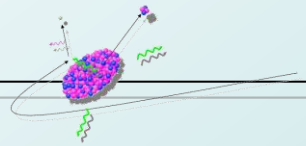
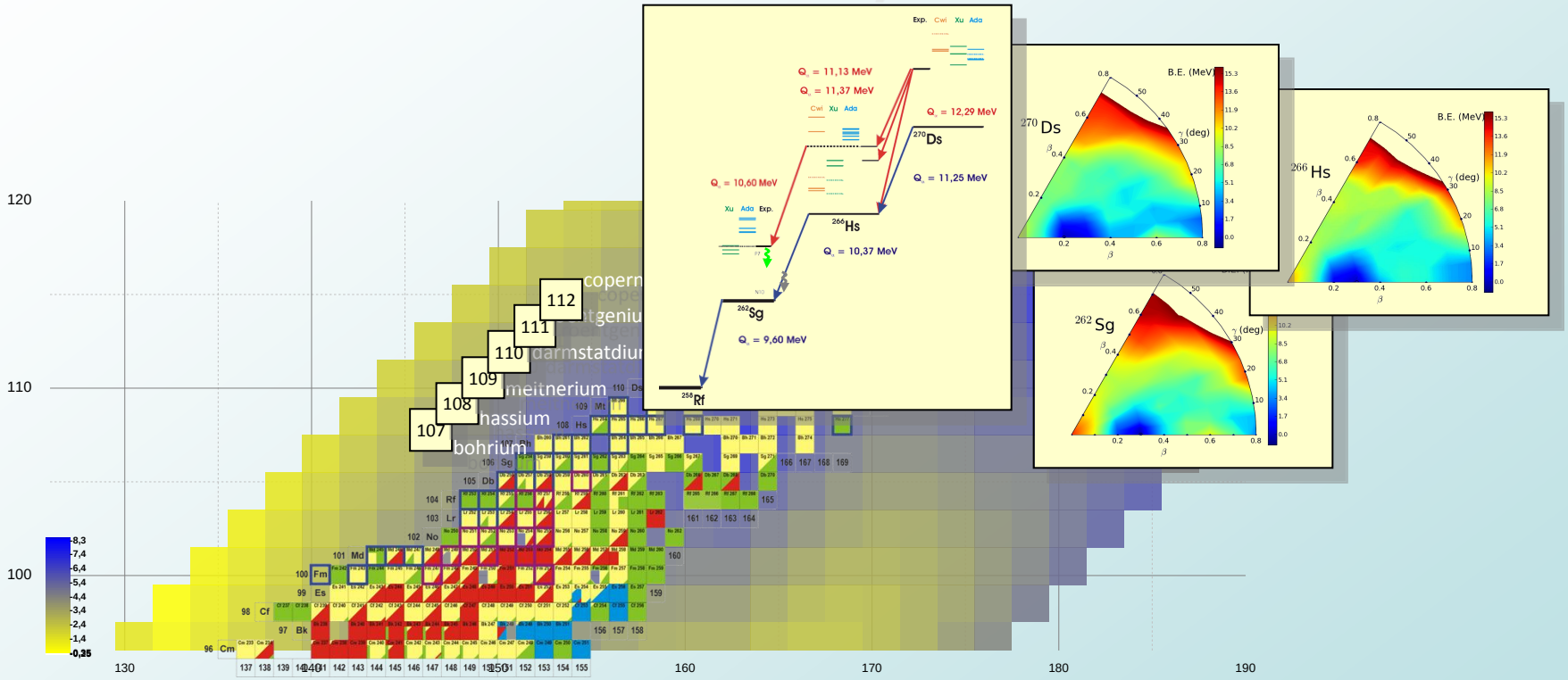


Paving the Road to the "Island of Stability"
– Nuclear Structure Studies and Synthesis of SHE



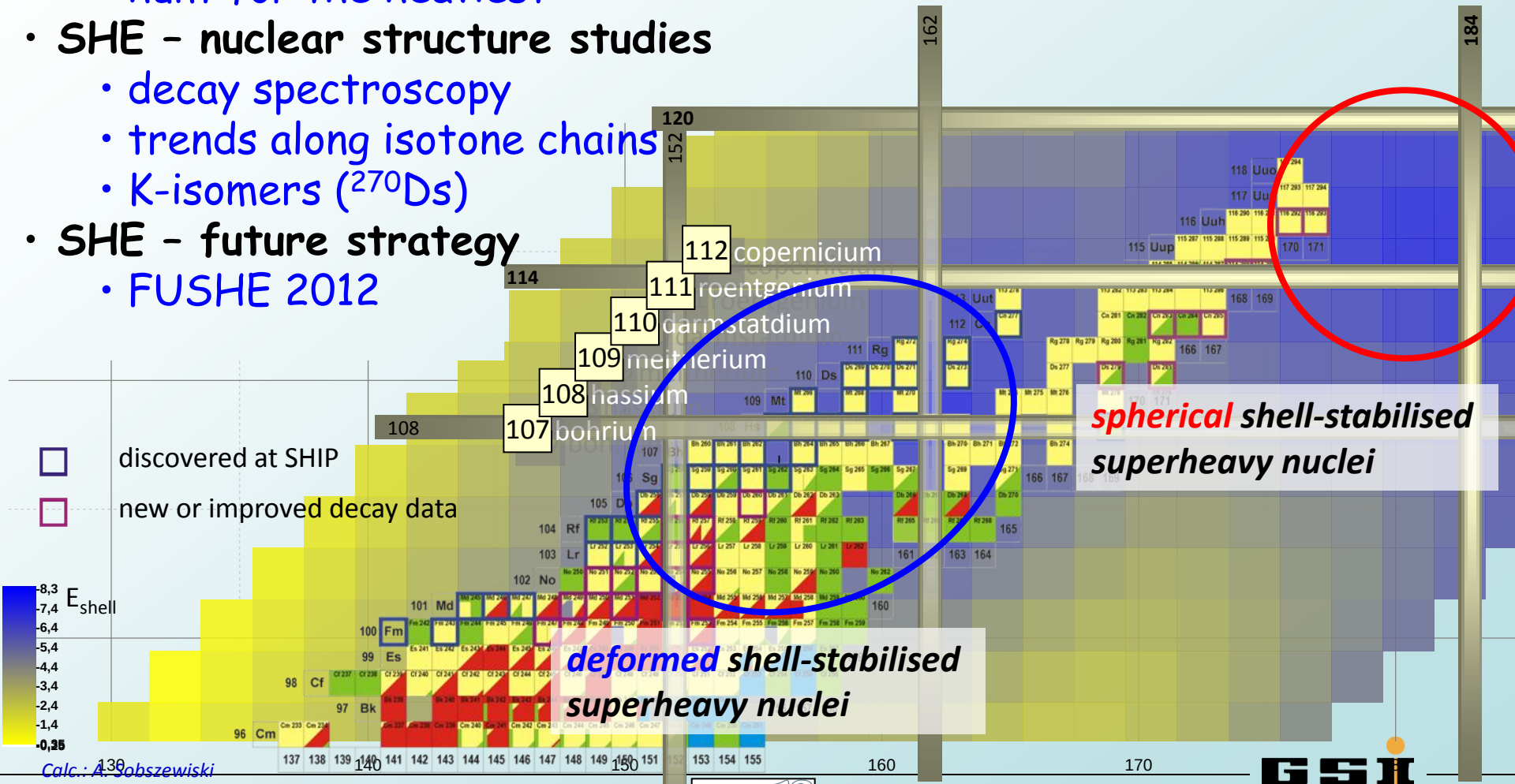
Dieter Ackermann
GSI
Helmholtzzentrum für Schwerionenforschung GmbH

Abano Terme, May 24th 2012

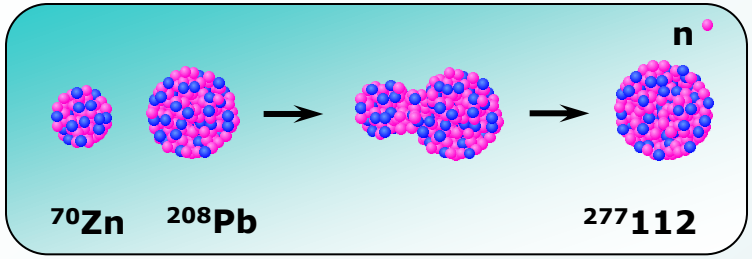
The Region of Superheavy Elements

- GSI/SHIP achievements and outline

- **SHE – synthesis**
  - confirmation of "hot fusion" decay patterns
  - hunt for the heaviest
- **SHE – nuclear structure studies**
  - decay spectroscopy
  - trends along isotone chains
  - K-isomers (^{270}Ds)
- **SHE – future strategy**
  - FUSHE 2012



Synthesis and Identification of SHE at SHIP



kinematic separation in flight

^{277}112 CN

11.45 MeV
280 µs

^{273}110

11.08 MeV
110 µ s

^{269}Hs

9.23 MeV
19.7 s

^{265}Sg

4.60 MeV (escape)
7.4 s

known

^{261}Rf

8.52 MeV
4.7 s

^{257}No

8.34 MeV
15.0 s

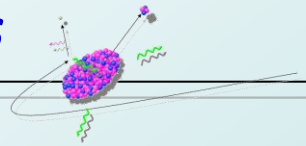
^{253}Fm

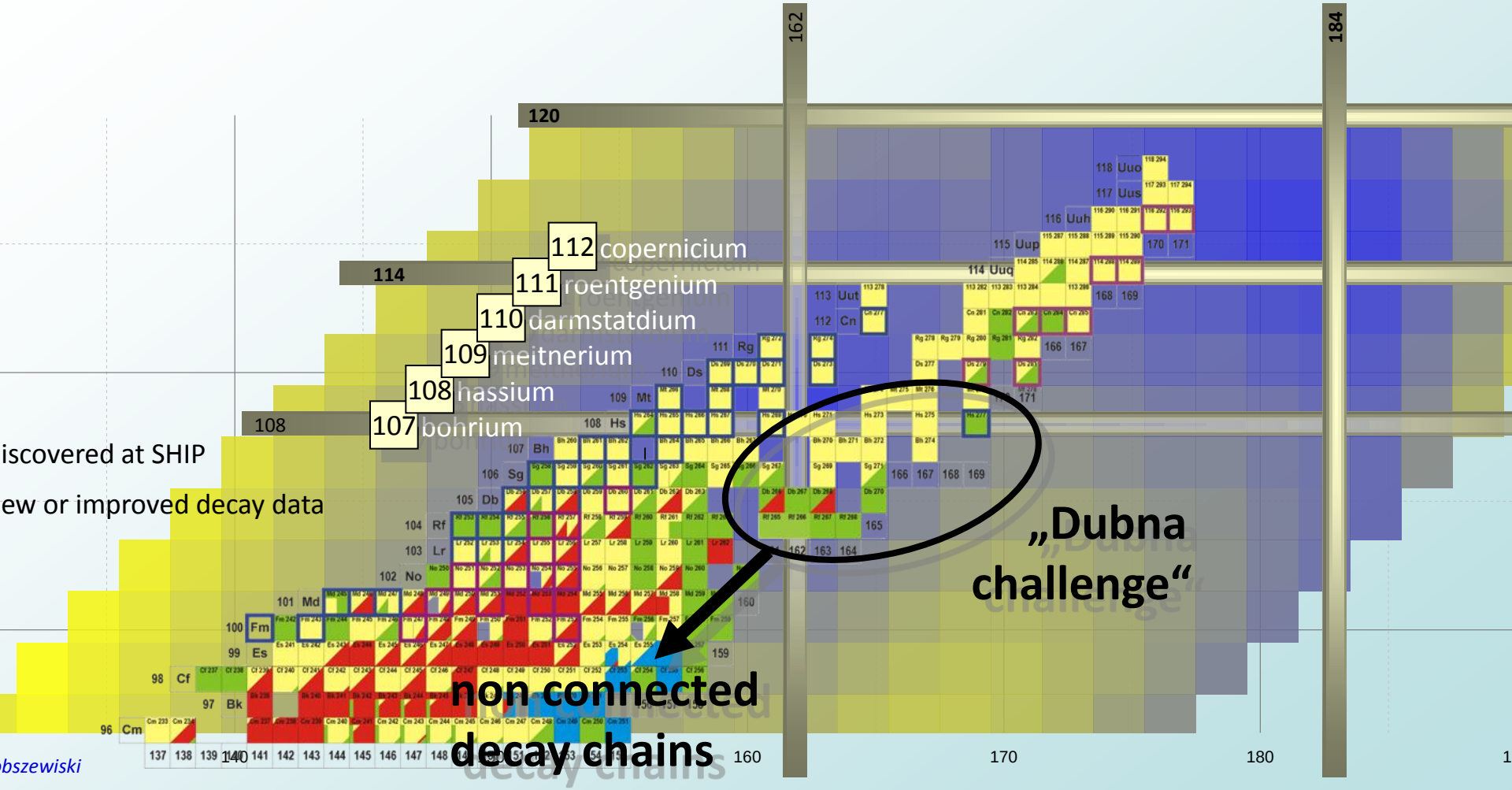
Date: 09-Feb-1996
Time: 22:37 h

identification by α-α correlations to known nuclides

“Hot Fusion” Studies

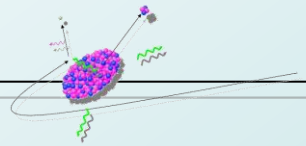
- ^{48}Ca (et al.) Induced Reactions on Actinide Targets





The "Dubna Challenge"

- $^{48}Ca + ^{248}Cm \rightarrow ^{296}116^*$ at GSI



tentative assignment

02-July-2010, 01:07 h; chain 1
10.06 MeV, 6.3 mm, strip 4

$^{293}116$ → CN

10.503 MeV
29 ms

$^{289}114$

10.029 MeV
406 ms

^{285}Cn

9.707 MeV
5.8 s

^{281}Ds

9.315
356 ms

^{277}Hs

210 MeV
49 s

08/09-July-2010, chain 6
21 MeV, 11.4 mm, strip 8

$^{293}116$ → CN

10.559 MeV
55 ms

$^{289}114$

9.813 MeV
118 ms

^{285}Cn

9.100 MeV
5.8 s

^{281}Ds

226 MeV
6.0 s

FLNR

$^{293}116$ → CN

10.54 MeV
89 ms

$^{289}114$

9.81 MeV
3.9 ms

^{285}Cn

9.110 MeV
66 s

^{281}Ds

197 MeV
16.5 s

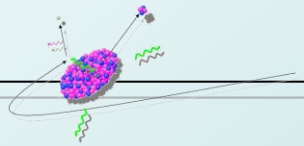
5 events

Yu.Ts. Oganessian,
J. Phys. G 34 (2007) R165

$^{48}Ca + ^{248}Cm \Rightarrow ^{293}116 + 3n$

The "Dubna Challenge"

- $^{48}Ca + ^{248}Cm \rightarrow ^{296}116^*$ at GSI



02-July-2010, 01:57 h; chain 2
8.96 MeV, 10.4 mm, strip 4

$^{292}116$ — CN

2,75 MeV (escape)
53.3 ms

$^{288}114$

9.93 MeV
993 ms

^{284}Cn

$^{48}Ca + ^{248}Cm$
$\Rightarrow ^{292}116 + 4n$

03-July-2010, 20:01 h; chain 3
18 MeV, 27.4 mm, strip 2

$^{292}116$ — CN

10.63 MeV
76 µs

$^{288}114$

9.90 MeV
1.3 s

^{284}Cn

197 MeV
269 ms

172 I
50 m

FLNR

$^{292}116$ — CN

10,66 MeV
26 ms

$^{288}114$

9.91 MeV
1.17 s

^{284}Cn

6 events

190 MeV
130 ms

195 I
121 ms

Yu.Ts. Oganessian,
J. Phys. G 34 (2007) R165

07-July-2010, 09:01 h; chain 5
21 MeV, 28 mm, strip 12

$^{292}116$ — CN

≈10,6 MeV (stop + box)
11.6 ms

$^{288}114$

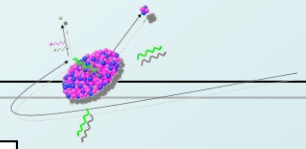
≈10.0 MeV (stop + box)
72 ms

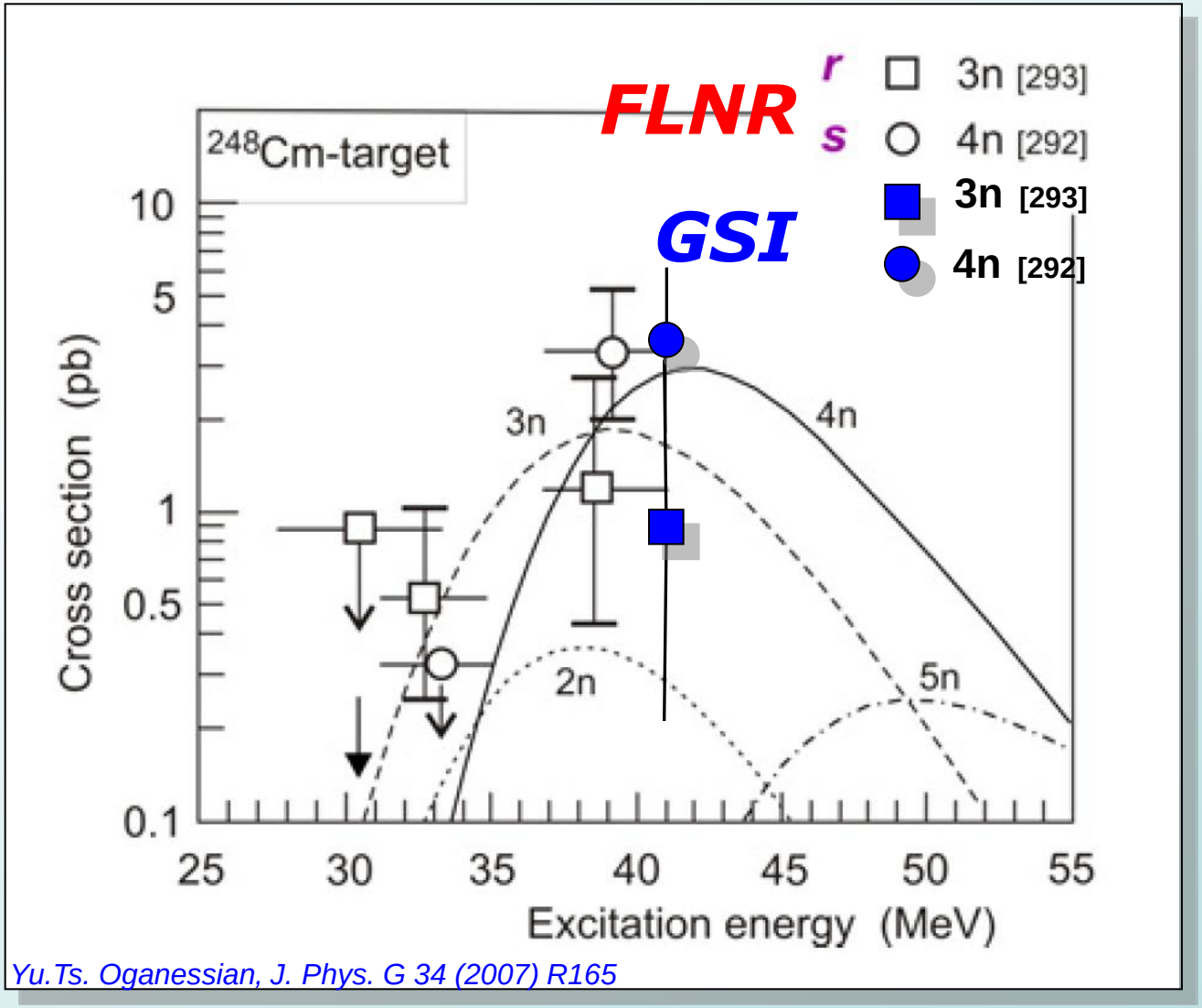
^{284}Cn

185 MeV
25 ms

The "Dubna Challenge"

- $^{48}Ca + ^{248}Cm \rightarrow ^{296}116^*$ at GSI

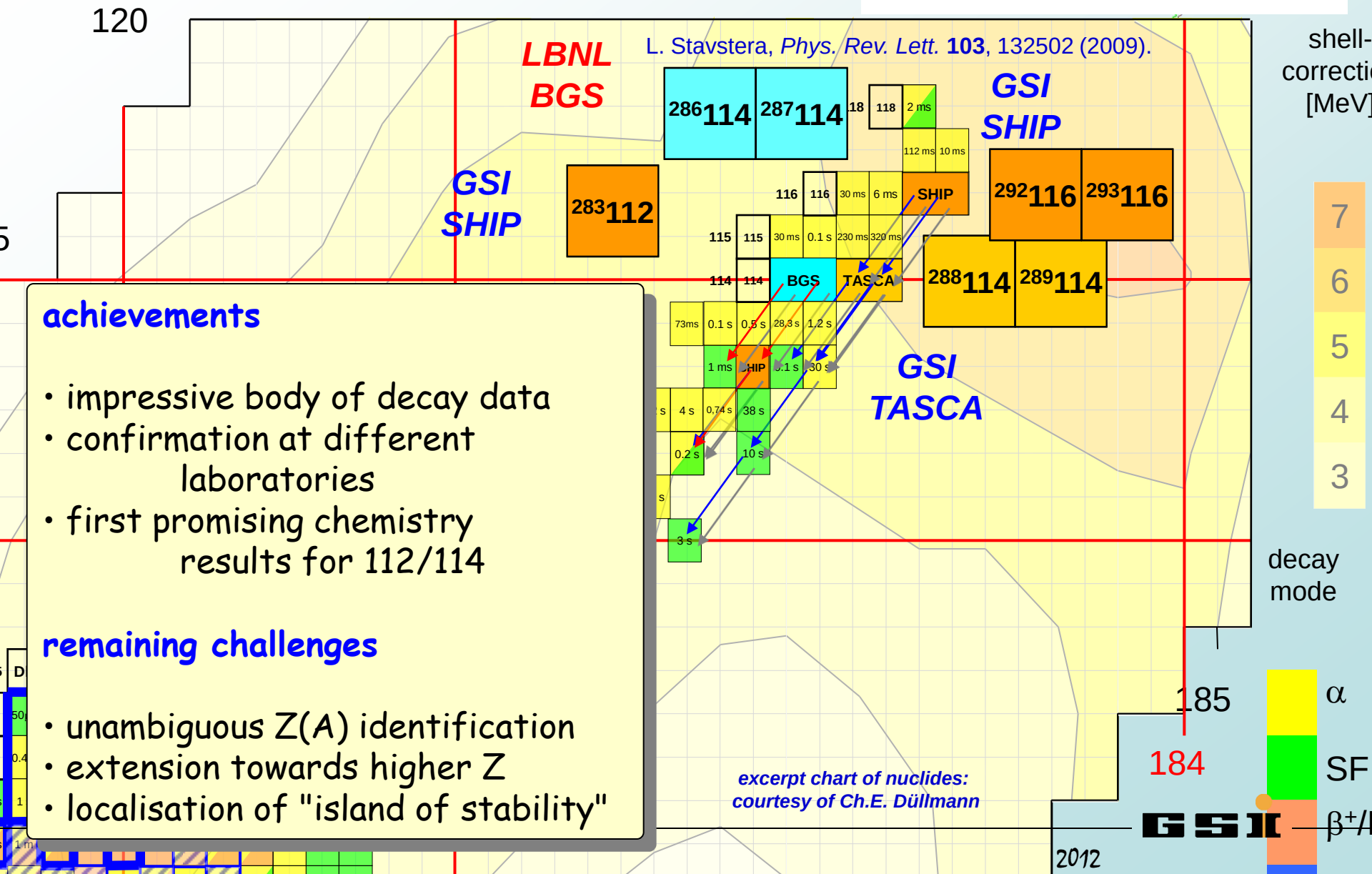




Yu.Ts. Oganessian, J. Phys. G 34 (2007) R165

Confirmation of FLNR Results

- Summary



achievements

- impressive body of decay data
- confirmation at different laboratories
- first promising chemistry results for 112/114

remaining challenges

- unambiguous Z(A) identification
- extension towards higher Z
- localisation of "island of stability"

Hunt for the heaviest

towards element 119,120 at SHIP and TASCA

JYFL Accelerator News

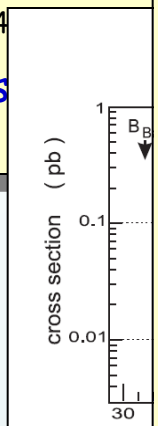
Accelerator Laboratory, Department of Physics
University of Jyväskylä, Finland

Volume 20, No. 1 March 2012

120 days / σ_{lim}

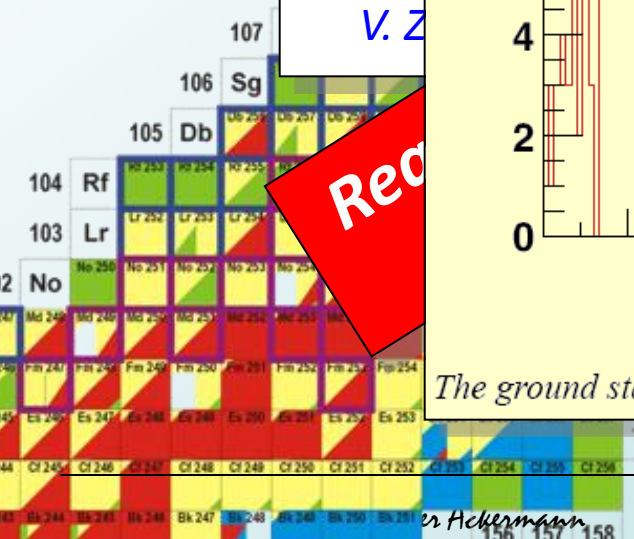
2. ^{54}Cr + ^{24}

36 days

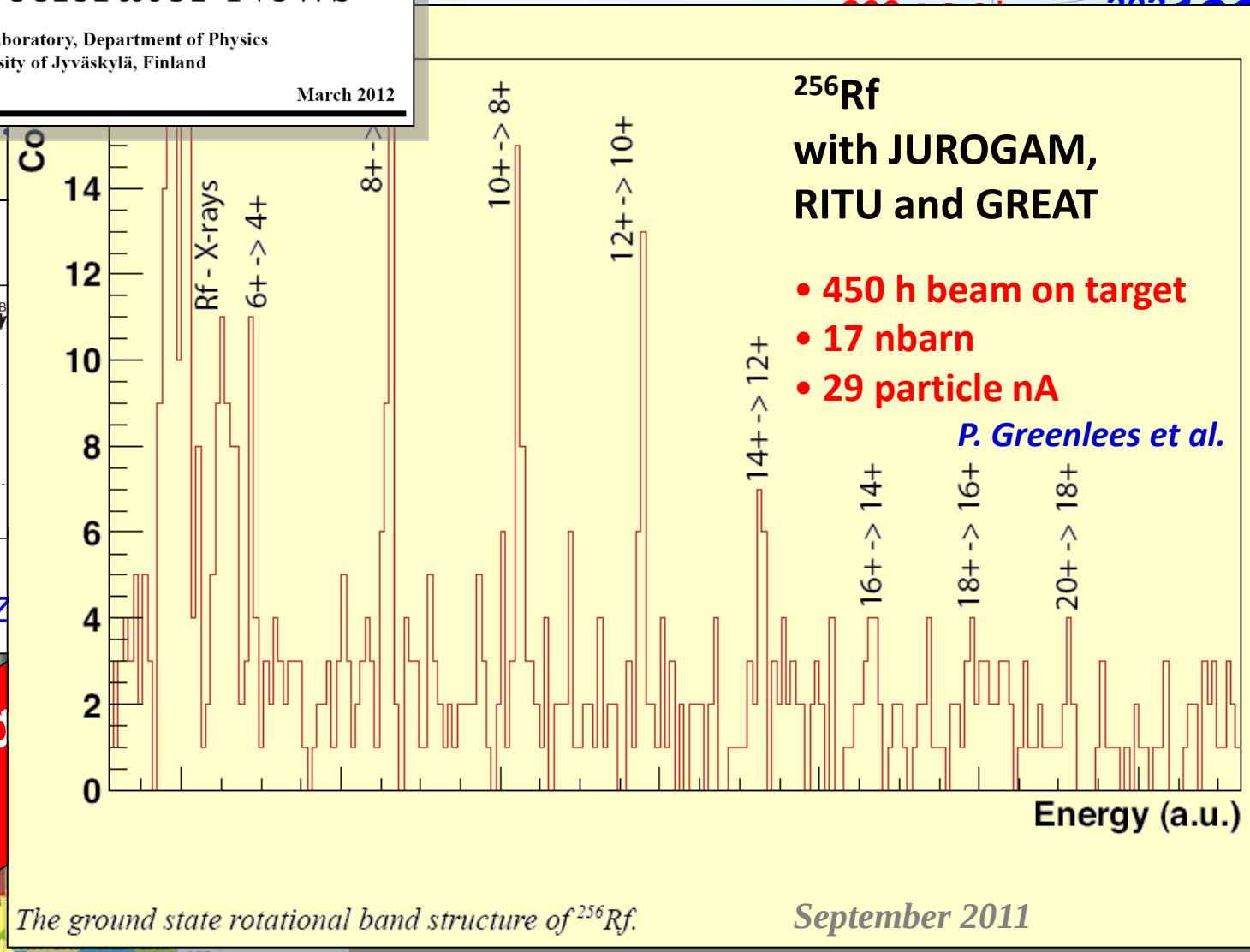


V. Z

Rec



er Heckermann



^{256}Rf with JUROGAM, RITU and GREAT

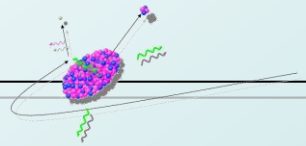
- 450 h beam on target
- 17 nbarn
- 29 particle nA

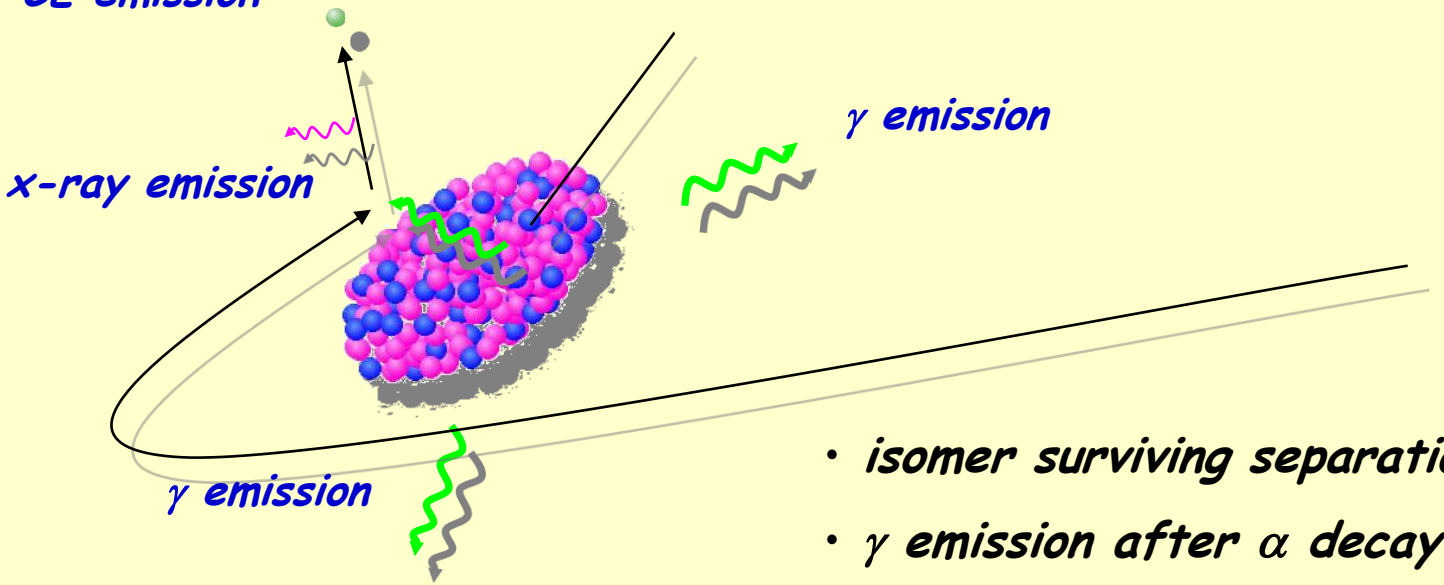
P. Greenlees et al.

The ground state rotational band structure of ^{256}Rf. *September 2011*

Nuclear Structure of SHE

- Decay Spectroscopy at SHIP/TASCA



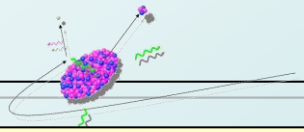


evaporation residue after separation

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

Nuclear Structure of SHE

- Decay Spectroscopy at SHIP/TASCA

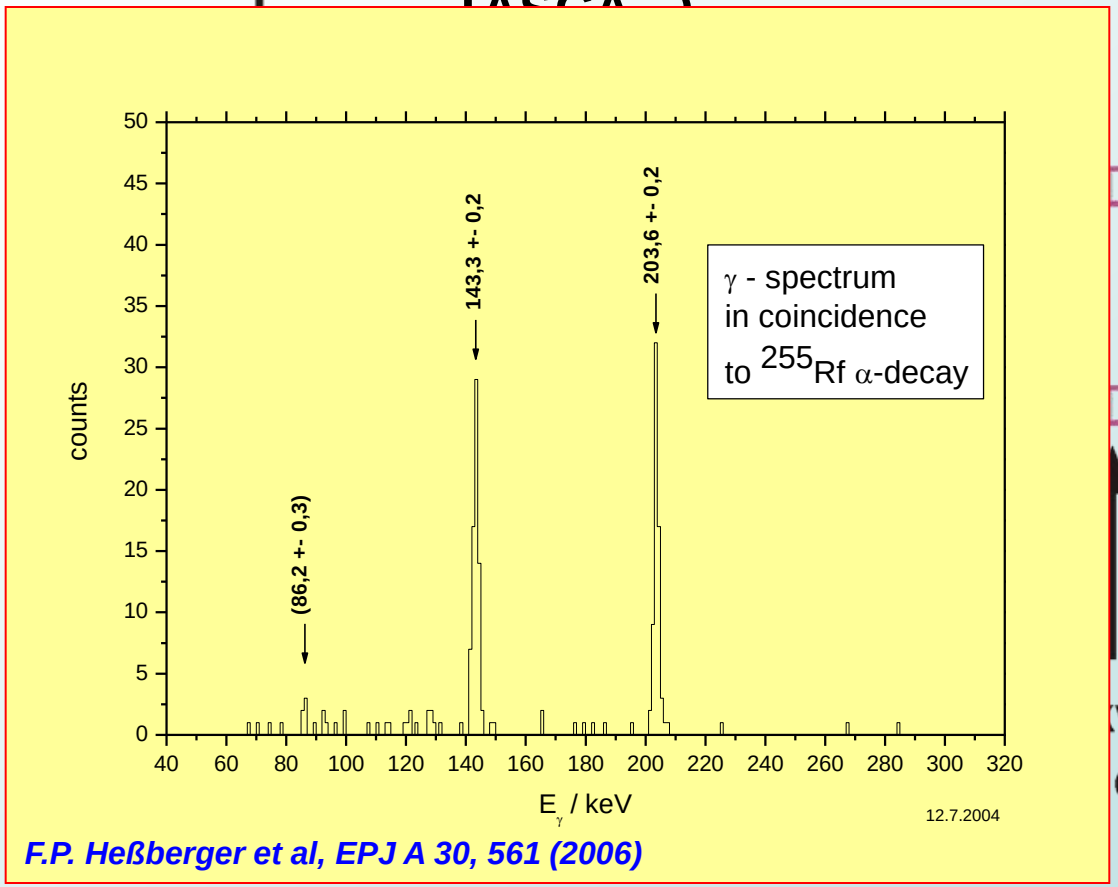


- **inclusive measurement**
  - ER, α's, γ's and e⁻
- **clean**
  - particle discrimination
  - ER-α-γ correlations
- **highly efficient**
  - close geometry
  - stopped source

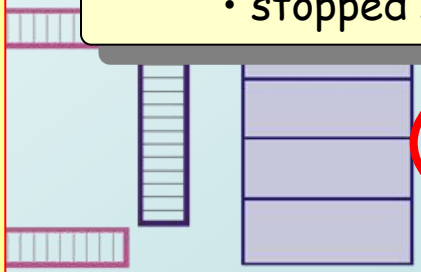
Target (rot. wheel)

Separator (e.g. SHIP, TASCA, ...)

Focal Plane



F.P. Heßberger et al, EPJ A 30, 561 (2006)



high eff.
ε ≈ 15%

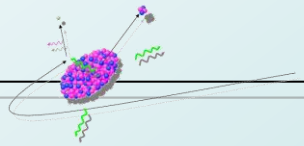
'STOP'
α

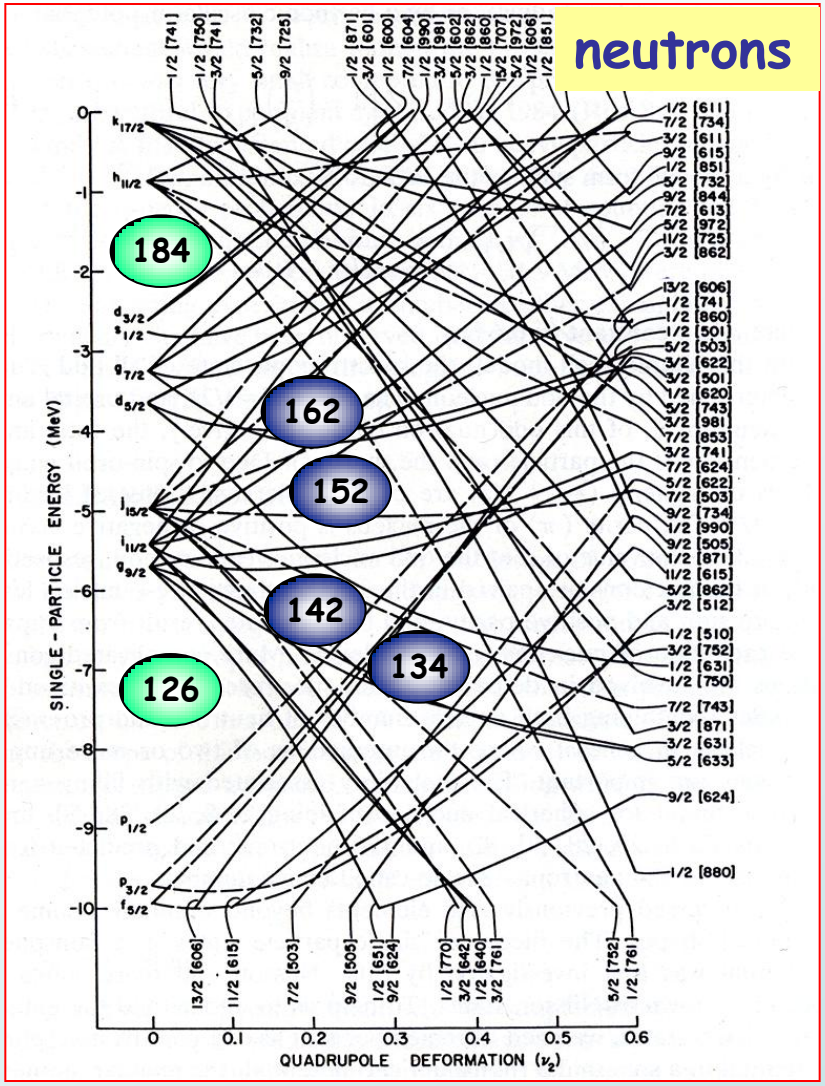
'ward'
CE

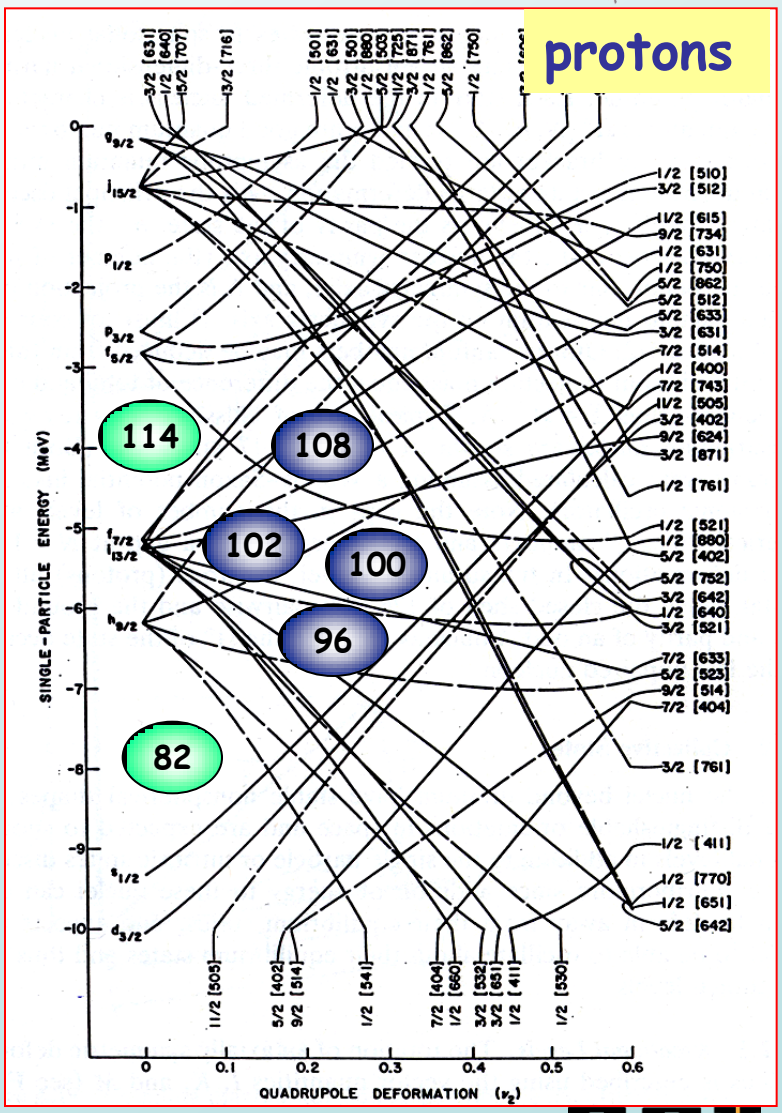
γ - ray
(segmented)

Nuclear Structure of Heavy Nuclei

- Single Particle Levels and Deformation

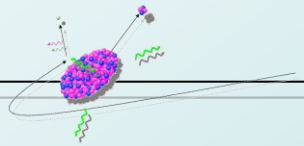


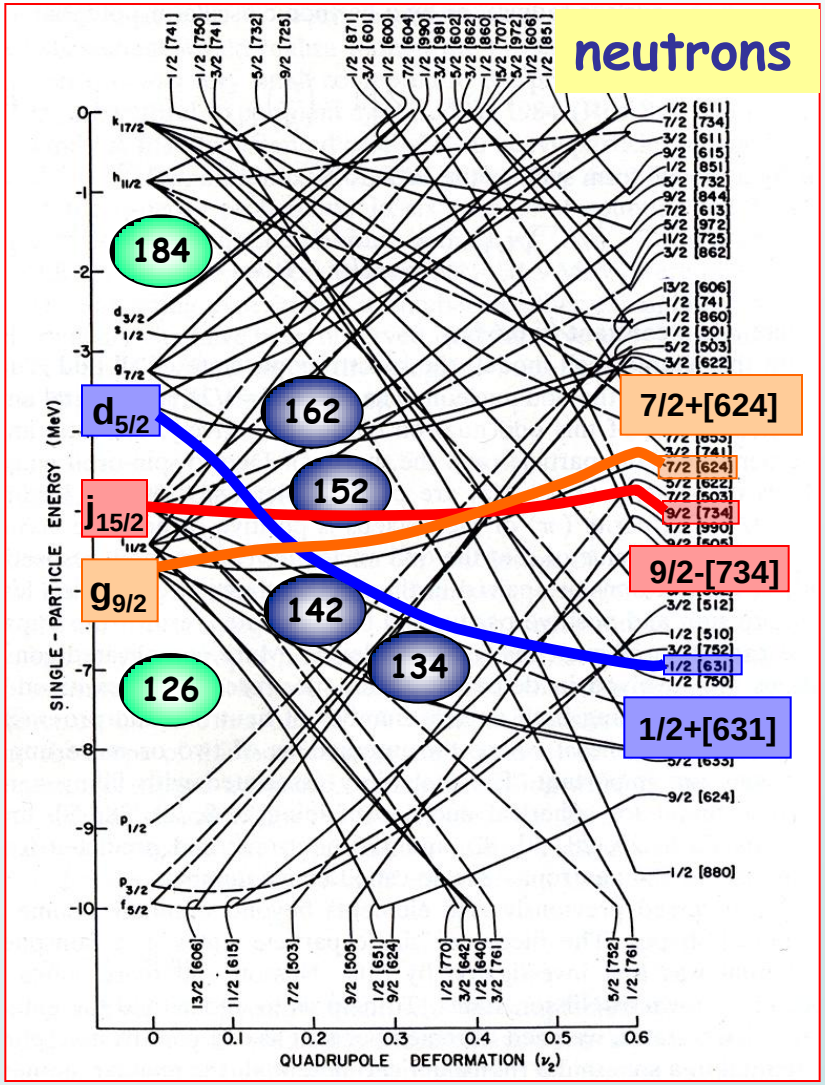


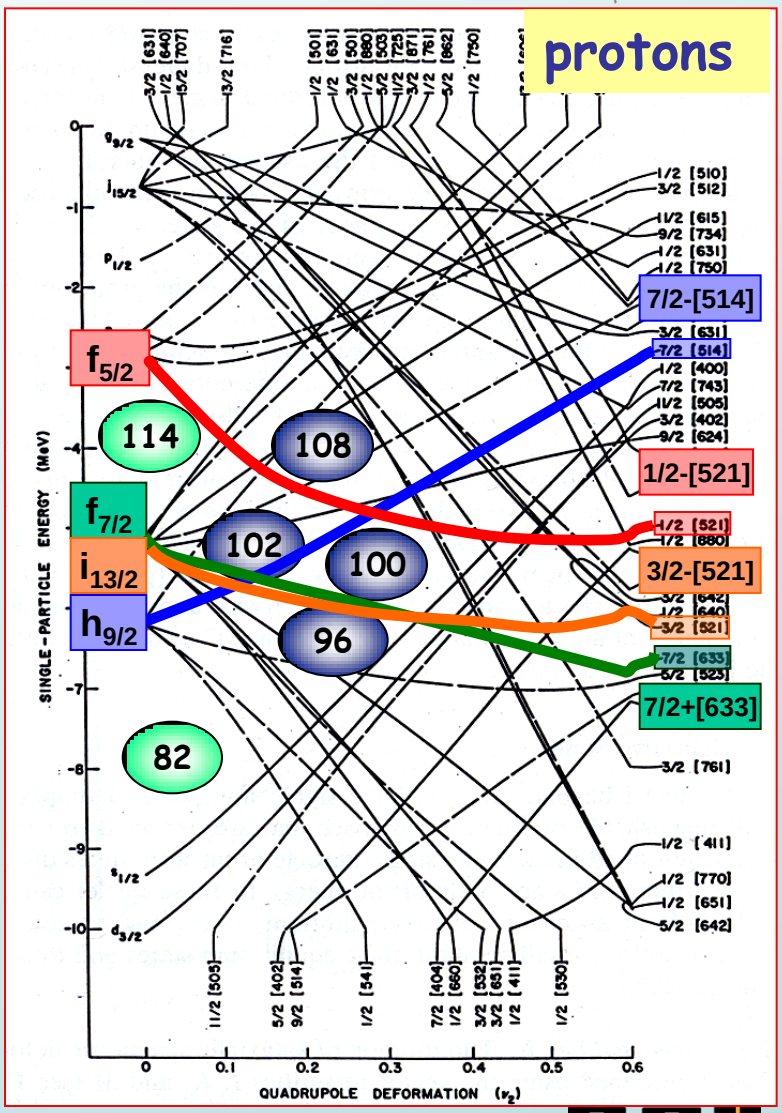


Nuclear Structure of Heavy Nuclei

- Single Particle Levels and Deformation



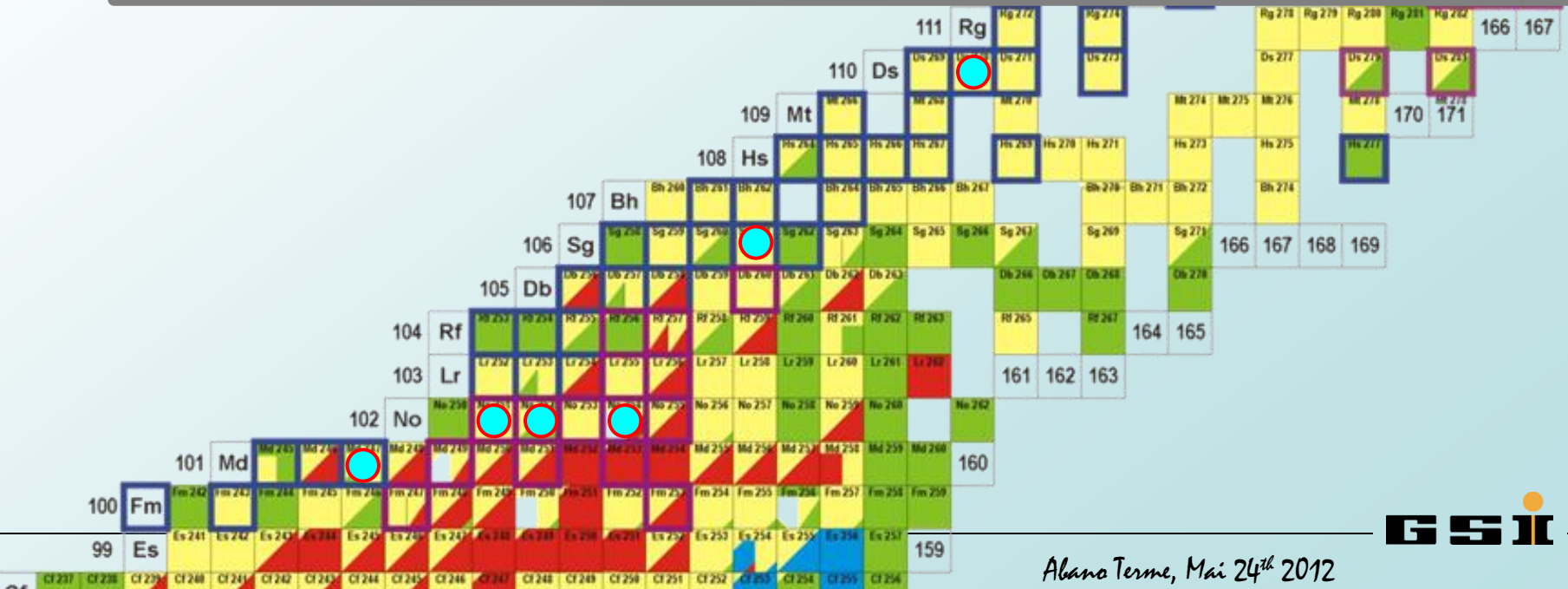




Nuclear Structure of the Heaviest Nuclei:

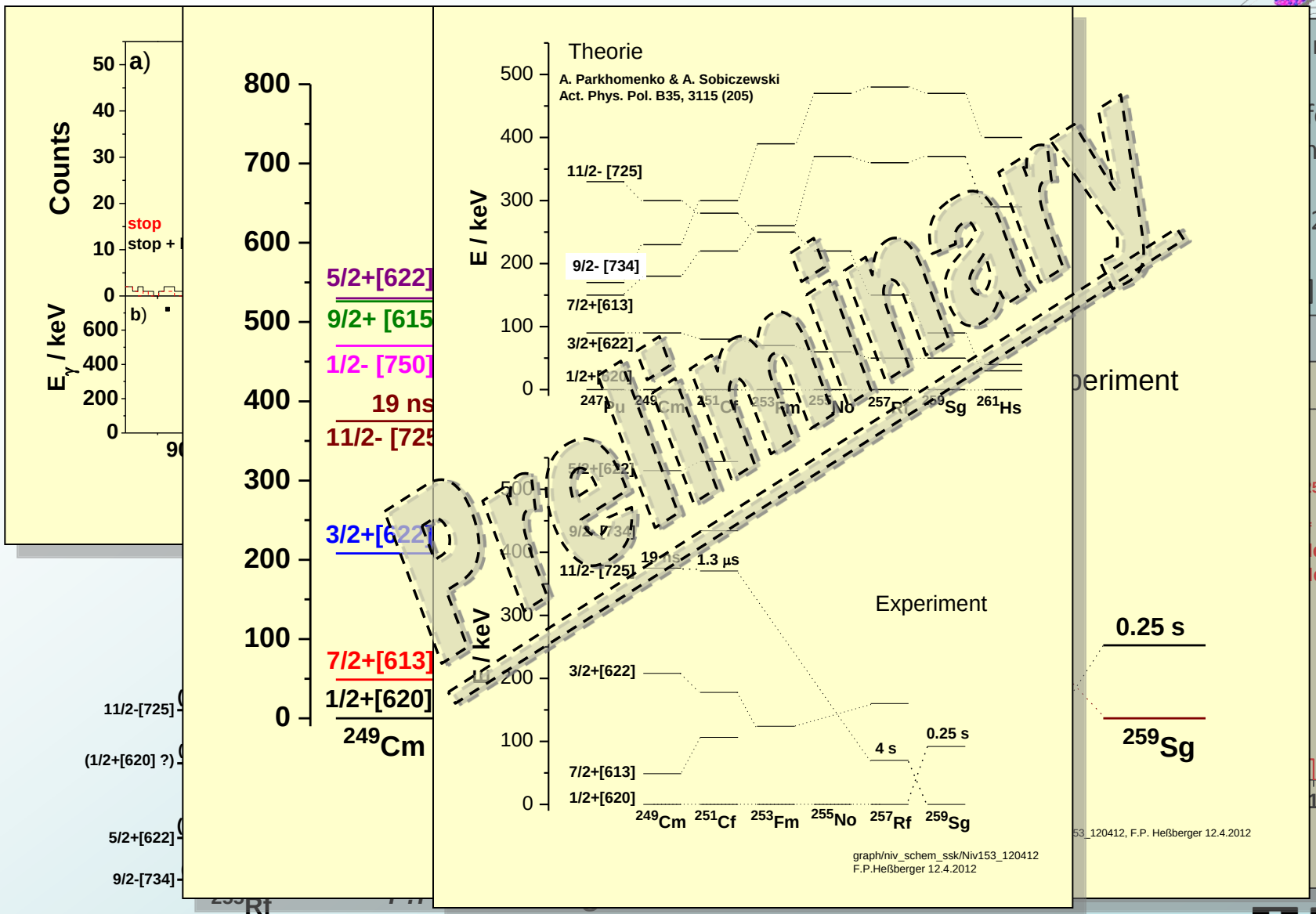
- Production Rates

reaction	σ/nbarn	I_{beam}/pμA	countrate
$^{208}Pb(^{48}Ca,2n)^{254}No$	2000	1	15000 /h
		(at RITU/Jyväskylä	200 /h)
$^{206}Pb(^{48}Ca,2n)^{252}No$	430	1	3300 /h
$^{206}Pb(^{48}Ca,3n)^{251}No$	25	1	200 /h
$^{209}Bi(^{40}Ar,2n)^{247}Md$	7	3	80 /h
$^{208}Pb(^{54}Cr,1n)^{261}Sg$	2	1	15 /h
$^{207}Pb(^{64}Ni,1n)^{270}Ds$	0.013	0.5	1 /d



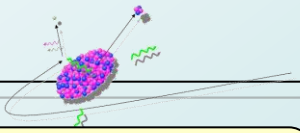
Decay Study of ^{259}Sg (Z=106)

- sf Properties, Low Lying States and Trend for N=153 Isotones

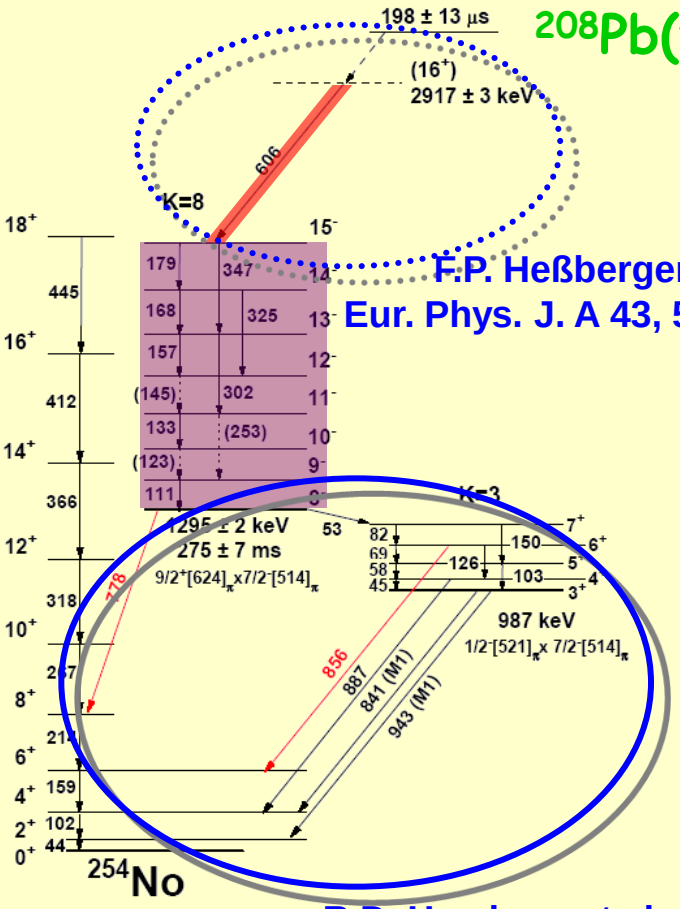


Nuclear Structure of the Heaviest Nuclei:

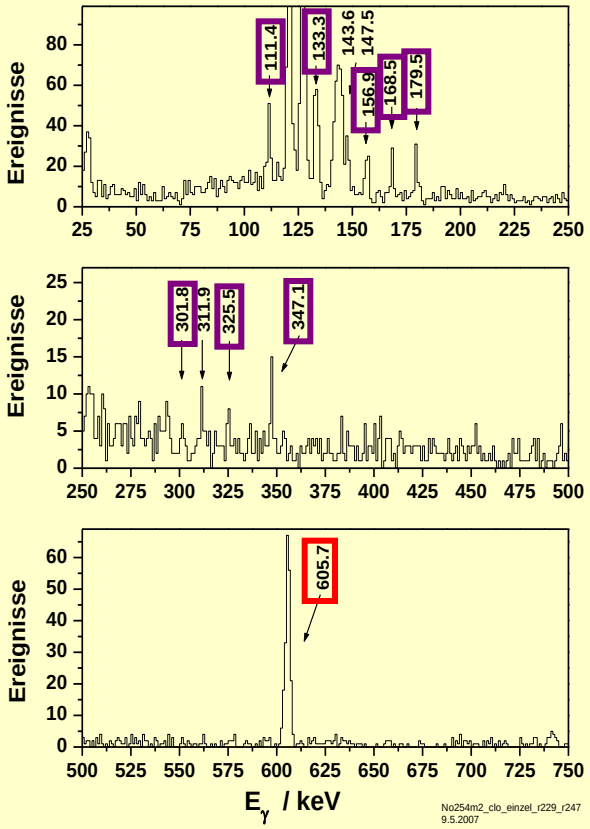
- Isomeric states: ^{254}No



$^{208}Pb(^{48}Ca,2n)^{254}No$



F.P. Heßberger et al.,
Eur. Phys. J. A 43, 55-66 (2010)



R.D. Herzberg et al.,
Nature 442, 896 (2006);
S.K. Tandel et al.,
Phys. Rev. Lett. 97, 082502 (2006)

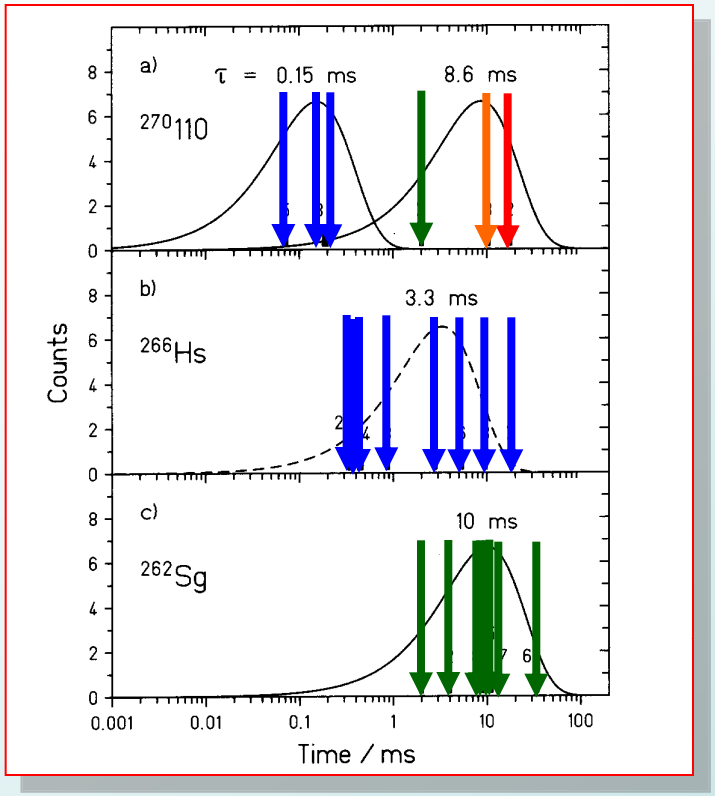
^{270}Ds and its Decay Products

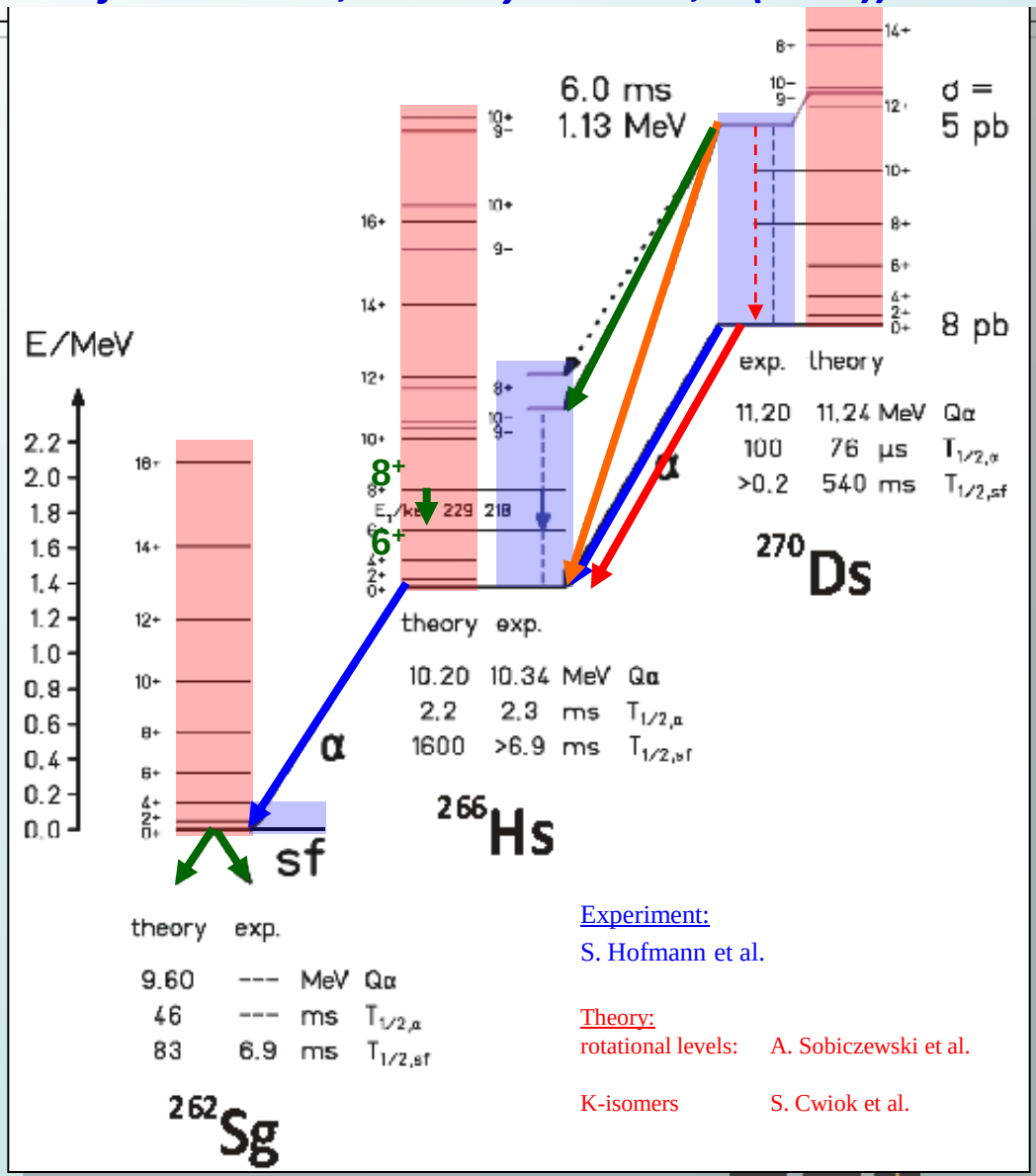
- 1st experiment in 2000 (S. Hofmann et al., Eur. Phys. J. A 10, 5 (2001))

^{270}Ds→^{266}Hs (6 chains)
chain# 1, 3 and 5
chain# 2
chain# 8
chain# 7

^{266}Hs→^{262}Sg (8 chains)
chain# 1-8

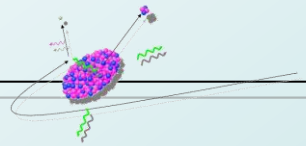
^{262}Sg decay (8 chains)
chain# 1-8



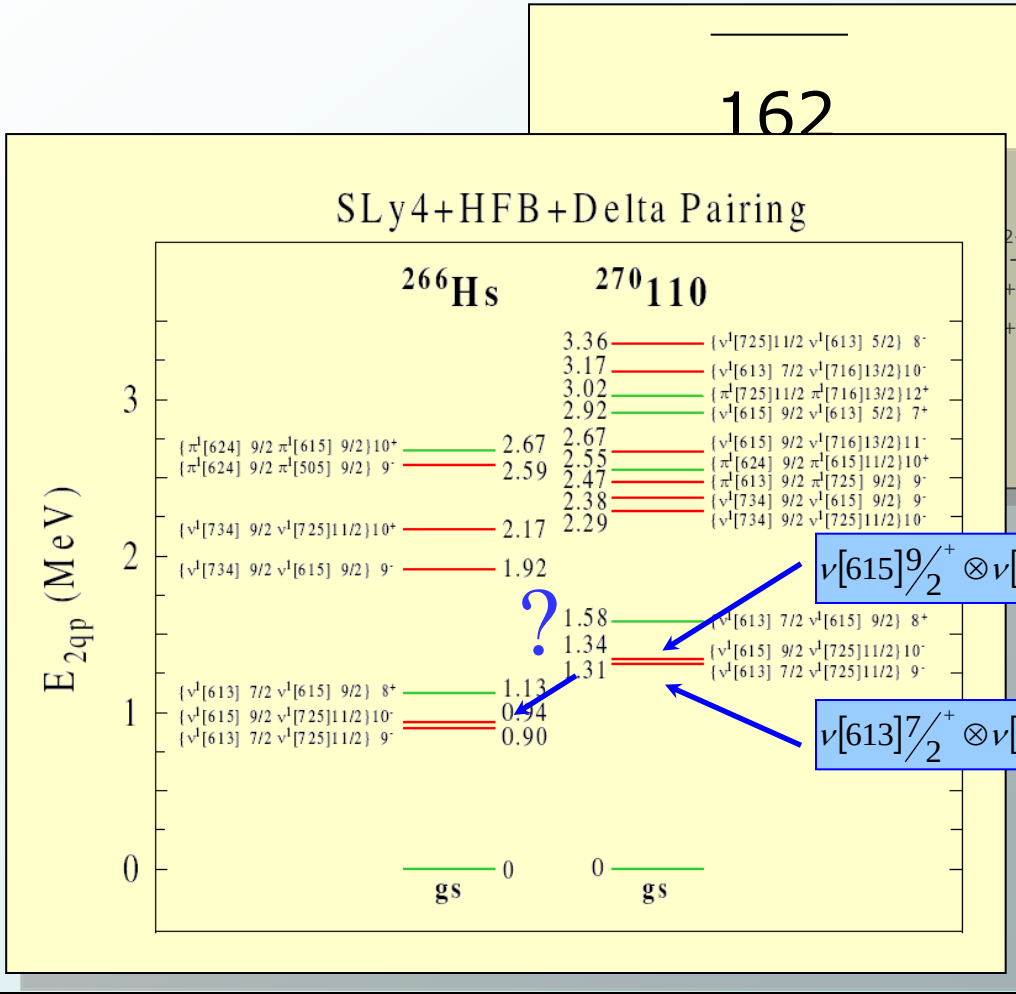


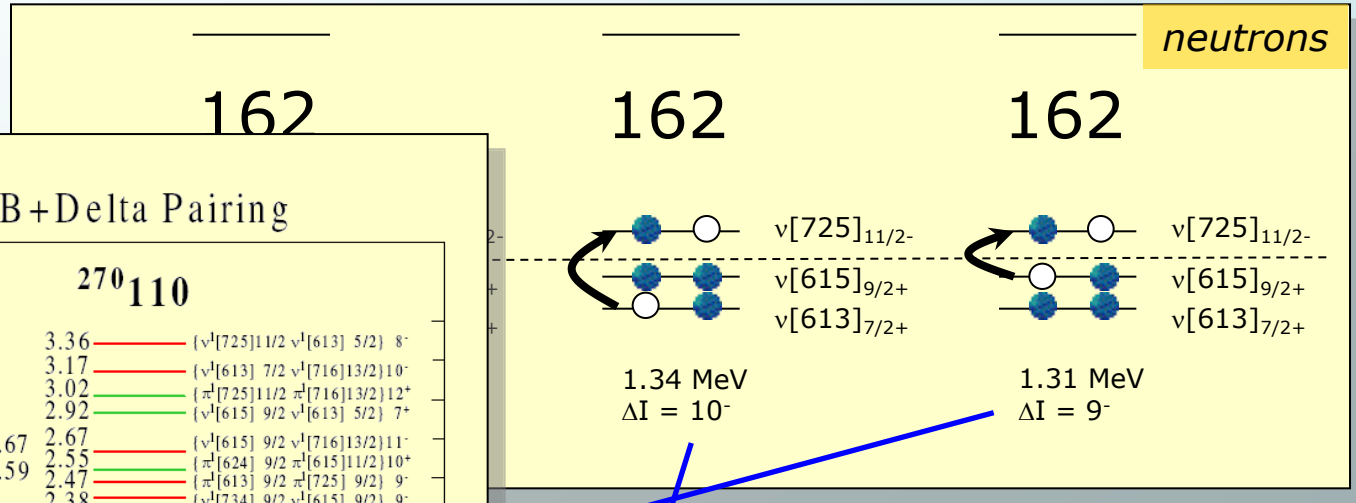
K-isomer in ^{270}Ds

- Theory Predictions: quasi particle excitation



^{270}Ds: Z=110 N= 160





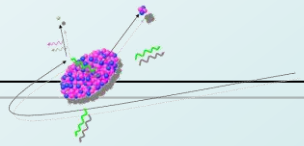
$\nu[615]^{9}/_{2}^{+} \otimes \nu[725]^{11}/_{2}^{-}$

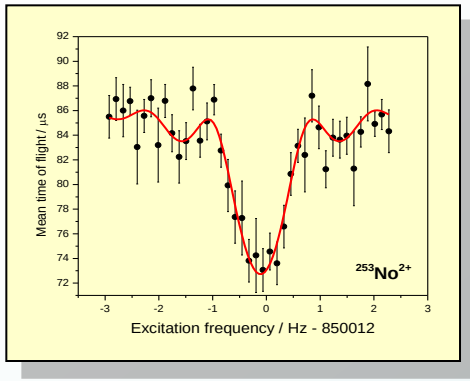
$\nu[613]^{7}/_{2}^{+} \otimes \nu[725]^{11}/_{2}^{-}$

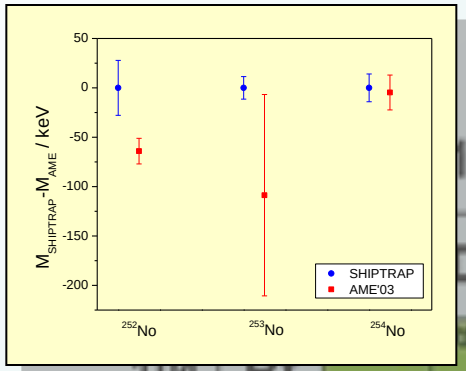
S. Ćwiok, et al.
HFB

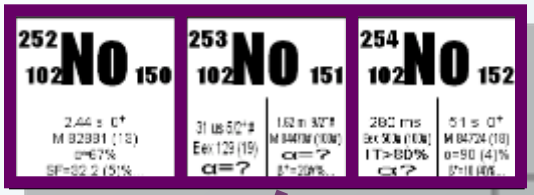
Decay Chain of ^{270}Ds from ^{64}Ni+^{207}Pb

- Results from October 2000 and Possible Extension









SHIPTRAP
August 2008

α?

110 Ds

109 Mt

108 Hs

107 Bh

106 Sg

Db

Rf

103 Lr

102 No

161 162 163

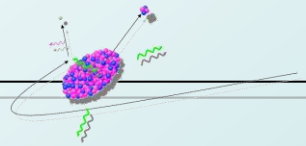
160

GSI

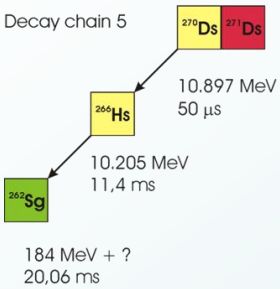
2012

2010: Observed types of decay chains I

- ER-α-α-sf



a) ER-a-a-sf



ER:
Time: 761391.182
MP: 1531
Strip#: 11
E: 38.72 MeV
Posyt: 14.75 mm
Posyb: 18.41 mm
ToF:1409

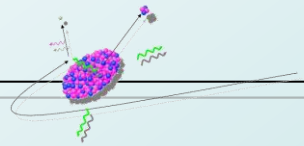
270Ds:
Time: 761391.182
MP: 1581
Strip#: 11
Estop: 10897 keV
Posyt: 15.36 mm
Posyb: 20.45 mm
Posyb(HE): 18.32 mm
Egamma1: 1126.9 keV

266Hs:
Time: 761391.193
MP: 12976
Strip#: 11
Estop: 10205.4 keV
Posyt: 15.29 mm
Posyb: 20.57 mm
Posyt(HE): 10.25 mm

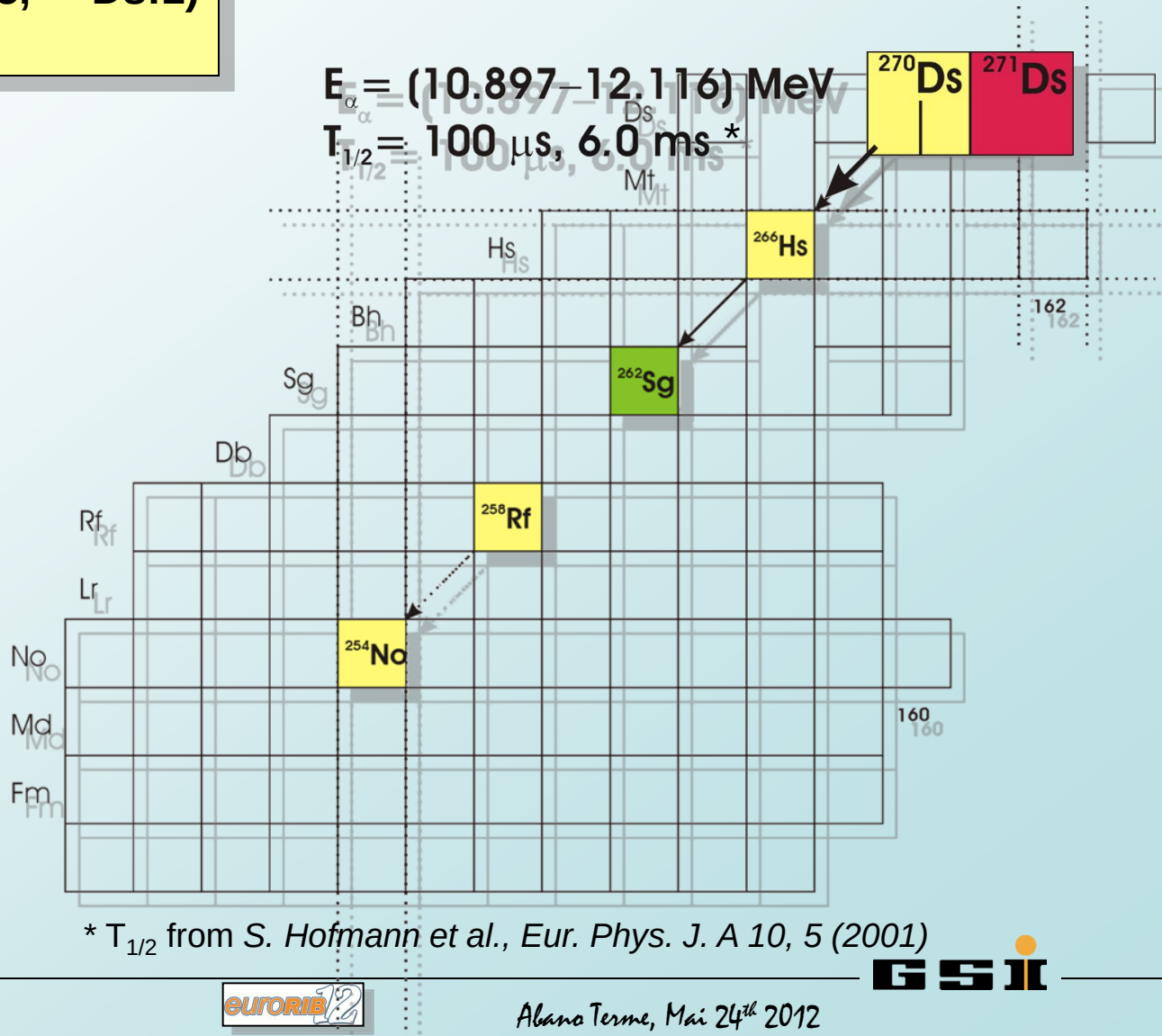
262Sg:
Time: 761391.213
MP: 13036
Strip#: 11
Estop: 184.58 MeV
Posyt: 14.70 mm
Posyb: 18.85 mm
Box#: 20
Ebox: --- MeV
Egamma3: 678.8 keV

15 chains

- ^{270}Ds α-decay



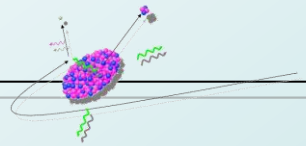
- 26 decay chains (^{270}Ds: 25, ^{271}Ds:1)
- new spectroscopic data



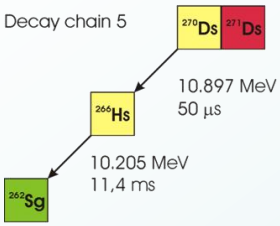
* $T_{1/2}$ from *S. Hofmann et al., Eur. Phys. J. A 10, 5 (2001)*

2010: Observed types of decay chains II

- ER-α-sf



a) ER-α-α-sf



ER:
Time: 761391.182
MP: 1531
Strip#: 11
E: 38.72 MeV
Posyt: 14.75 mm
Posyb: 18.41 mm
ToF:1409

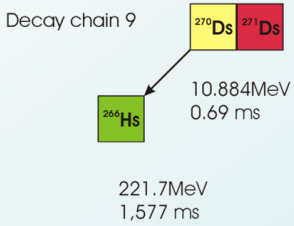
270Ds:
Time: 761391.182
MP: 1581
Strip#: 11
Estop: 10897 keV
Posyt: 15.36 mm
Posyb: 20.45 mm
Posyb(HE): 18.32 mm
Egamma1: 1126.9 keV

266Hs:
Time: 761391.193
MP: 12976
Strip#: 11
Estop: 10205.4 keV
Posyt: 15.29 mm
Posyb: 20.57 mm
Posyt(HE): 10.25 mm

262Sg:
Time: 761391.213
MP: 13036
Strip#: 11
Estop: 184.58 MeV
Posyt: 14.70 mm
Posyb: 18.85 mm
Box#: 20
Ebox: --- MeV
Egamma3: 678.8 keV

15 chains

b) ER-α-sf



ER:
Time: 1281611.582
MP: 1547
Strip#: 9
E: 47.65 MeV
Posyt: 17.63 mm
Posyb: 15.95 mm
ToF:1417

270Ds:
Time: 1281611.582
MP: 2235
Strip#: 9
Estop: 10883.9keV
Posyt: 18.10 mm
Posyb: 16.50 mm
Posyt(HE): 18.18 mm
Posyb(HE): 16.09 mm
Box#: 21
Ebox: 12047.2 keV

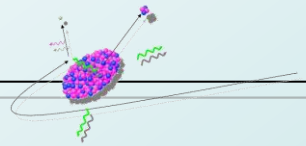
266Hs:
Time: 1281611.584
MP: 3812
Strip#: 13
Estop: 221.71 MeV
Posyt: 17.74 mm
Posyb: 16.03 mm
Box#: ---
Ebox: --- MeV
Egamma: --- keV

8 chains

⇒ sf(^{266}Hs) = 24%

^{270}Ds

- ^{266}Hs sf-branch



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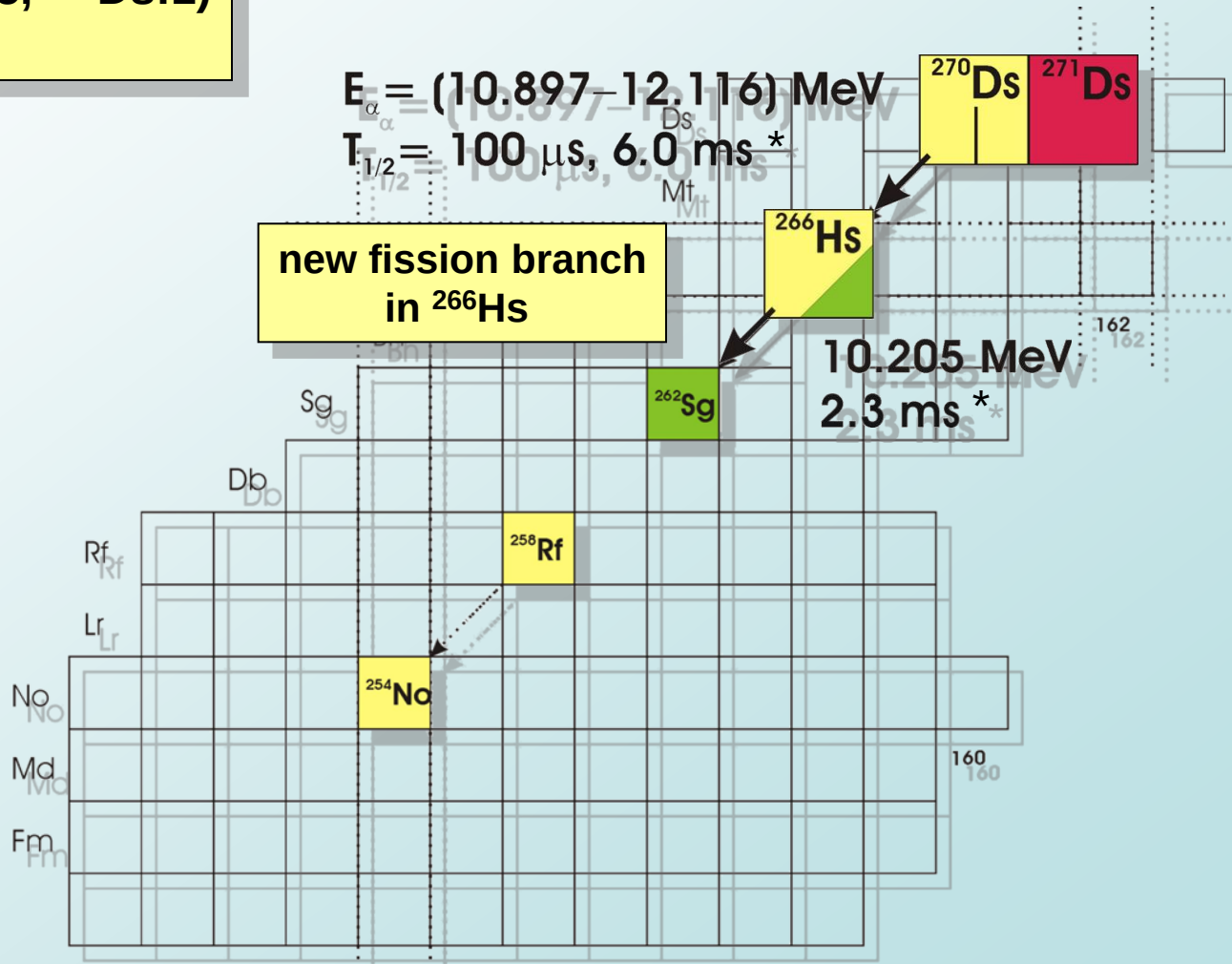
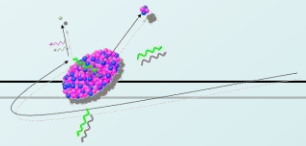


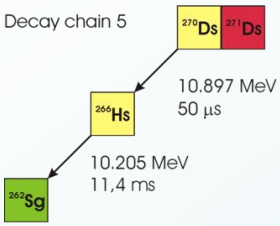
* T$_{1/2}$ from *S. Hofmann et al., Eur. Phys. J. A 10, 5 (2001)*

2010: Observed types of decay chains III

- ER-α-α-α-sf



a) ER-α-α-sf



15 chains

ER:
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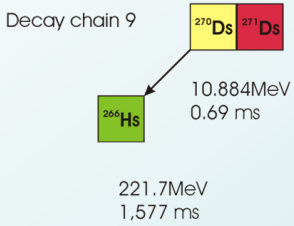
MP: 1531
Strip#: 11
E: 38.72 MeV
Posyt: 14.75 mm
Posyb: 18.41 mm
ToF:1409

270Ds:
Time: 761391.182
MP: 1581
Strip#: 11
Estop: 10897 keV
Posyt: 15.36 mm
Posyb: 20.45 mm
Posyb(HE): 18.32 mm
Egamma1: 1126.9 keV

266Hs:
Time: 761391.193
MP: 12976
Strip#: 11
Estop: 10205.4 keV
Posyt: 15.29 mm
Posyb: 20.57 mm
Posyt(HE): 10.25 mm

262Sg:
Time: 761391.213
MP: 13036
Strip#: 11
Estop: 184.58 MeV
Posyt: 14.70 mm
Posyb: 18.85 mm
Box#: 20
Ebox: --- MeV
Egamma3: 678.8 keV

b) ER-α-sf



8 chains

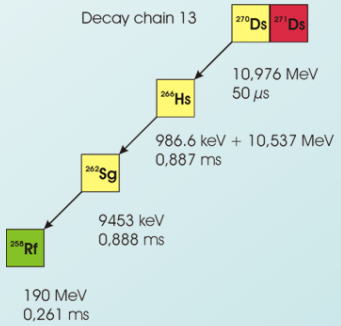
⇒ sf(^{266}Hs) = 24%

ER:
Time: 1281611.582
MP: 1547
Strip#: 9
E: 47.65 MeV
Posyt: 17.63 mm
Posyb: 15.95 mm
ToF:1417

270Ds:
Time: 1281611.582
MP: 2235
Strip#: 9
Estop: 10883.9keV
Posyt: 18.10 mm
Posyb: 16.50 mm
Posyt(HE): 18.18 mm
Posyb(HE): 16.09 mm
Box#: 21
Ebox: 12047.2 keV

266Hs:
Time: 1281611.584
MP: 3812
Strip#: 13
Estop: 221.71 MeV
Posyt: 17.74 mm
Posyb: 16.03 mm
Box#: ---
Ebox: --- MeV
Egamma: --- keV

c) ER-α-α-α-sf



2 chains

⇒ α(^{262}Sg) = 6%

ER:
Time: 1960630.182
MP: 1940
Strip#: 10
E: 40.79 MeV
Posyt: 18.36 mm
Posyb: 17.83 mm
ToF: 1413

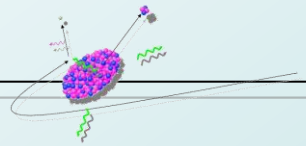
270Ds:
Time: 1960630.182
MP: 1990
Strip#: 10
Estop: 10975.9 keV
Posyt: 15.23 mm
Posyb: 18.55 mm
Posyt(HE): 19.43 mm
Posyb(HE): 15.66 mm

266Hs:
Time: 1960630.183
MP: 2867
Strip#: 10
Estop: 986.6 keV
Posyt: 15.04 mm
Posyb: 17.53 mm
Box#: 4
Ebox: 10536.8 keV

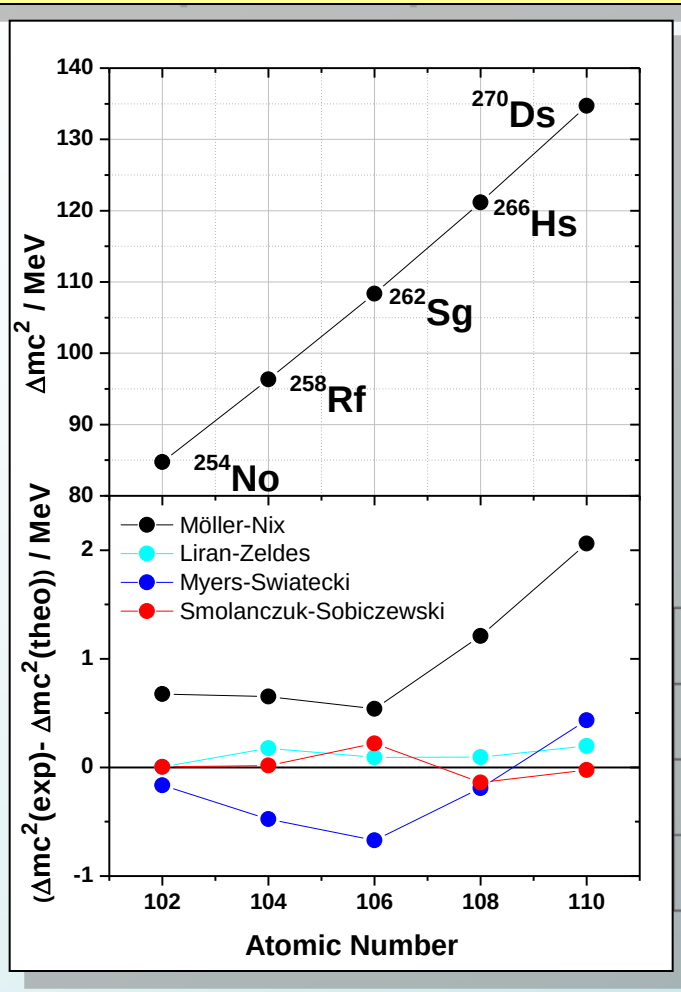
262Sg:
Time: 1960630.184
MP: 3755
Strip#: 10
Estop: 9453.1 keV
Posyt: 15.17 mm
Posyb: 18.60 mm
Posyt(HE): 20.43 mm
Posyb(HE): 15.62 mm

258Rf:
Time: 1960630.184
MP: 4016
Strip#: 9
Estop: 189.78 MeV
Posyt: 18.14 mm
Posyb: 18.65 mm
Egamma2: 309.7 keV
Egamma3: 1055.3 keV
Egamma4: 1095.5 keV

- News III – ^{262}Sg α-branch → link to ^{254}No



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



E_α = (10.897–12.116) MeV

$T_{1/2}$ = 100 μs, 6.0 ms *

^{270}Ds ^{271}Ds

^{266}Hs

new fission branch in ^{266}Hs

^{262}Sg

10.205 MeV

2.3 ms *

α-decay link ^{262}Sg → ^{258}Rf

^{258}Rf

9.453 MeV

6.9 ms *

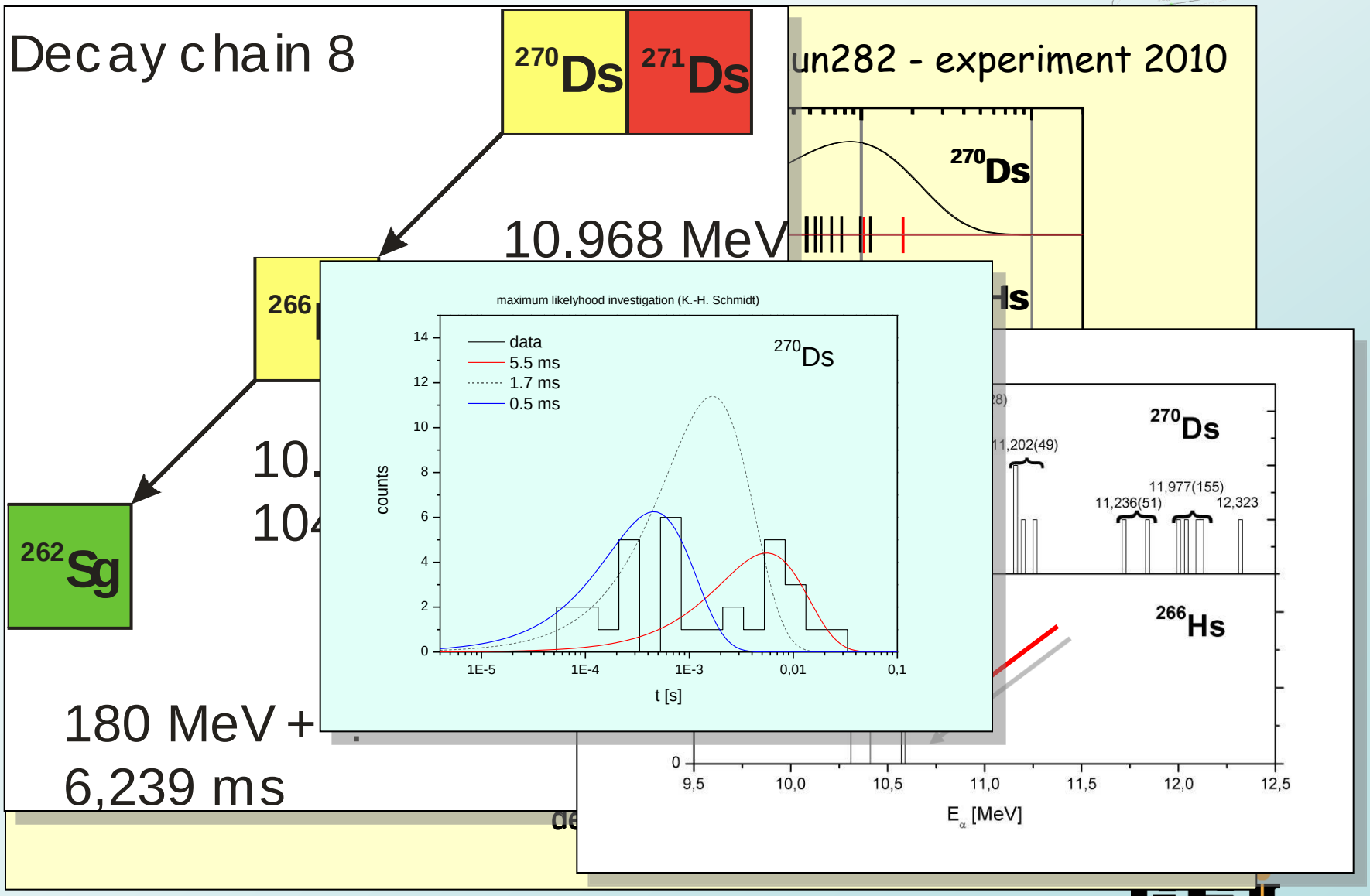
→J. M. GATES et al. PRC 77, 034603 (2008)

^{254}No

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

Decay details

- time distributions



^{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:

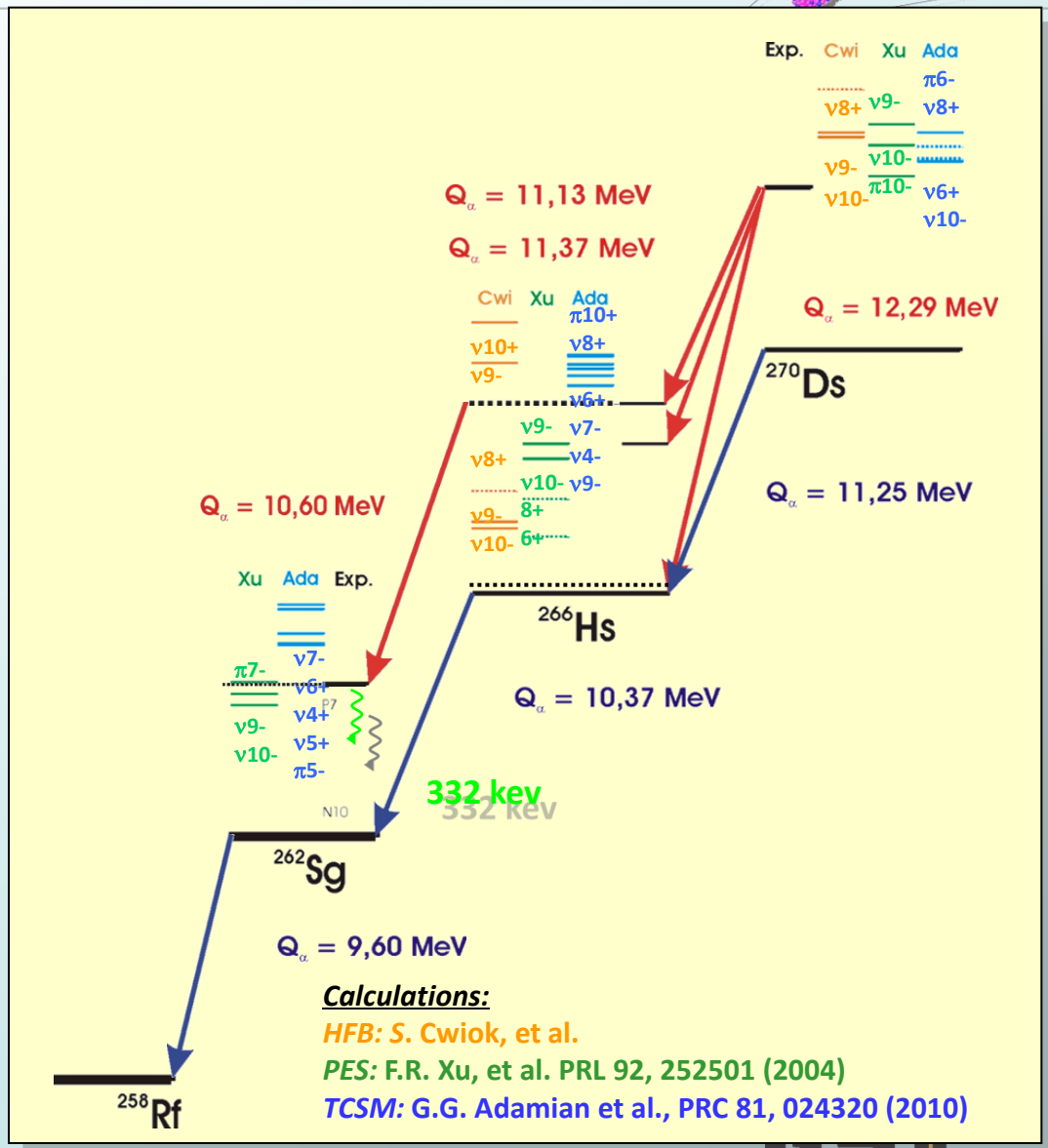
$E_\alpha \approx 200$ keV higher

$E_\nu = 332$ keV

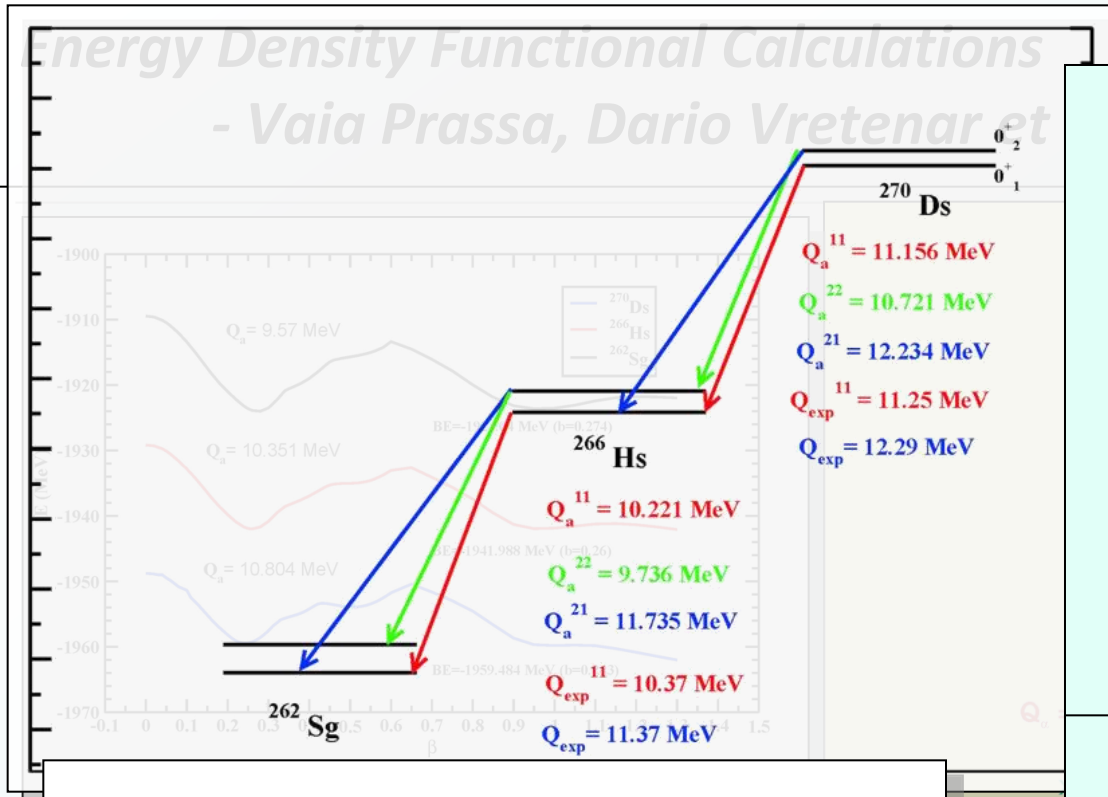
^{262}Sg:

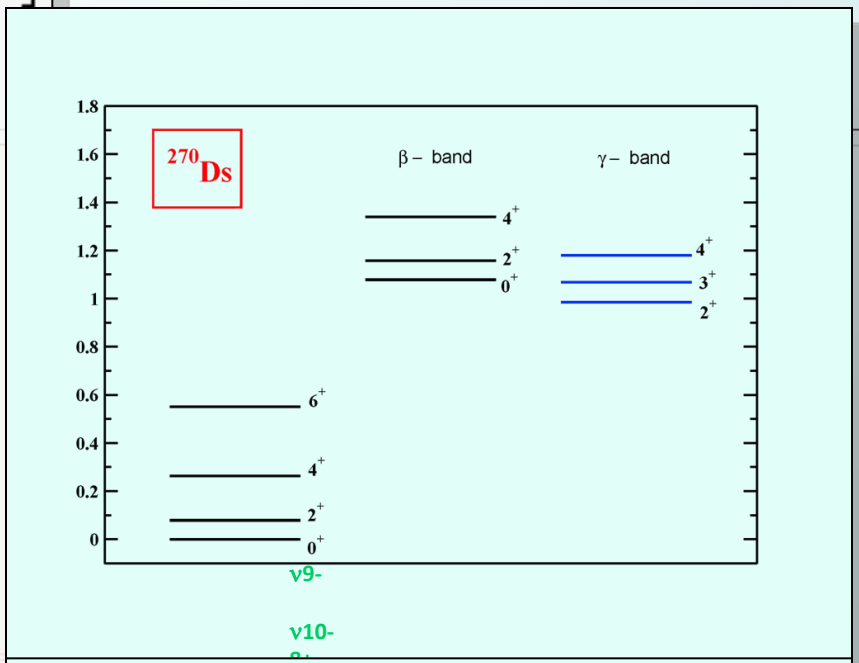
α decay observed for the first time

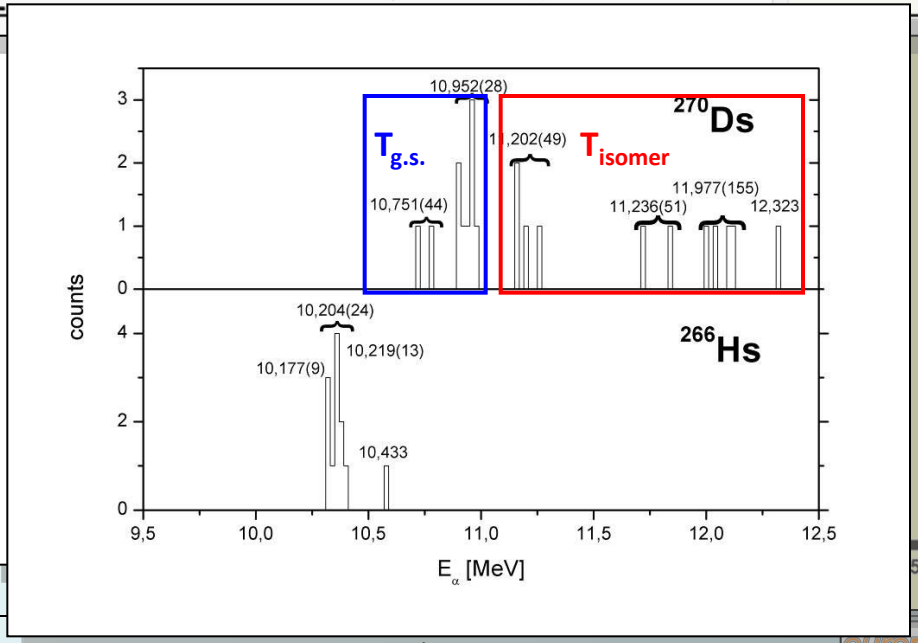
(1 full E, 1 escape)

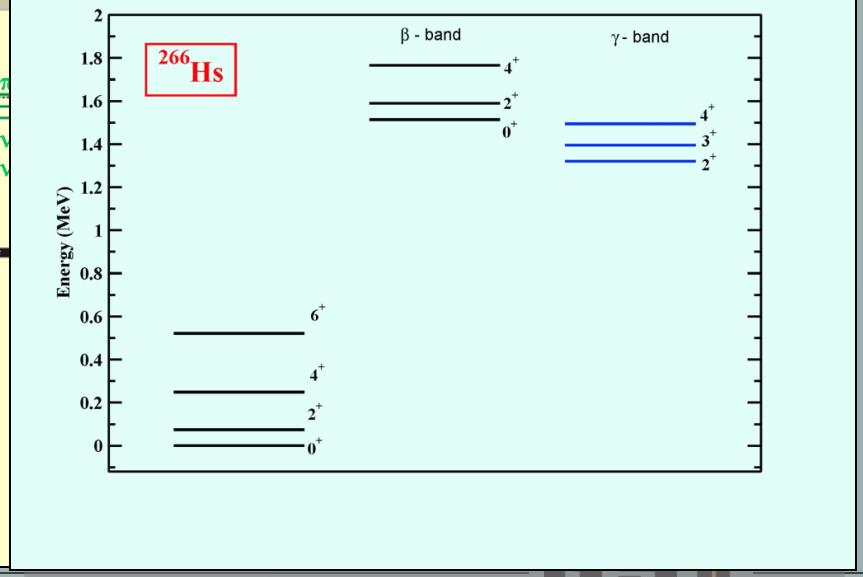


Energy Density Functional Calculations
- Vaia Prassa, Dario Vretenar et



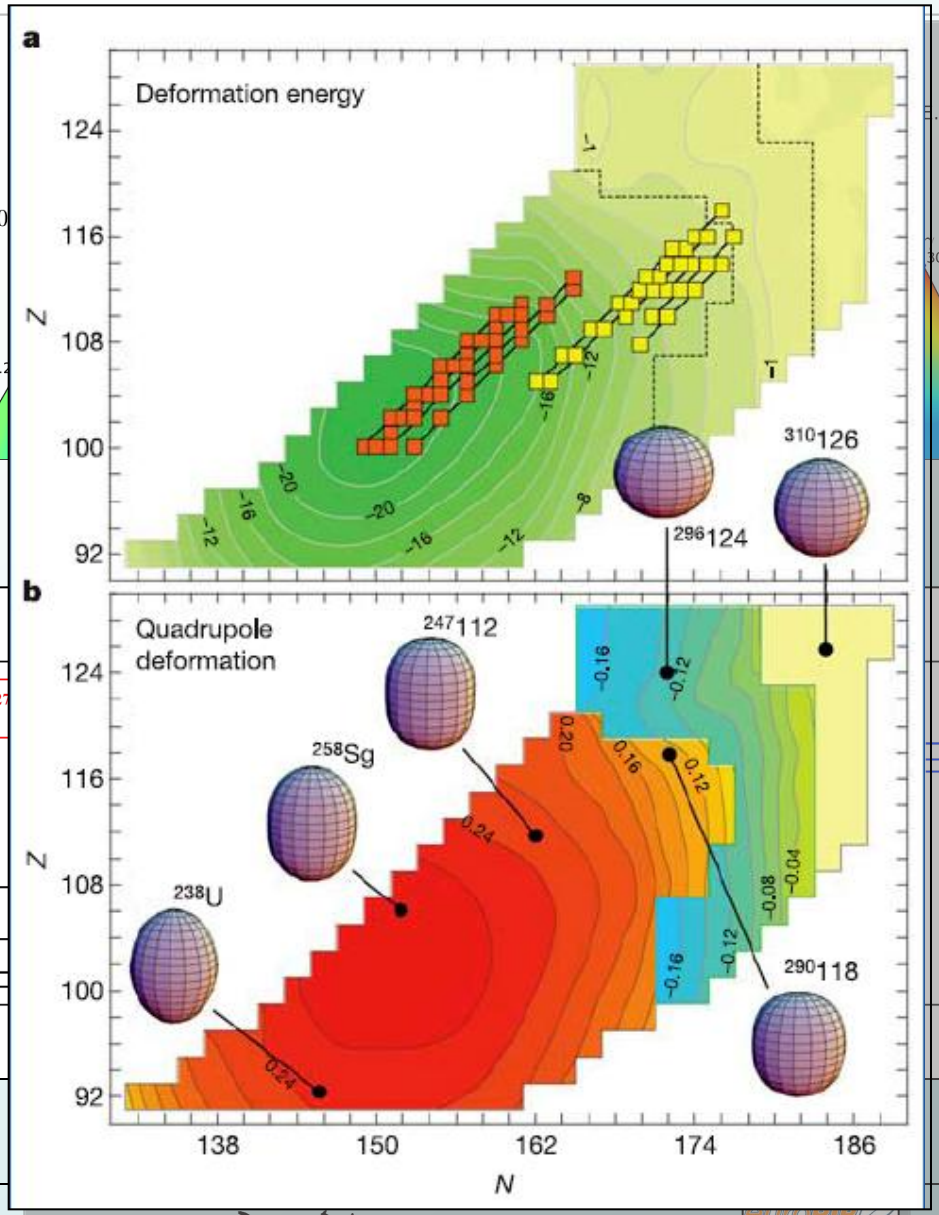




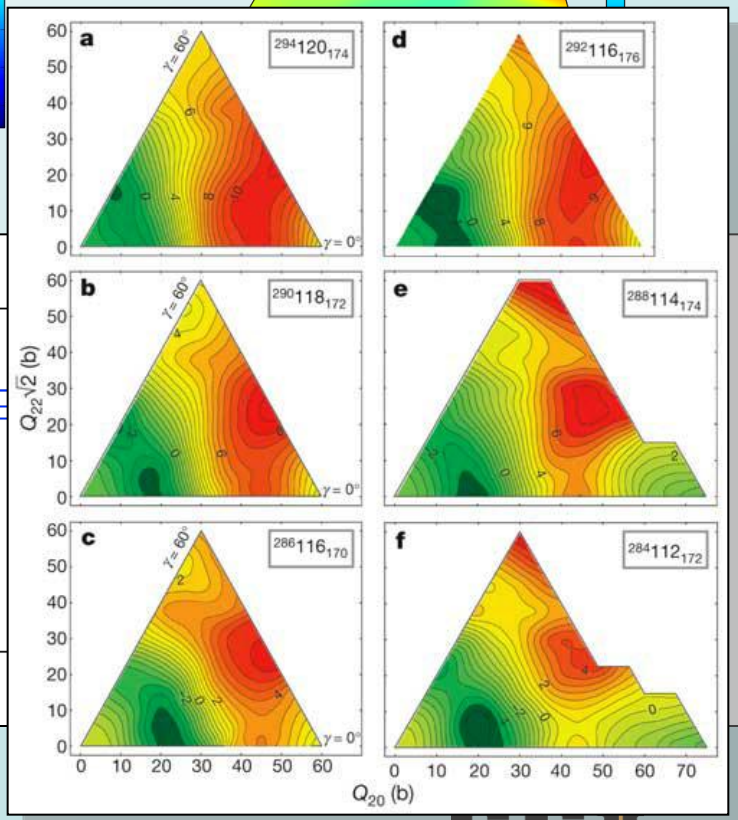


Energy Density Functional Calculations

- Vaia Prass, Dario Vretenar et al.



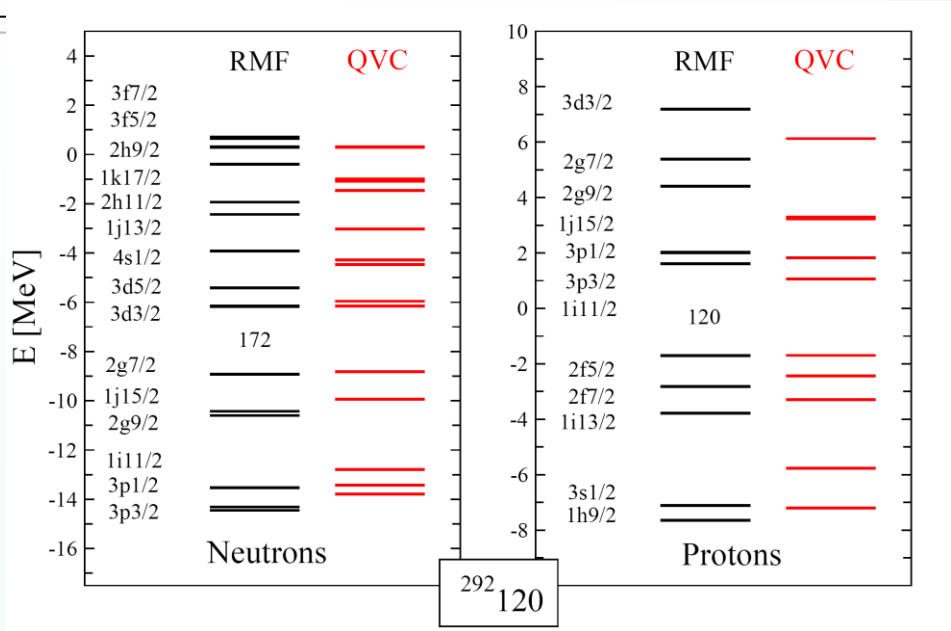
S. Ćwiok et al., NATURE, 433 (2005)
HFB + SLy4

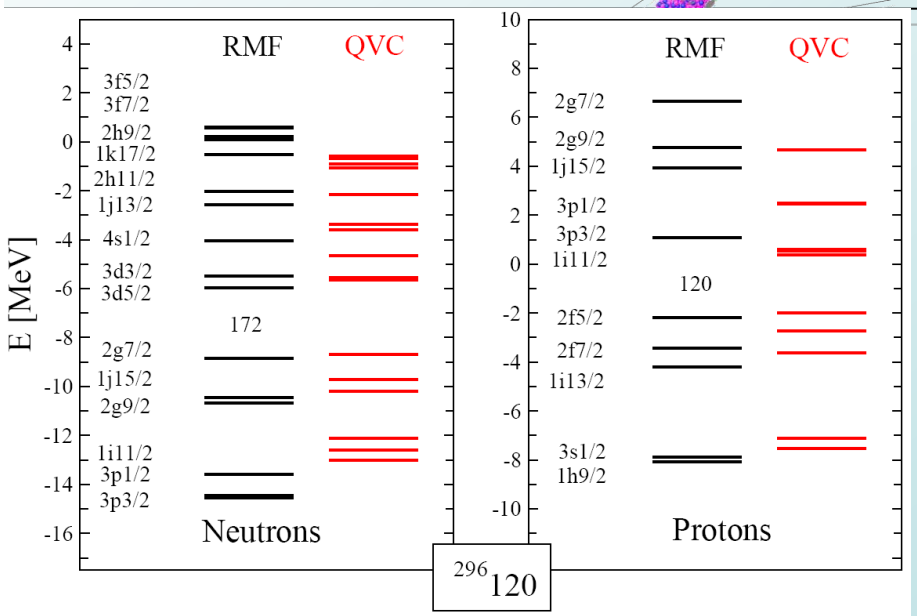


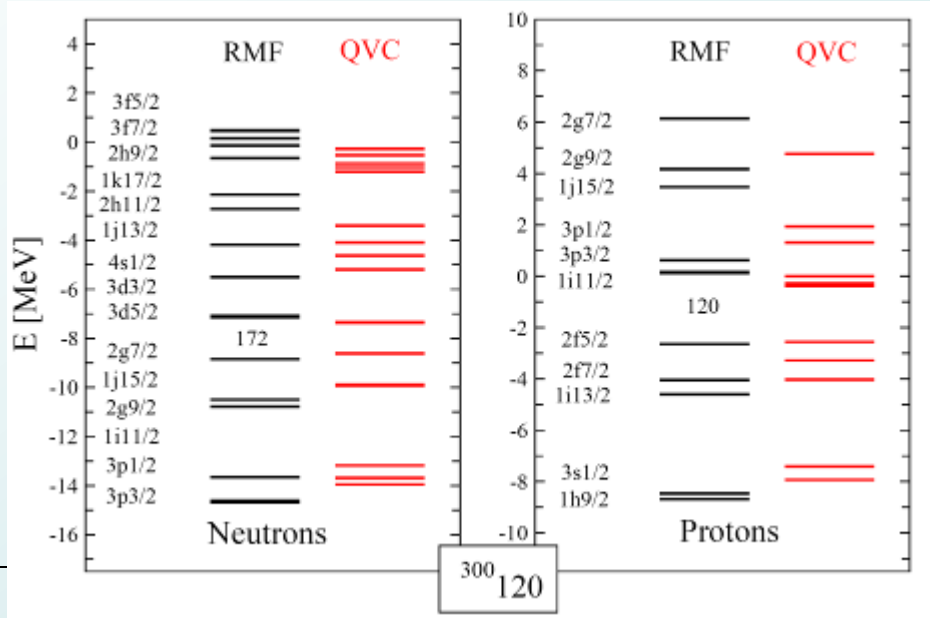
Elena Litvinova

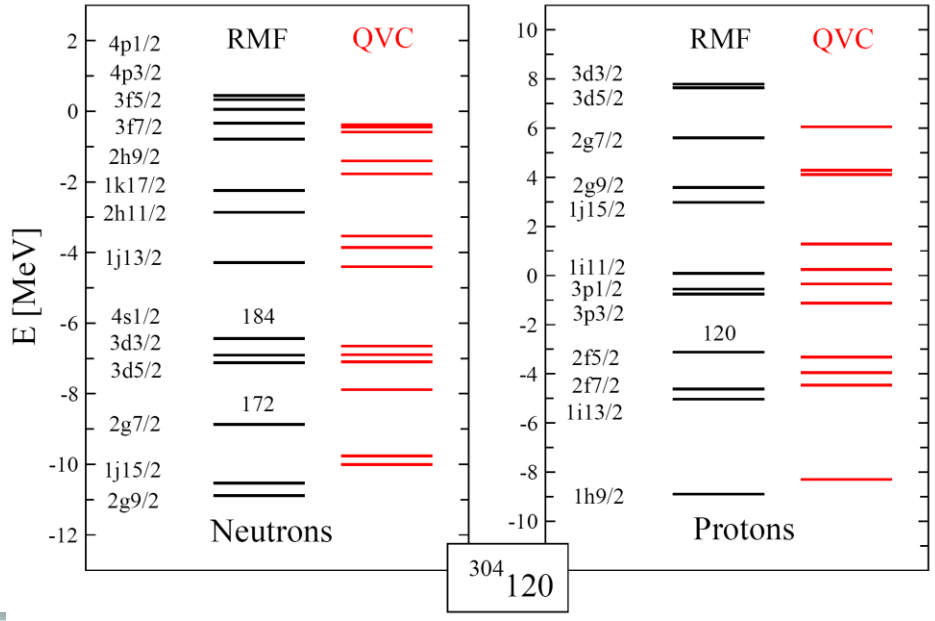
PRC 85, 021303(R) 2012

„Semi-magic" Z = 120 isotopes with N = 172-184: neutron pairing + phonon coupling







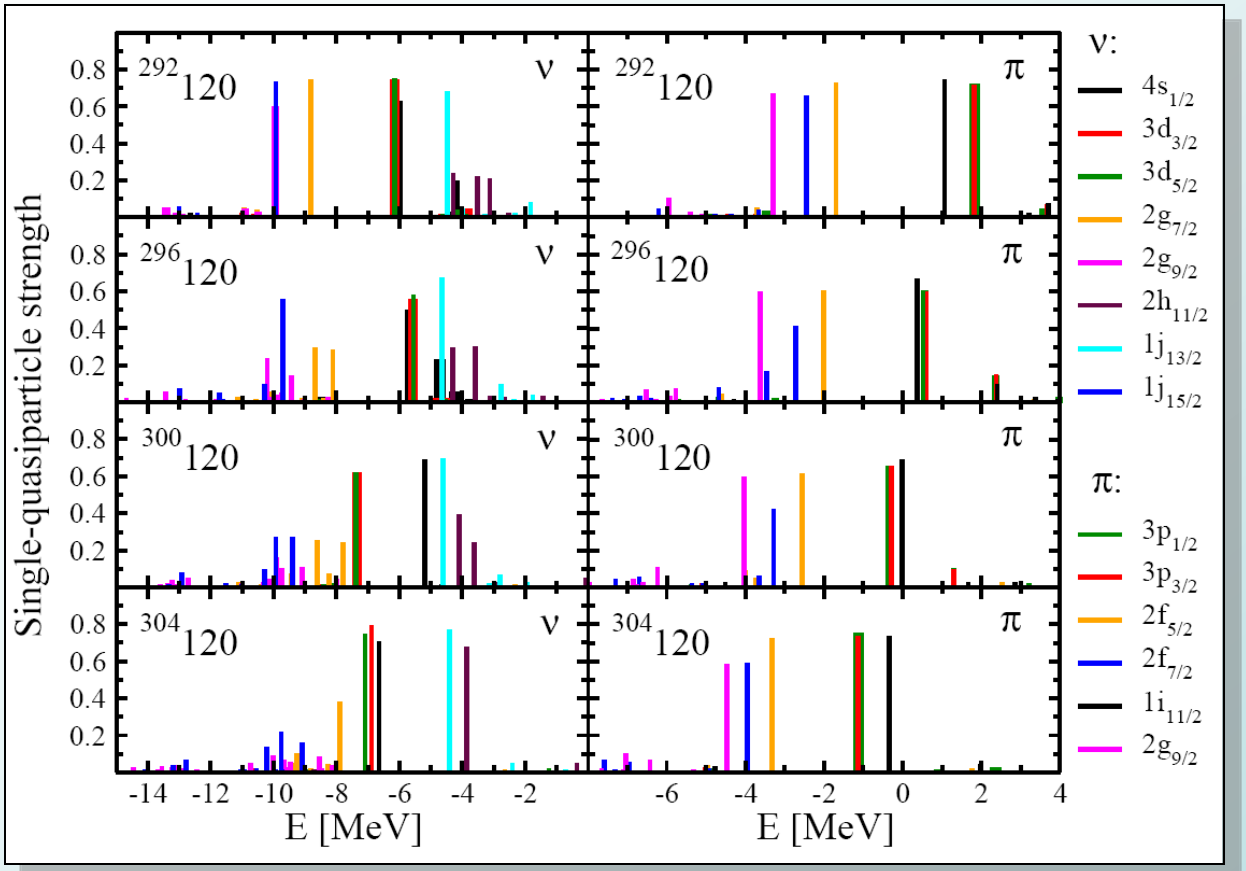


Elena Litvinova

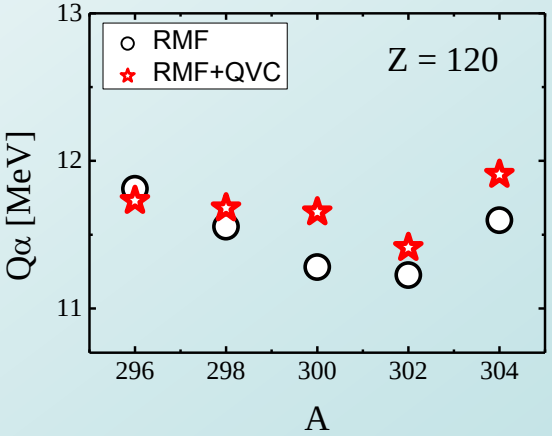
PRC 85, 021303(R) 2012

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:

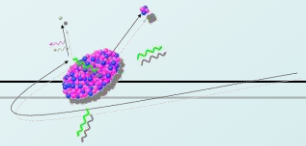
1. Impact on the shell gaps
2. Smearing of the shell effects

E.L., arXiv:1108.3508

Shell stabilization & vibration stabilization/destabilization (?)

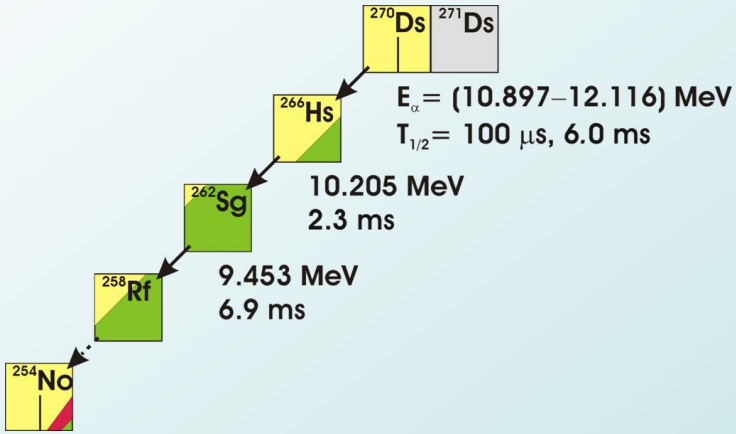
Summary

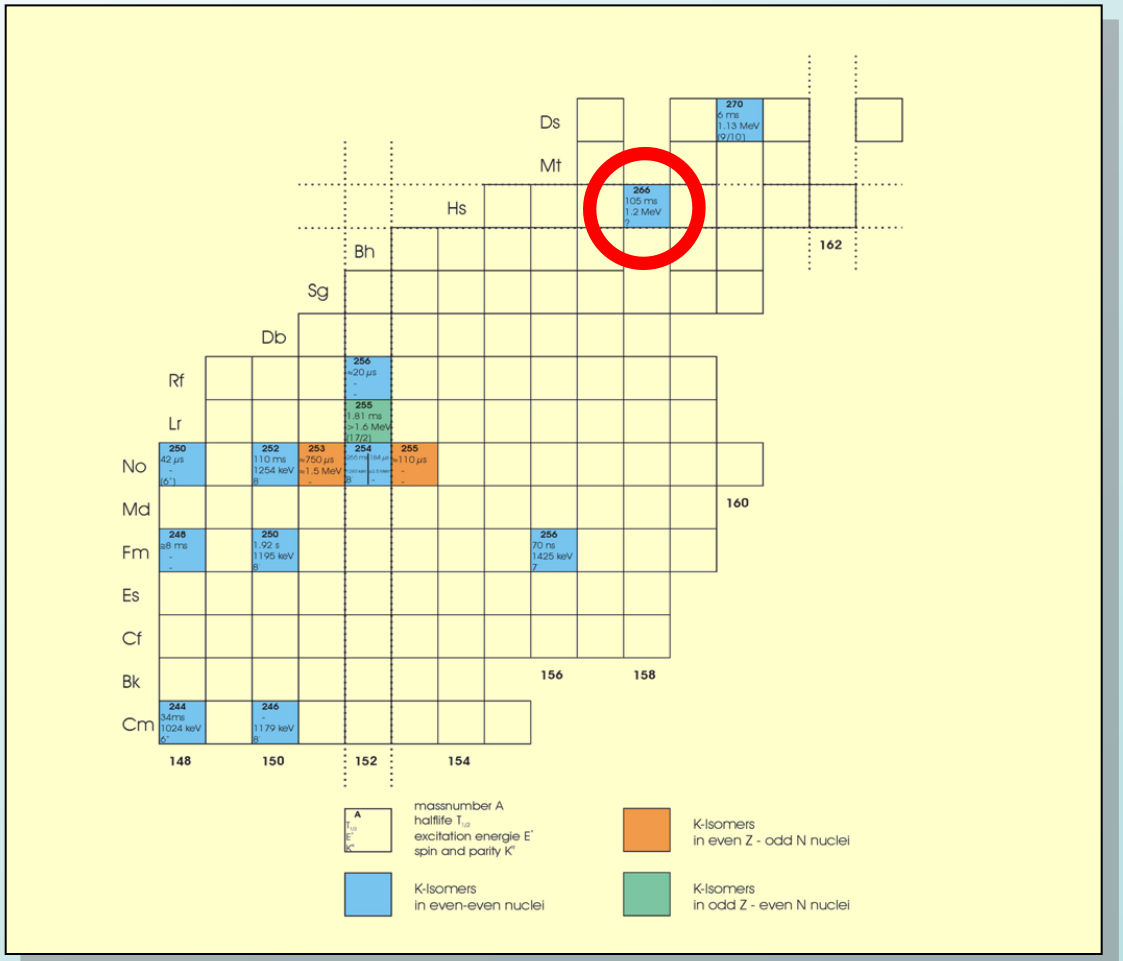
- Achievements



ground state, decay and structure properties up to Z=110

- α-γ coincidences (total: 4)
- fission branch in ^{266}Hs
- experimental mass for ^{270}Ds
- new K-isomer ^{266} Hs

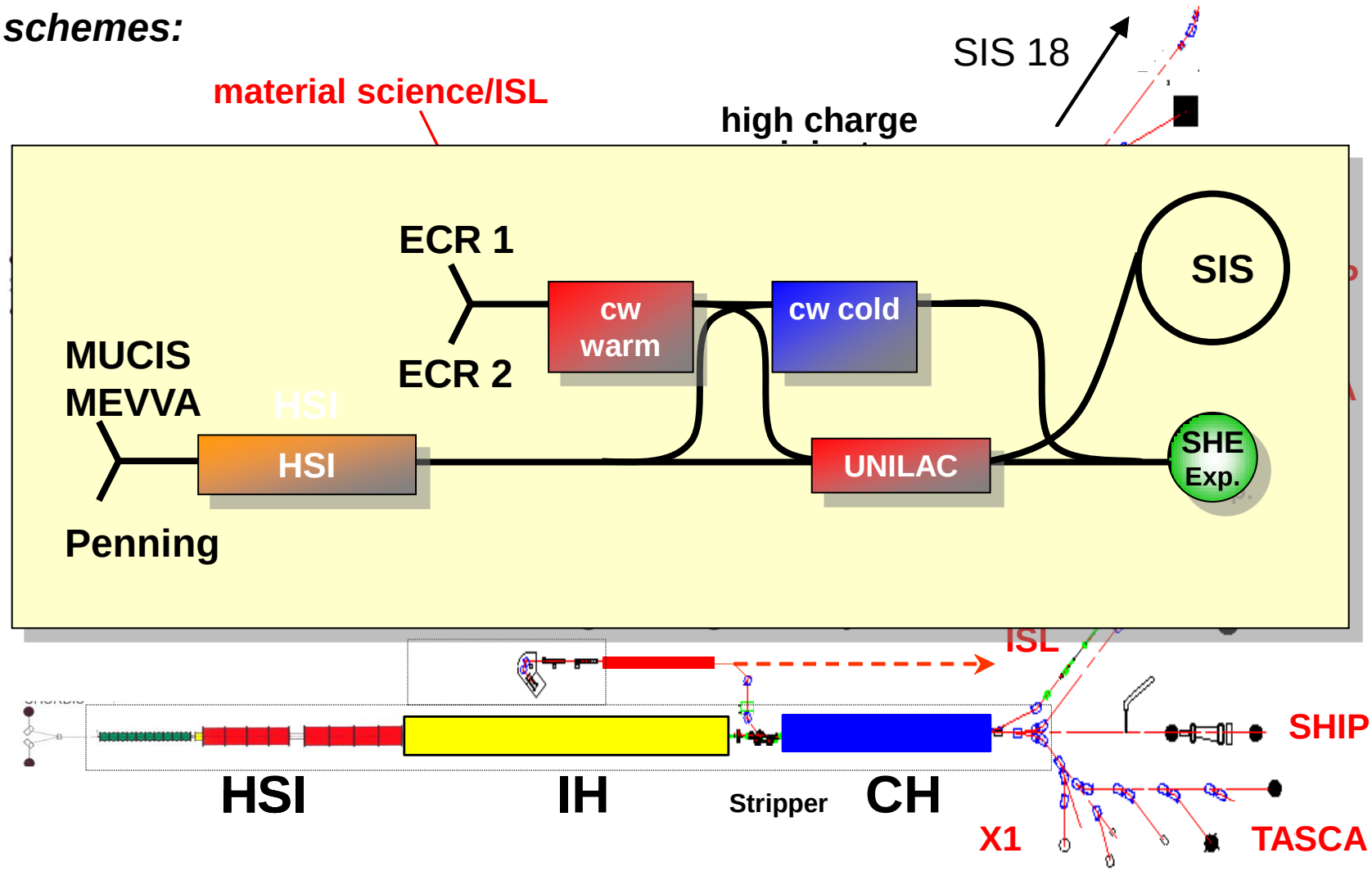




SHE Synthesis and Nuclear Structure of SHE

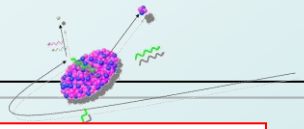
- Roadmap/Long Term

Possible GSI acc. schemes:



FAIR reaction rates

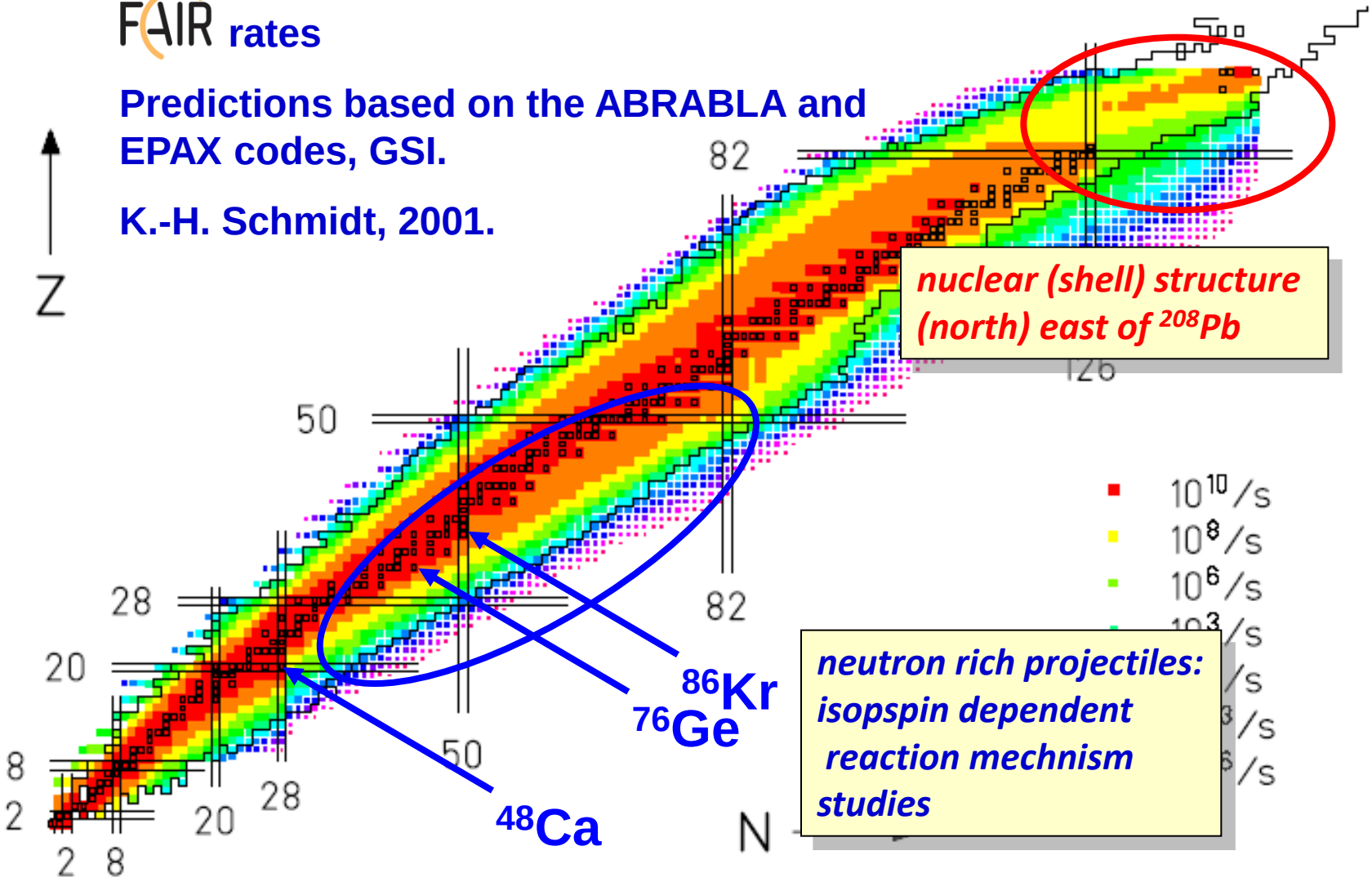
- optimum rates from projectile fission and fragmentation



FAIR rates

Predictions based on the ABRABLA and EPAX codes, GSI.

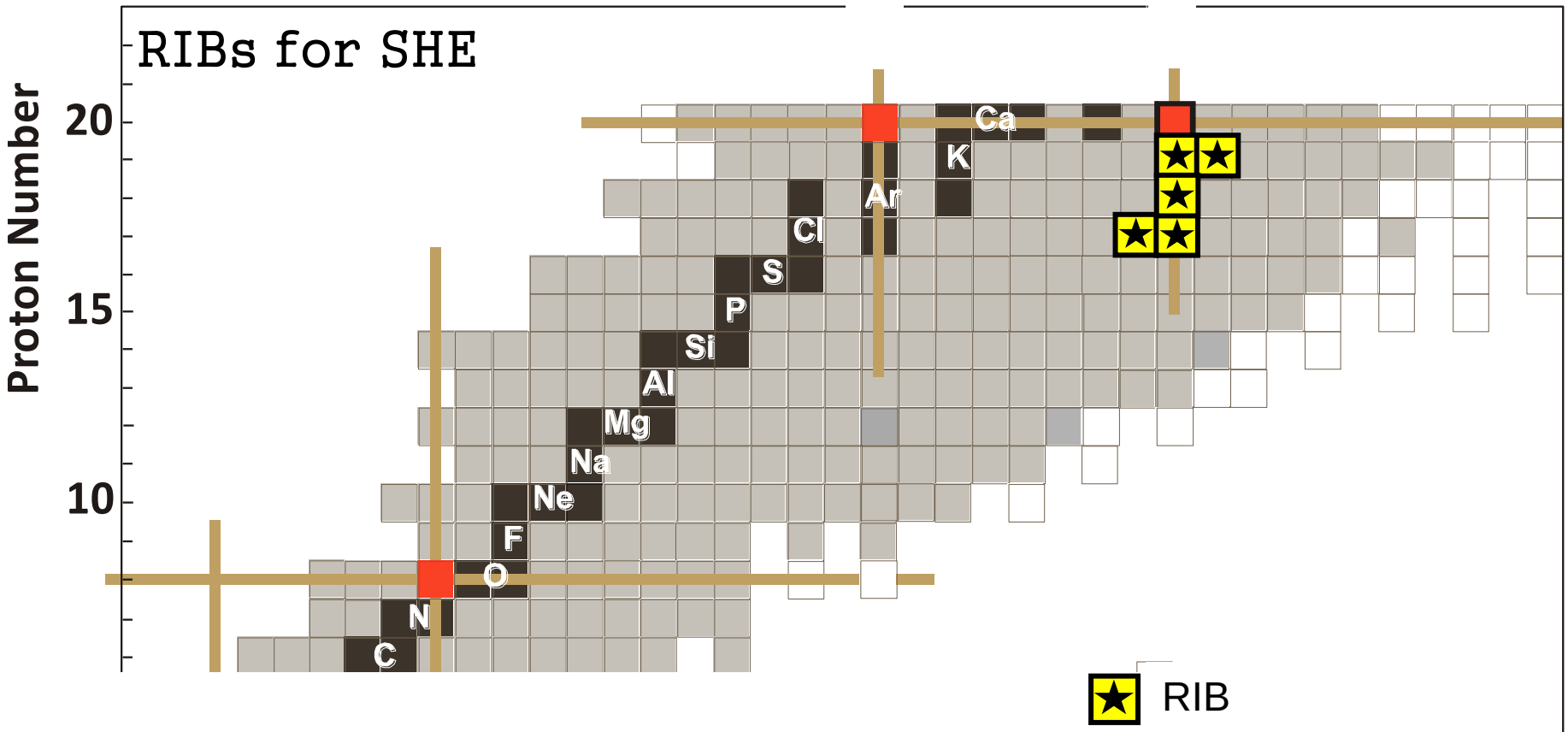
K.-H. Schmidt, 2001.



nuclear (shell) structure (north) east of ^{208}Pb

neutron rich projectiles: isopspin dependent reaction mechnism studies

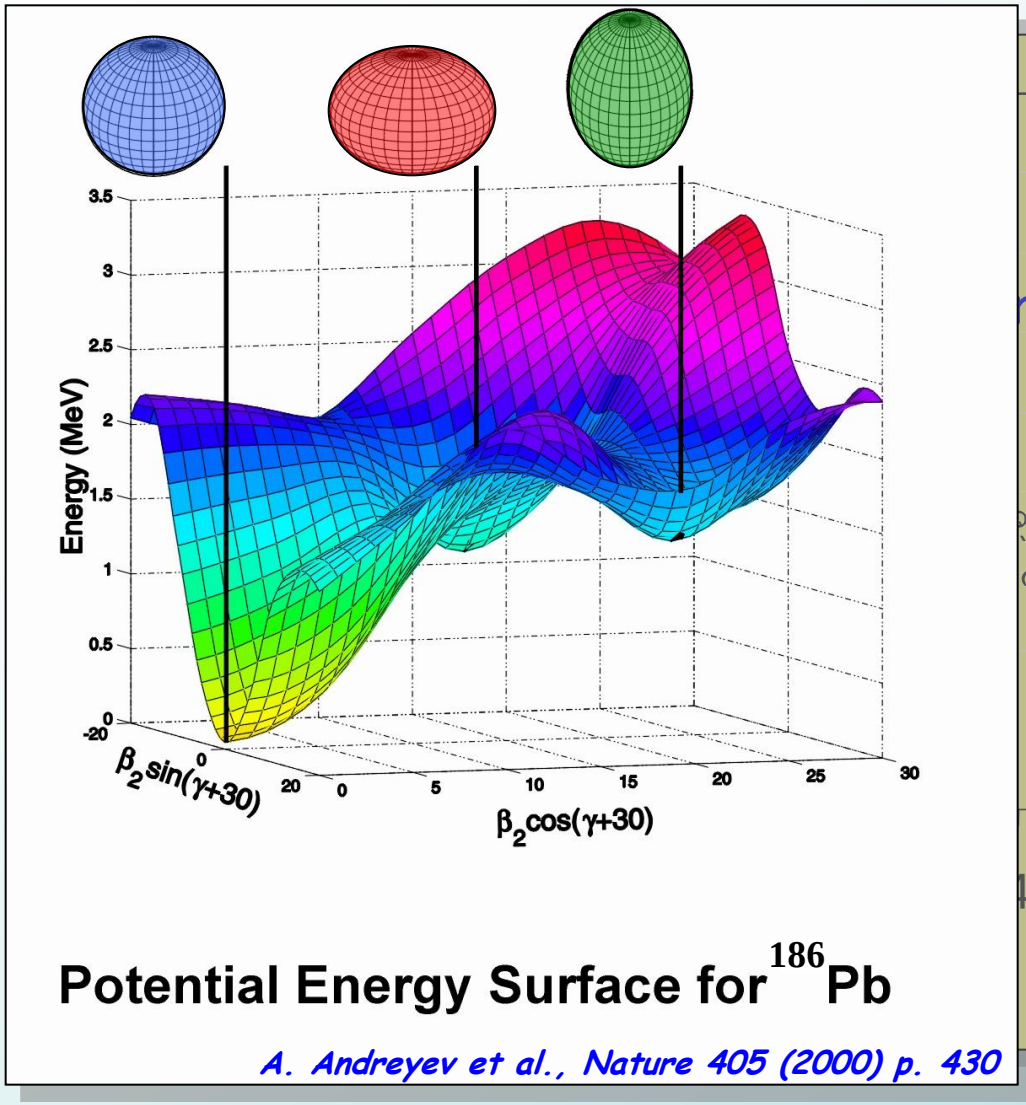
Yu.Ts. Oganessian - FUSHE 2012



Realistic RIB intensities for the synthesis of SHE could be obtained for the isotopes close to 48Ca produced in simplest reaction - like stripping, nucleon transfer, knock-out, charge exchange etc.

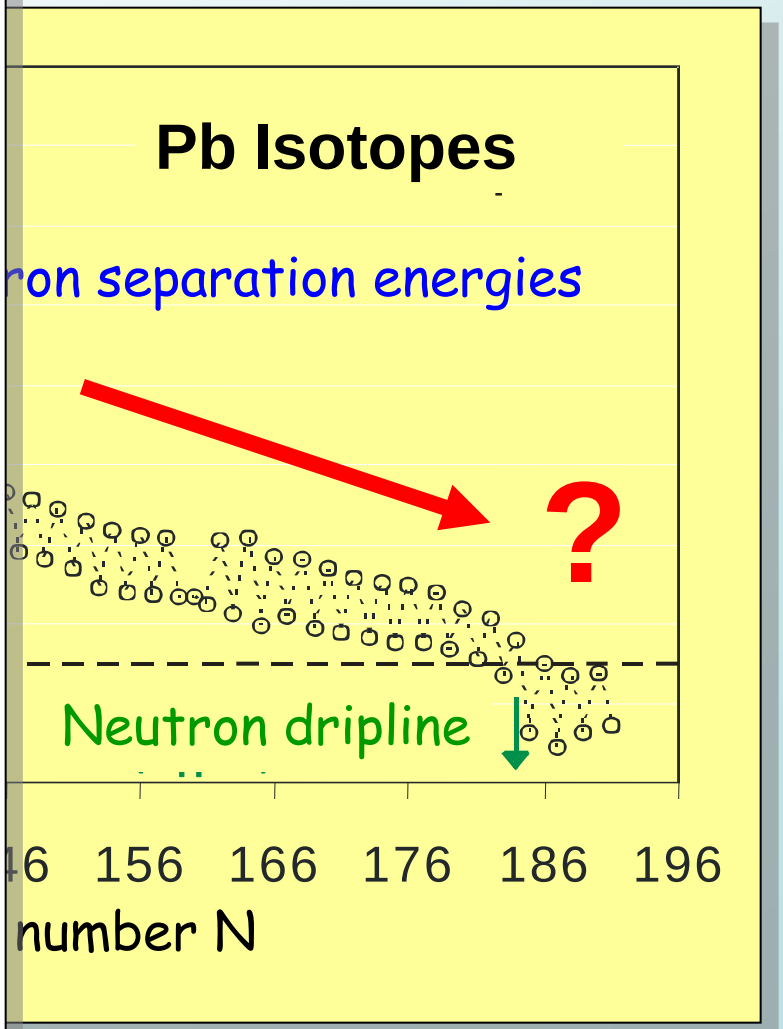
Evolution of Shell Gaps

- S_n values for Pb isotopes



Potential Energy Surface for ^{186}Pb

A. Andreyev et al., Nature 405 (2000) p. 430



The **ECOS** Network Activity in the **ENSAR** framework of the EU FP7 program has among others with its Task 2 the objective to promote **synergies in the field of Super-Heavy Element (SHE) research**, described as follows:

*"For this task ECOS is aiming for **bringing together the groups with research activities on SHE using high-intensity ion beams** for an exchange of new ideas and techniques related to the use of very high intensity stable beams. In particular, Task 2 will propose an **optimisation of resources** (beam time, target technology, detectors) in the field of SHE research **among TNA facilities**."*

The **ENSAR-ECOS** Workshop on **FU**ture **S**uper-**H**eavy **E**lement **S**trategy – **FUSHE 2012** is one very important milestone in this process. It will provide a **forum for the SHE community to discuss and define the future strategy to reach** the common goal – the establishment and investigation of the region of spherical shell-stabilised super-heavy nuclei – the so called **"Island of Stability".**

Workshop Structure and Goal

- The workshop
  - attended by ≈ **90 participants** from all institutions involved in SHE research worldwide –
  was organised in **7 x ½-day sessions** with a strong emphasis on discussions including **Theory, Experiment and Instrumentation** arguments

- The sessions were organised as a combination of **invited talks followed by a topical discussion for the subjects:**
  - **SHE Synthesis**
  - **Nuclear Structure of SHE**
  - **Chemistry**
  - **Atomic Physics and Alternative Approaches**

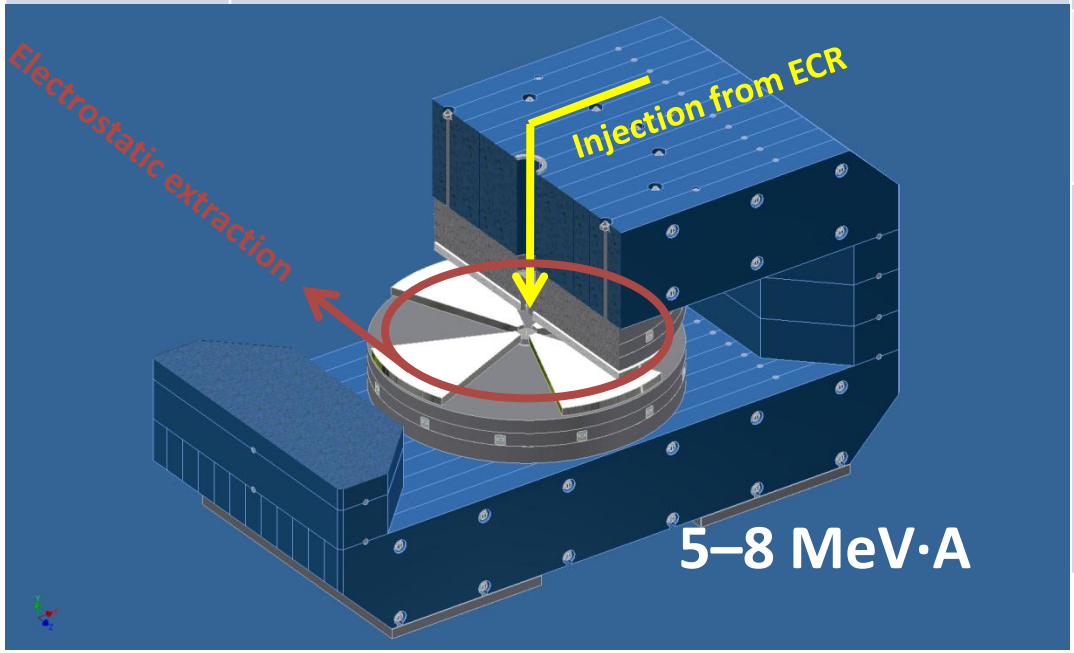
- As a main deliverable of the workshop a **paper laying out the – near and far - future strategy in SHE research** will be produced and published

Production

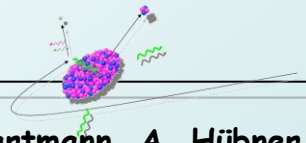
today: $4.5 \cdot 10^{19}$ with factory: $1.3 \cdot 10^{21}$

factor: 30

Increase a beam dose			
it requires to Increase:	**beam intensity**	and	**beam time**
	⇩		⇩
	New accelerator		**SHE-Factory**
			⇩
			~ 7000 h/year
			⇩
			new laboratory



The SHIP Collaboration



D.A., M. Block, H.G. Burkhard, Ch. Dröse, M. Dworschak, F.P. Heßberger, S. Hofmann, W. Hartmann, A. Hübner, B. Kindler, J. Khuyagbaatar*, I. Kojouharov, B. Lommel, R. Mann, J. Maurer, E. Minaya, J. Steiner

Gesellschaft für Schwerionenforschung (GSI)
D-64220 Darmstadt, Germany

A.G. Popeko, A.V. Yeremin
Flerov Laboratory of Nuclear Reactions, JINR
Ru-141 980 Dubna, Russia

S. Antalic, S. Šaro
Department of Nuclear Physics,
Comenius University
SK-84248 Bratislava, Slovakia

M. Leino, J. Uusitalo
Department of Physics, University of Jyväskylä
FIN-40351 Jyväskylä, Finland

V.F. Comas, J.A. Heredia
Higher Inst. of Technologies and Appl. Sciences
Havana 10600, Cuba

K. Nishio
Japan Atomic Energy Research Institute
Tokai, Ibaraki 319-1195, Japan

R. Grzywaczb, K. Miernikc,
J.B. Roberto, K.P. Rykaczewski
ORNL Oak Ridge band Univ. of T
ennessee cand Univ. of Warsaw

K. Eberhardt, J. Runke,
P. Thörle-Pospiech, N. Trautmann
University Mainz, Germany

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