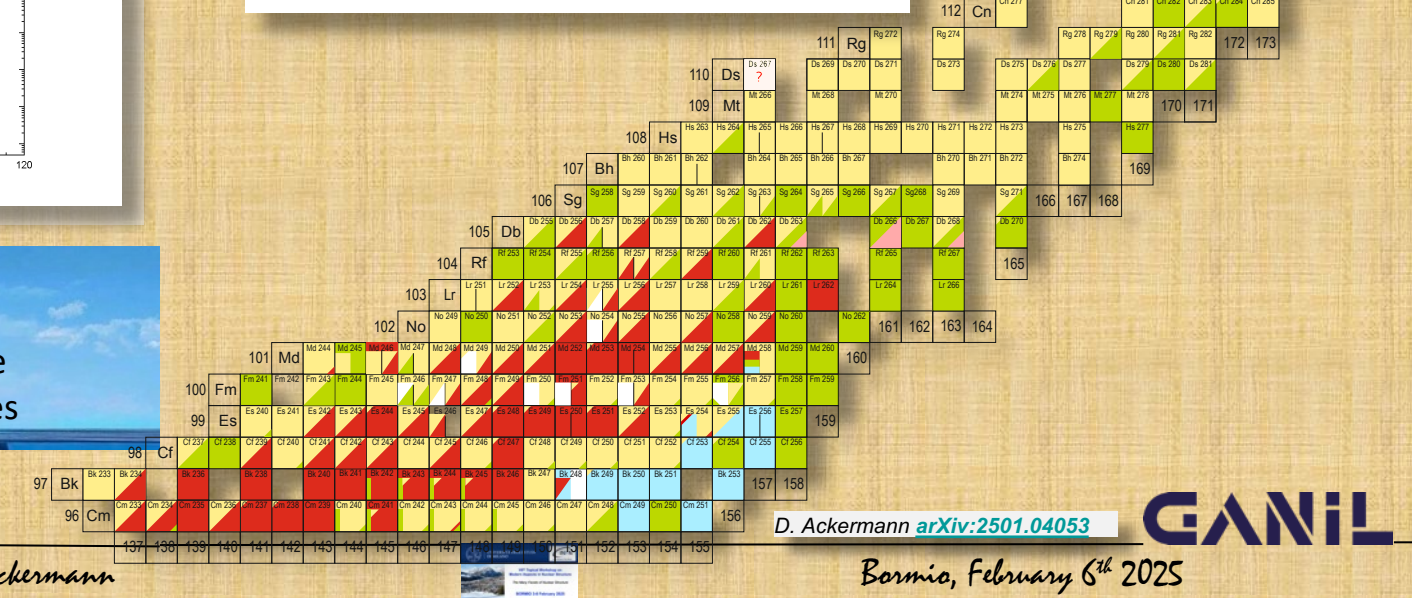
→ nature rules success chances

→ production probabilities: **x-sections**



SHE synthesis

- new element/isotope
- basic decay properties



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Decay modes, stability and quantum mechanics

SHE synthesis

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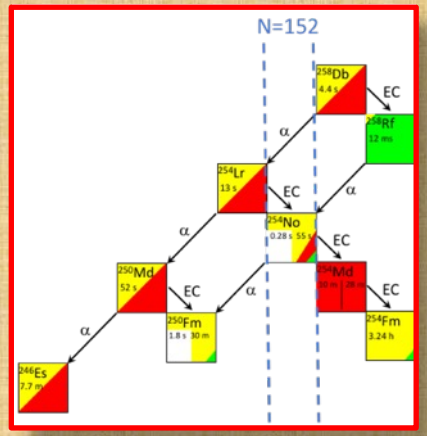
SHN Nuclear structure

- single particle levels and the spherical shell gaps at the *"island of stability"*
- isomeric states – ***K*-isomers** for deformed nuclei
- nuclear stability and decay mode (α, SF, …) competition
- deformation …
- …

… role of the odd particle



Isomers in superheavy nuclei
Eur. Phys. J. Spec. Top. (2024) 233:1017–1036

D. Ackermann
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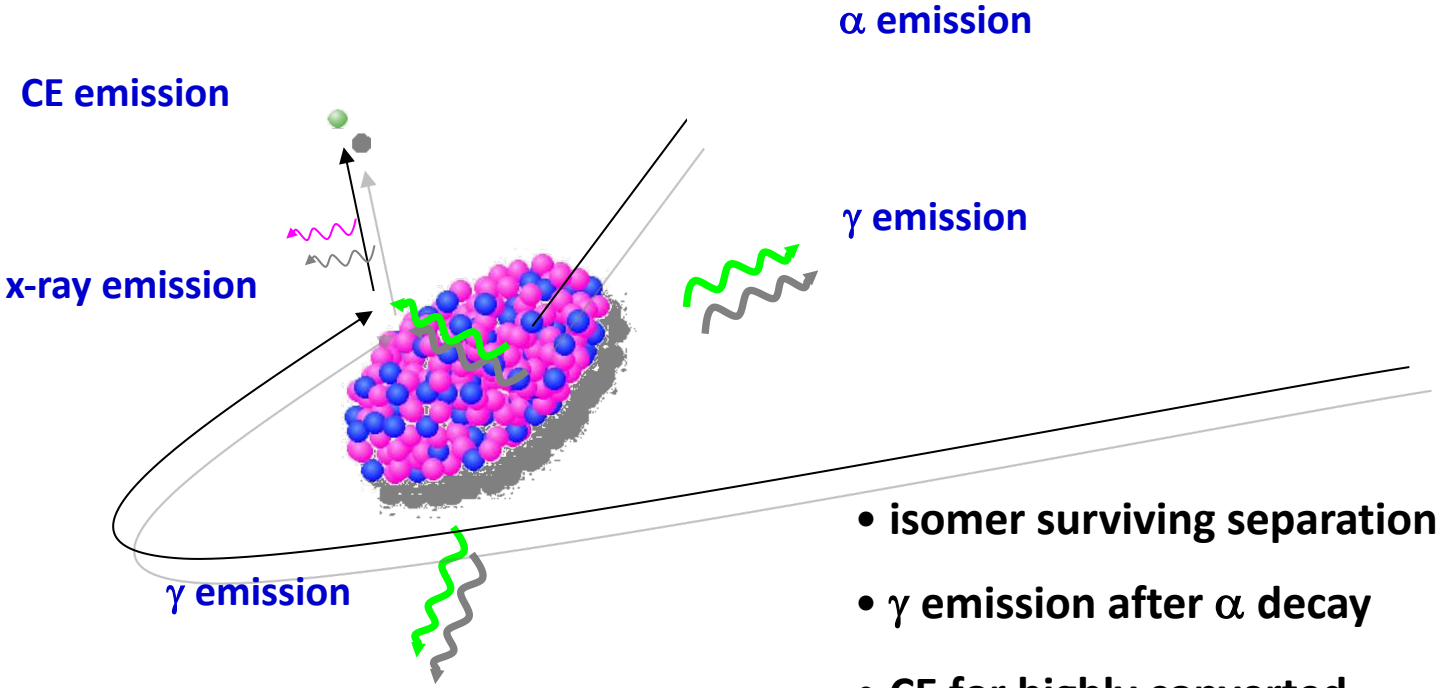
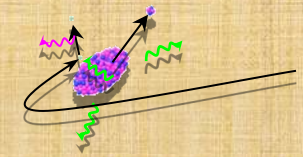


- isomer surviving separation
- γ emission after α decay
- CE for highly converted transitions
  + X-ray emission

DSAS
– Decay Spectroscopy After Separation



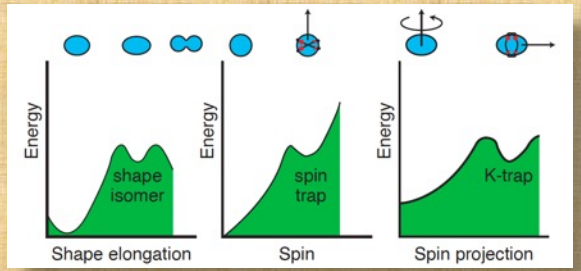
Isomers in SHN –
- types and decay modes

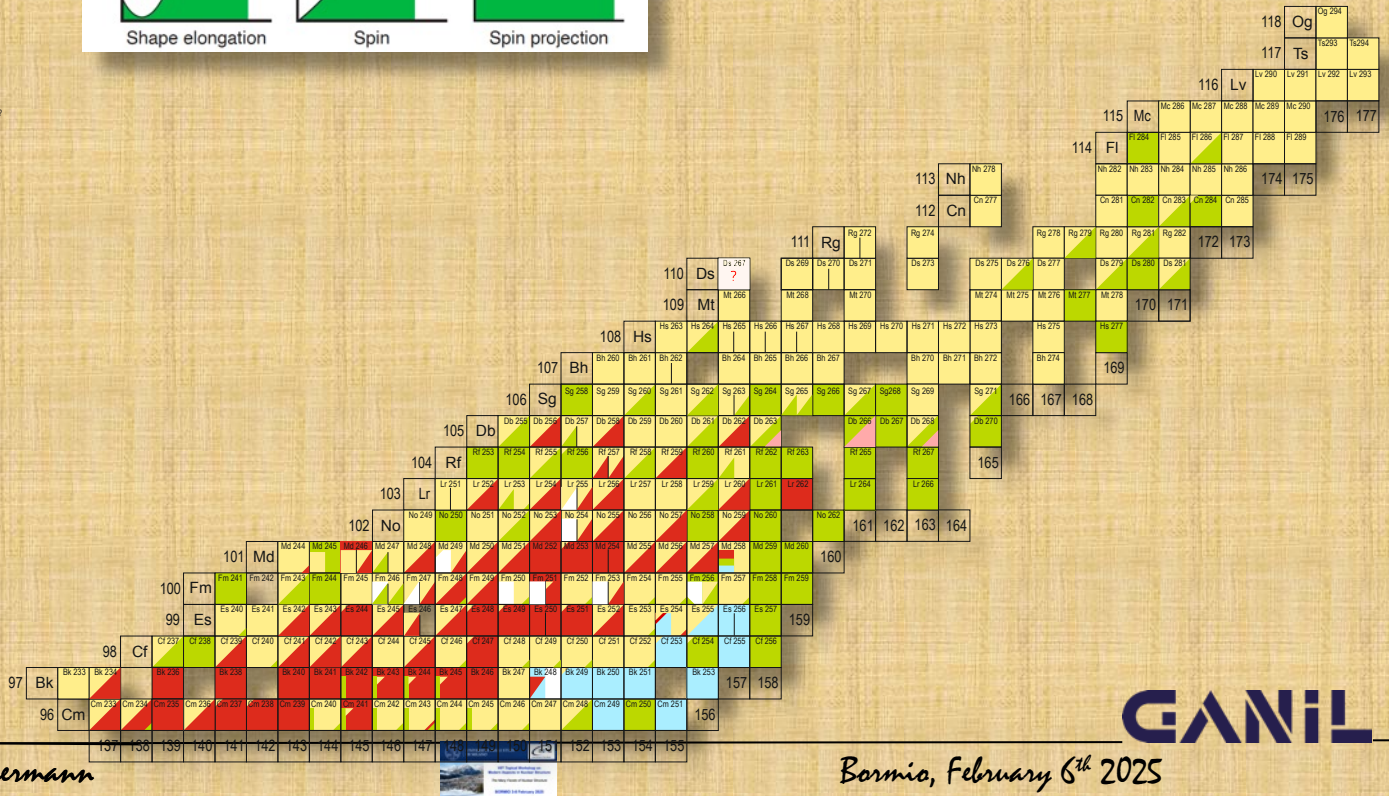
Three types of isomers

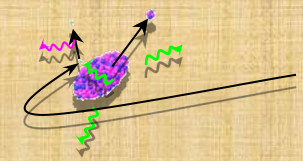
- shape isomers
- spin traps
- K-traps

Decay modes

- β
- internal transitions (γ, internal conversion)
- spontaneous fission
- α







Isomers in heavy nuclei

first isomer - one of the heaviest nuclei known in 1936

1921 *Otto Hahn* observed

2 β activities produced by β decay of a substance called UX_1

O. Hahn, Naturwissenschaften 9, 84 (1921)s

In 1936 *Carl Friedrich von Weizsäcker* coined the notion of isomers in nuclei:

"β-labile Kerne... in zwei 'isomeren' Sorten … "

→ β-unstable nuclei... of two 'isomeric' kinds

"Der erste bekannte Fall ist die von Hahn sehr wahrscheinlich gemachte Isomerie von UX_2 und UZ."

→ "The first known case is the by Hahn most probably produced isomerism of UX_2 and UZ

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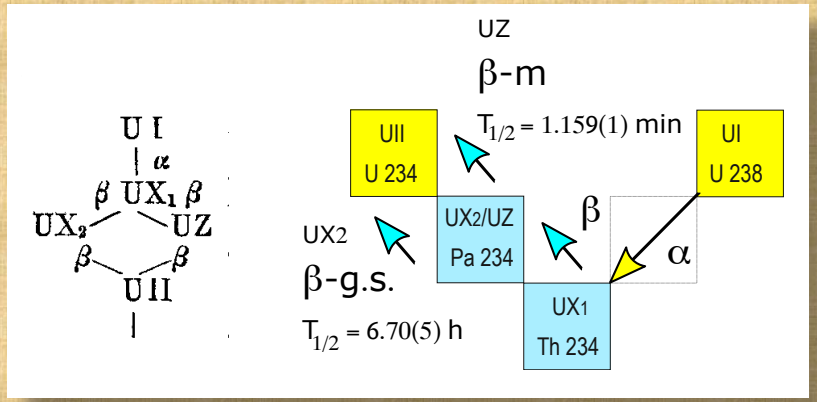

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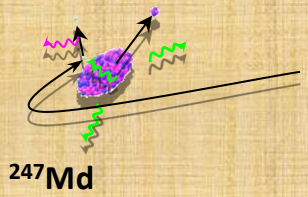
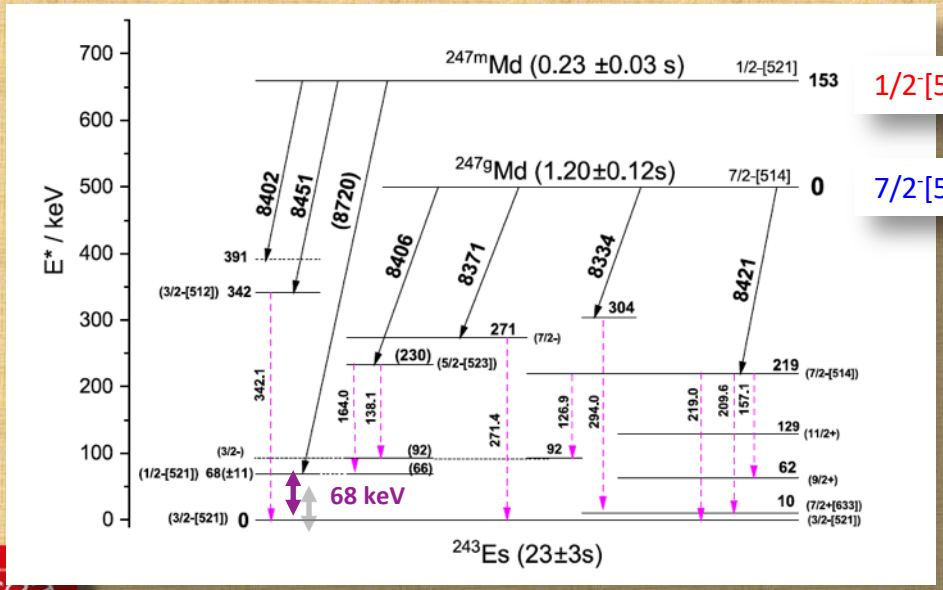


^{247m}Md and SF-α decay competition
- SF barrier dependence on level spin

1/2-[521] (isomer) SF branching: 0.20(2)

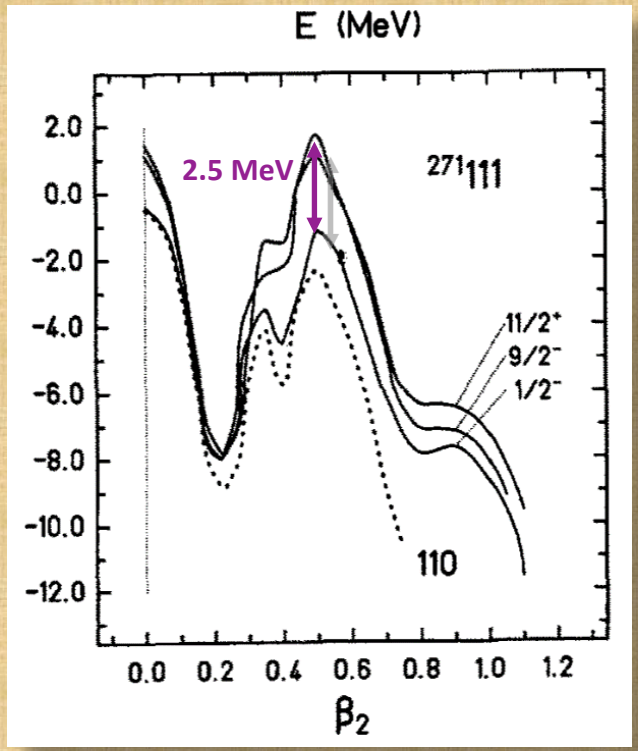
7/2-[514] (g.s.) SF branching: $8.6\times10^{-3}(10)$

→ **SF branching (strongly) depends on SPL structure**

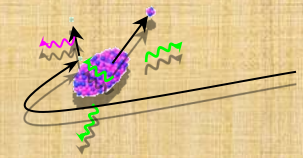


F.P. Heßberger et al., Eur. Phys. J. A 58 (2022) 11

SF barrier as a function of deformation



S. Ćwiok et al., Nucl. Phys. A 573 (1994) 356



Nuclear deformation and metastability
- K-isomers in the region of SHN

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→ high values of *K* and
high *ΔK between initial and availible final state*
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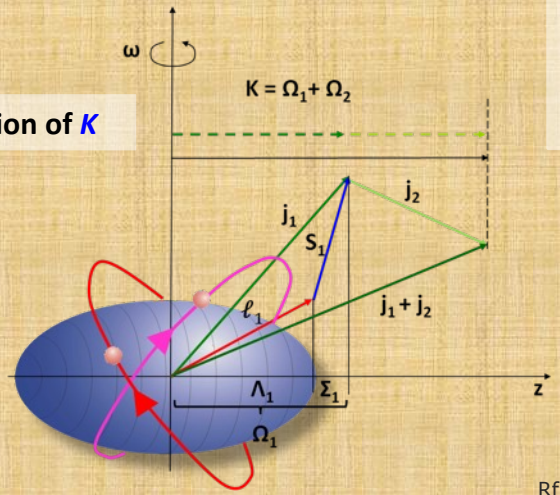
definition of *K*



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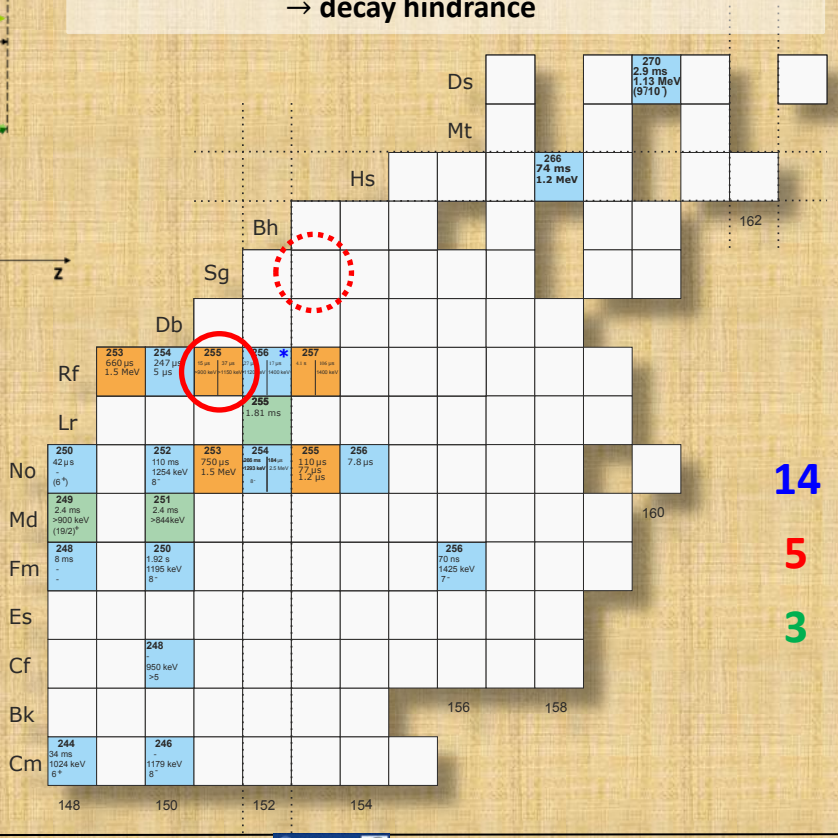

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Eur. Phys. S.T. 233 (2024) 1017–1036

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14	K-Isomers in even Z - even N nuclei
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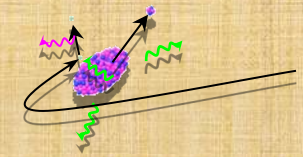


^{255}Rf structure from ^{259}Sg α-decay
- SF/SPL properties

Production: ^{206}Pb(^{54}Cr,1n)^{259}Sg, σ ≈ 1 nb

SF-α competition

- α-decay from both low lying levels - $T_{1/2}$(, ^{259}Sg) ≈ 411 ms/254 ms
- SF from 1/2$^+$[620] only - $T_{1/2}$(SF, ^{259}Sg) ≈ 235 ms

→ **SF hindrance by quantum mechanics**

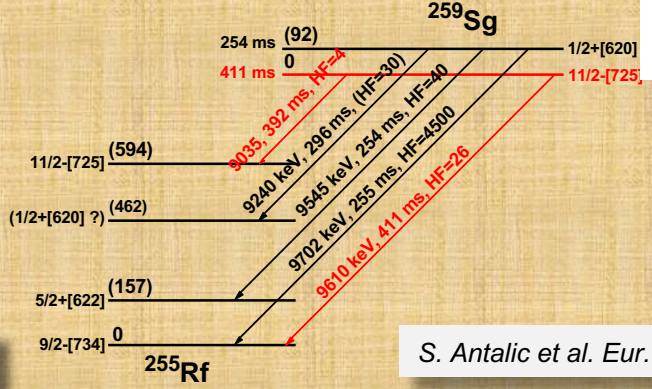
SF properties

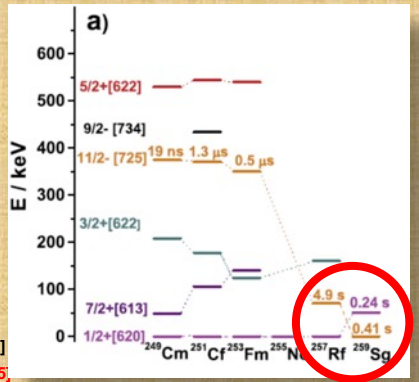
- TKE(SF) of ^{259}Sg >15 MeV higher than for ^{255}Rf
- change from asymmetric to symmetric fission

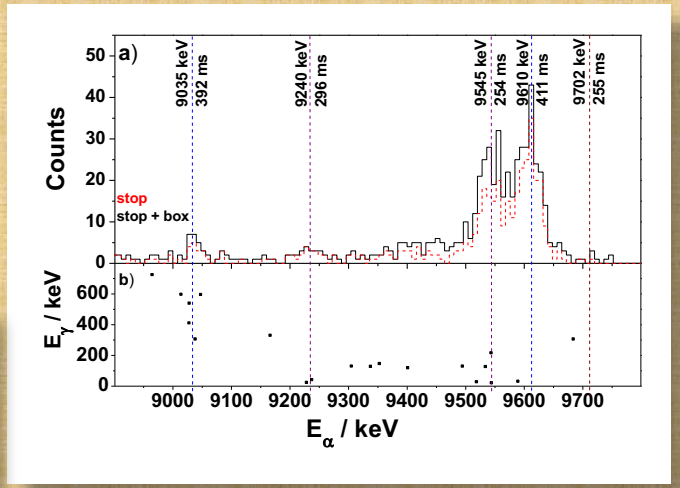
SPL systematics

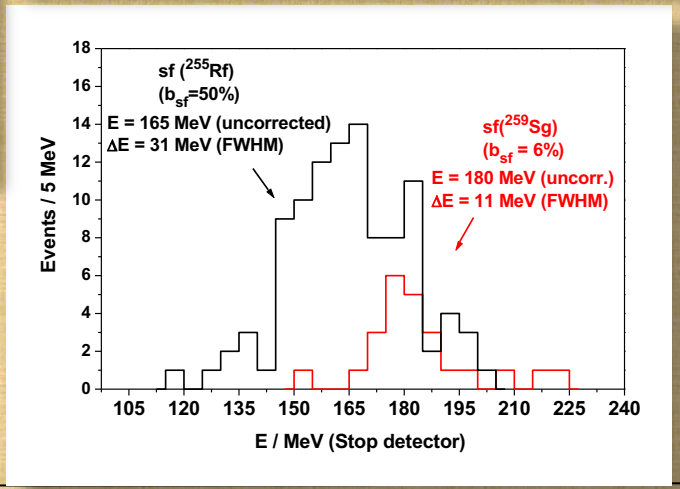
- change of g.s. config. in N = 153 isotones

→ **1/2$^+$[620] to 11/2$^-$[725]**

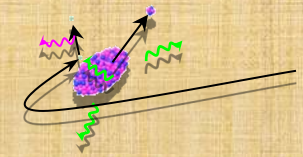








S. Antalic et al. Eur. Phys. J. A 51, (2015) p. 41



^{255}Rf direct production

- ER-CE-(CE)-γ-SF/α correlations

Production: ^{207}Pb(^{50}Ti,2n)^{255}Rf, σ ≈ 11 nb

^{255}Rf

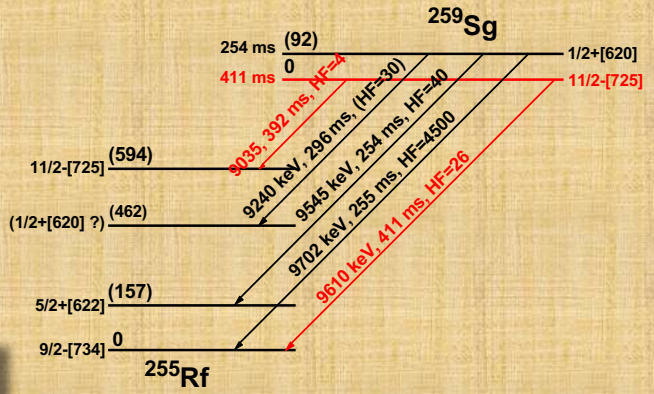
two high-K isomers

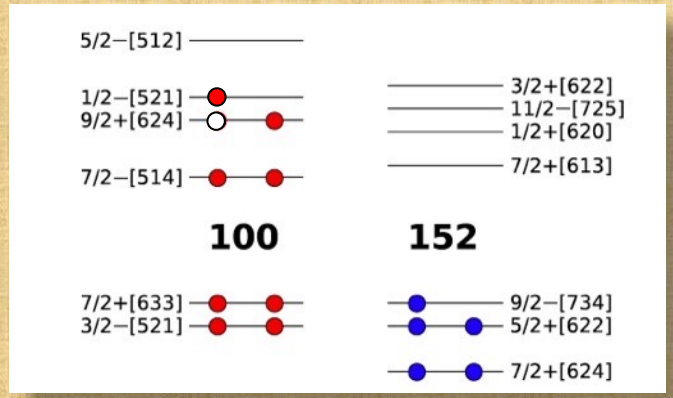
$T_{1/2}$ 15(+6/-4) μs and 38(+12/-7) μs

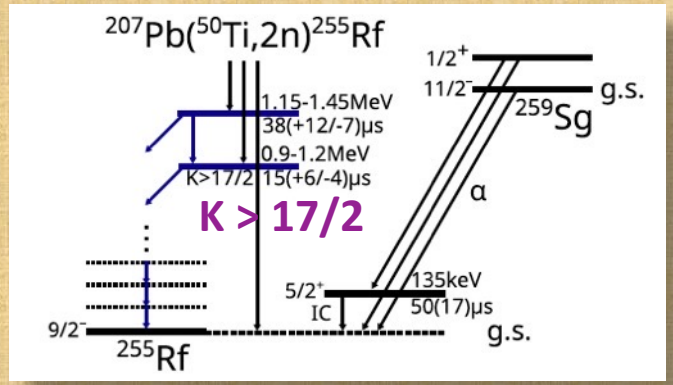
a possible quasi-particle coupling

1/2−[521]π ⊗ 9/2+[624]π ⊗ 9/2−[734]ν → K = 19/2+ with ΔK = 5

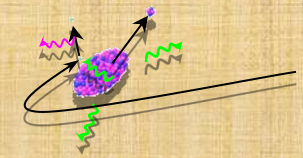
→ **K > 17/2**







P. Mosat et al. PHYSICAL REVIEW C 101, 034310 (2020)



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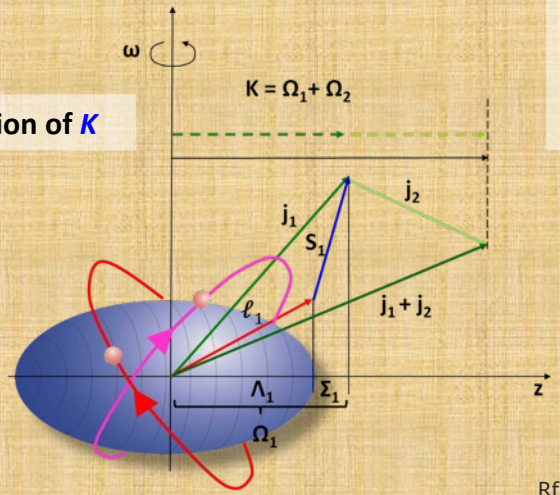

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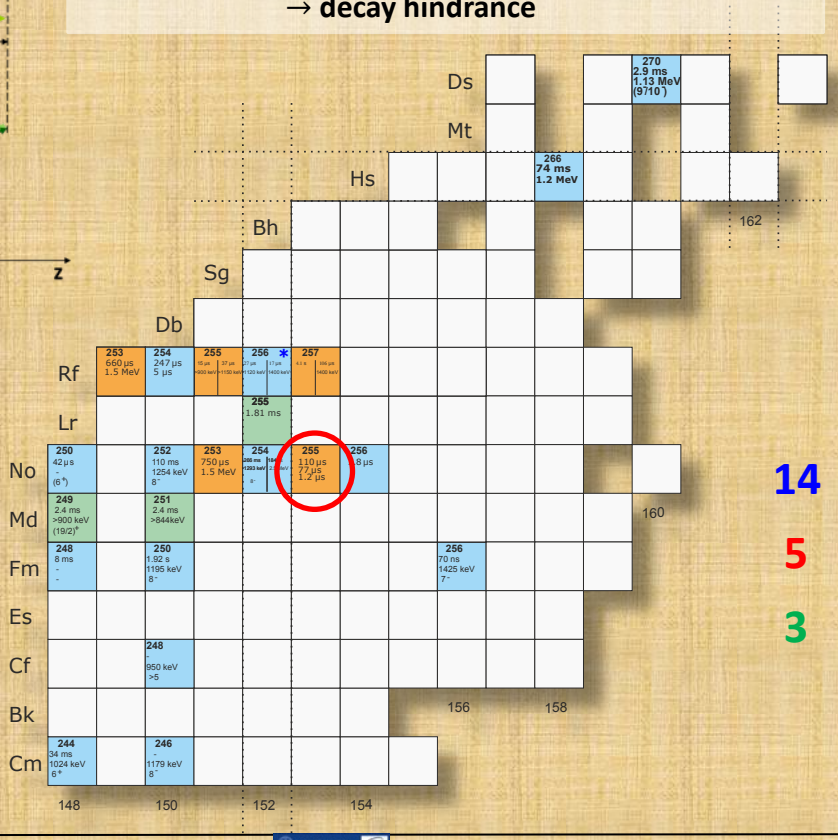

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ER-γ-CE coincidence sum energies

839 keV line → $E(E_\gamma+E_{CE1})_{max}$ = 1219 keV

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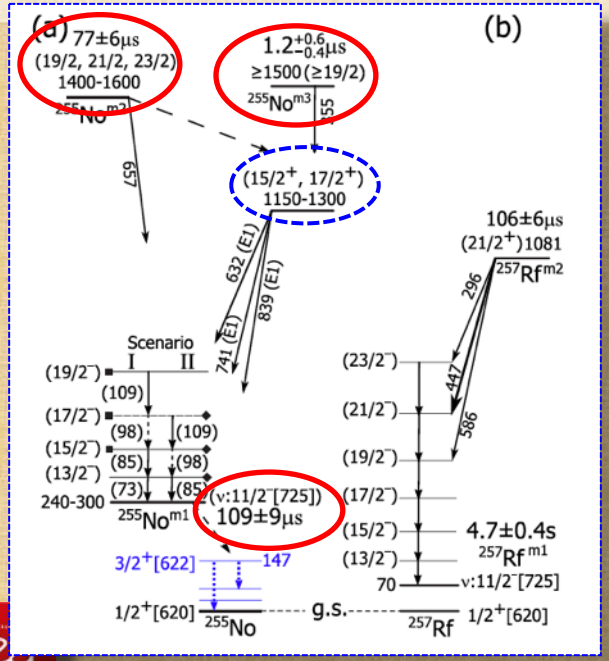

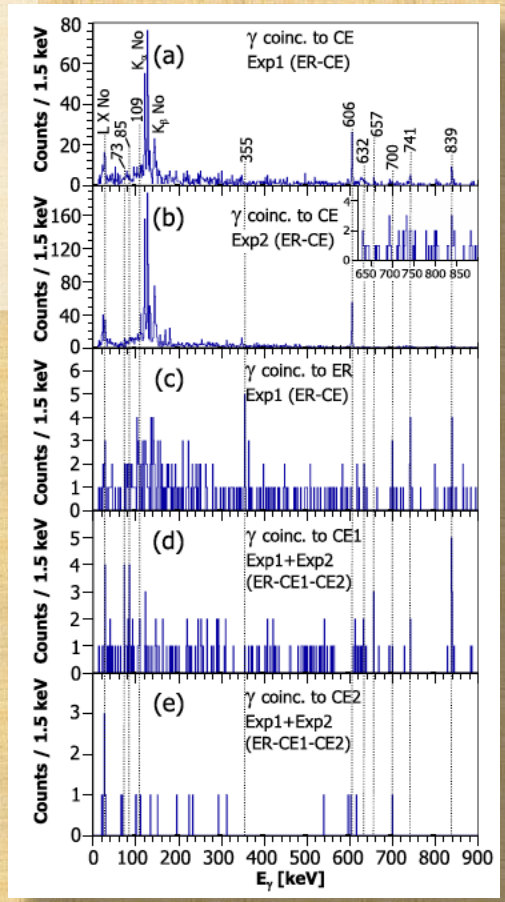

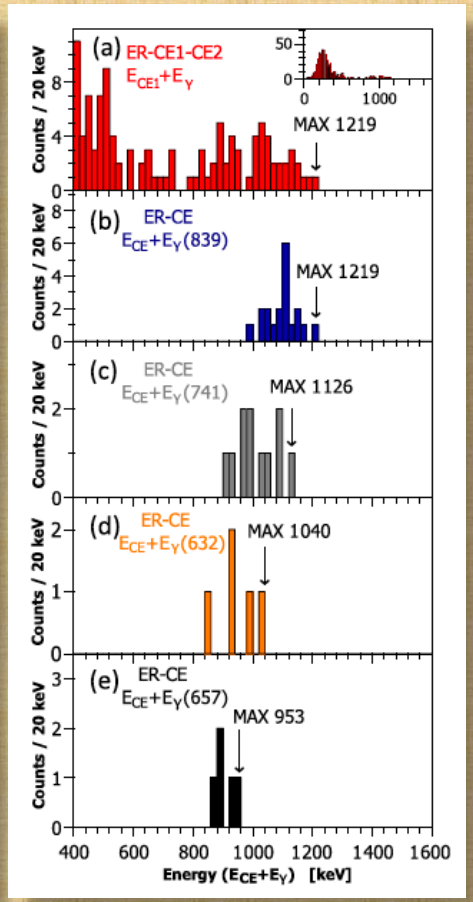

A. Bronis al., PHYSICAL REVIEW C 106, (2022) 014602

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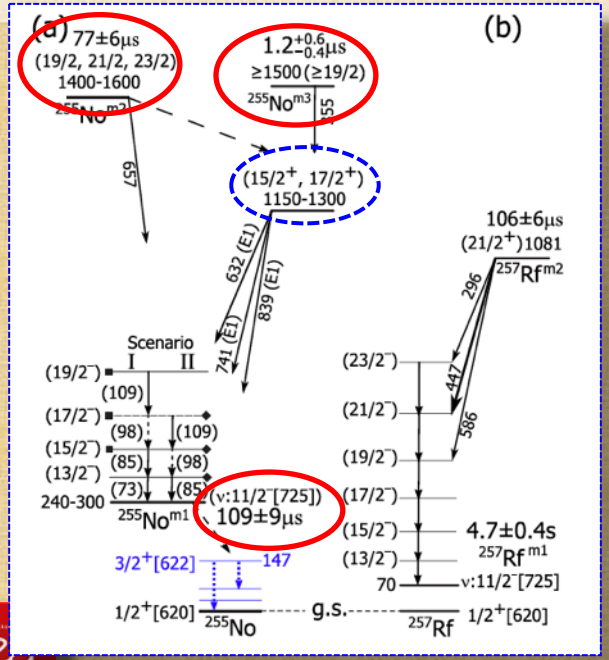
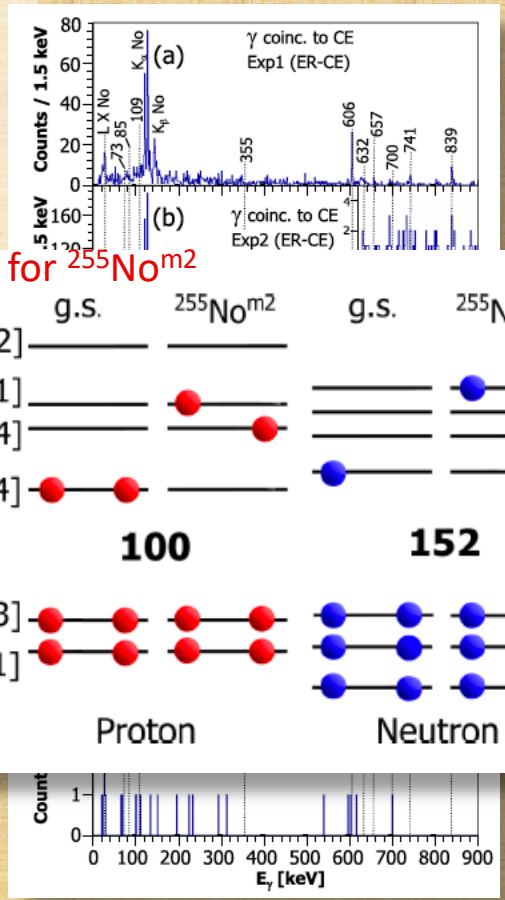
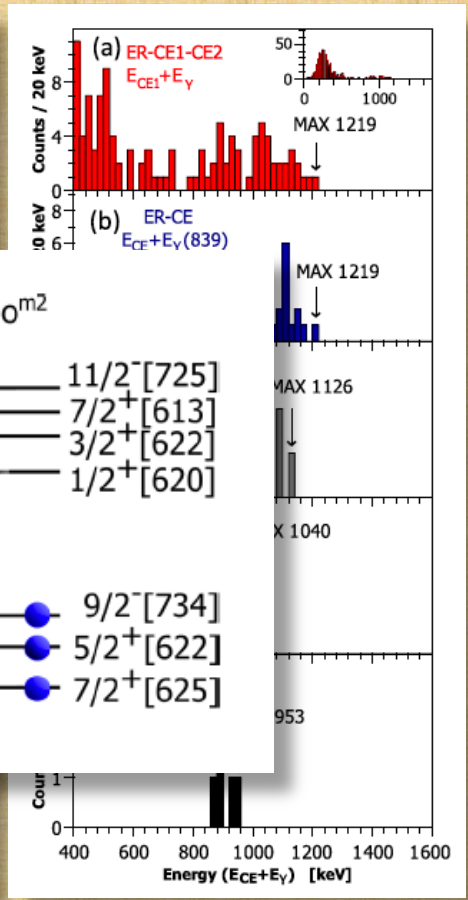






scenarii for ^{255}No^{m2}

A. Bronis al., PHYSICAL REVIEW C 106, (2022) 014602

^{255}No – revisited (ER-γ-CE-α/SF correlations)

- CE correlations → observation of 2 new K isomers

ER-γ-CE coincidence sum energies

839 keV line → $E(E_\gamma+E_{CE1})_{max}$ = 1219 keV

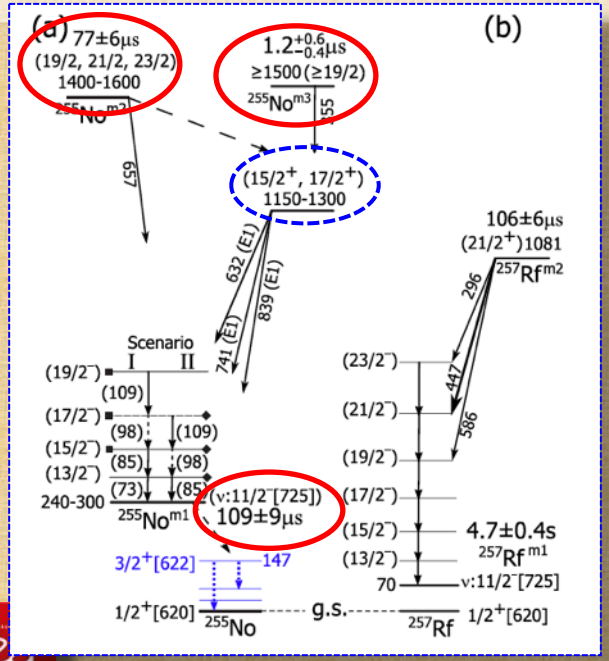
ER-γ-CE coincidence sum energies

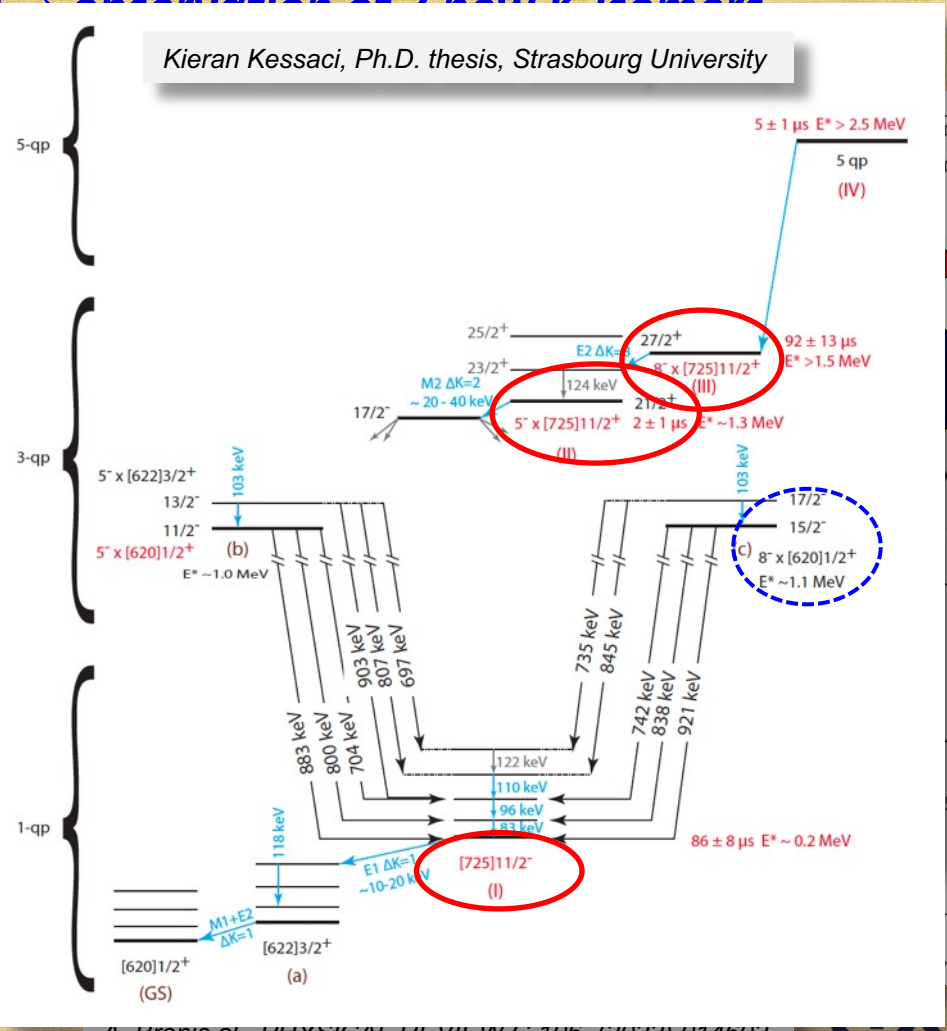
839 keV line → $E(E_\gamma+E_{CE})_{max}$ = 1219 keV

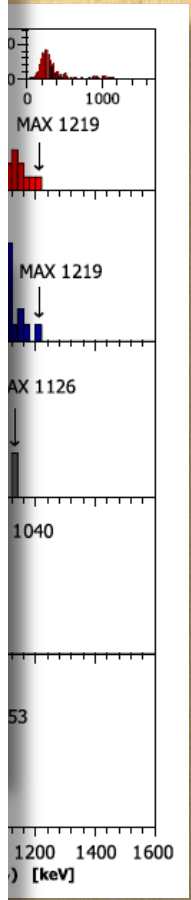
741 keV line → $E(E_\gamma+E_{CE})_{max}$ = 1126 keV

632 keV line → $E(E_\gamma+E_{CE})_{max}$ = 1040 keV

657 keV line → $E(E_\gamma+E_{CE})_{max}$ = 953 keV







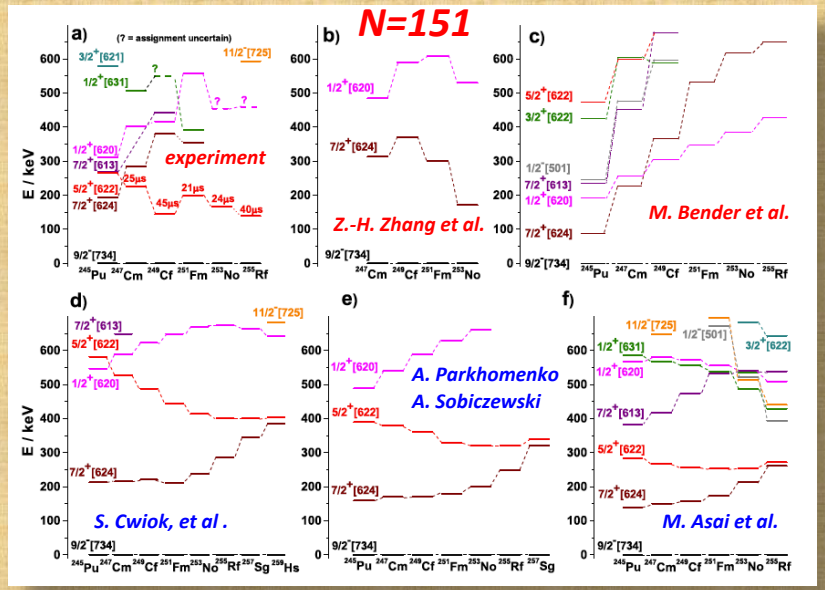
A. Bronis al., PHYSICAL REVIEW C 106, (2022) 014602

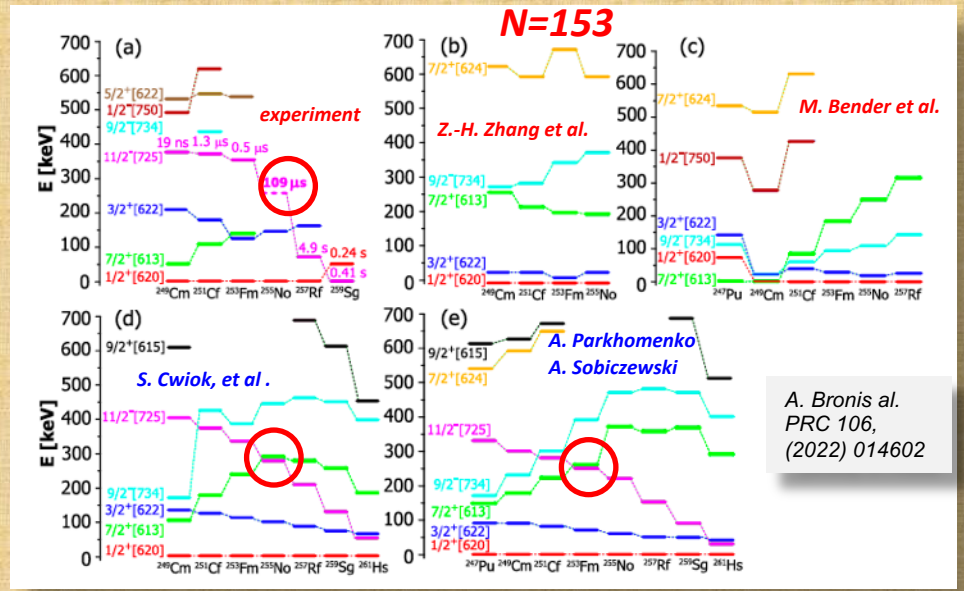
SHN Nuclear structure
- isotonic trends close to N=152

Comparison experiment – theory

red: *self-consistent models*

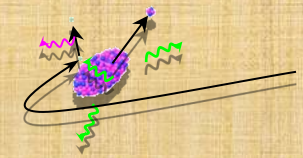
blue: *mic-mac model*





A. Bronis al. PRC 106, (2022) 014602

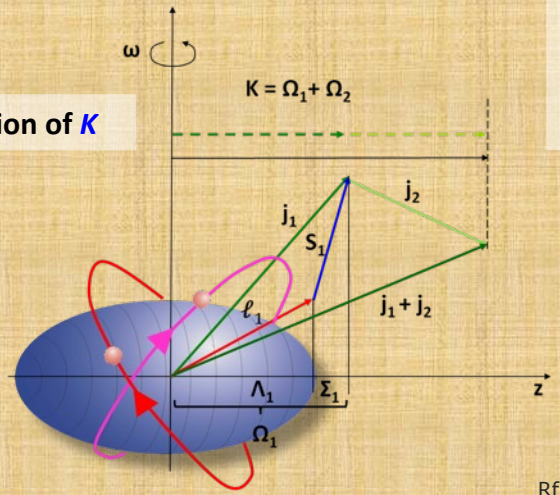
M. Asai, A. Lopez-Martens and F.P. Heßberger, NPA 944, (2015) 308–332



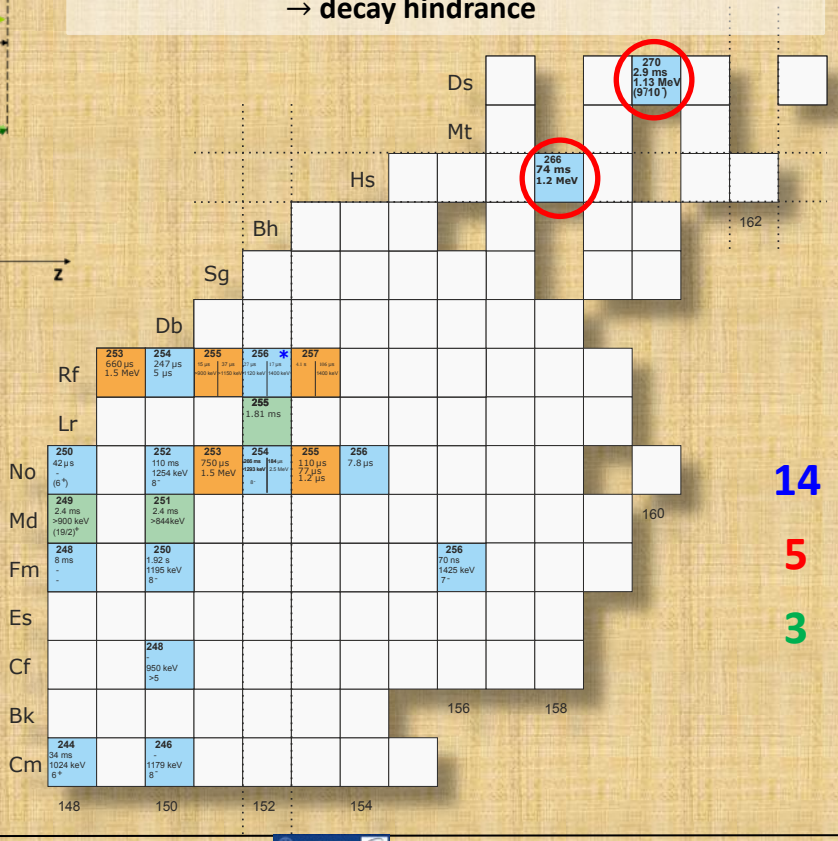
Nuclear deformation and metastability
- K-isomers in the region of SHN

high *J* orbitals in the vicinity of *Z* = 100 and *N* = 152
→ high values of *K* and
high *ΔK between initial and availible final state*
→ decay hindrance

definition of *K*



Λ_i	projection of the orbital angular momentum ℓ of the nucleon on the symmetry axis z
Σ_i	projection of the spin S of the nucleon on z
Ω_i	projection of the total angular momentum j on z: $\Omega_i = \Lambda_i + \Sigma_i$
K	sum of all projections Ω_i on z : $K = \Omega_1 + \Omega_2 + ...$



D. Ackermann
S. Antalic
F.P. Heßberger
Eur. Phys. S.T. 233 (2024) 1017–1036

14 K-Isomers in even Z - even N nuclei

5 K-Isomers in even Z - odd N nuclei

3 K-Isomers in odd Z - even N nuclei

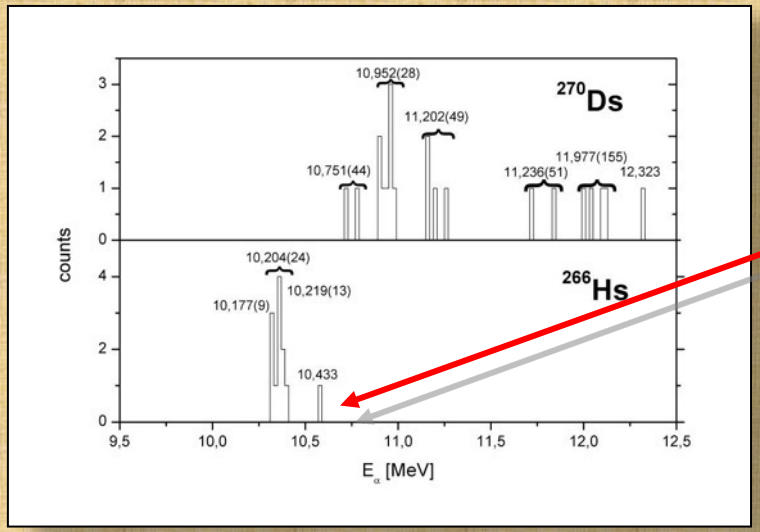
K-Isomers in odd Z - odd N nuclei

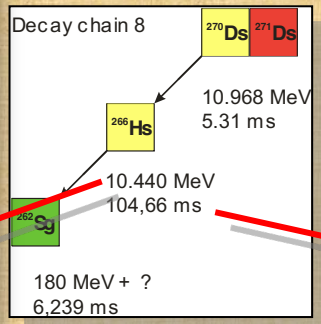
massnumber A
halflife $T_{1/2}$
excitation energie E^*
spin and parity K^{π}

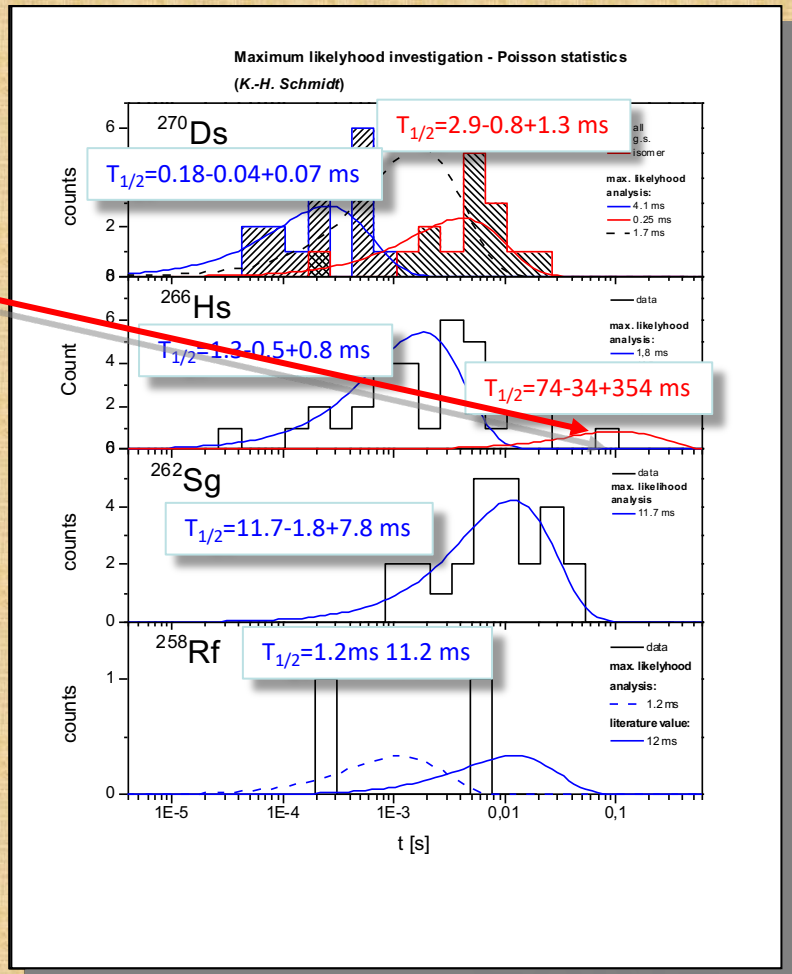
* values for the lowest two of more isomers shown

Decay details

- time distributions







^{266}Hs

K-isomer (1 event)

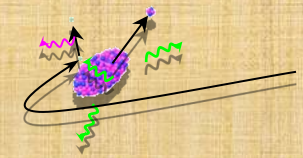
→ E_α = 10.43 MeV – ≈ 200 keV higher than main activity

→ $T_{1/2}$ = 74 ms – ≈ 56 times slower then main activity

^{270}Ds:

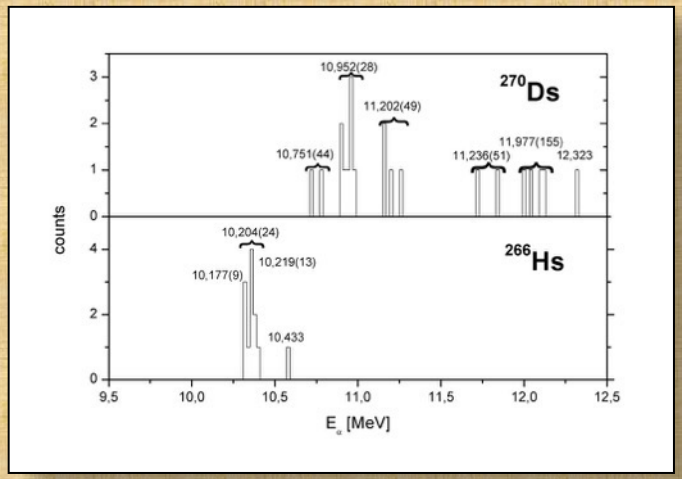
clearly (at least) 2 activities

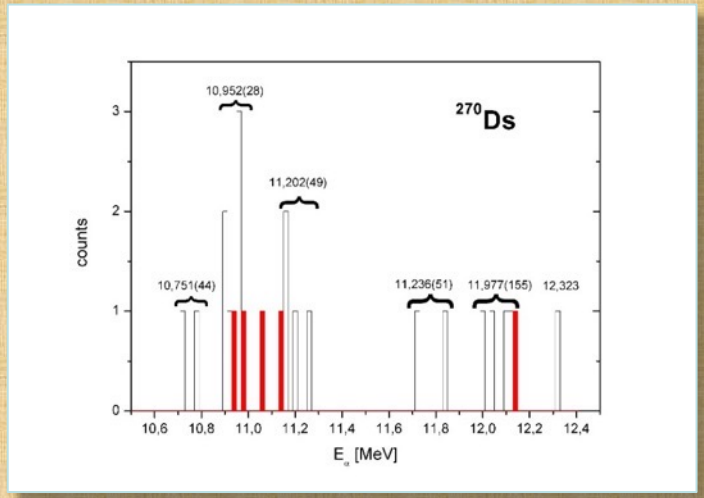
highly fragmented α spectrum



^{270}Ds decay

- α decay and α-γ coincidences





E$_\alpha$

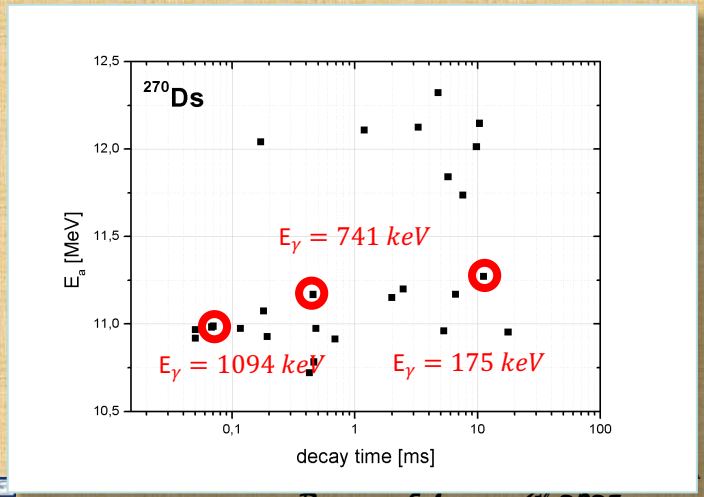
two groups at 11 MeV and 12 MeV
both fragmented
→ several transitions from isomer and g.s.

E$_\alpha$ vs decay time

again two groups:

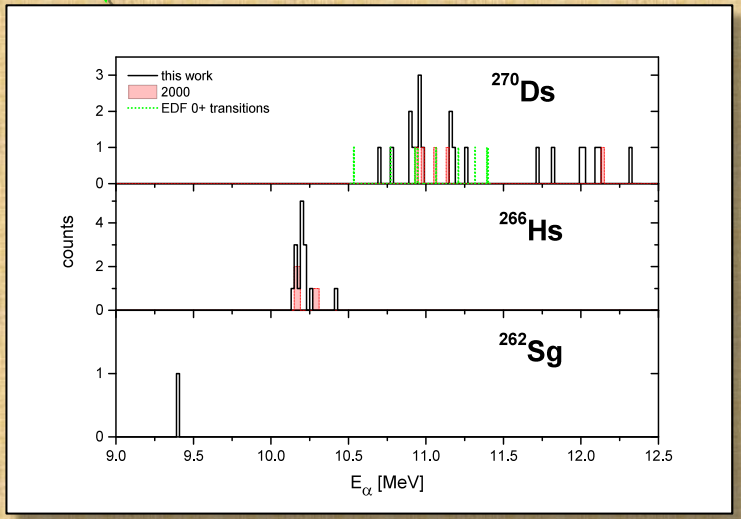
1. 50 μs to 0.6 ms
2. 1 ms to 20 ms

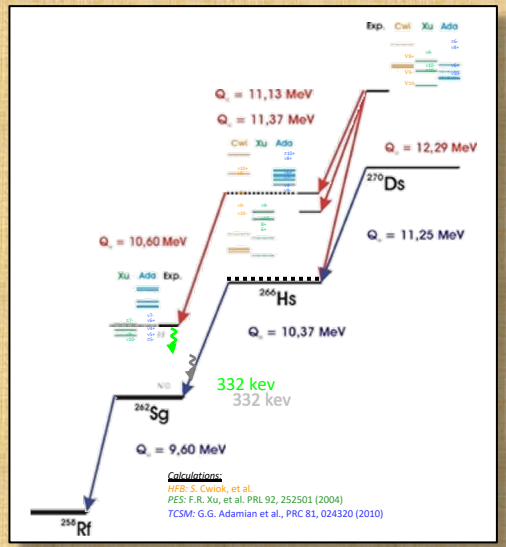
→ different delay factors
→ transition dependent hindrance
→ γ's for low-E group only

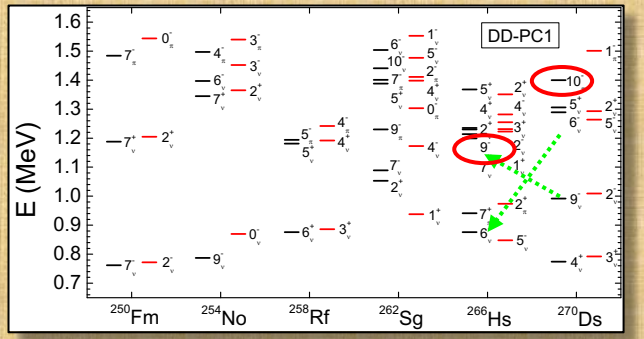


Energy Density Functional Calculations

- Dario Vretenar, Vaia Prassa et al.







^{266}Hs	$\nu 1/2^+[631] \otimes \nu 11/2^-[725]$	0.848	5^-_ν	0.876	6^-_ν	1.020
	$\pi 5/2^-[512] \otimes \pi 9/2^-[505]$	0.974	2^+_π	0.941	7^+_π	1.143
	$\nu 3/2^+[622] \otimes \nu 1/2^+[631]$	1.223	1^+_ν	1.230	2^+_ν	1.382
	$\nu 3/2^+[622] \otimes \nu 11/2^-[725]$	1.282	4^-_ν	1.199	7^-_ν	1.396
	$\nu 11/2^-[725] \otimes \nu 7/2^+[613]$	1.231	2^-_ν	1.214	9^-_ν	1.376
	$\nu 1/2^+[631] \otimes \nu 7/2^+[613]$	1.255	3^+_ν	1.235	4^+_ν	1.397
	$\nu 3/2^+[622] \otimes \nu 7/2^+[613]$	1.351	2^+_ν	1.368	5^+_ν	1.511
^{270}Ds	$\nu 1/2^+[631] \otimes \nu 7/2^+[613]$	0.792	3^+_ν	0.774	4^+_ν	0.934
	$\nu 11/2^-[725] \otimes \nu 7/2^+[613]$	1.009	2^-_ν	0.992	9^-_ν	1.150
	$\nu 3/2^+[622] \otimes \nu 7/2^+[613]$	1.293	2^+_ν	1.306	5^+_ν	1.448
	$\nu 11/2^-[725] \otimes \nu 1/2^+[631]$	1.264	5^-_ν	1.289	6^-_ν	1.434
	$\pi 9/2^-[505] \otimes \pi 11/2^+[615]$	1.501	1^-_π	1.400	10^-_π	1.638

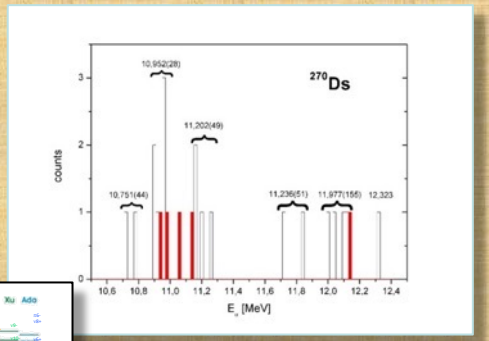
EDF predictions (DD-PC1 interaction)

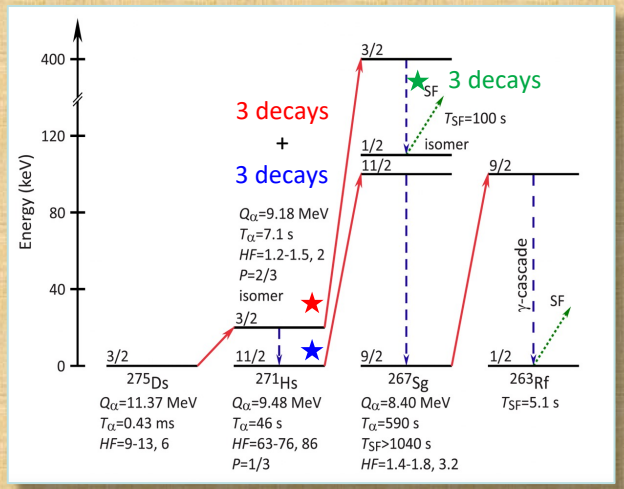
- 2-quasi-particle states in ^{270}Ds and ^{266}Hs up to K=9/10
  - → transitions into analog daughter states spanning E range of 900 keV
  - → fragmentation of E_α
  - → timing ruled by transition energy (Geiger-Nuttal)
- initial states with no matching final partner (e.g. 10^-)
  - → Retardation due to $\Delta K > 0$
- **K-isomers decaying by α decay**
  - → **sensitive probe for detailed 2(4)-quasi-particle structure**

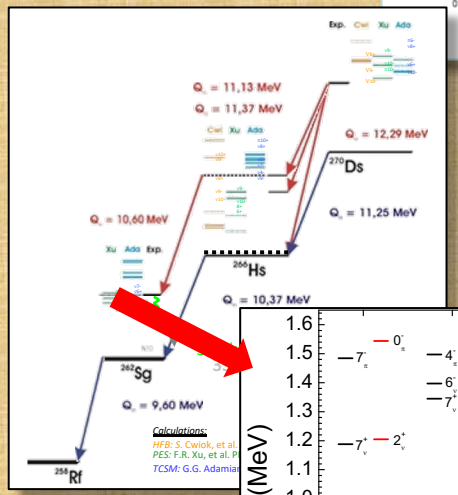
^{275}Ds decay @ FLNR/JINR SHE-factory

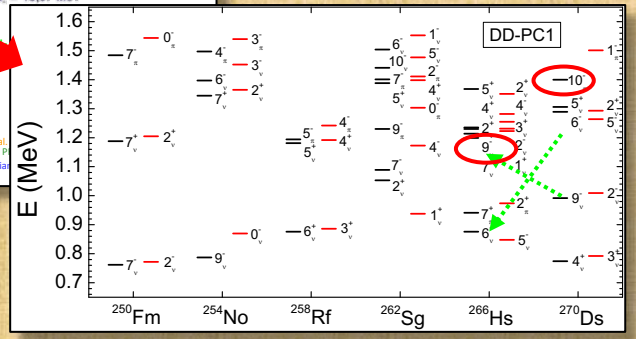
- SF-α competition, isomers and courageous decay scheme construction

Yu.Ts. Oganessian et al., PRC 109, 054307 (2024)









level/decay scheme assignments
based on **di-nuclear system model**

I.S. Rogov et al., PRC 100, 024606 (2019)/PRC 105, 034619 (2022)

High-K isomers in trans-actinide nuclei close to N=162

- Energy Density Functional Calculations, Vaia Prassa et al.

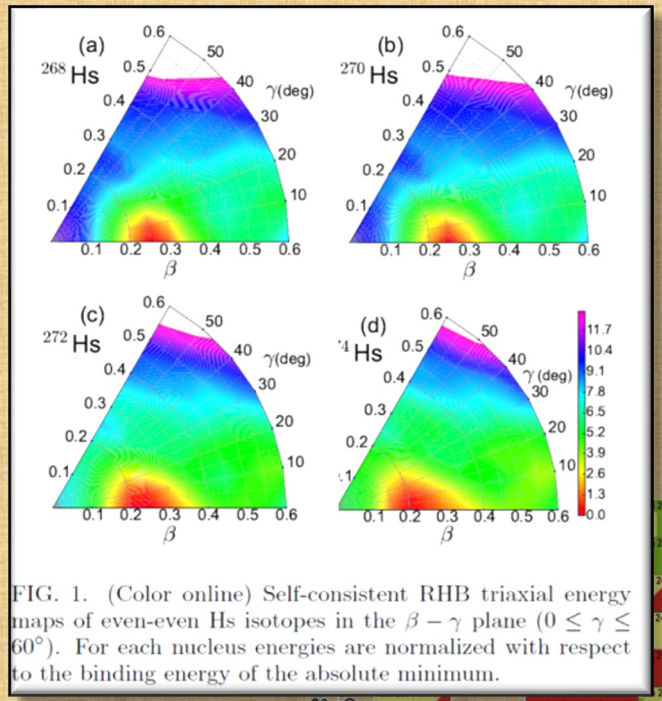


FIG. 1. (Color online) Self-consistent RHB triaxial energy maps of even-even Hs isotopes in the $\beta - \gamma$ plane ($0 \leq \gamma \leq 60°$). For each nucleus energies are normalized with respect to the binding energy of the absolute minimum.

Vaia Prassa et al.
PRC 91, 034324 (2015)

selfconsistent constraint triaxial HFB calculations based on the DD-PC1 functional (PRC 88, 044324 (2013)

High-K isomers in trans-actinide nuclei close to N=162

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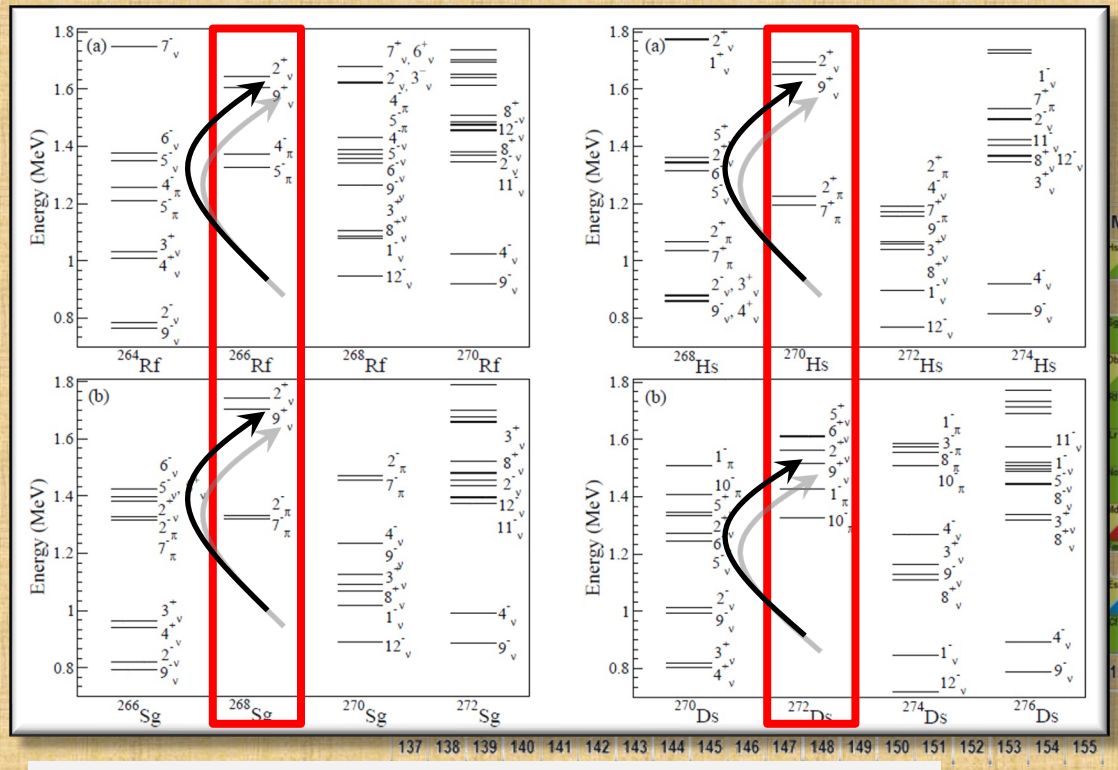
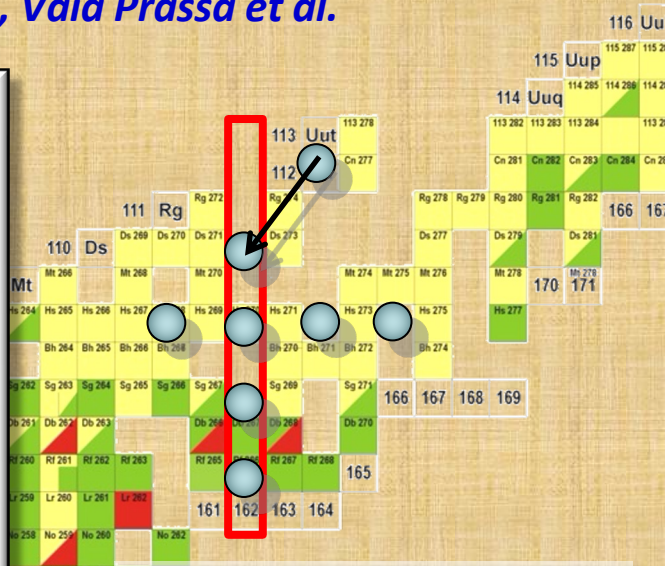




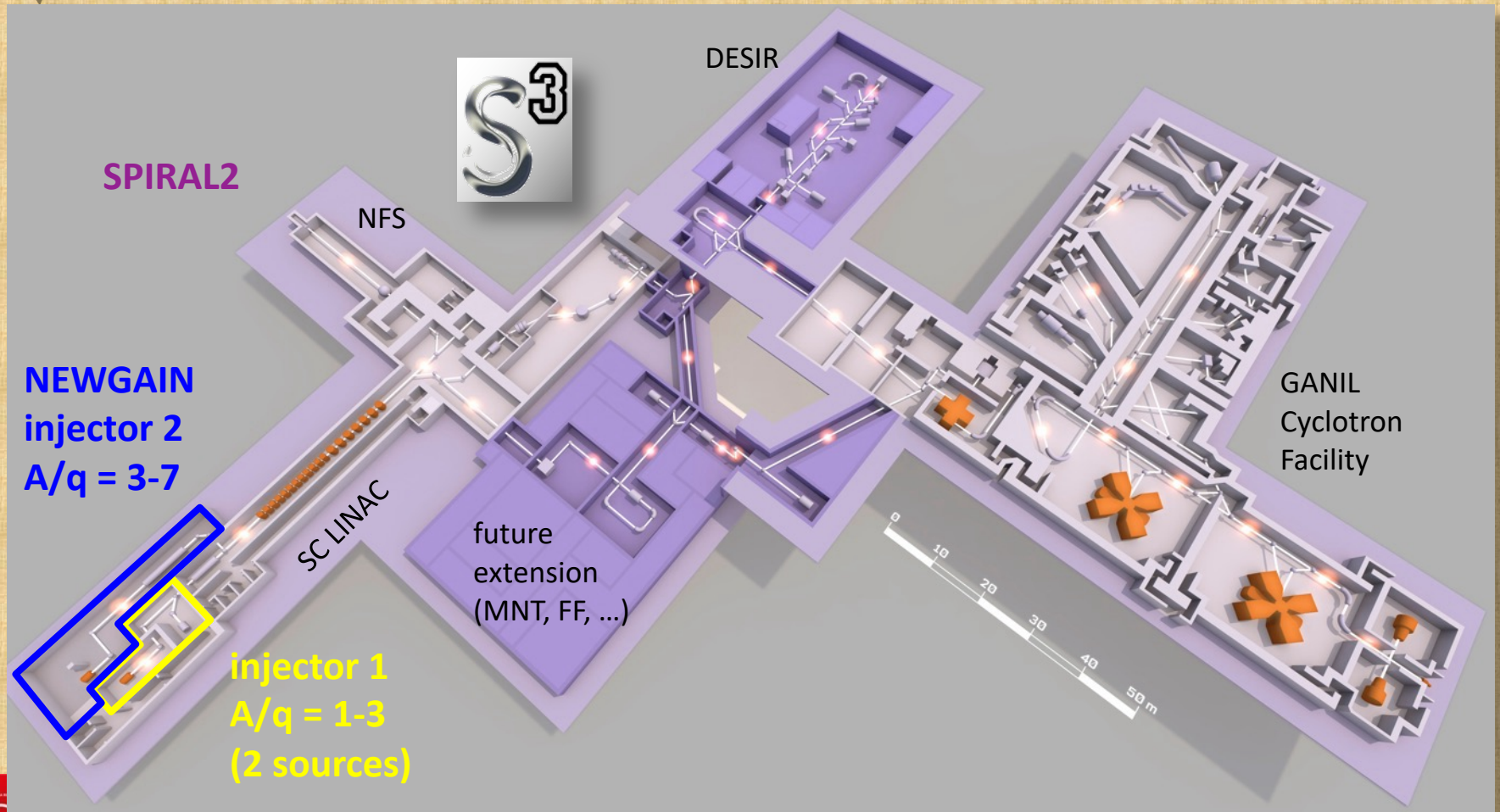
- proton single particle states elevated to higher excitation energies for N=162
- ^{270}Hs → ^{248}Cm(^{26}Mg, 4n)
  J. Dvorak et al., PRL 97, 242501 (2006)
- ^{272}Ds → α- daughter of ^{207}Pb(^{70}Zn, 1n)^{276}Cn

→ *HI-LINAC (e.g. GSI cw-Linac, FLNR SHE-factory , SPIRAL2 LINAG, ...)*

Vaia Prassa et al.
PRC 91, 034324 (2015)

selfconsistent constraint triaxial HFB calculations based on the DD-PC1 functional (PRC 88, 044324 (2013)

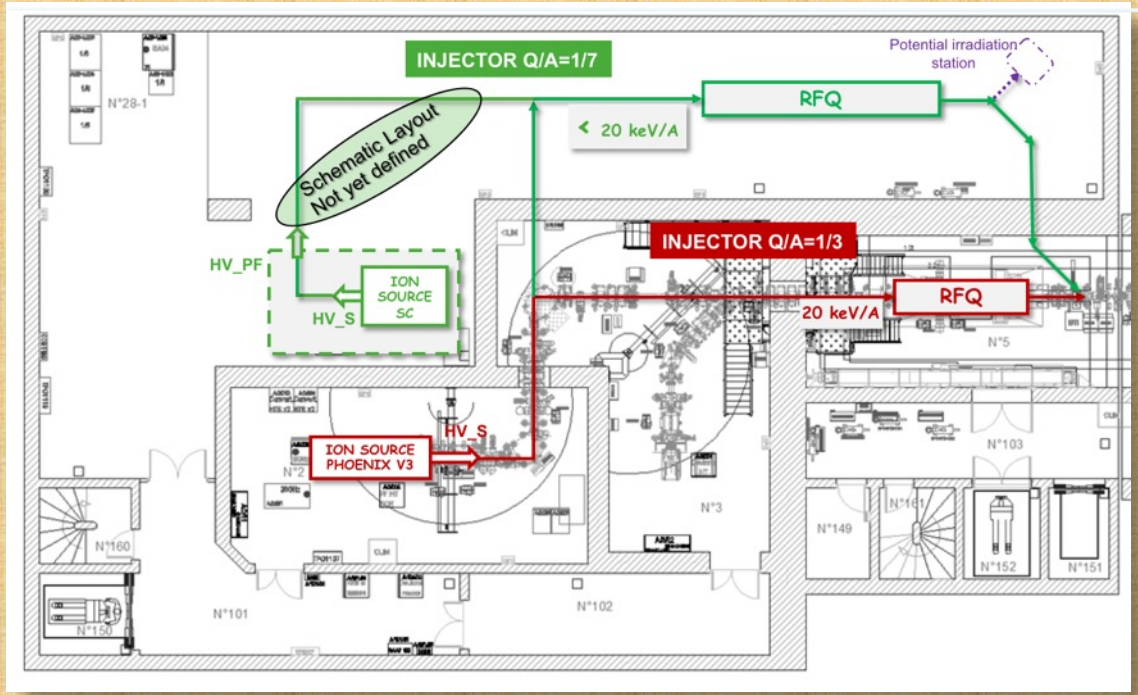
Perspectives: GANIL/SPIRAL2
- LINAG+NEWGAIN and S³



SPIRAL2 - NEWGAIN

- floorplan and design intensities

NEWGAIN
NEW GANIL INJECTOR



beam intensities	injector1 2023	NEWGAIN (injector2) 2028	NEWGAIN (injector2) ≥ 2030
Ions	Intensity (pμA) Phoenix V3 RFQ A/Q≤3	Intensity (pμA) Phoenix V3 RFQ A/Q≤7	Intensity (pμA) SC Ion Source RFQ A/Q≤7
^{18}O	80	*	375
^{19}F	>15	>40	>40
^{36}Ar	16	70	45
^{40}Ar	3.6	70	45
^{36}S	2.3	*	*
^{40}Ca	2.9	10	20
^{48}Ca	1.2	10	20
^{58}Ni	1.1	4	**8**
^{84}Kr	0.1	10	**20**
^{139}Xe	0.001	7	**>10**
^{238}U	<<0.001	0.1	**6**

Measured | Estimated

* -> no estimation

NEWGAIN

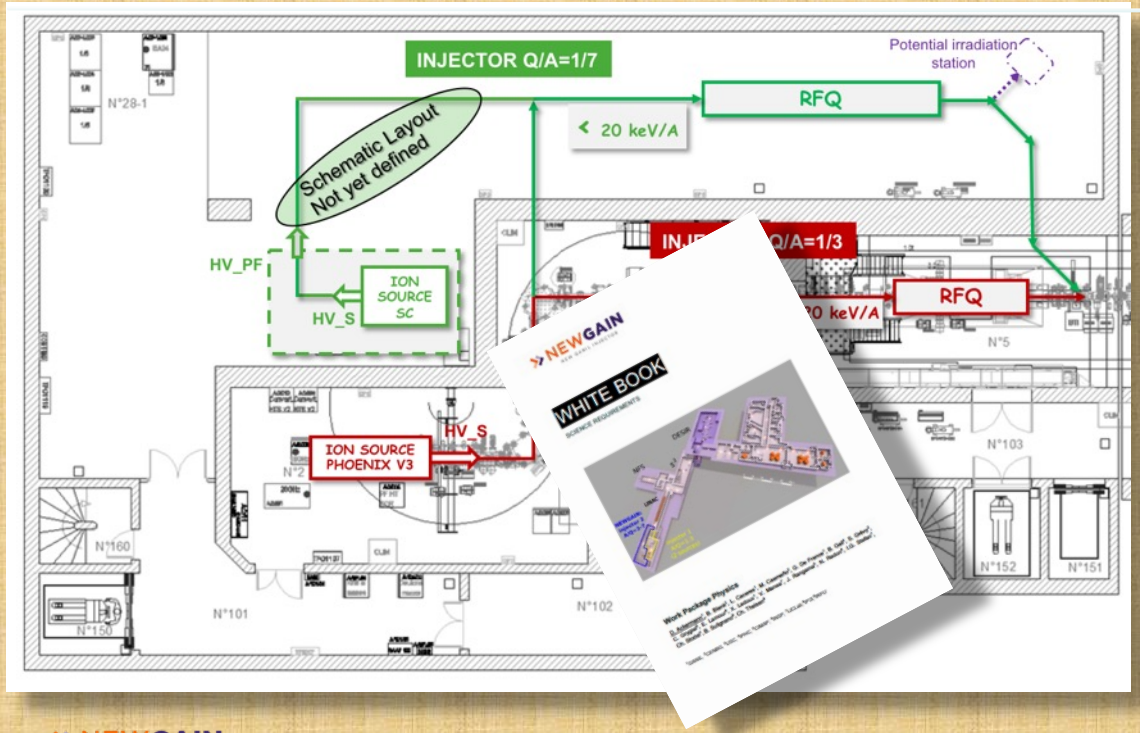
NEWGAIN time line

2020	2021	2022	2023	2024	2025	2026	2027	2028
Study Phase				Construction Phase				first beam

SPIRAL2 - NEWGAIN

- floorplan and design intensities

NEWGAIN
NEW GANIL INJECTOR



beam intensities	injector1 2023	NEWGAIN (injector2) 2028	NEWGAIN (injector2) ≥ 2030
Ions	Intensity (pμA) Phoenix V3 RFQ A/Q≤3	Intensity (pμA) Phoenix V3 RFQ A/Q≤7	Intensity (pμA) SC Ion Source RFQ A/Q≤7
^{18}O	80	*	375
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^{36}Ar	16	70	45
^{40}Ar	3.6	70	45
^{36}S	2.3	*	*
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^{48}Ca	1.2	10	20
^{58}Ni	1.1	4	**8**
^{84}Kr	0.1	10	**20**
^{139}Xe	0.001	7	**>10**
^{238}U	<<0.001	0.1	**6**

Measured | Estimated

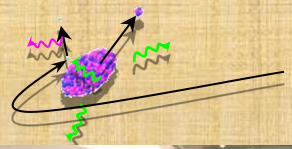
* -> no estimation

NEWGAIN **White Book**

https://www.ganil-spiral2.eu/scientists/ganil-spiral-2-facilities/accelerators/newgain/

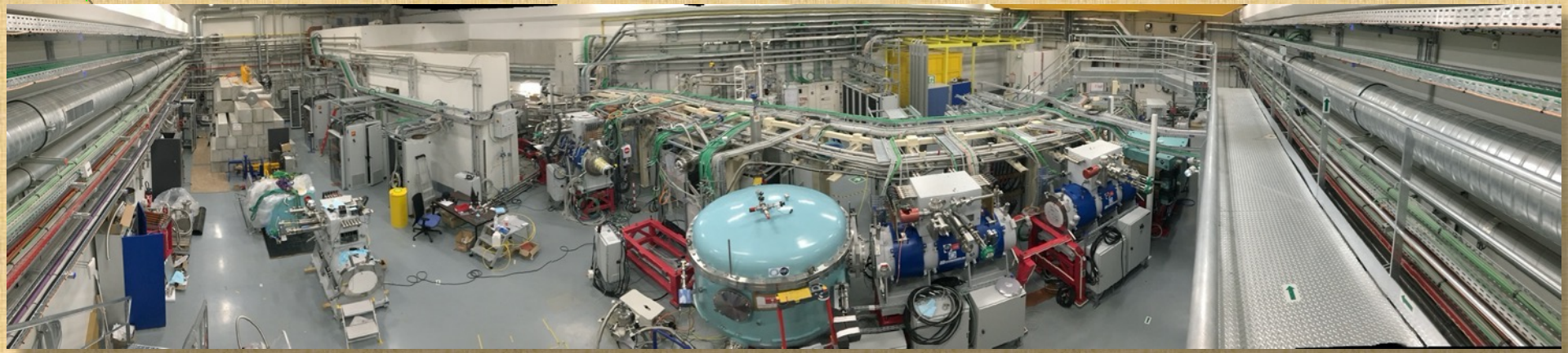
NEWGAIN **time line**

2020	2021	2022	2023	2024	2025	2026	2027	2028
Study Phase				Construction Phase				first beam



Perspectives: GANIL/SPIRAL2

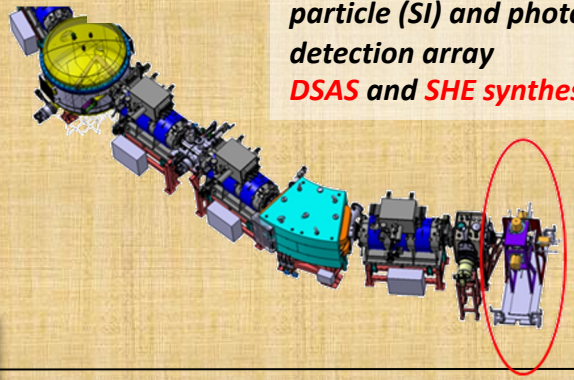
- S^3 and its 2 focal plane set-ups



S^3-SIRIUS

(Spectroscopy & Indentification of Rare Ions Using S^3)

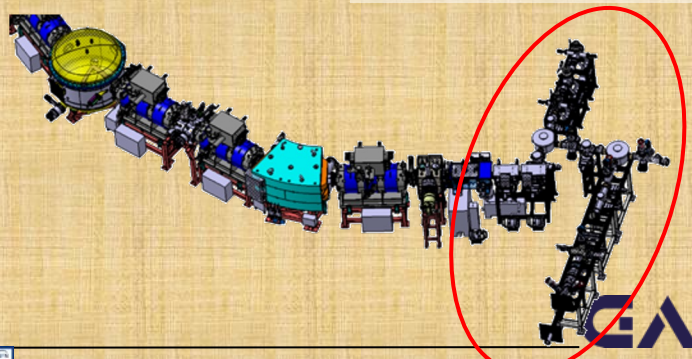
particle (SI) and photon (Ge) detection array
DSAS and SHE synthesis



S^3-LEB

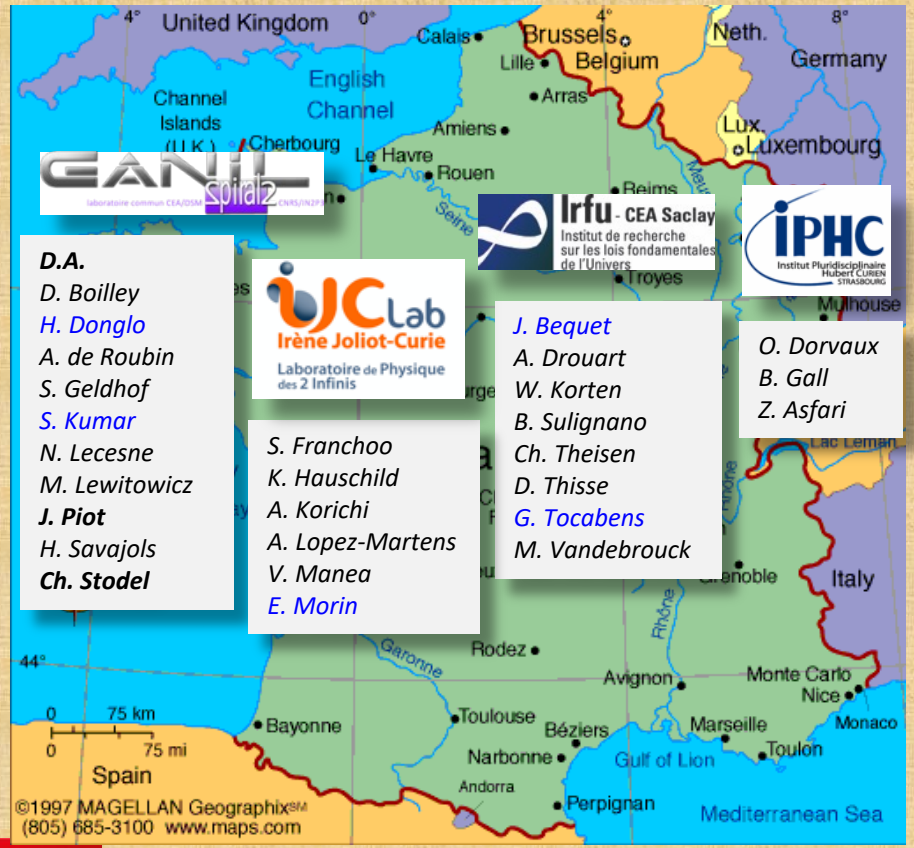
(Low Energy Branch)

gas-stoping/lasers/MRToF/ Si-Ge installation
laser spec, mass measurement and DSAS



Collaboration

SHE France



GANIL SPIRAL2 (laboratoire commun CEA/DSM – CNRS/IN2P3)

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