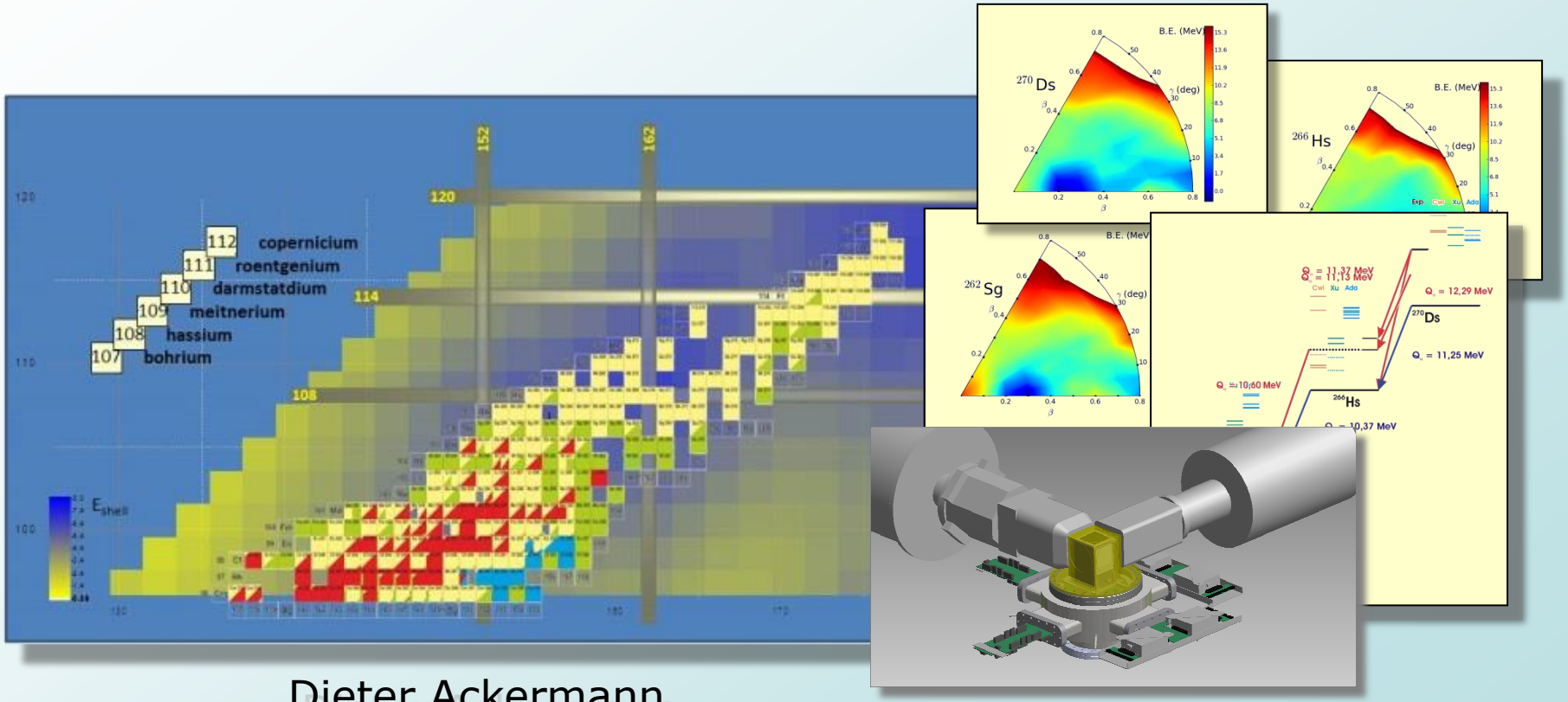
Super Heavy Nuclei
International Symposium
Texas A & M University, College Station TX, USA
March 31 - April 02, 2015

Paving the way to the island of stability

- superheavy element research at GSI and beyond



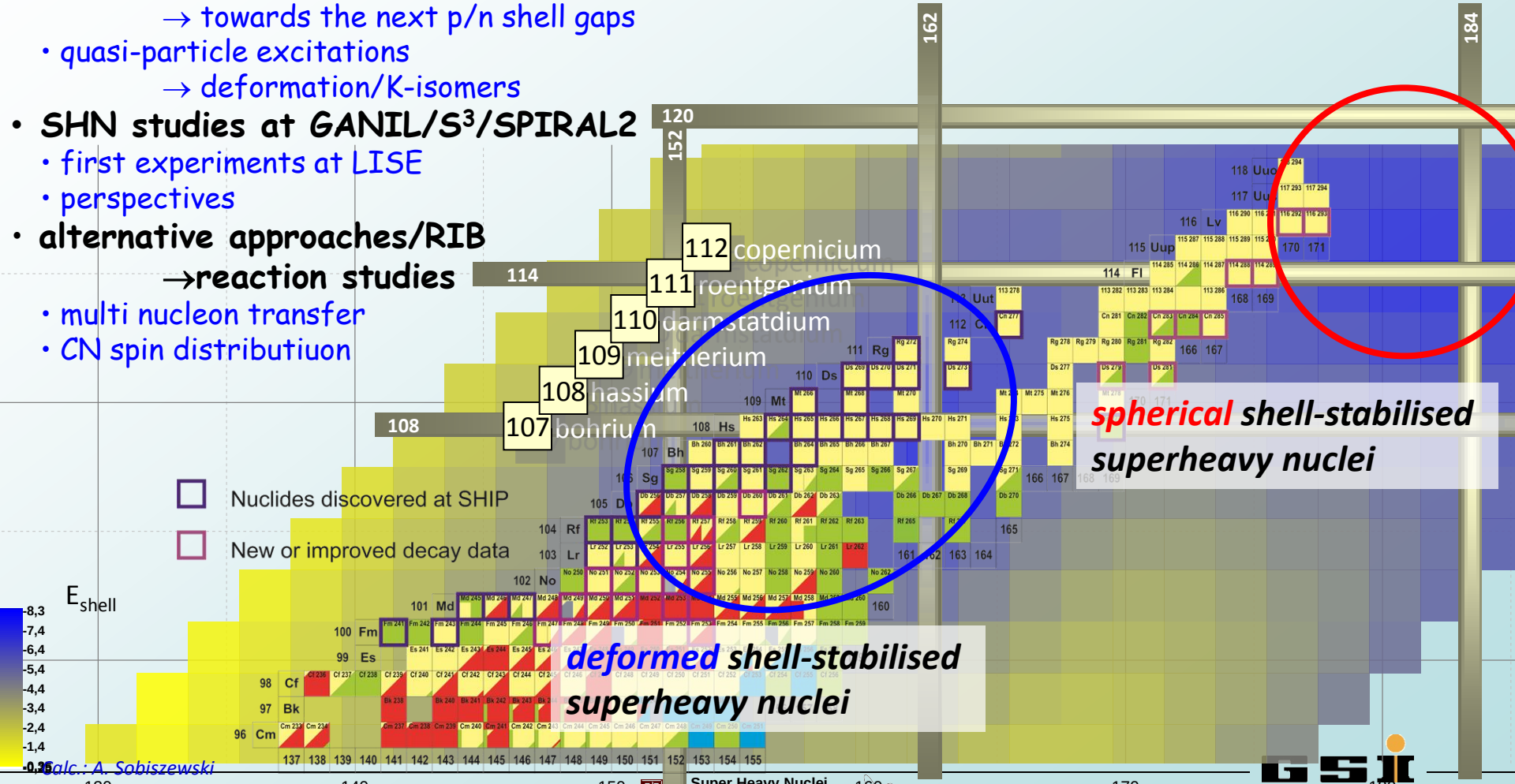
Dieter Ackermann
GSI
Helmholtzzentrum für Schwerionenforschung GmbH

College Station, March 31st 2015

SHE investigations – stable and exotic beams

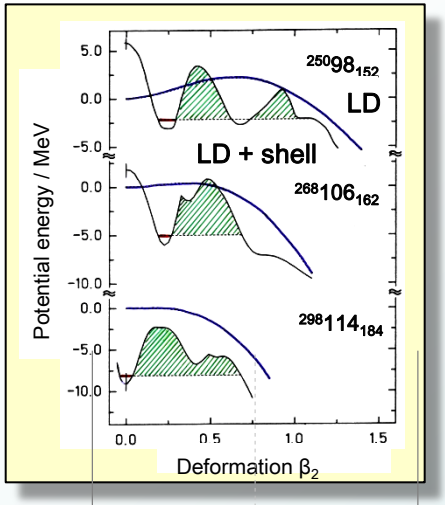
- outline

- **intro - towards the island of stability**
  - model predictions
- **nuclear structure features of superheavy nuclei (decay spectroscopy after separation)**
  - isotopic/isotonic trends of single particle levels
    → towards the next p/n shell gaps
  - quasi-particle excitations
    → deformation/K-isomers
- **SHN studies at GANIL/S³/SPIRAL2**
  - first experiments at LISE
  - perspectives
- **alternative approaches/RIB**
  →reaction studies
  - multi nucleon transfer
  - CN spin distributiuon



SHE and the origin of the "island of stability"

- liquid drop limit and quantum mechanical extension



existence only due to quantum mechanics and the strong nuclear interaction

different Z predictions (120-126)
self-consistent models (relativistic meanfield RMF/ Hartree-Fock-Bogoliubov HFB)

spherical shell-stabilised superheavy nuclei

background:
E_{shell} microscopic-macroscopic calculation (A. Sobiczewski)

deformed shell-stabilised superheavy nuclei

112 copernicium
111 roentgenium
110 darmstadtium
109 meitnerium
108 hassium
107 bohrium

Nuclides discovered at SHIP
New or improved decay data

E_{shell}

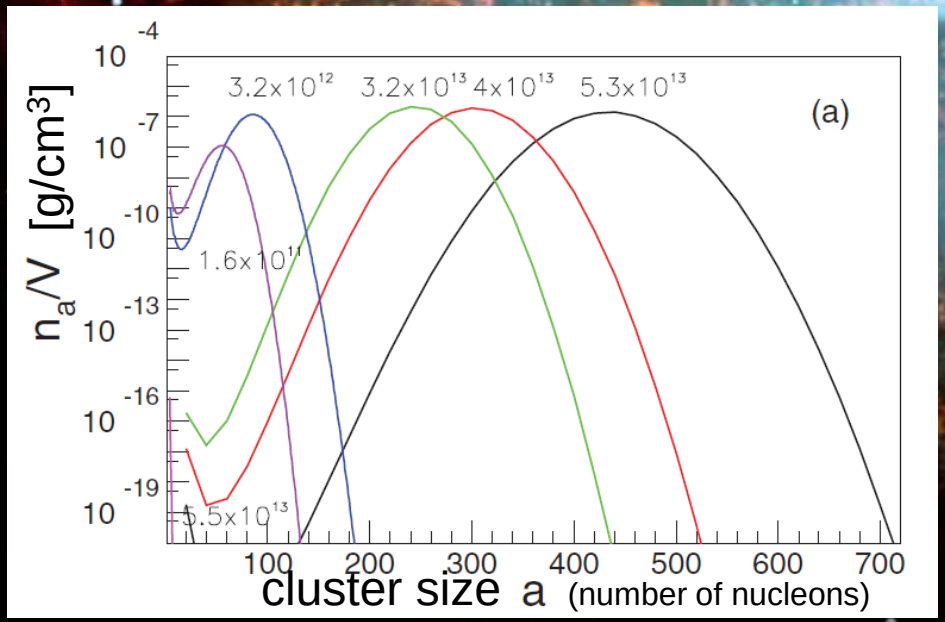
Calc.: A. Sobiszewski

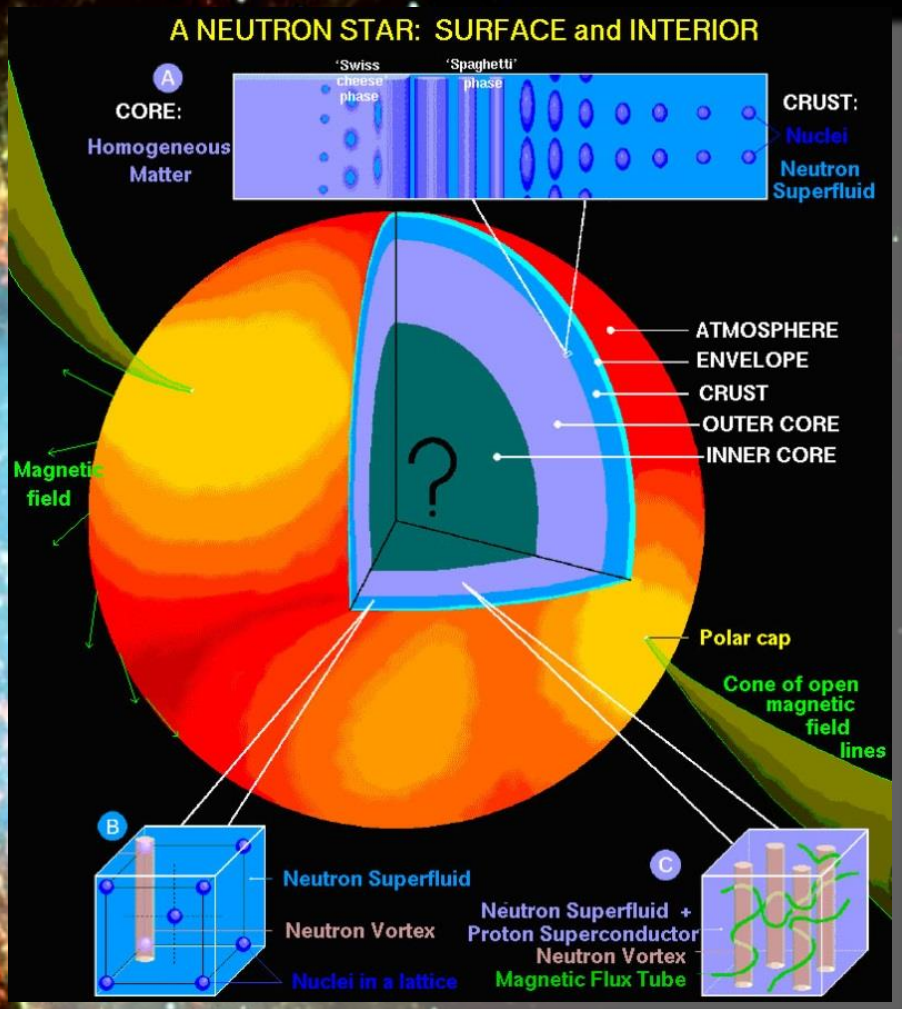
SHN in Nature (EOS calculations)

Superheavy nuclear clusters in core collapse super novae and the crust of neutron stars

- ***dense core of core collapse SN and low density outer crust of n-stars***
- ***superheavy nuclei imbedded in neutron superfluid (e^- screening)***
  → increased lifetime

→ experimental input on nuclear structure features needed also for n-rich superheavy nuclei



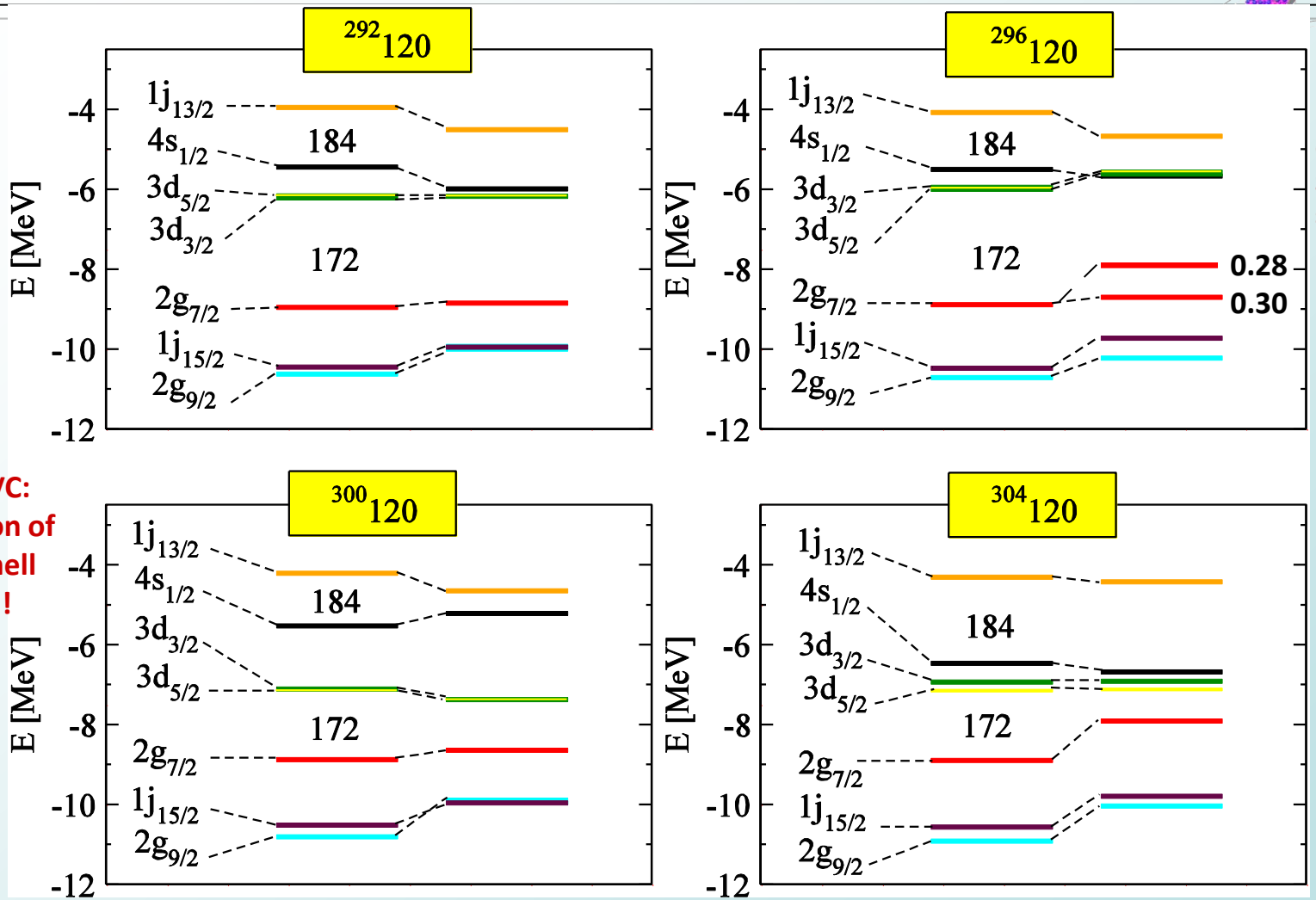


F. Gulminelli, Phys. Rev C 85, 025803 (2012)

Elena Litvinova

PRC 85, 021303(R) 2012

Shell evolution in superheavy Z = 120 isotopes: QVC in relativistic framework – dominant n-states



Comparable Spectroscopic strengths

PC+QVC: Formation of the „shell gap“ !

RMF+BCS

...+QVC

RMF+BCS

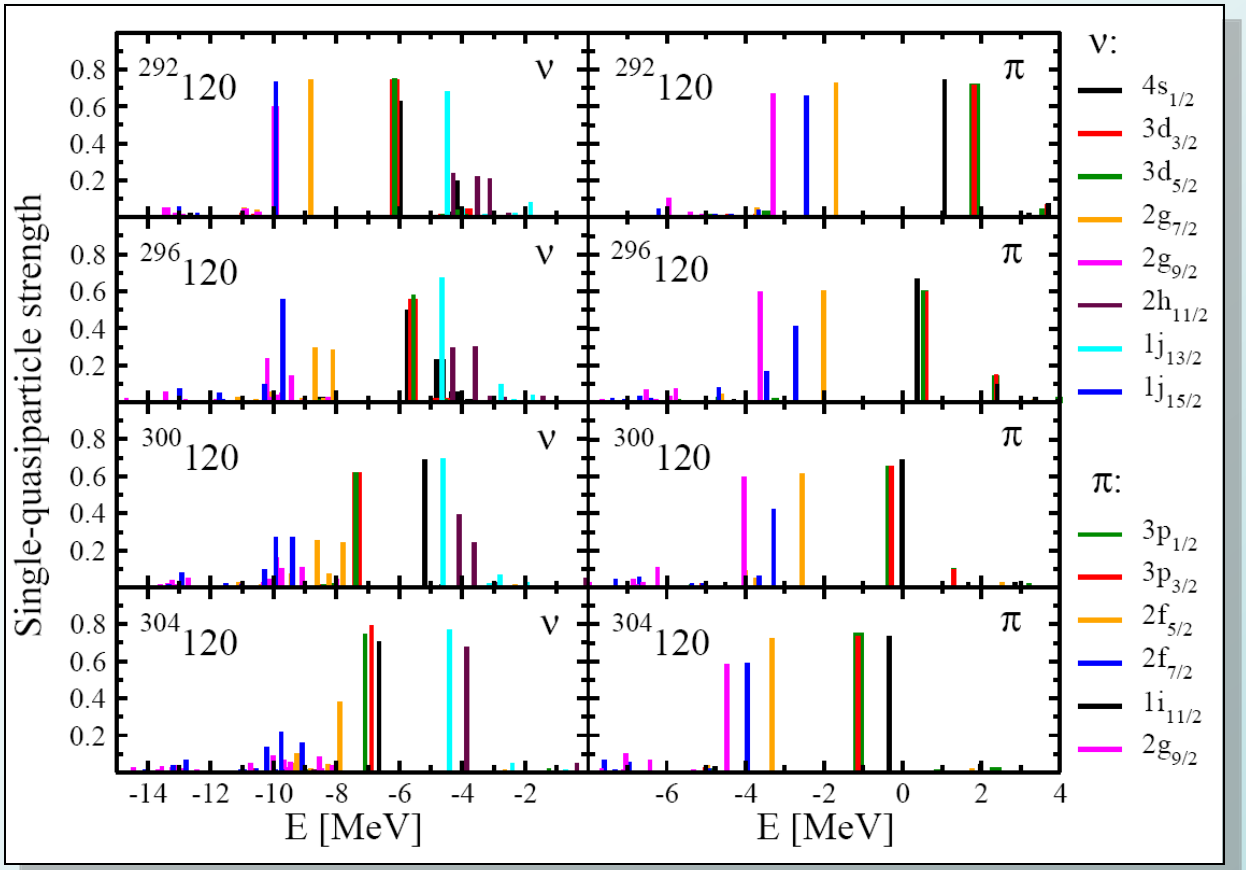
...+QVC

Elena Litvinova

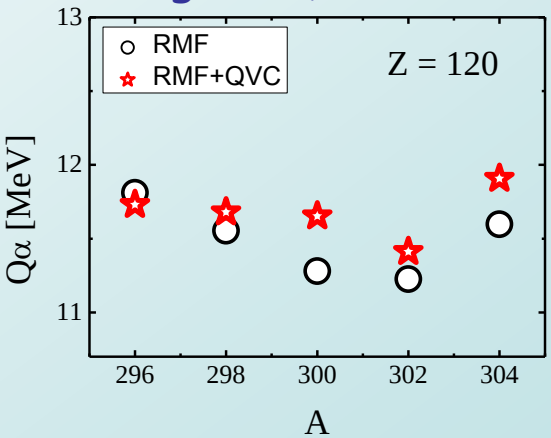
PRC 85, 021303(R) 2012

Shell evolution in superheavy Z = 120 isotopes: QVC in relativistic framework

1. Relativistic Mean Field: spherical minima
2. Small amplitude vibrations: RQRPA
3. Very soft nuclei: large amount of low-lying collective vibrational modes (~100 phonons below 15 MeV)



Vibration corrections to alpha decay energies Qα [MeV]



Vibrational corrections:

1. Impact on the shell gaps
2. Smearing of the shell effects

E.L., arXiv:1108.3508

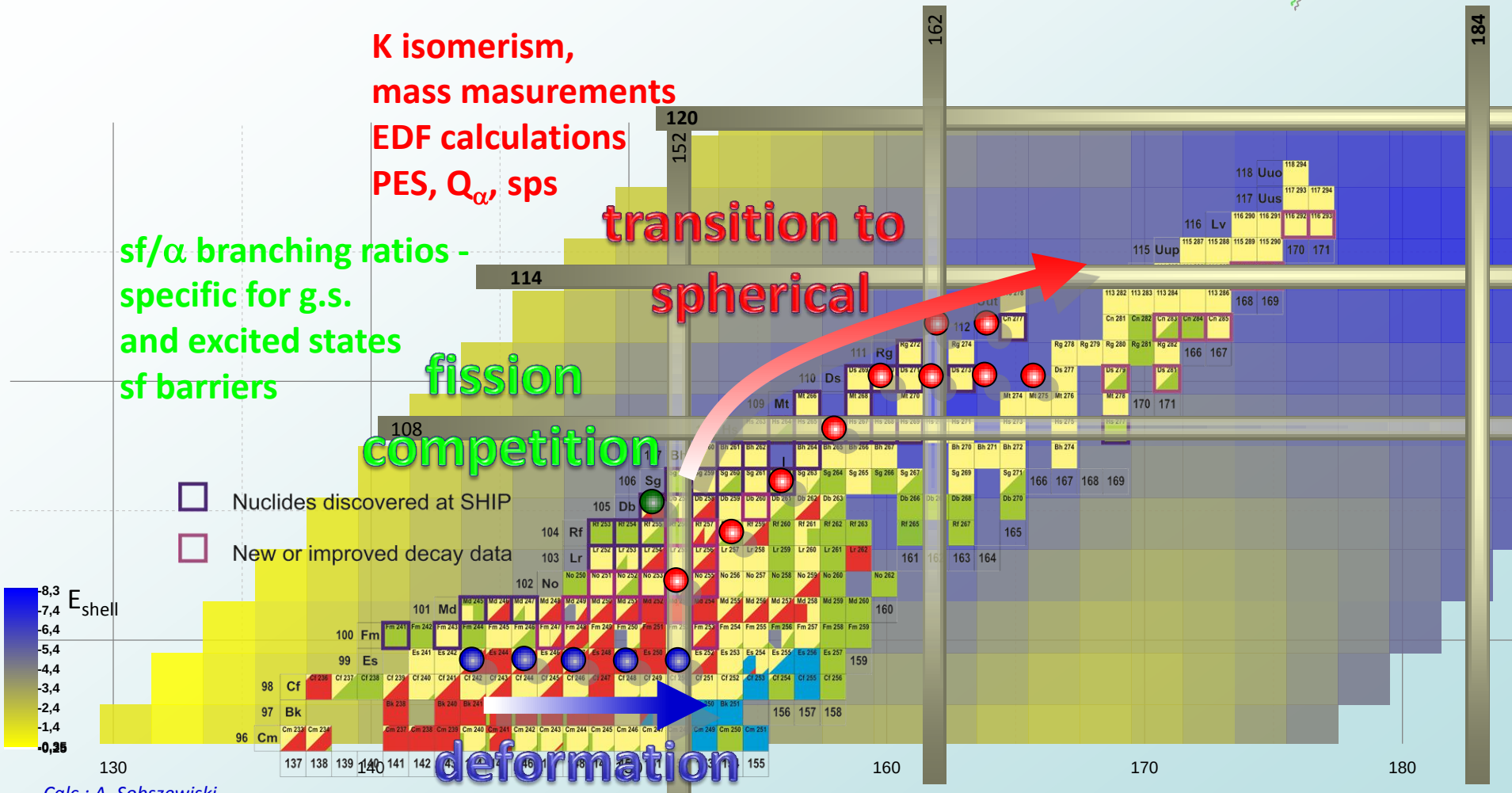
Shell stabilization & vibration stabilization/destabilization (?)

Decay spectroscopy

- access to a wide v of nuclear structure features in SHN

K isomerism,
mass masurements
EDF calculations
PES, Q_α, sps

sf/α branching ratios - specific for g.s. and excited states
sf barriers



Calc.: A. Sobszewiski

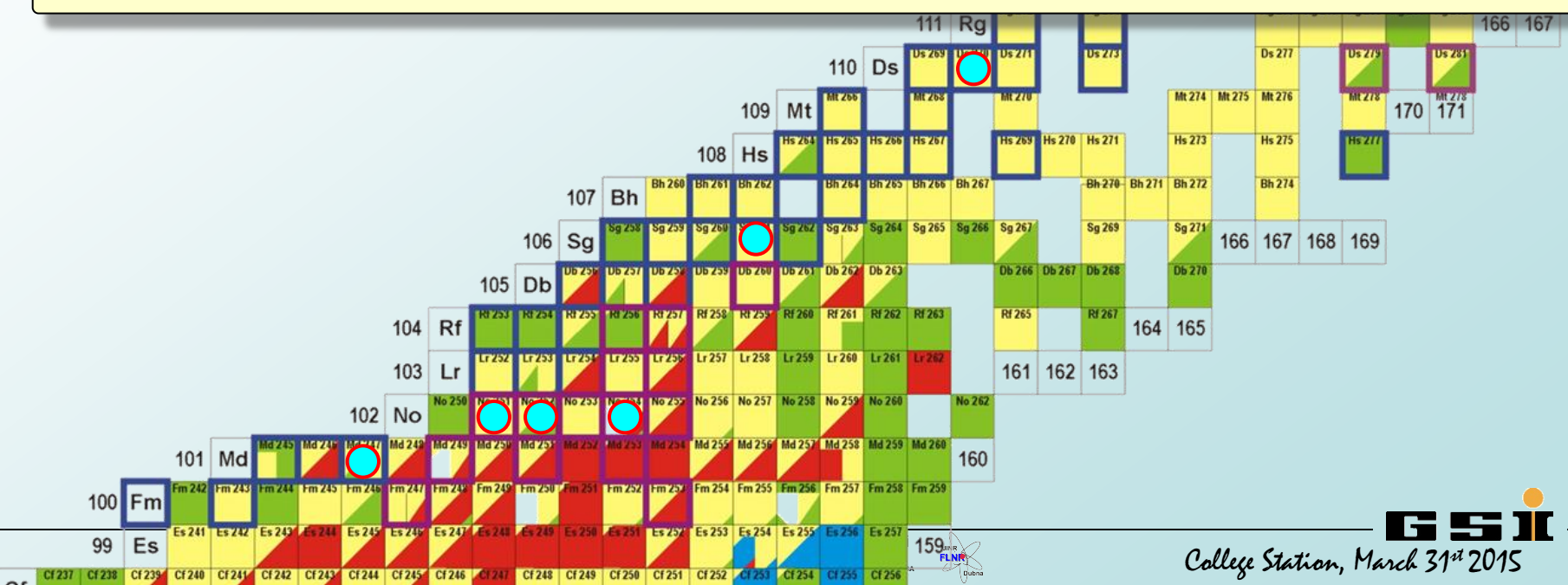
single particle states (sps)
transition energies

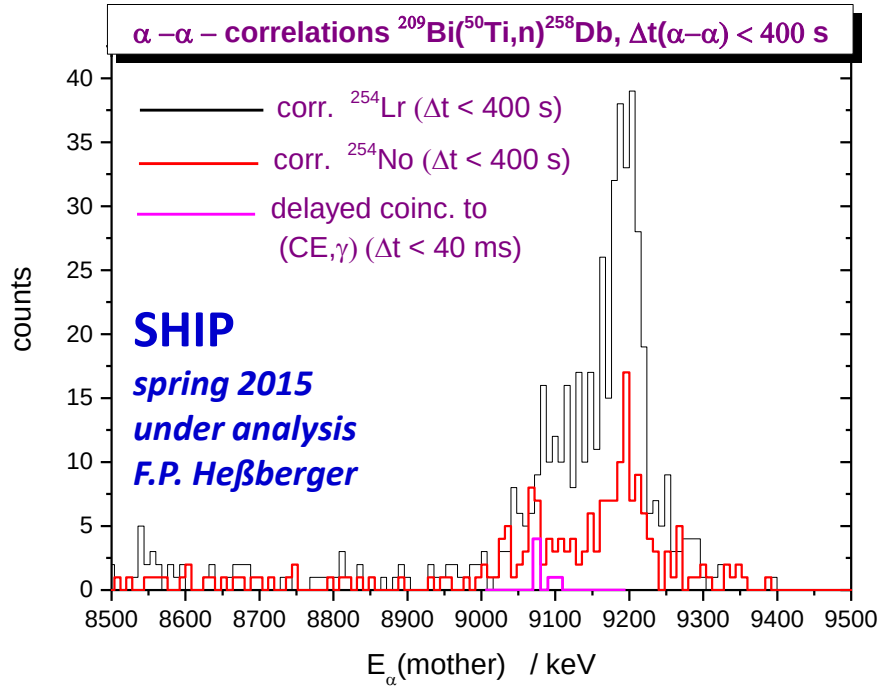
Nuclear Structure of the Heaviest Nuclei:

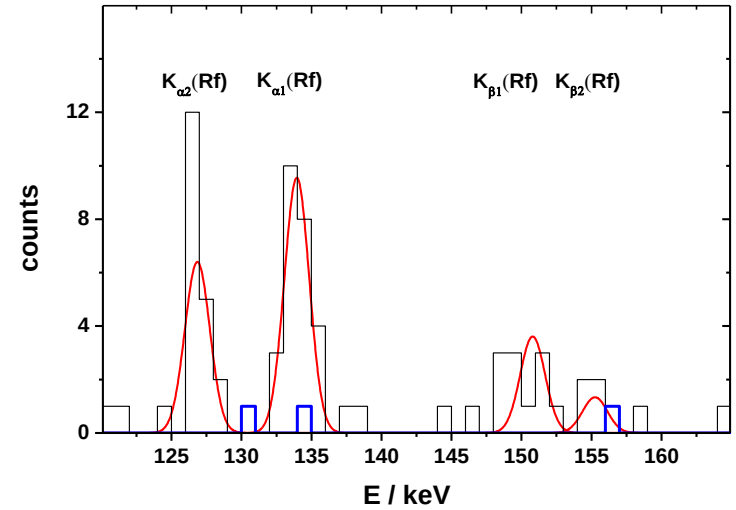
- Production Rates

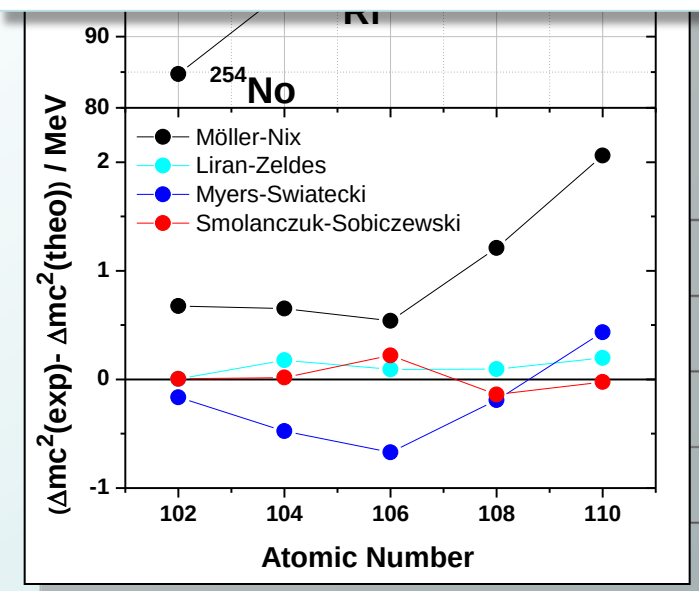
UNILAC intensities (≈ 1pμA/10^{12} particles/s) → **SPIRAL2 day 1** → phase 1++

reaction	σ/nbarn	countrate/countrate/countrate
$^{208}Pb(^{48}Ca,2n)^{254}No$	2000	15000 /h → 40.000 /h → 240.000 /h
$^{206}Pb(^{48}Ca,2n)^{252}No$	430	3300 /h → 8.000 /h → 48.000 /h
$^{206}Pb(^{48}Ca,3n)^{251}No$	25	200 /h → 500 /h → 3.000 /h
$^{209}Bi(^{40}Ar,2n)^{247}Md$	7	80 /h → 300 /h → 1.000 /h
$^{208}Pb(^{54}Cr,1n)^{261}Sg$	2	15 /h → 30 /h
$^{207}Pb(^{64}Ni,1n)^{270}Ds$	0.013	1 /d → 2 /d → 0.5 /h

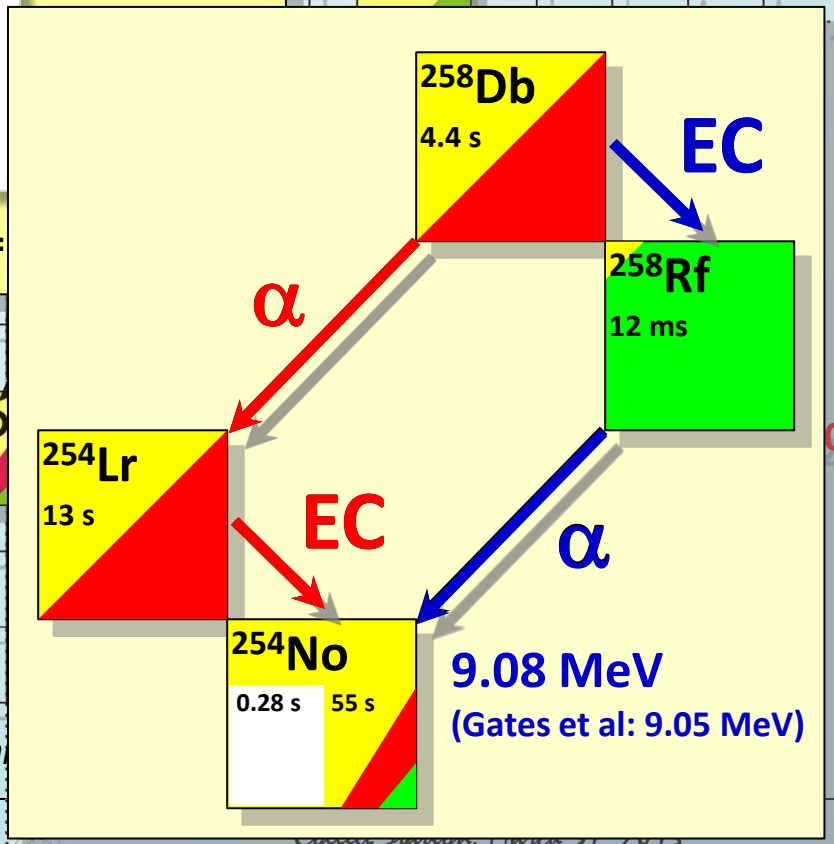








α-decay link
^{262}Sg → ^{258}Rf

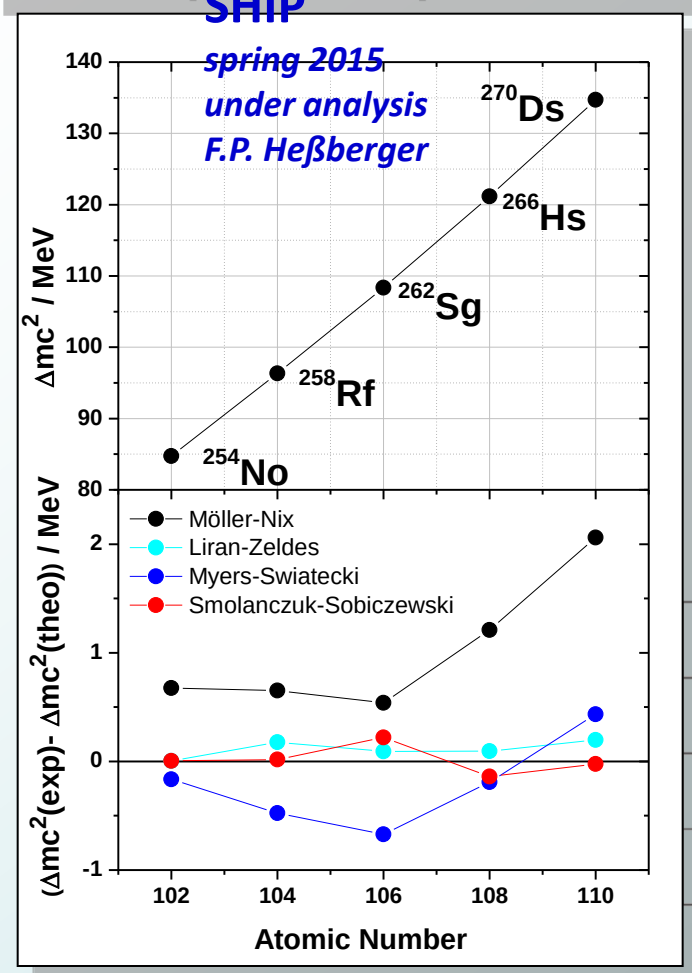


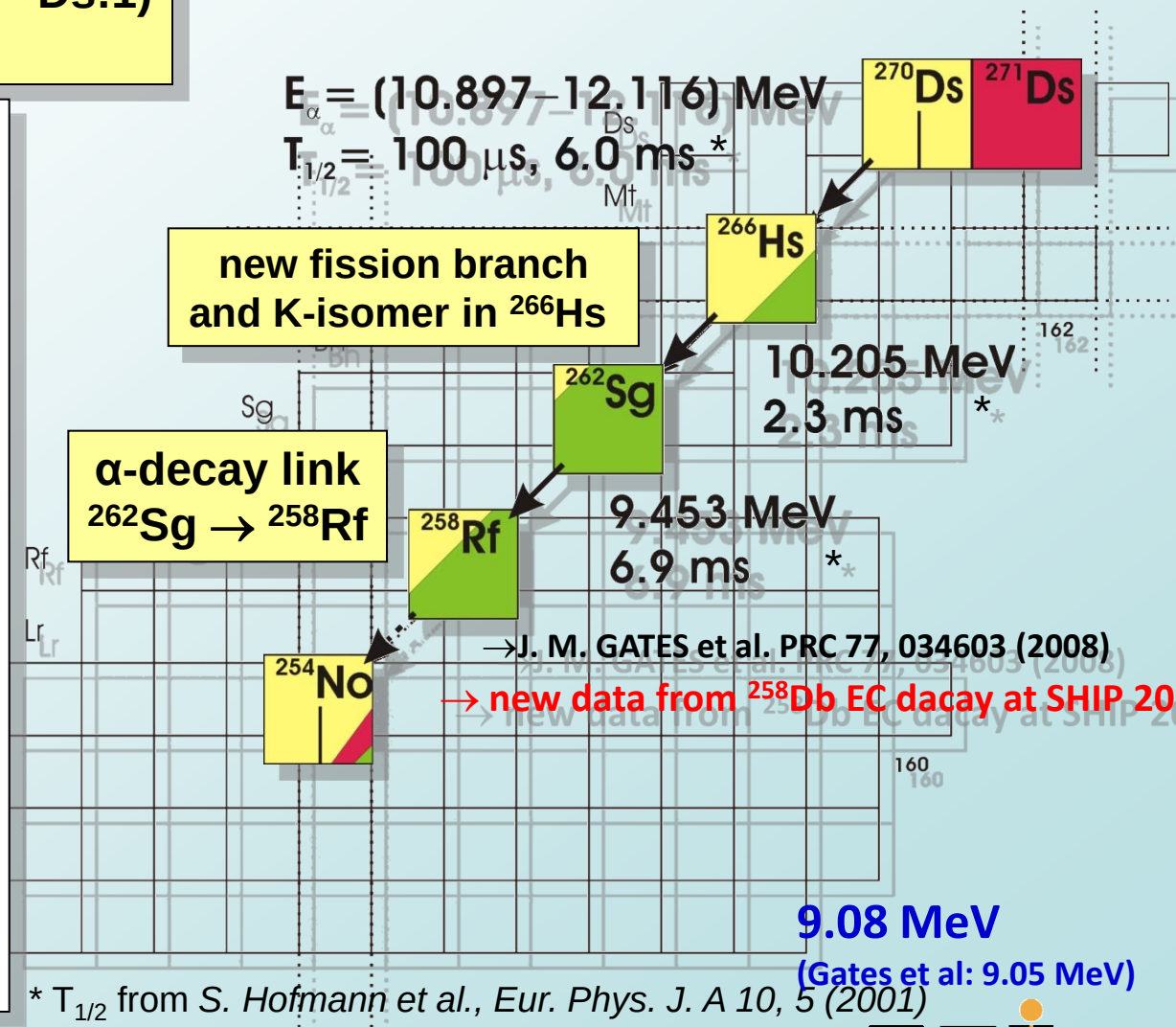
* $T_{1/2}$ from *S. Hofmann*

^{270}Ds

- News – ^{266}Hs sf-branch - ^{262}Sg α-branch → link to ^{254}No

- 26 decay chains (^{270}Ds: 25, ^{271}Ds:1)
- new spectroscopic data





* $T_{1/2}$ from *S. Hofmann et al., Eur. Phys. J. A 10, 5 (2001)*

^{270}Ds Decay Scheme

^{270}Ds:

12 g.s. decays

13 isomer decays - 2 γ's: 175/741 keV

(in 2000: 3:3 + 1 γ)

chain 8:

E_α 200-300 keV lower

^{266}Hs:

16 g.s. decays

1 isomer decay

with a 332 keV γ-ray

chain 8:

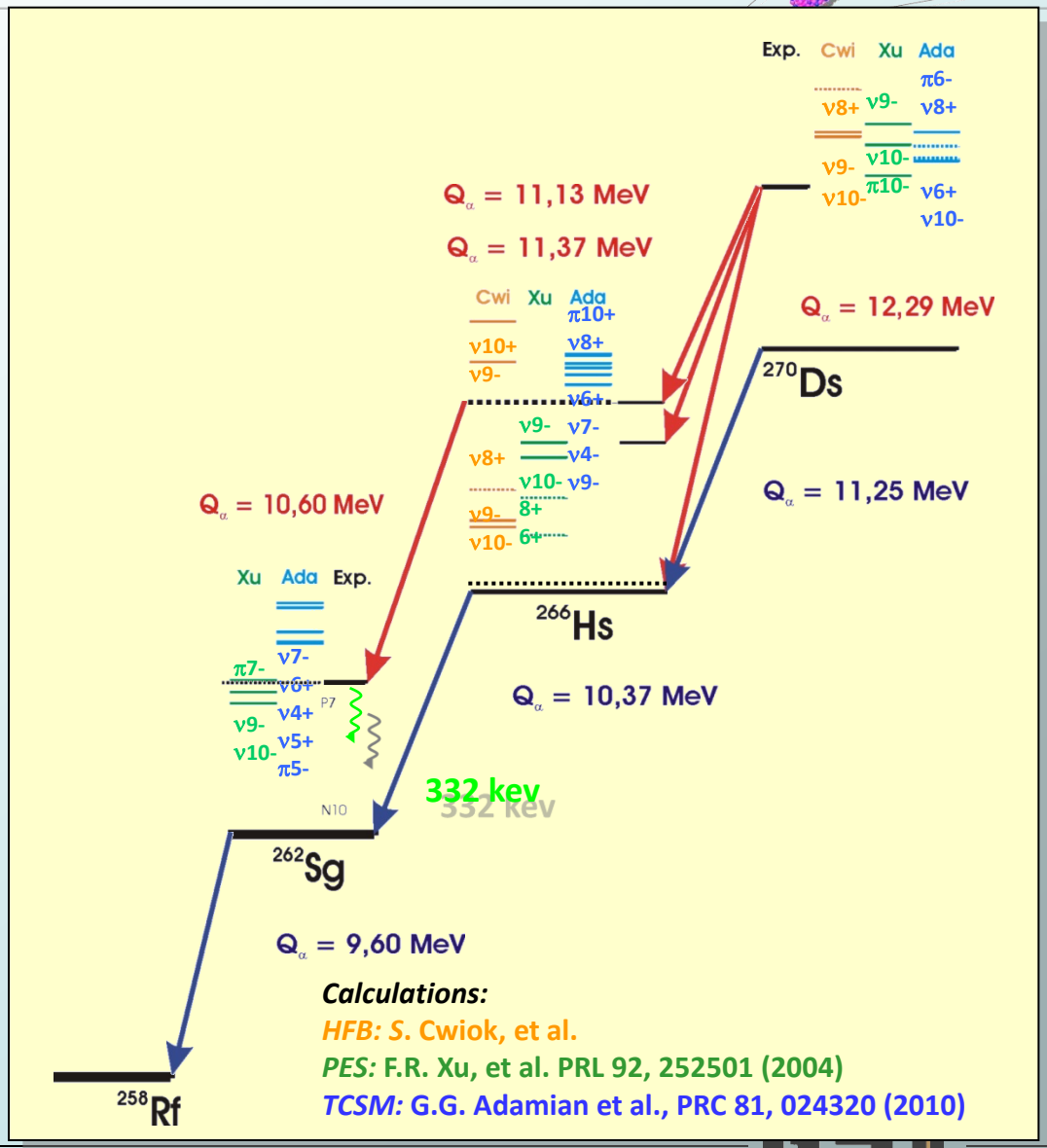
$E_\alpha \approx$ 200 keV higher

E_γ = 332 keV

^{262}Sg:

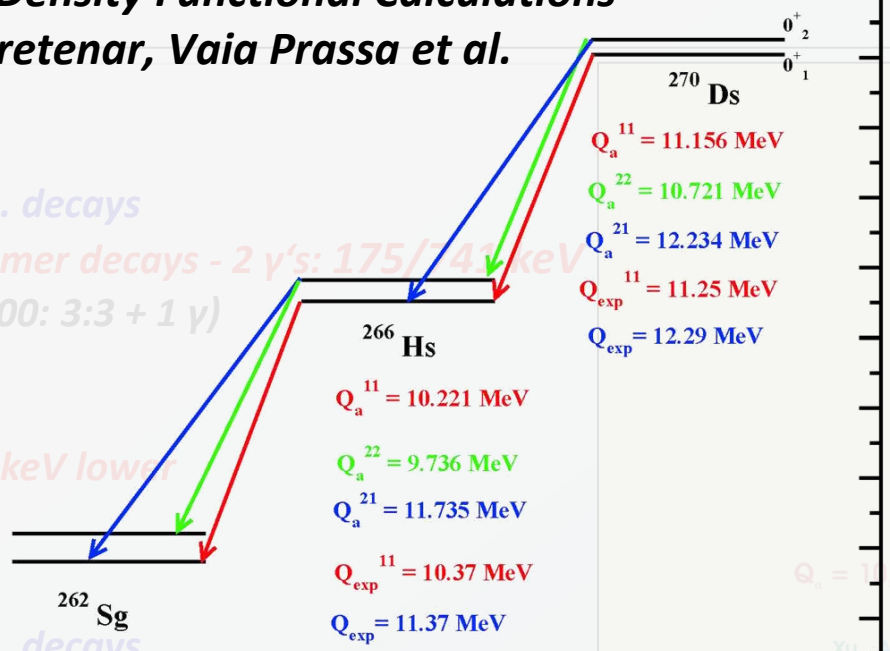
α decay observed for the first time

(1 full E, 1 escape)



^{270}Ds Decay Scheme

Energy Density Functional Calculations
Dario Vretenar, Vaia Prassa et al.



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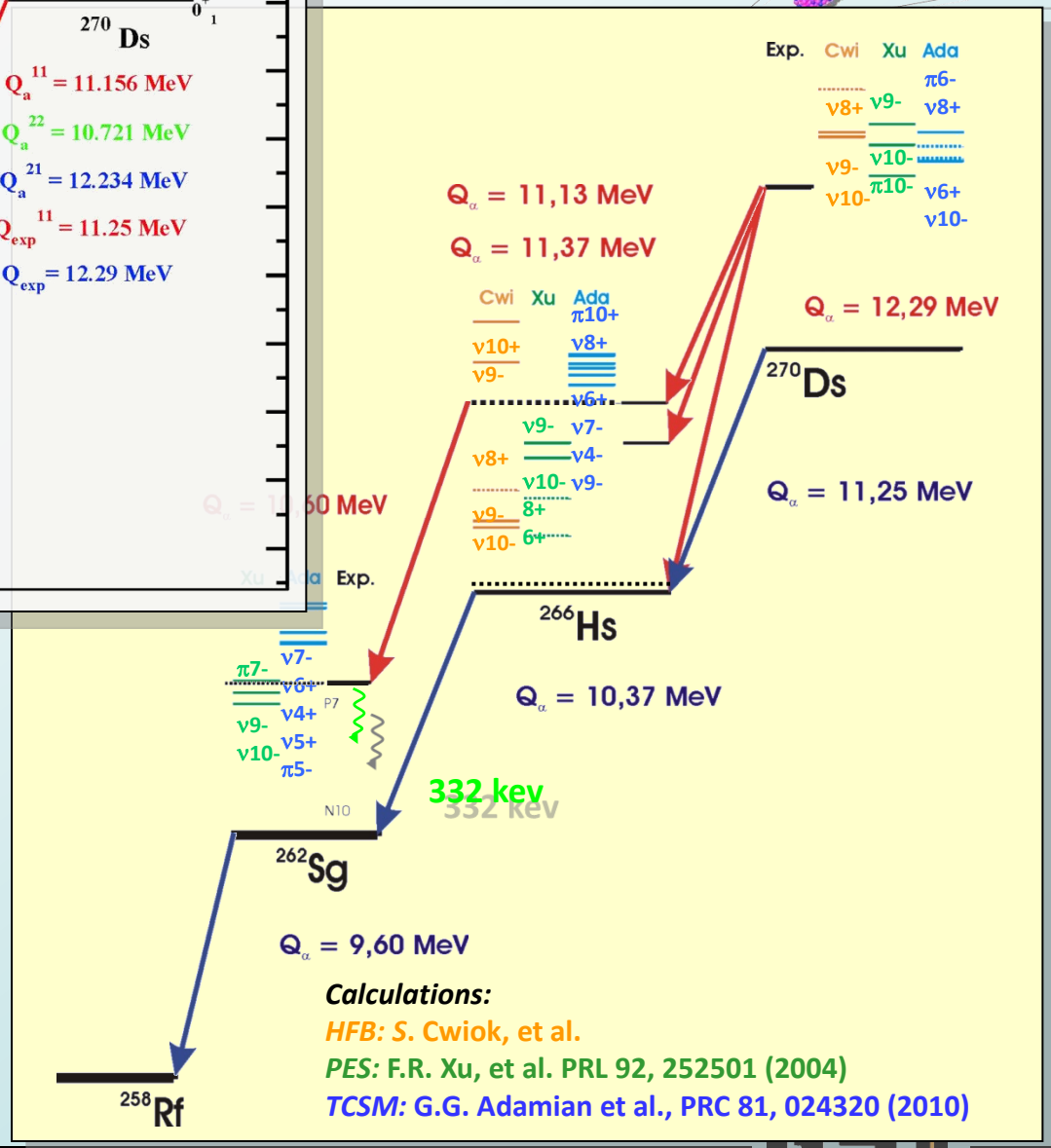

Calculations:

HFB: S. Cwiok, et al.

PES: F.R. Xu, et al. PRL 92, 252501 (2004)

TCSM: G.G. Adamian et al., PRC 81, 024320 (2010)

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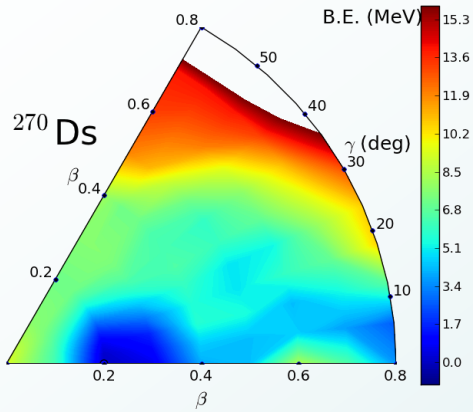
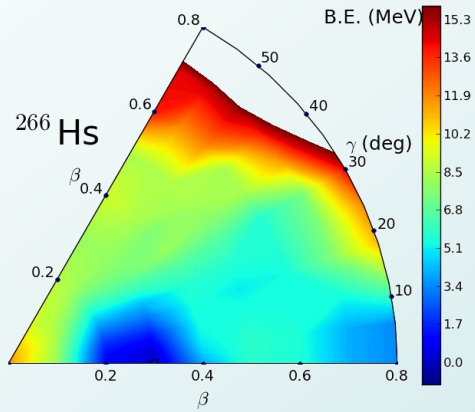
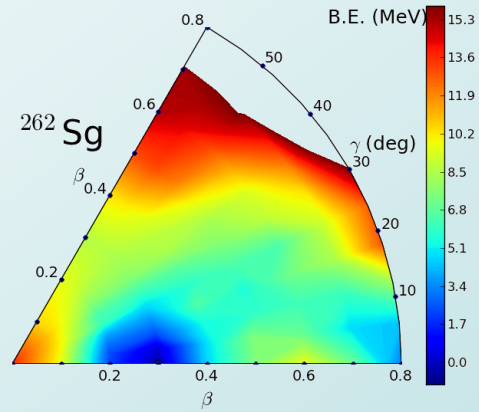
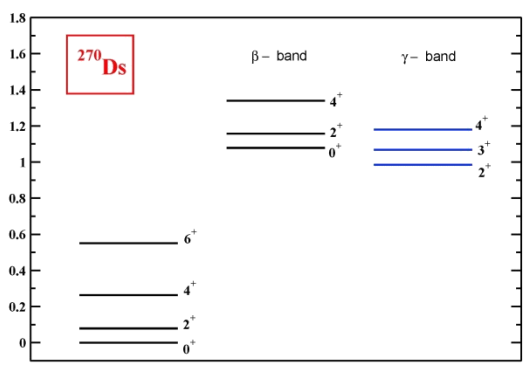
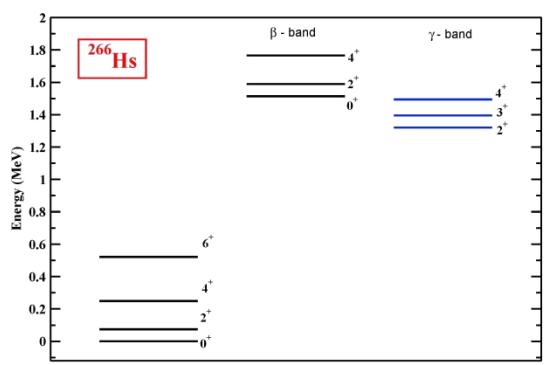
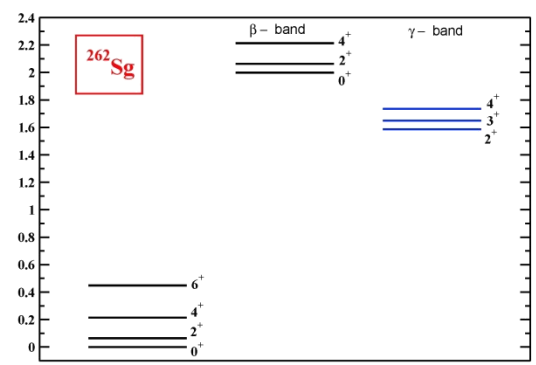




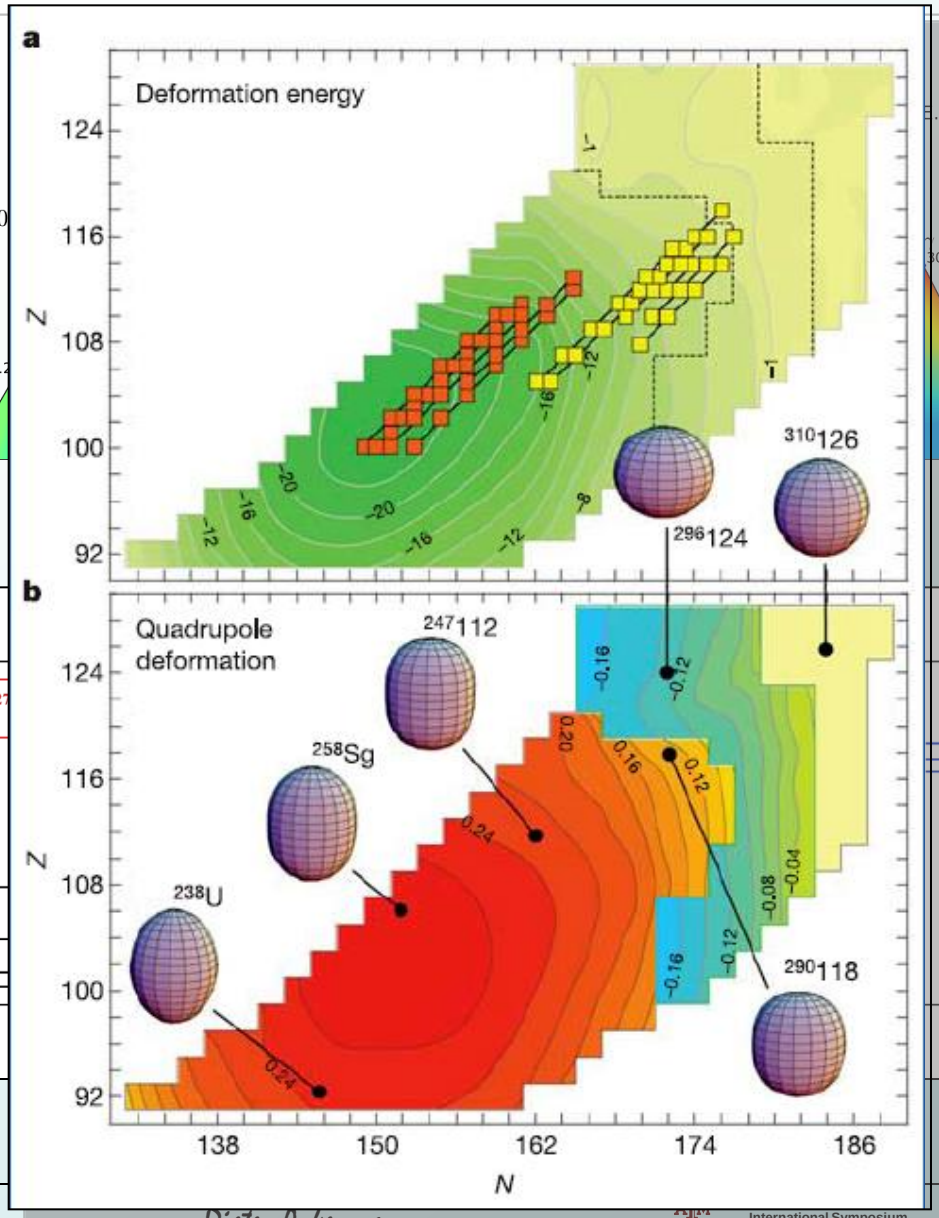




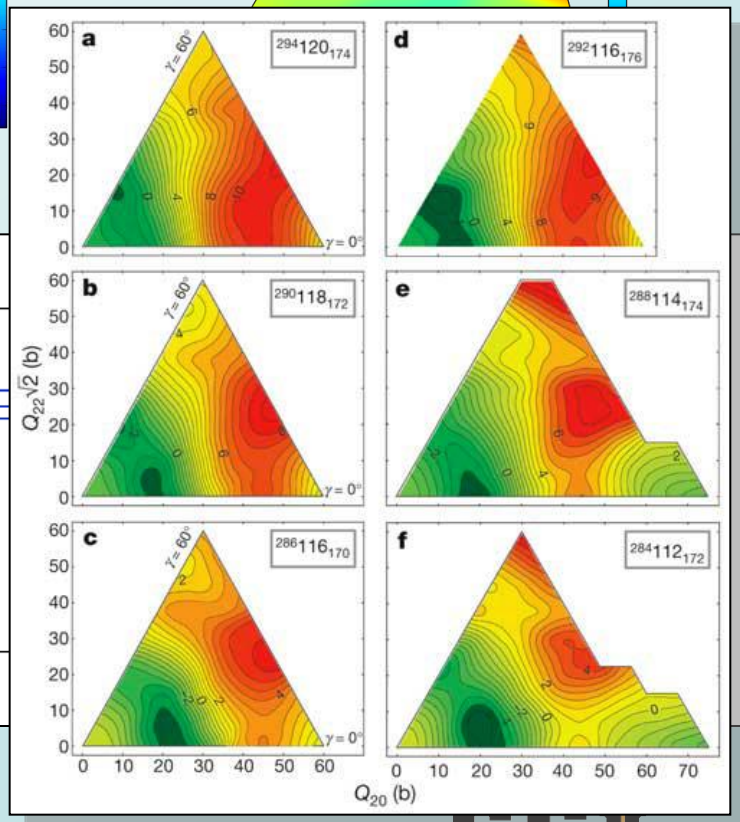




Energy Density Functional Calculations
- Dario Vretenar, Vaia Prassa et al.



S. Ćwiok et al., NATURE, 433 (2005)
HFB + SLy4



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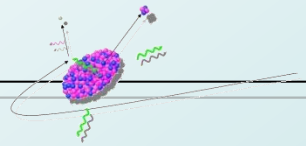


16 nuclides with K-isomeric states known for Z = 96 to 110

→ **tool to map deformation towards spherical SHE**

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

K-Isomers in even-even nuclei

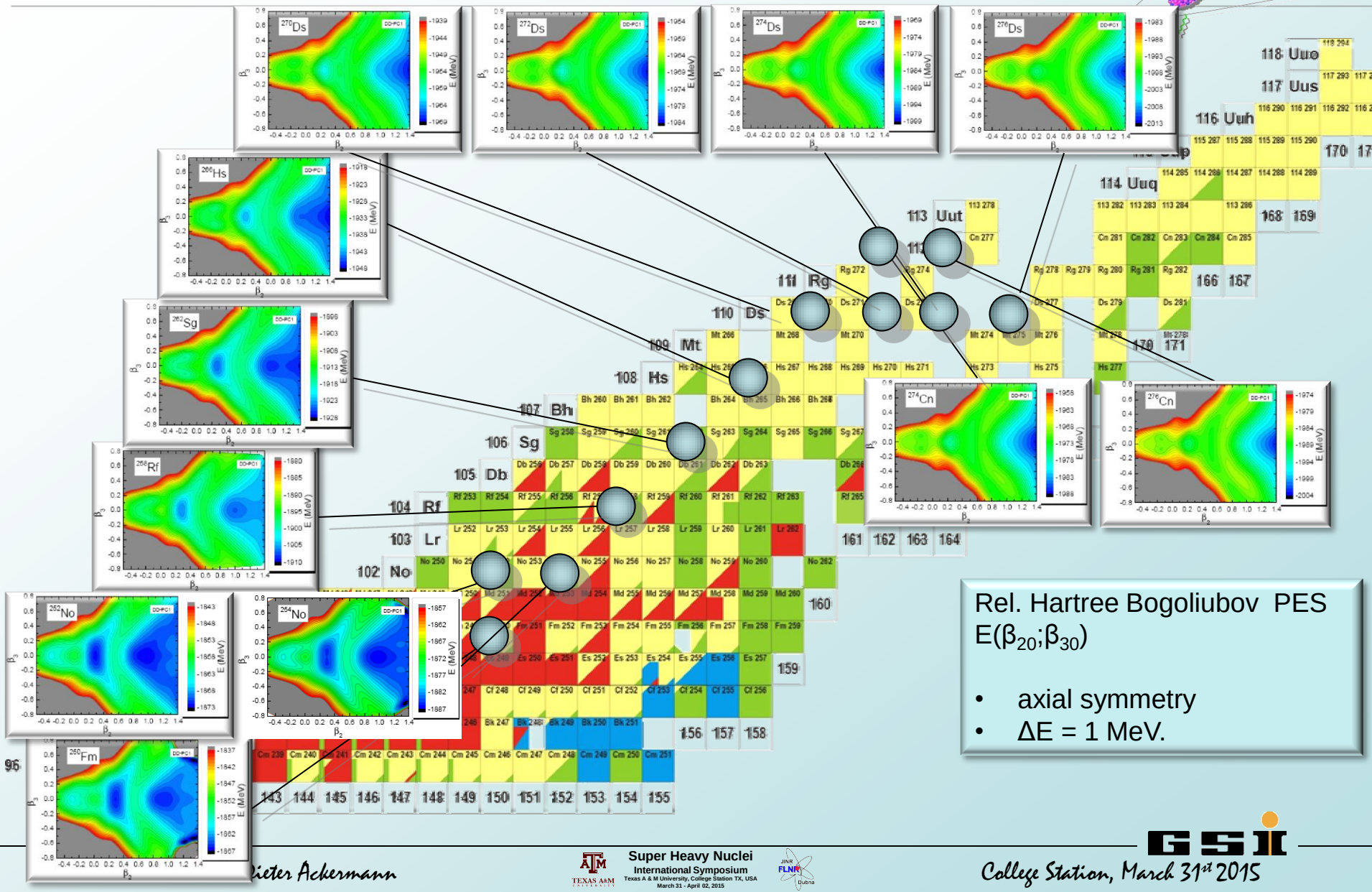
K-Isomers in even Z - odd N nuclei

K-Isomers in odd Z - even N nuclei

, NATURE, 433 (2005)

Potential E surface Calculations (rel. HFB)

- Bingnan Lu, Dario Vretenar et al.

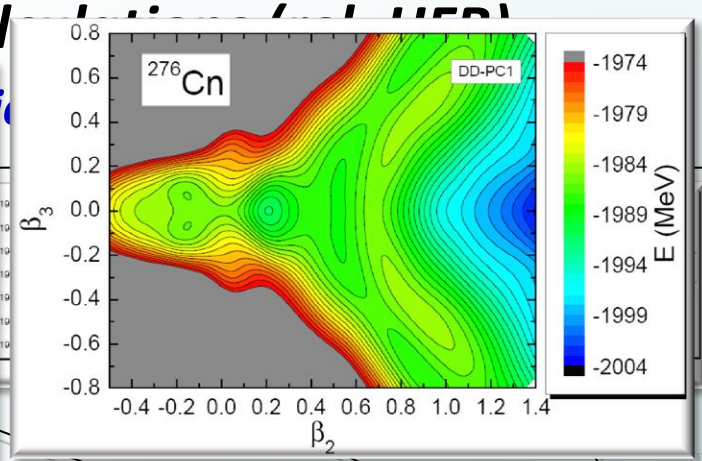


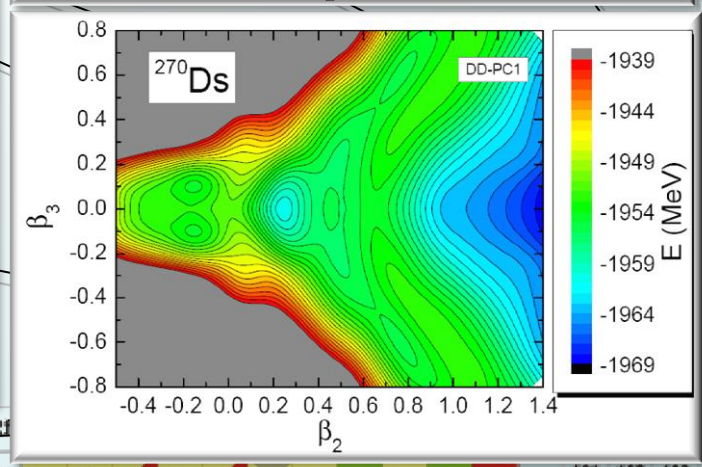
Rel. Hartree Bogoliubov PES $E(\beta_{20};\beta_{30})$

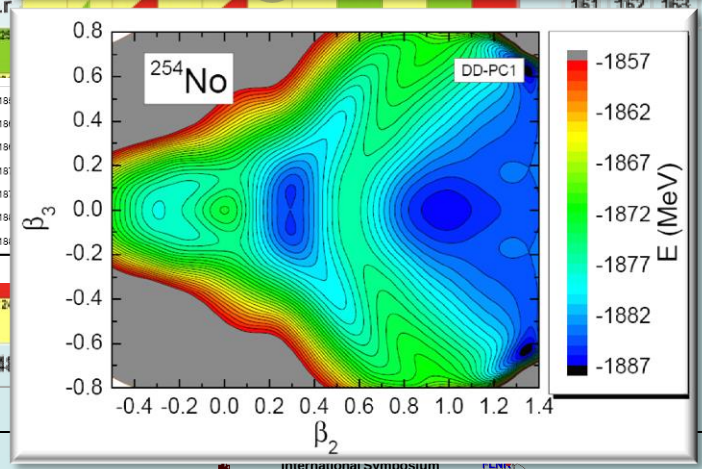
- axial symmetry
- $\Delta E = 1$ MeV.

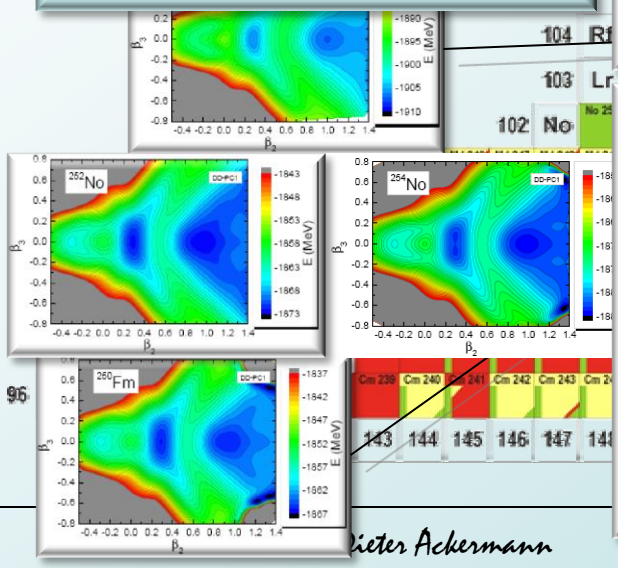
Potential E surface Cal

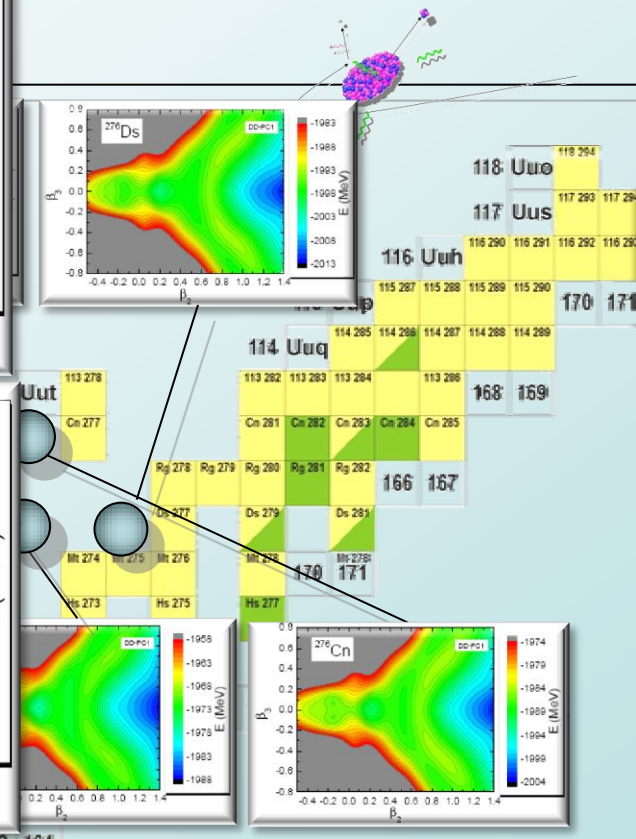
- g.s. deformation varies slowly from Z=100 to 112
- wide octupole range for minimum for Fm and No isotopes
- minimum decreases → K-isomer in ^{276}Cn?
- Z = 112: at the edge of the spherical shell stabilized region - "island of stability"?









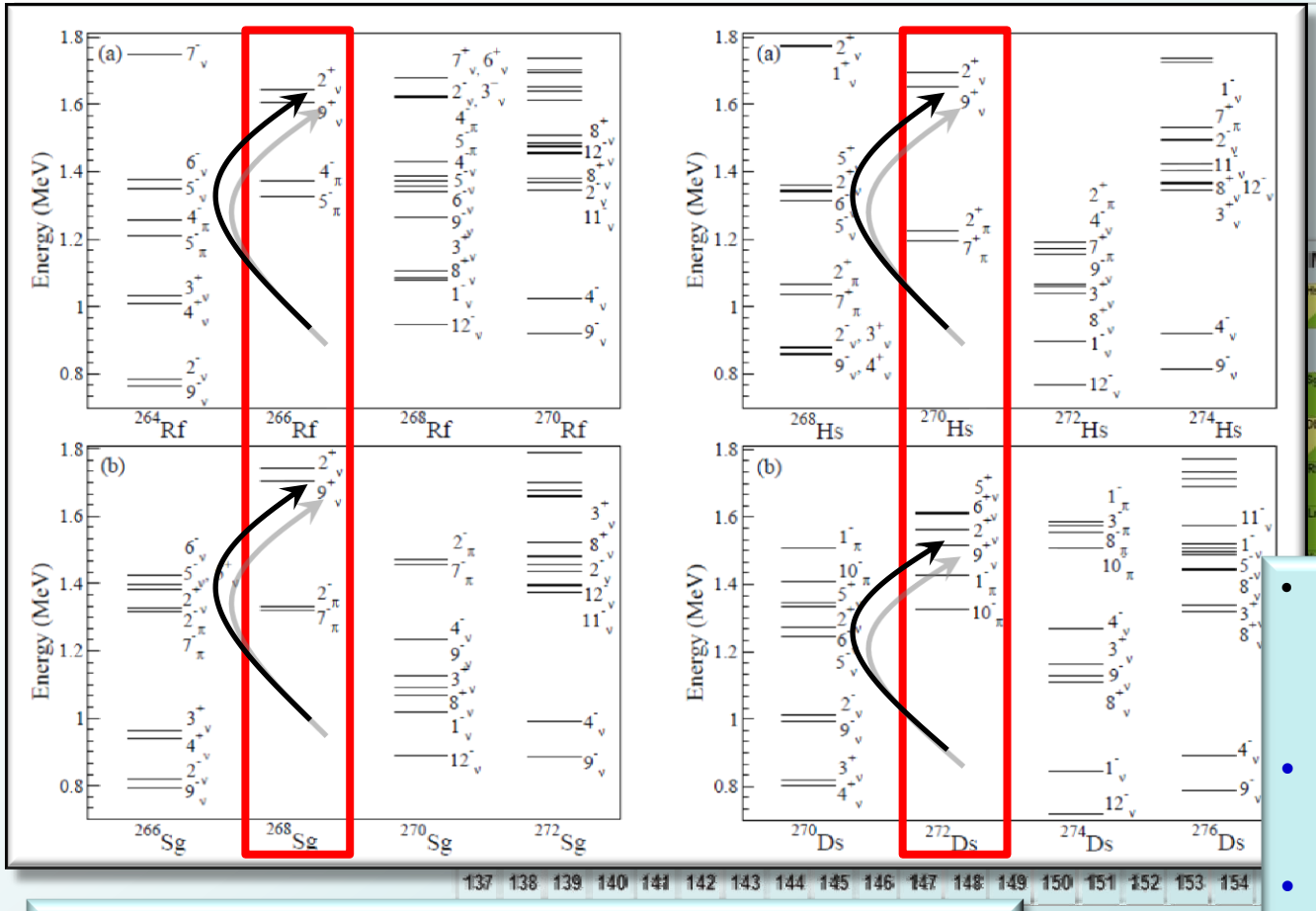


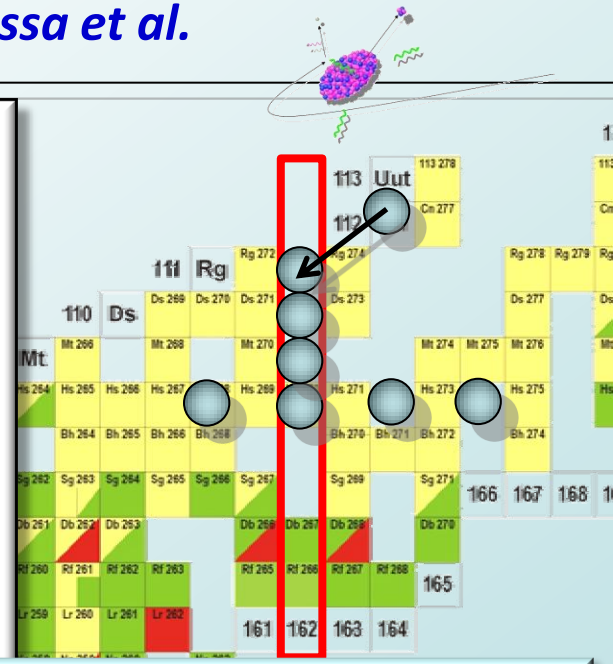
Rel. Hartree Bogoliubov PES $E(\beta_{20};\beta_{30})$

- axial symmetry
- ΔE = 1 MeV.

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

- Energy Density Functional Calculations, Vaia Prassa et al.





- **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)

Day 1 SPIRAL2 Phase 1
- SHE LoI(s)

LoI 2009:

"Production and spectroscopy of heavy and superheavy elements using S^3 and LINAG"

- ***Neutron deficient nuclei around Z=92 N=126***
- ***K-isomerism studies in the Z=100-110 region***
- ***study of neutron rich isotopes produced by asymmetric reactions***
- ***Production of SHE with Z=106-108-112 with Uranium target***

Addendum 2012:

"Detailed spectroscopy of high-K states in ^{254}No and ^{256}Rf: location of single--particle states close to the Z=100 and N=152 deformed shell gaps"

Spokespersons:

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Karl Haushild, CSNSM
Amel Korichi, CSNSM
Christophe Theisen, Irfu/SPhN
Stodel Christelle, GANIL

Other participants:
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*K.Hauschild, A.Lopez-Martens, A.Korichi, (**CSNSM Orsay, France**)*
*D. Boilley, E. Clément, G.De France, F.Rejmund, H.Savajols, C.Schmitt, C.Stodel (**GANIL, France**)*
*J.Uusitalo, P.Jones, C.Scholey, R.Julin, M.Leino (**University of Jyväskylä, Finland**)*
*B.Gall, J.Piot, O.Dorvaux, (**IPHC Strasbourg, France**)*
*D.Ackermann, (**GSI, Germany**)*
*R.-D.Herzberg, (**University of Liverpool, U.K.**)*
*Eduard Kozulin, Galina Knyazheva, Dmitry Gorelov (**FLNR JINR Dubna, Russia**)*
*R. Janssens, J. A. Nolen, G. Savard (**Argonne National Laboratory, Argonne, U.S.A.**)*
*Zhongzhou REN (**Nanjing University, China**)*
*Y. Bulent (**Ankara University, Turkey**)*
*W. Meczynski, J. Styczen, A. Maj, M. Kmiecik, K. Mazurek (**IFJ PAN Krakow, Poland**)*
*N. Redon et O. Stezowski (**IPN Lyon, France**)*

Beam intensities

- SPIRAL2 day 1/phase 1+

Ion	I_{max} [pμA]	
	SPIRAL 2 day 1	SPIRAL2 phase 1+
^{12}C	30	
^{18}O	30	
^{19}F	30	
^{24}Mg	25	
^{22}Ne	25	
^{28}Si	25	
^{36}Ar	20	
^{40}Ar	5.8	20
^{32}S	14.6	25
^{36}S	9.2	25
^{40}Ca	6	15
^{48}Ca	2.5	15
^{50}Cr	4	
^{46}Ti	5	
^{58}Ni	2.2	12

SPIRAL2 day 1:

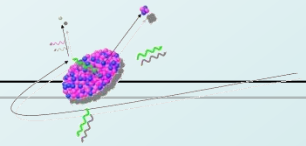
- injector A/Q=3
- conventional phoenix ECR

SPIRAL2 phase 1++ (not funded so far):

- injector A/Q=6-7
- new ECR supra conducting source

Day 1 experiments at S^3 (SPIRAL2/GANIL)

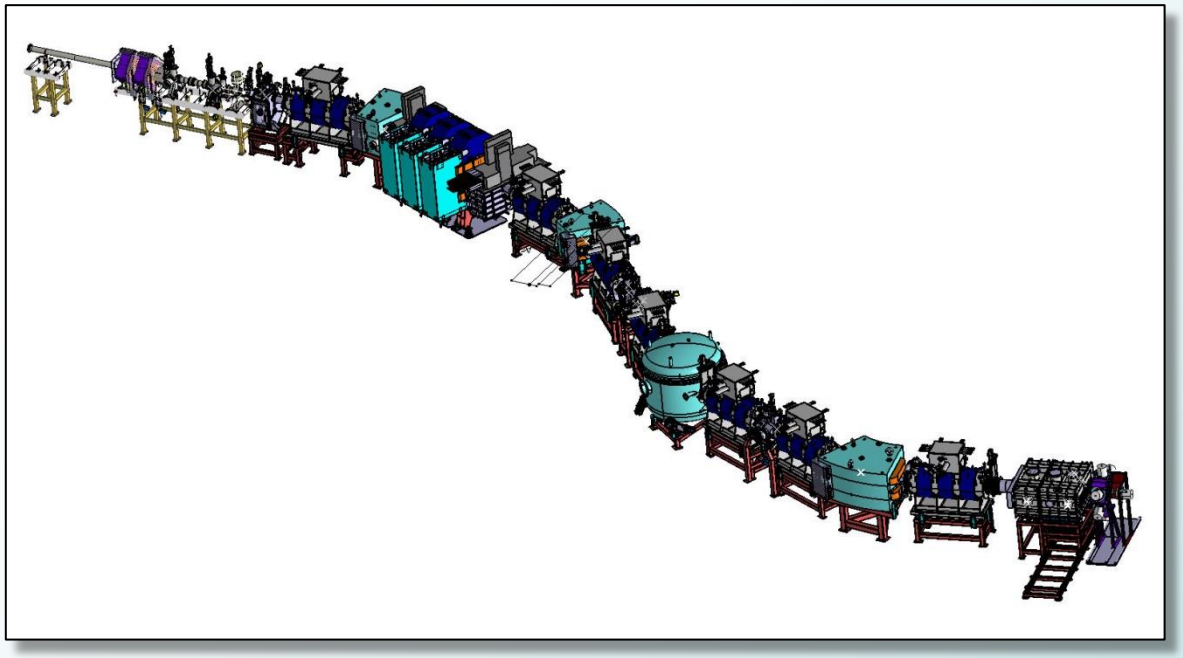
- rate summary



nuclide	reaction	feature	X-section [pbarn]	rate [Hz]	integral counts(21UT)	
					day 1	phase 1++
^{254}No	^{48}Ca+^{208}Pb	K-isomer	2000×10^3	60.000	1×10^7	6×10^7
^{256}Rf	^{50}Ti+^{208}Pb	K-isomer	17×10^3	550	90.000	540.000
^{266}Hs	^{64}Ni+^{207}Pb	ER	15 (^{270}Ds)	0.34	57	285
^{266m}Hs	^{64}Ni+^{207}Pb	K-isomer	15 (^{270}Ds)	0.01	2.5	12.5
^{270}Ds	^{64}Ni+^{207}Pb	ER	15	0.45	76	380
^{270m}Ds	^{64}Ni+^{207}Pb	K-isomer	15 (^{270}Ds)	0.22	38	190
^{262}Sg	^{64}Ni+^{207}Pb	α-decay	15 (^{270}Ds)	0.02	5	25
^{276}Cn	^{70}Zn+^{207}Pb	K-Isomer search	0.5 (^{277}Cn)	0.01	*2.5*	12.5
^{288}115	^{48}Ca+^{243}Am	ER	10	0.3	*50*	300
^{288}115	^{48}Ca+^{243}Am	L X-rays	10	1,8	*300*	1800

SHN research at SPIRAL2/GANIL

- decay spectroscopy at S^3

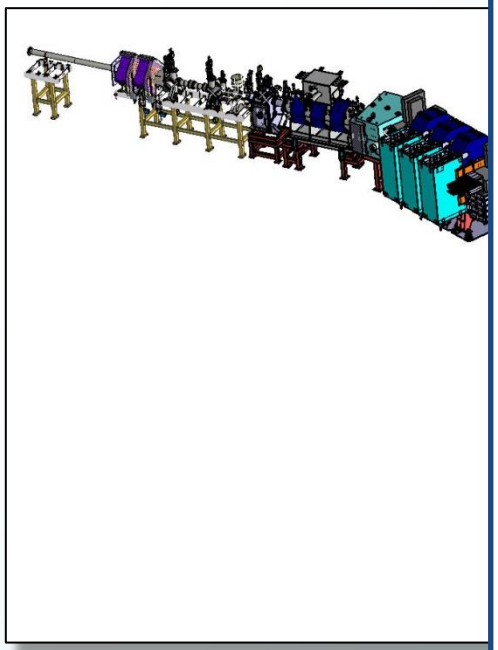


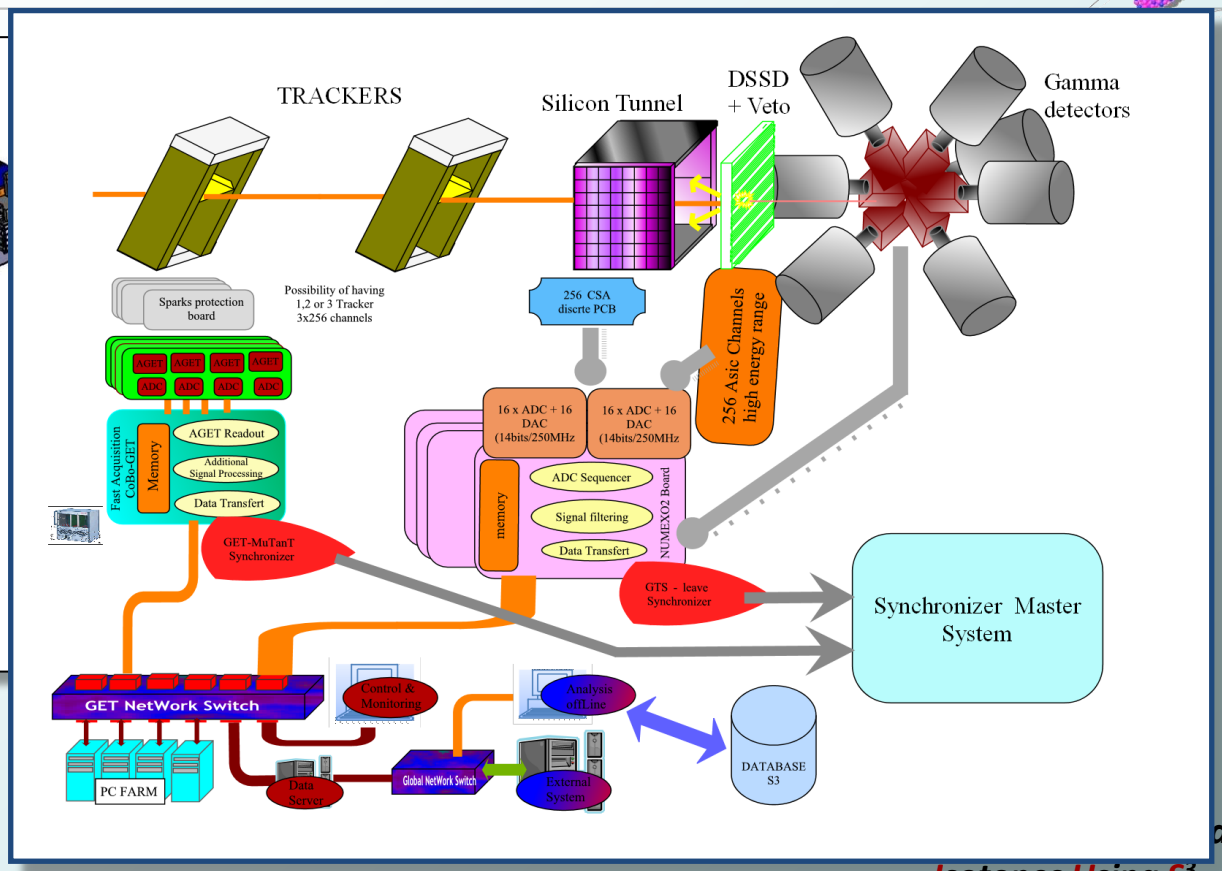
comprehensive focal plane detector setup SIRIUS

- *trackers for ToF and veto*
- *Si detector array for charged particle detection*
  - *ER, α's, e^-*
- *photon detector array*
  - *γ's, X-rays*

SHN research at SPIRAL2/GANIL

- decay spectroscopy at S^3





are

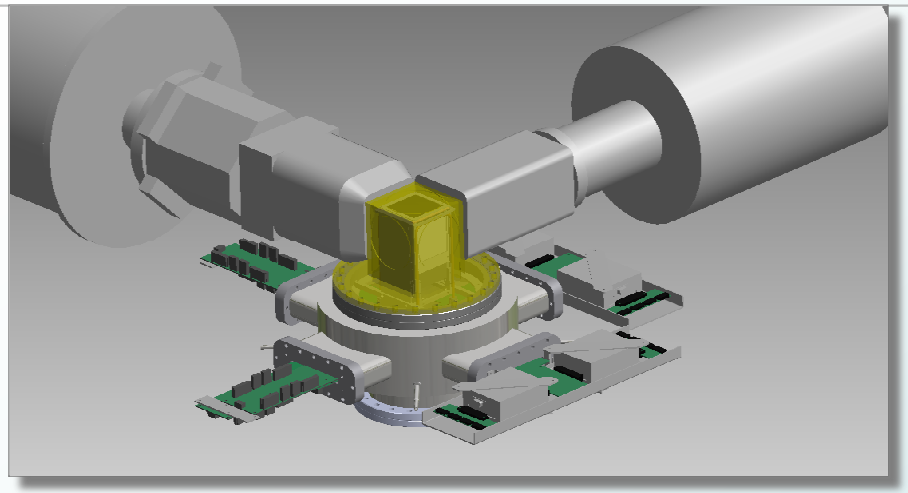
Isotopes Using S^3

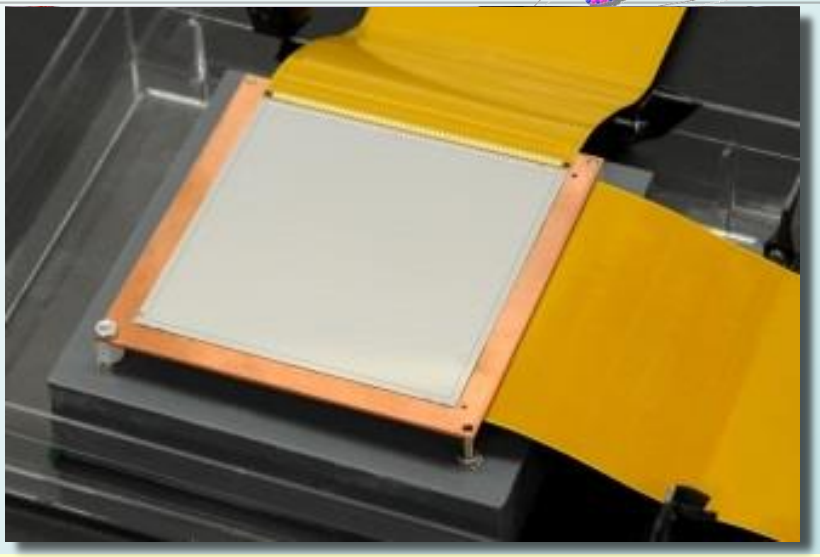
comprehensive focal plane detector setup SIRIUS

- *trackers for ToF and veto*
- *Si detector array for charged particle detection*
  - *ER, α's, e^-*
- *photon detector array*
  - *γ's, X-rays*

Mobile Decay Spectroscopy Set-up – MoDSS for SHE research

- Si stop+box (DSSD+SSSD) combined with large volume Ge-detectors





configuration *(similar to TASiSpec, L. Andersson et al.)*

- *stop detector: 1 × DSSD (60×60 strips)*
- *box detectors: 4 × SSSD (32 strips)*
- *γ efficiency ≈ 40%*

chamber

- *compact (overall length 35 cm)*
- *Al-cap with thin γ window (1,5 mm)*
- *compatible due to 150 mm standard flange*

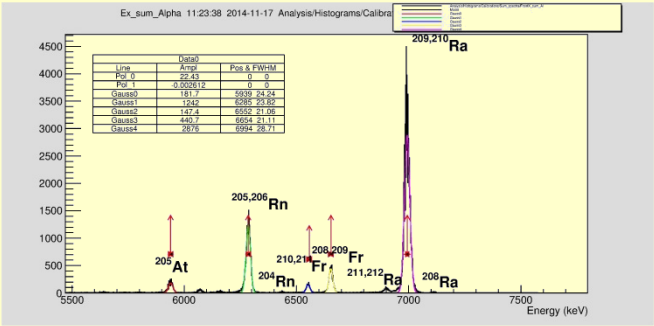
DSSD

- *integrated cooling (Cu-frame) and connection (flex-PCB)*
- *60×60 strips/mm (pitch 1 mm)*
- *300 µm*

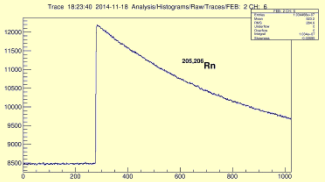
electronics (partly integrated in the vacuum)

- *analog and digital (FEBEX) options*

first α spectrum (test run at LISE/GANIL)
(ΔE: 20 keV)

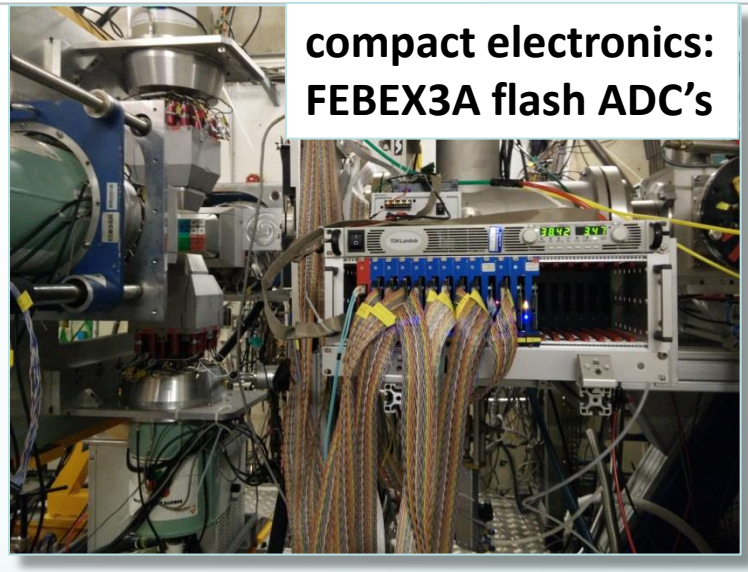


typical α-decay trace (FEBEX)

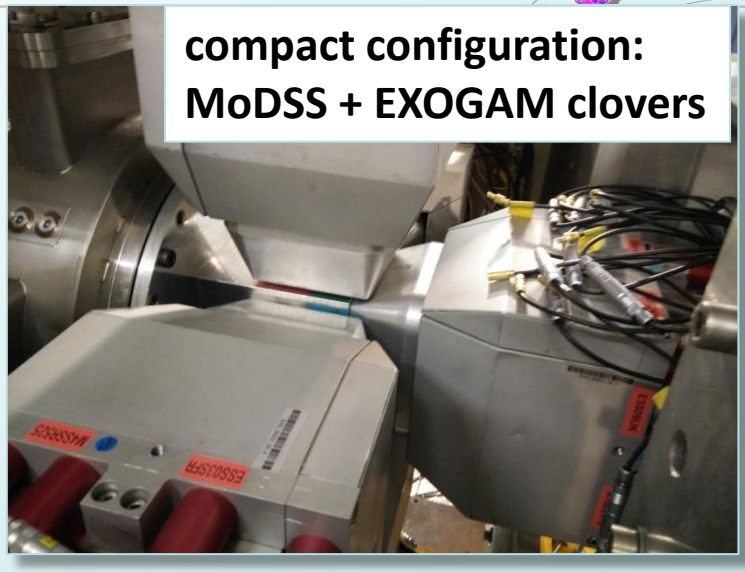


Mobile Decay Spectroscopy Set-up – MoDSS for SHE research

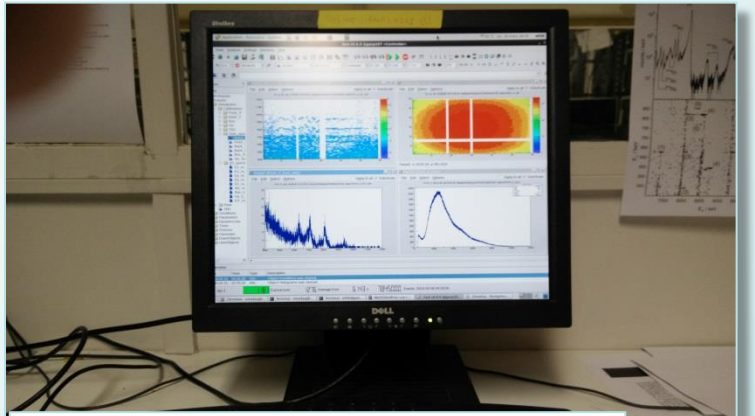
- starting from Sunday, March 29th in operation at GANIL/LISE for ^{50}Ti + ^{209}Bi



compact electronics: FEBEX3A flash ADC's



compact configuration: MoDSS + EXOGAM clovers



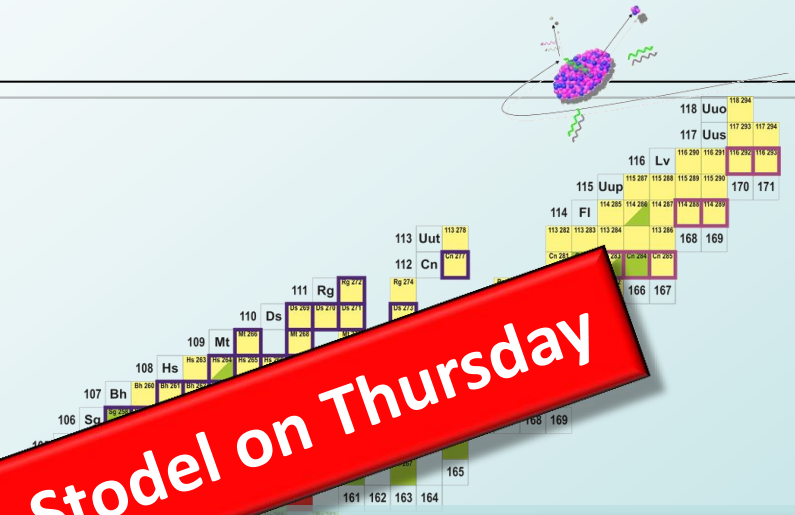
first Th-α's from ^{50}Ti^{+170}Er: March 30th 2015 at 4:30 a.m.

the night shift

SHE research at S³/SPIRAL2

- physics and requirements

- **nuclear structure features of SHN**
  - quasi-particle excitations → deformation/K-isomers
  - X-ray Z-identification (LoI GANIL-FLNR for Z=115)
  - in-beam studies/in-beam X-rays?
- **reaction studies**
  - isospin dependent investigations
- **instrumentation**
  - GSI Si-array MoDSS → SIRIUS
- **accelerator and targets**
  - A/q = 6-7 (SPIRAL2 phase 1+)
  - actinide target technolog



See contribution of Christelle Stodel on Thursday

Spokesperse

nt of Physics, University of Jyväskylä

SNSM

he Theisen, Irfu/SPhN

odel Christelle, GANIL

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