Spectroscopy of heavy and super heavy elements, perspectives with stable (high intensity) ion beams

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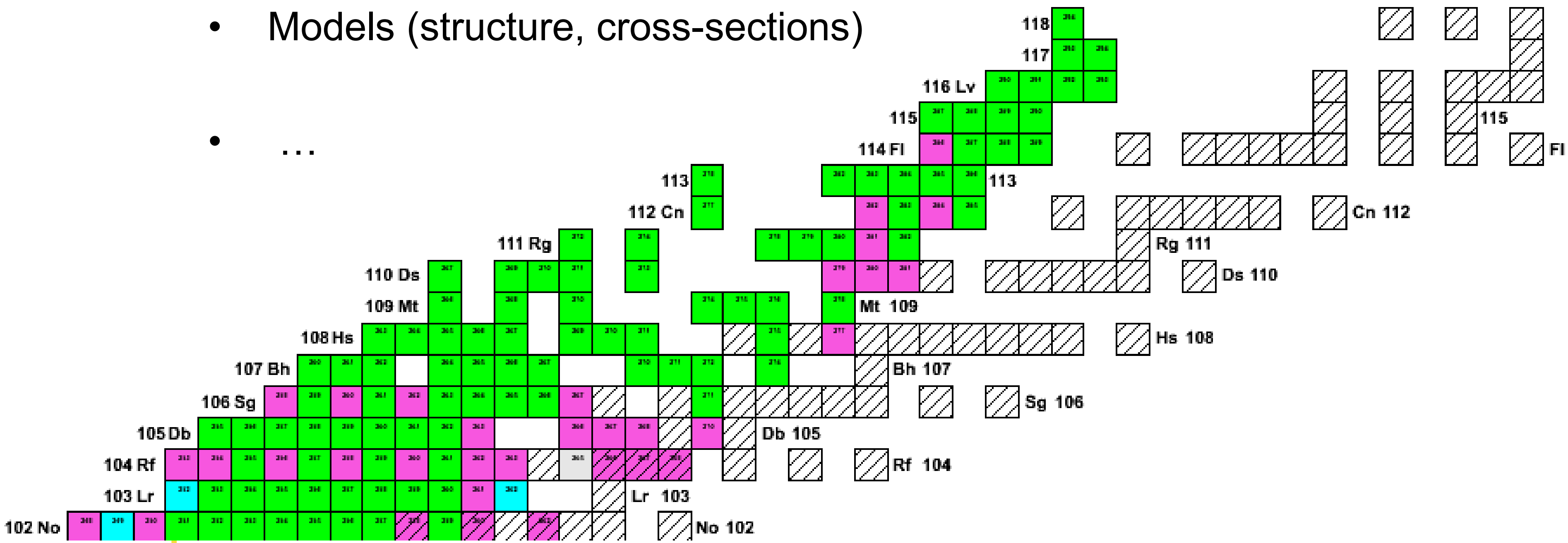
CEA Saclay

Introduction

- Nuclei with extreme mass and charge
- Structure :
  - Magic numbers (if any ?); Magnitude of shell effects; Evolution with A&Z
  - Deformed nuclei and collective properties : magic deformed numbers; Energy of sp decreasing with deformation (high-j shell); K-isomers
- Production : best method(s) to create nuclei; reach beta-stable nuclei and beyond
- Models (structure, cross-sections)
- …



Status, problems and outline

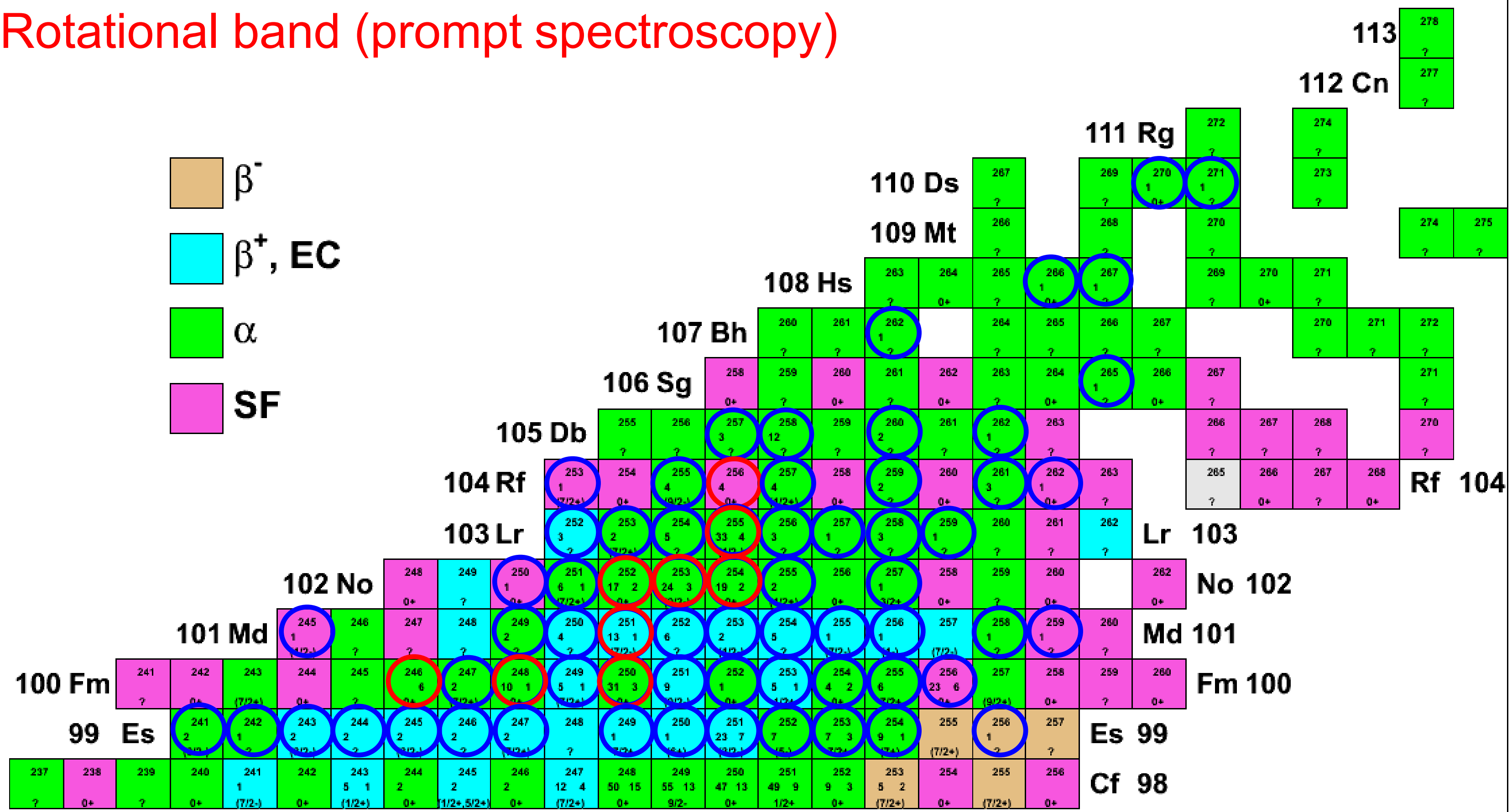
- Impressive progresses since few years but :
  - Still little known about structure. Almost nothing above Z=104
  - Production rates !!!
  - Production techniques (how to reach beta-stable and neutron rich nuclei ?) : reaction mechanism + best beams !
  - Selection and detection techniques (a less severe problem ?)

- Outline
  - VHE status
  - Why do we need highest beam intensities
  - LINAG and S3
  - Selected physics case
  - New possible production and experimental techniques
  - Prompt spectroscopy
  - Other facilities in Europe
  - Conclusions

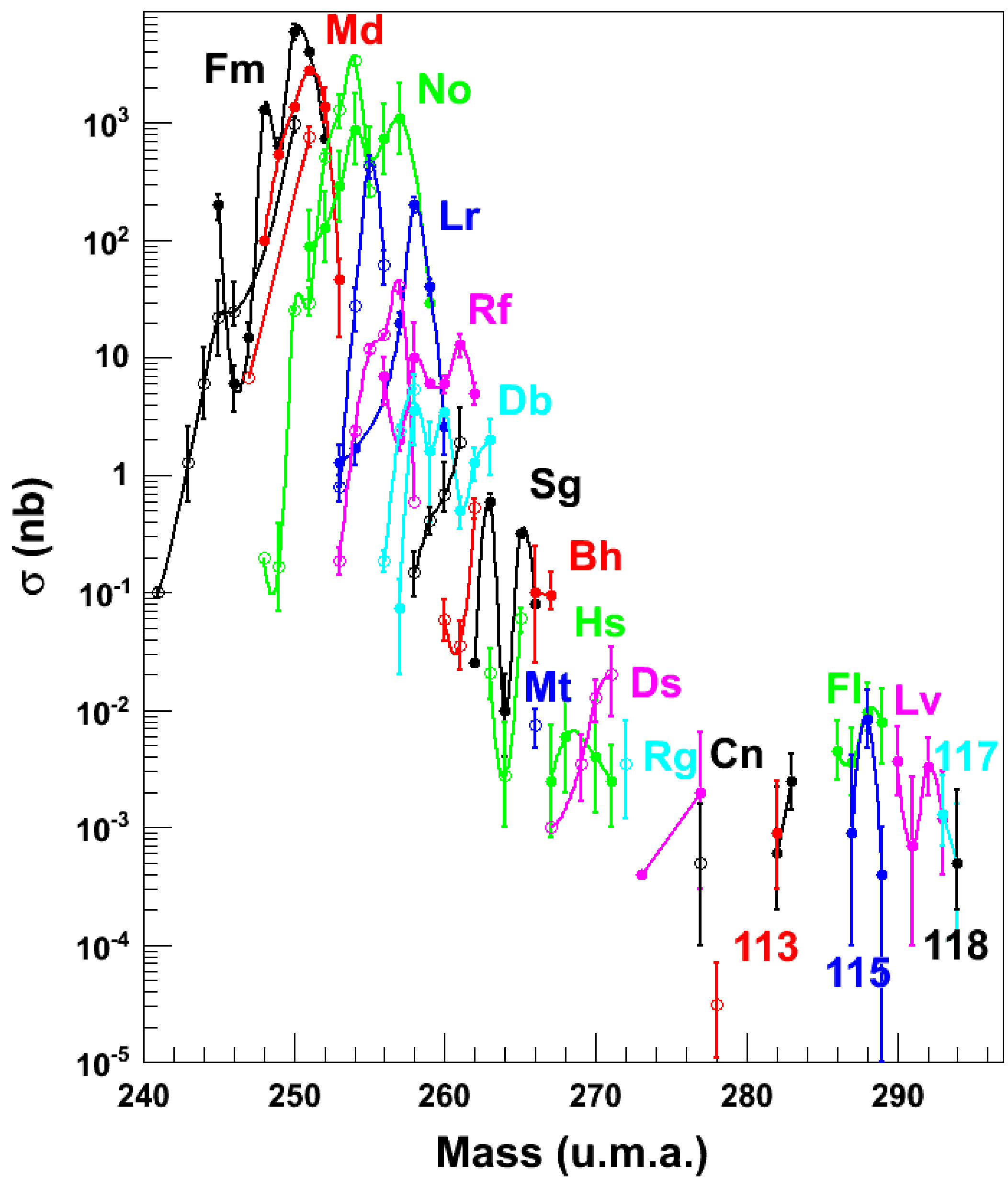
Excited states : status

At least an excited states known

Rotational band (prompt spectroscopy)



Cross sections



Why do we need highest beam intensities ?

Basically two experimental techniques :

- Prompt spectro. “high intensity” but not that much because of prompt detection limitation. Beam intensity is not (yet) the bottleneck (see e.g. ^{246}Fm@JYFL σ ~ 11 nb; I ~70 pnA)

- Decay spectro. : as much beam as possible… within the limit of separator/spectrometer and detection. Note : except in K-isomer studies, we must have a decaying (alpha) nucleus + need to produce mother nucleus (Z+2)

Spectrometer/separator :

- transmission as large as possible
- rejection as large as possible
- detection efficiency + need relevant measurement ! (alpha, beta, gamma, fission, $t_{1/2}$, electromagnetic moments, …)

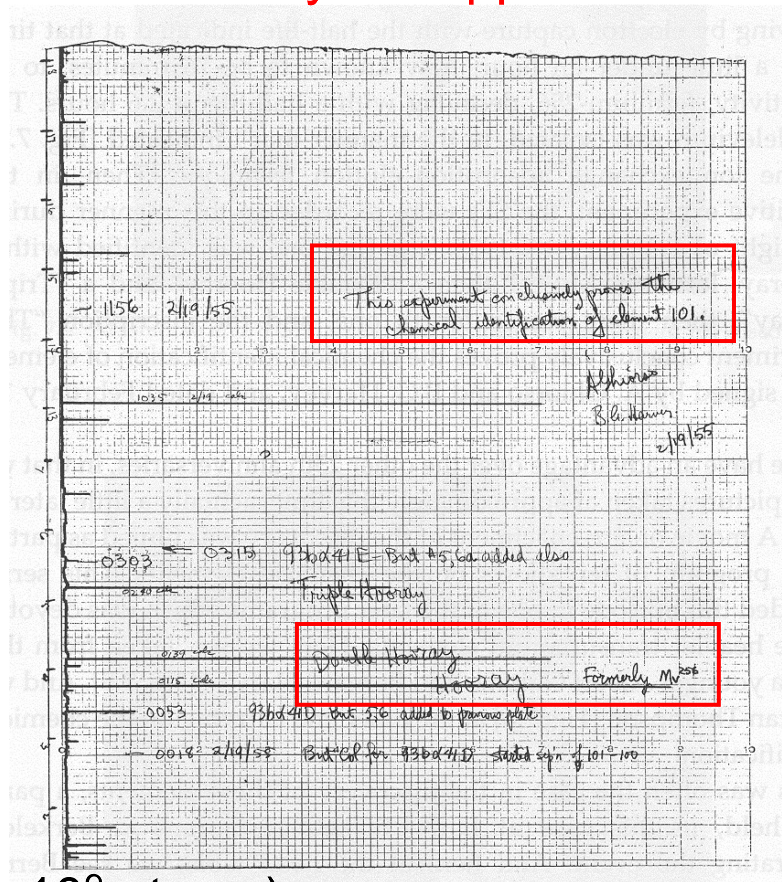
Transmission and detection can always be improved … but 100 % limit cannot be by passed

→ need the highest beam intensities

→ consequences on the spectrometer design ! (rejection, targets, …)

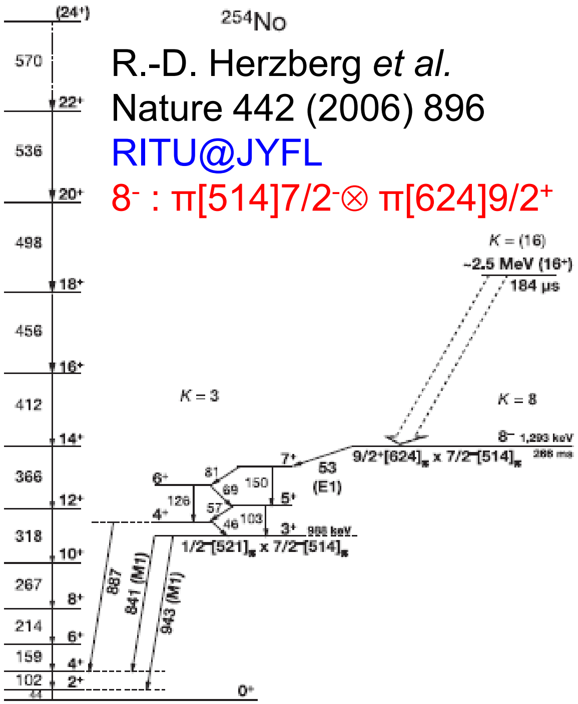
High beam intensities and SHE : an old story

- First identification of Md isotope by A. Ghiorso in 1955
- $^{253}Es(\alpha,n)^{256}Md$ Cyclotron beam intensity ~ 10 pμA
- Chemical identification



(Note also exotic ^{253}Es target ~ 10^9 atoms)

K isomerism in ^{254}No



R.-D. Herzberg *et al.*
Nature 442 (2006) 896
RITU@JYFL
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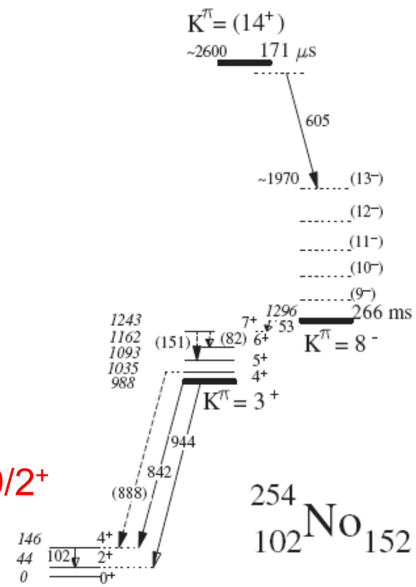

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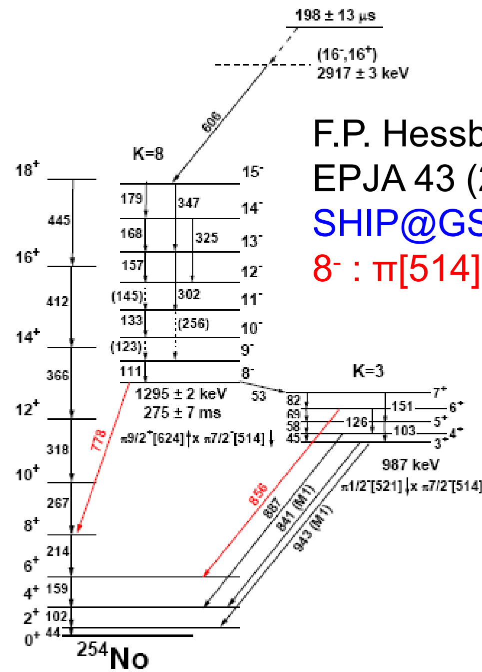

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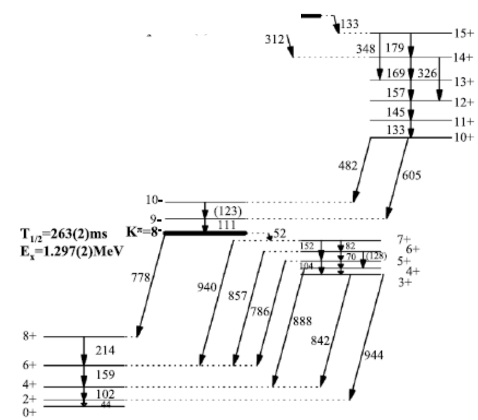

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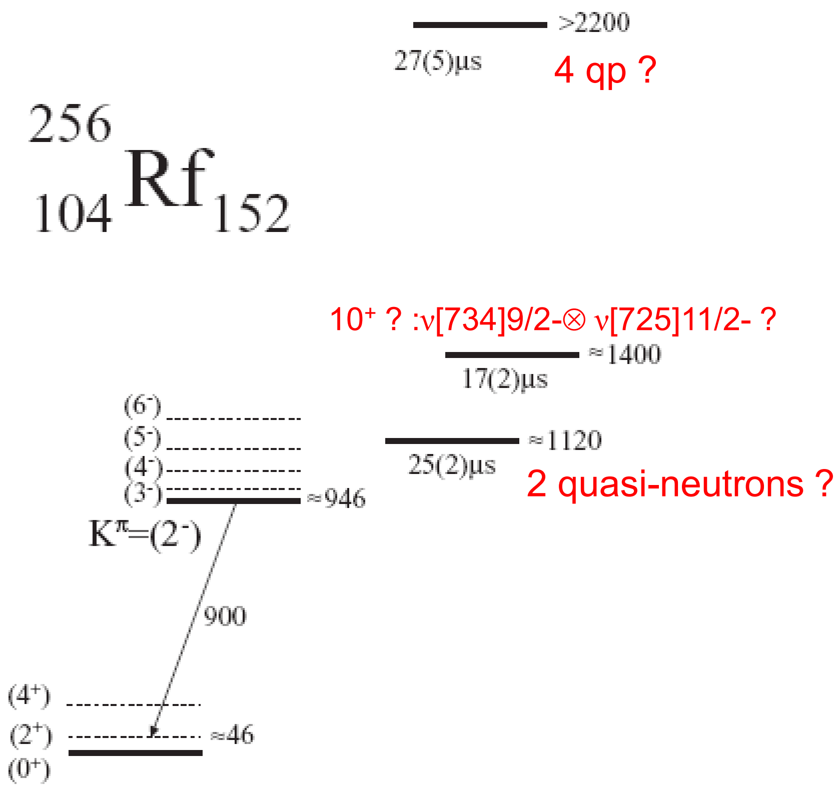
K isomerism in ^{256}Rf



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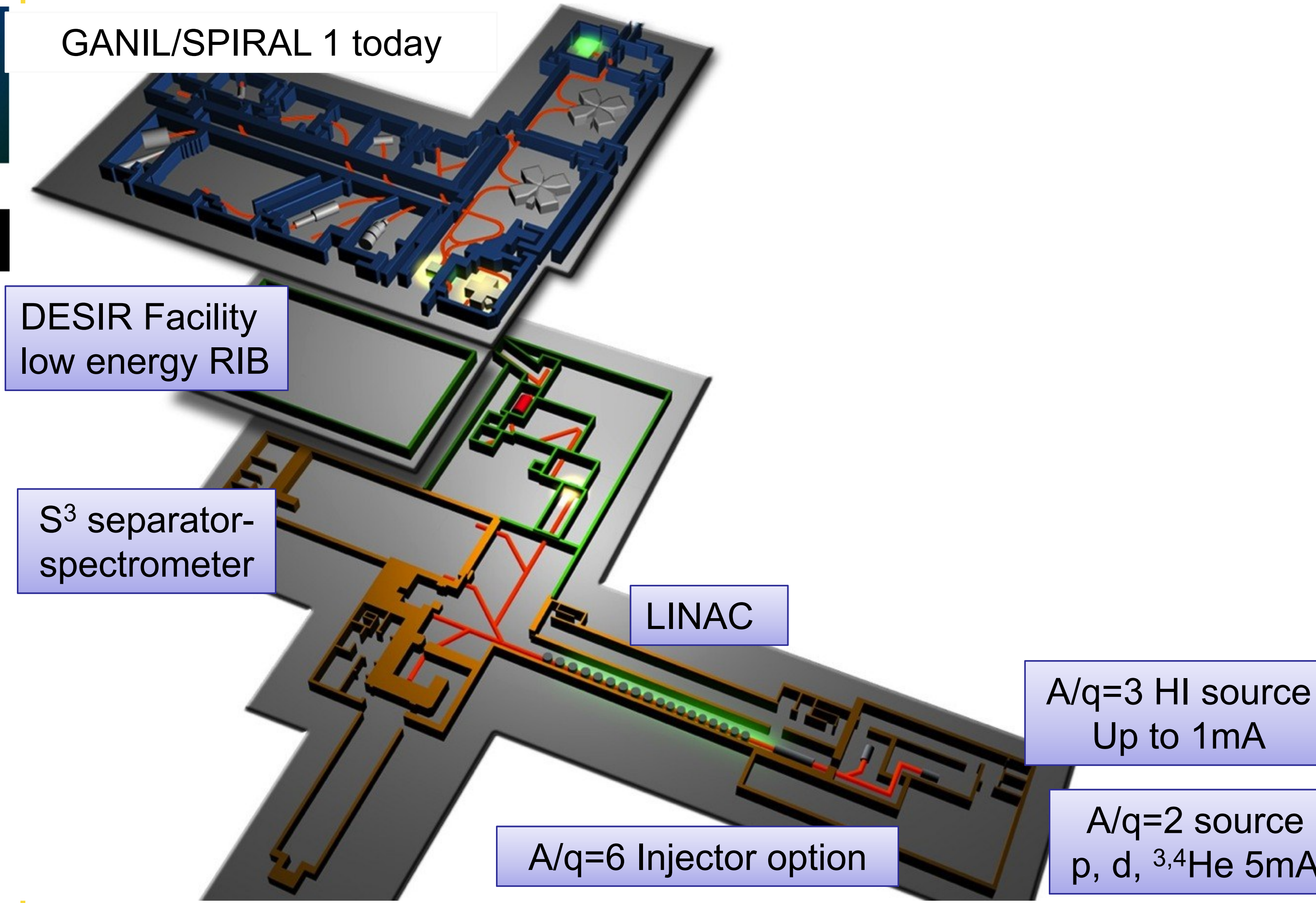
Only one isomer 17(5) µs 4qp ?

Level scheme and structure assignment tentative
Experimental differences difficult to reconcile

S3 and LINAG

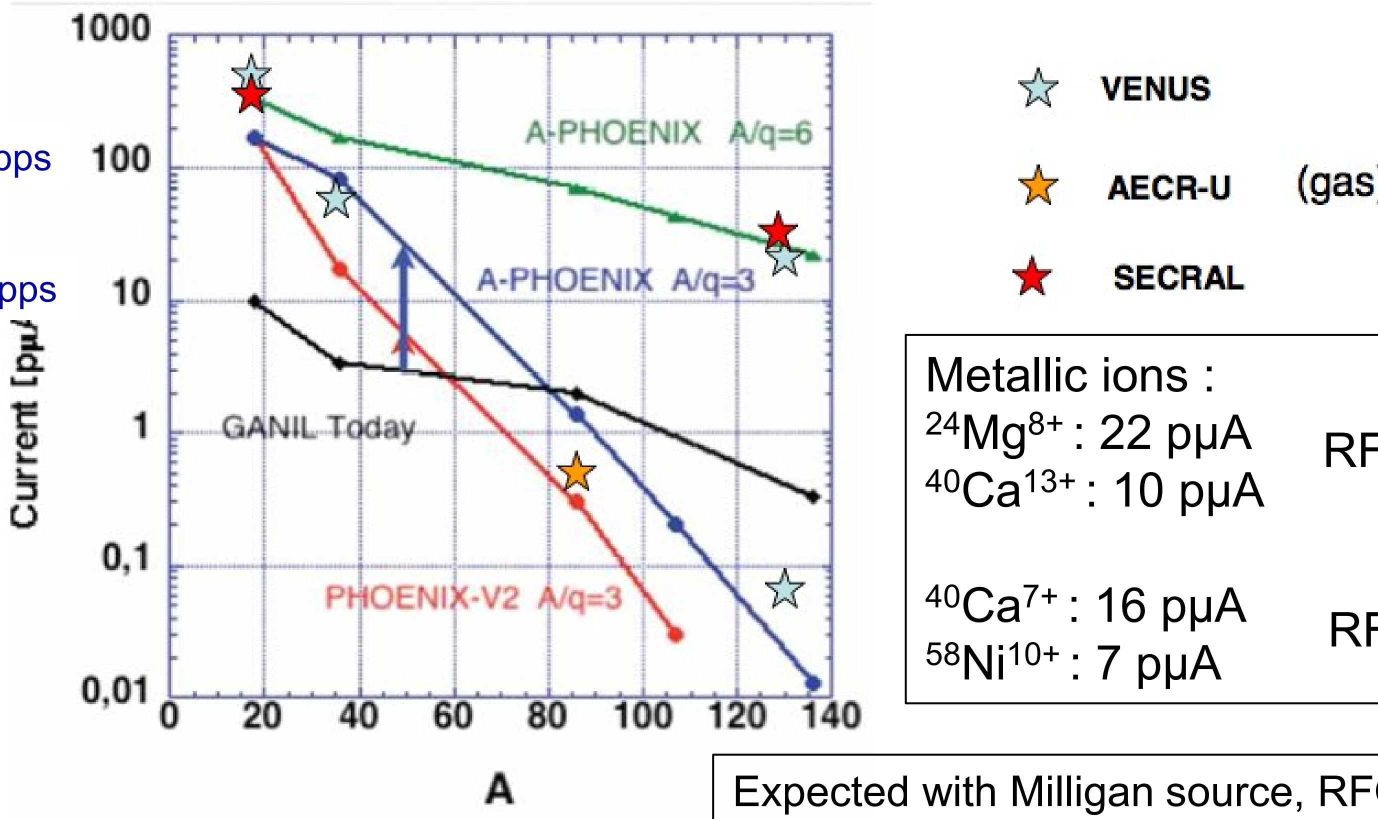


GANIL/SPIRAL 1 today
DESIR Facility
low energy RIB
S3 separator-
spectrometer
LINAC
A/q=3 HI source
Up to 1mA
A/q=2 source
p, d, 3,4He 5mA
A/q=6 Injector option

Linag beam intensities

6.10^{14}pps

6.10^{13}pps



Metallic ions :
$^{24}Mg^{8+}$: 22 pµA
$^{40}Ca^{13+}$: 10 pµA
RFQ 1/3

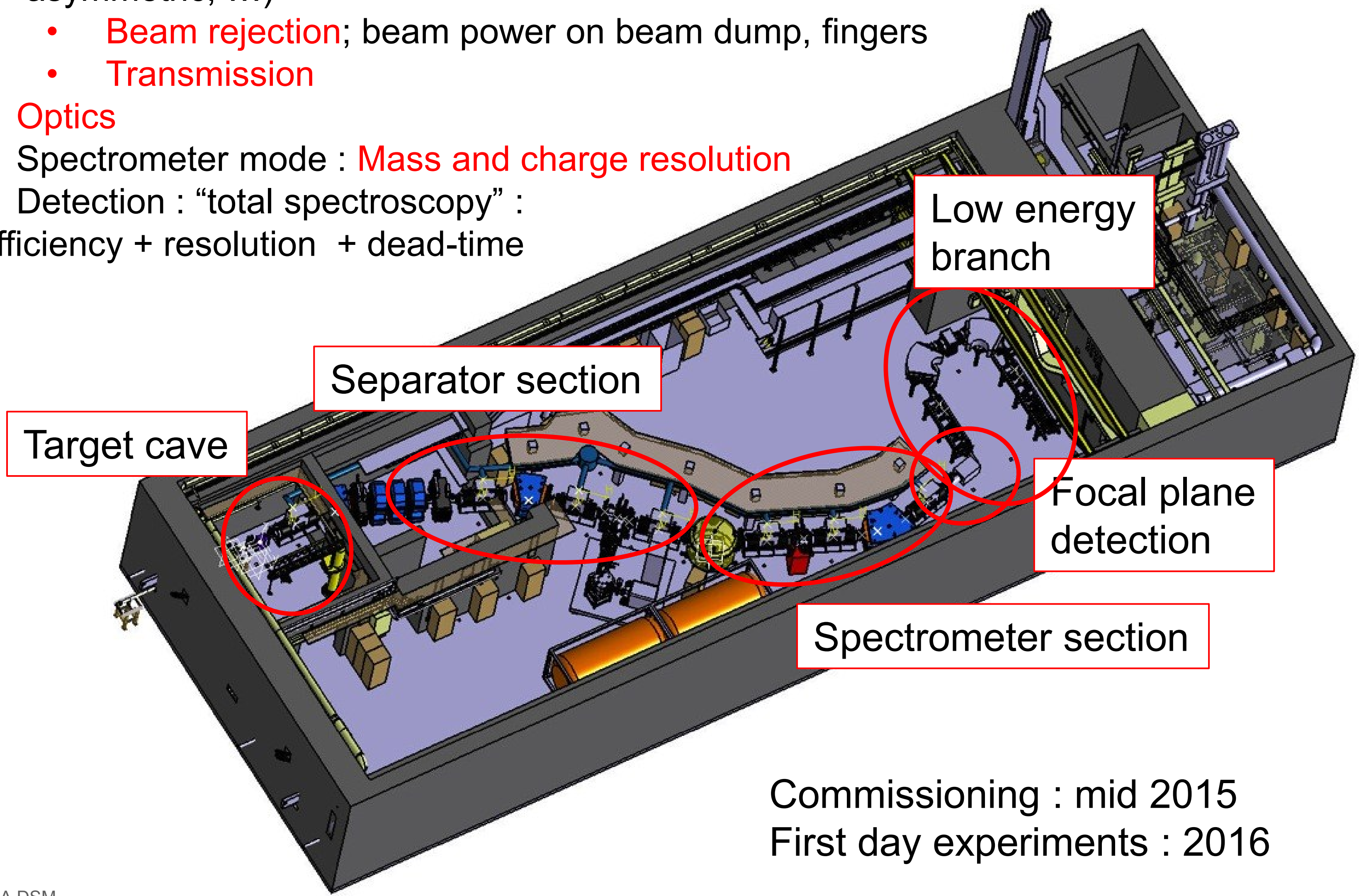
$^{40}Ca^{7+}$: 16 pµA
$^{58}Ni^{10+}$: 7 pµA
RFQ 1/6

Expected with Milligan source, RFQ 1/3
^{12}C : 257 pµA
^{20}Ne : 122 pµA; ^{22}Ne : 101 pµA
^{48}Ca : 9 pµA
^{58}Ni : 3,6 pµA
^{40}Ar : 19 pµA

S3

- Targets : up to highest beam intensities, actinide targets
- Best performances for wide reaction panel (symmetric, asymmetric, …)
  - Beam rejection; beam power on beam dump, fingers
  - Transmission
- Optics
- Spectrometer mode : Mass and charge resolution
- Detection : “total spectroscopy” :

efficiency + resolution + dead-time



Commissioning : mid 2015
First day experiments : 2016

Example : Lv Z=116

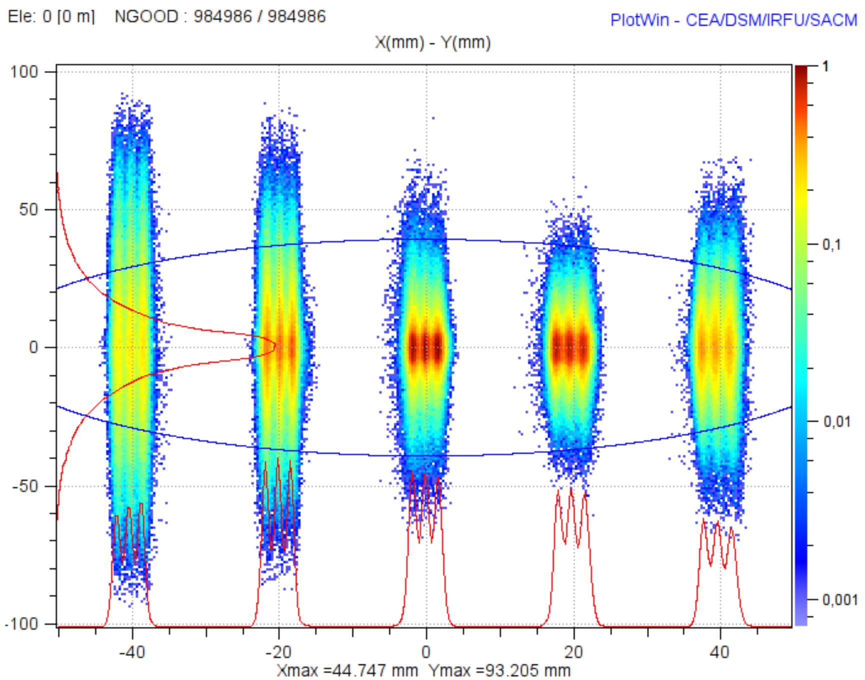
$^{48}Ca+^{248}Cm \rightarrow ^{292}Lv+4n$

$I=10p\mu A$ – $300\mu g/cm^2$ – $\sigma=3pb$

Transmission

+Q	*Population %*	*Transmission %*
18	15.3	39
19	17.3	85
20	16.2	87
21	12.6	75
22	8.4	29
Folded transmission :		**47%**

Image at focal plane

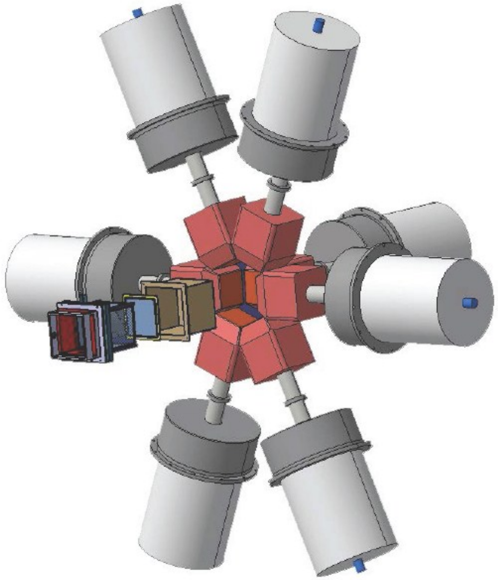


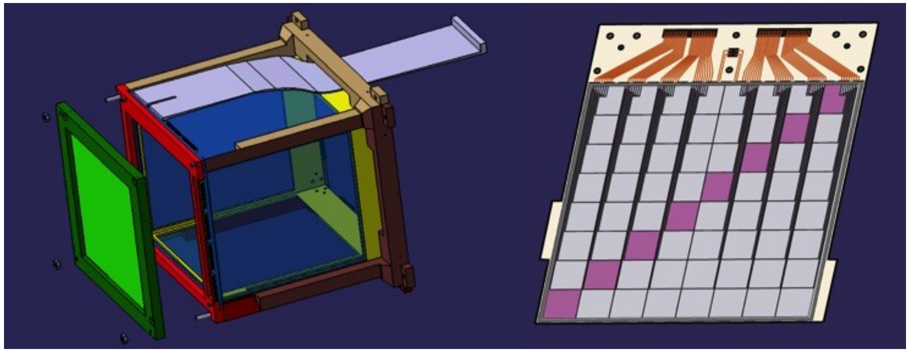
→ 40 implantations/week

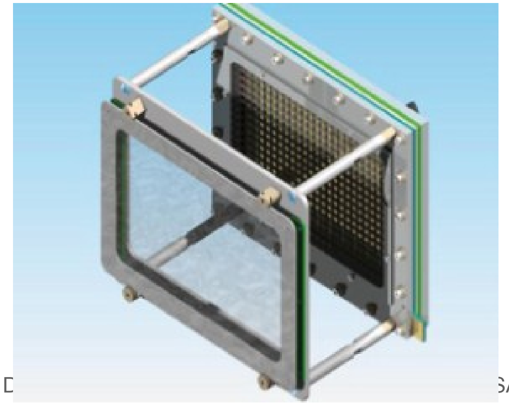
→ M/ΔM= 374 FWHM

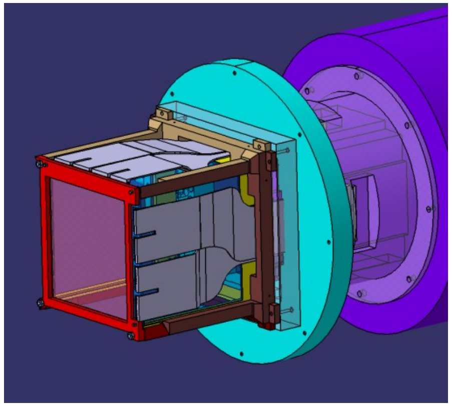
Focal plane detection

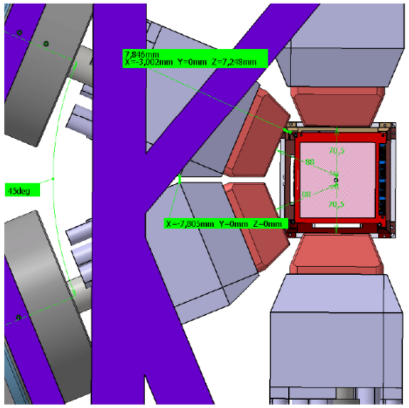
- ToF upstream detectors
- DSSSD Implantation
  - Threshold 100 keV or below
  - Resolution 20 keV for alphas
- Si Box for conversion electrons and escaping
  - 0<E<10 MeV range
- Ge detectors
  - 0<E<1.5 MeV range
  - Threshold 15 keV.
  - Efficiency as large as possible
- Electronics : small Si dead-time needed











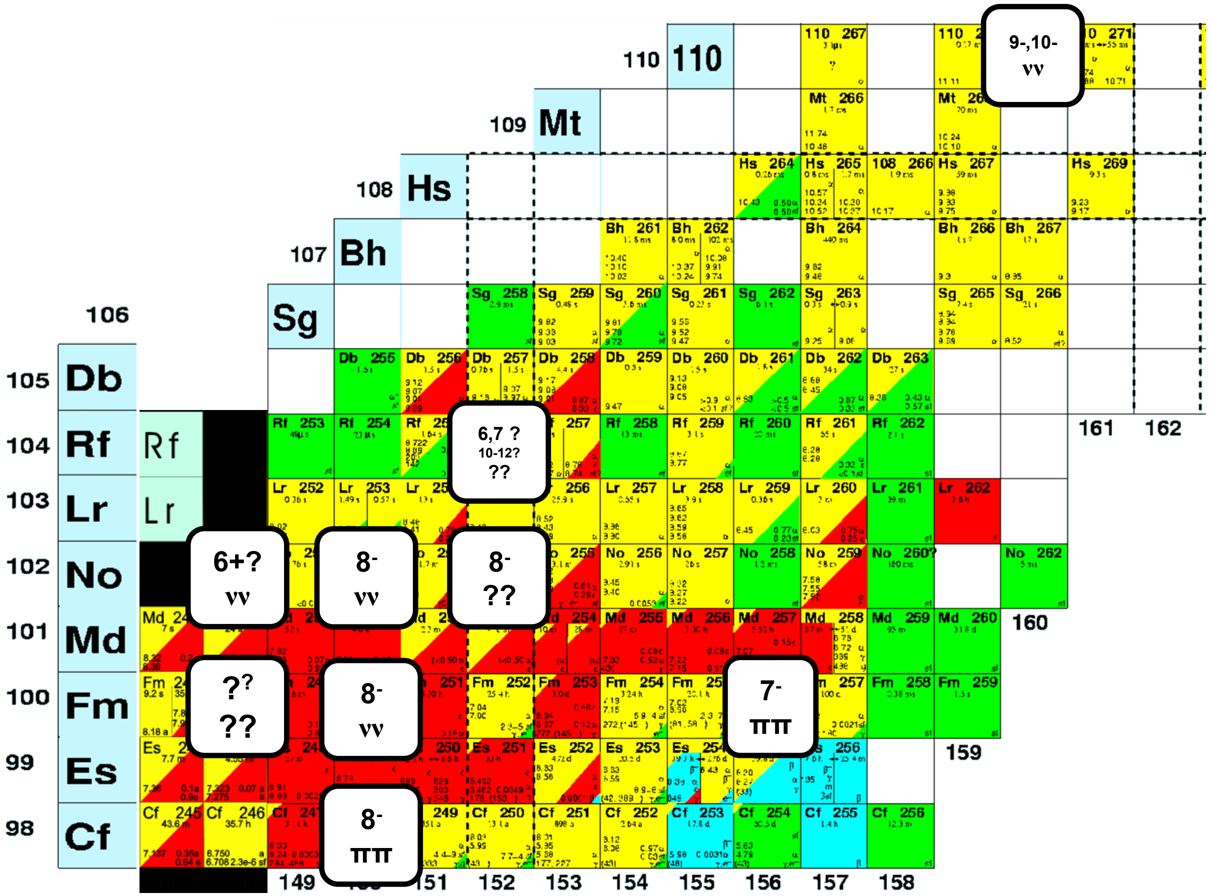
S3 in real

Oct. 2011

Dec. 2011

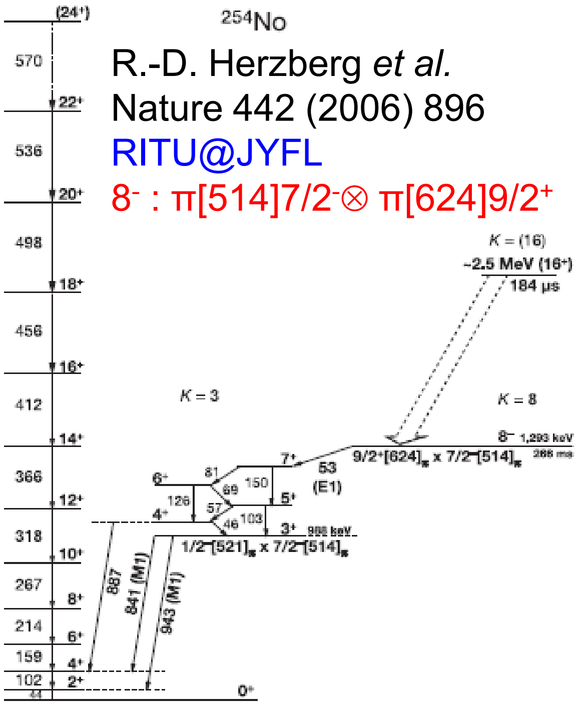
Mai. 2012

S3 first day experiments : K isomers in ^{254}No, ^{256}Rf



- No isomers known in Sg, Hs isotopes
- Experiments place stringent demands on focal plane set-up
- High-statistics allows better assignments of multipolarities, etc
- High discrepancies with theory (e.g. location of high-*l* states)

K isomerism in ^{254}No



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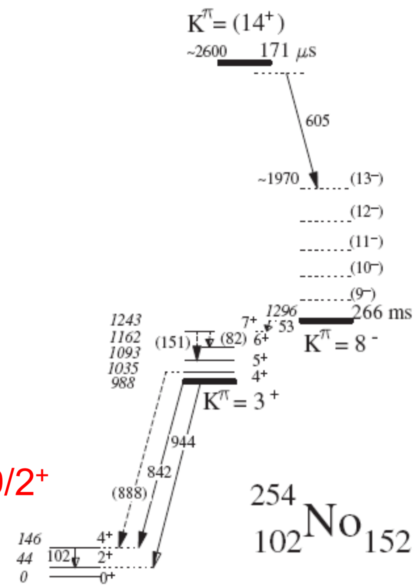

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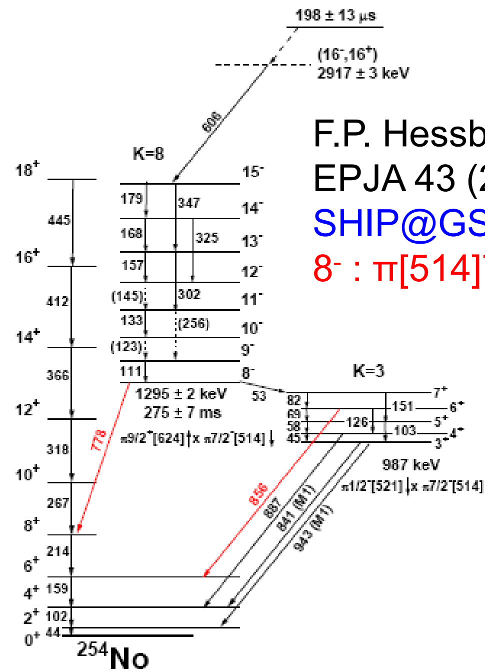

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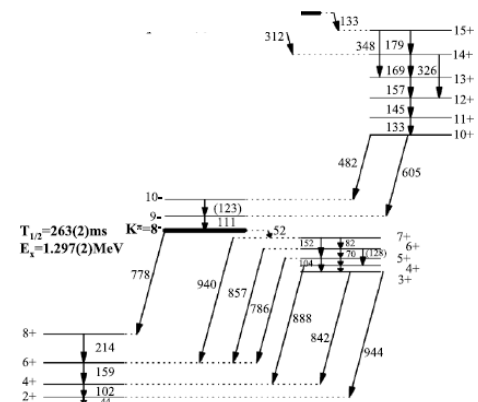

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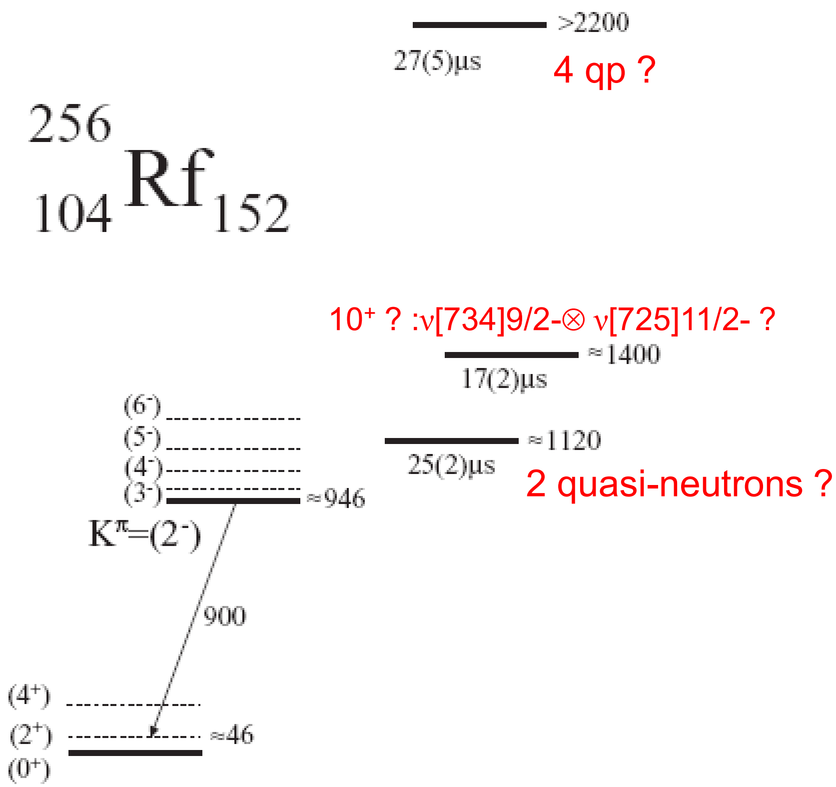

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Level scheme and structure assignment tentative
Experimental differences difficult to reconcile

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

Target thickness 500 μg/cm²
S3 transmission 50%

Beam ^{48}Ca 2 pμA (conservative)

→ 1000 residues / minutes
→ 1.0 10^7 residues in 21 UTs
(9.0 10^5 at LBNL)

$^{208}Pb(^{50}Ti,2n)^{256}Rf$
σ = 17 nb

Target thickness 500 μg/cm²
S3 transmission 50%

Beam ^{50}Ti 2 pμA

→ 9.2 residues / minutes
→ 90000 residues in 21 UTs
(5400 at LBNL)

After Day 1 : reactions with U targets

$^{32-36}S + ^{238}U \rightarrow ^{270-274}Hs^*$

$^{28-30}Si + ^{238}U \rightarrow ^{266-268}Sg^*$

^{262}Sg ~600 / week

^{263}Sg ~1500 / week

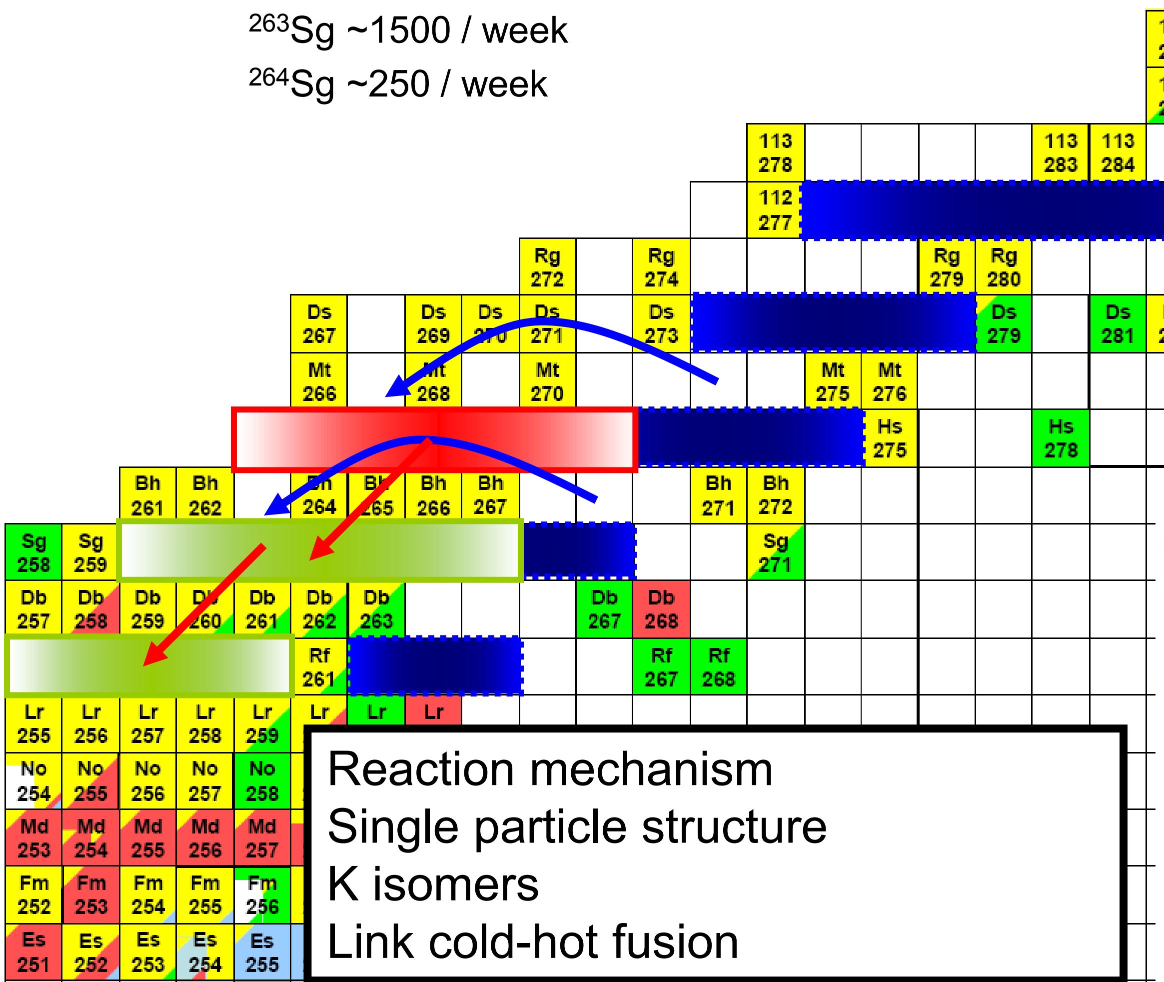
^{264}Sg ~250 / week

Also :

$^{40-48}Ca + ^{238}U \rightarrow ^{278-286}Cn^*$

$^{36-40}Ar + ^{238}U \rightarrow ^{274-278}Ds^*$

$^{24-26}Mg + ^{238}U \rightarrow ^{262-264}Rf^*$

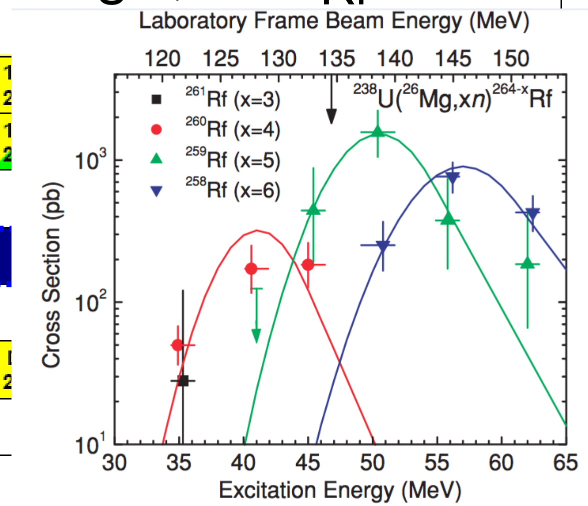


Reaction mechanism

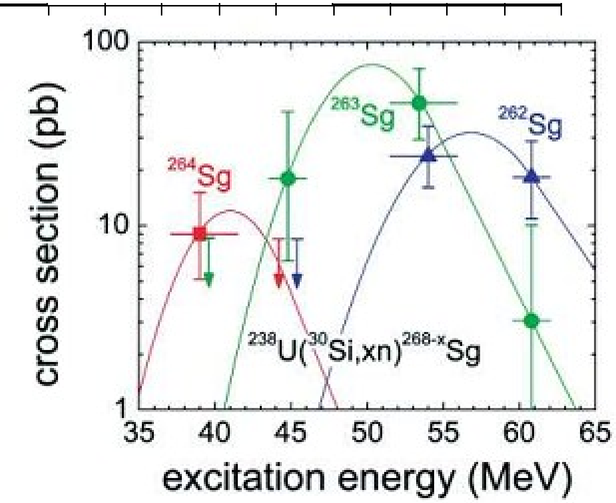
Single particle structure

K isomers

Link cold-hot fusion



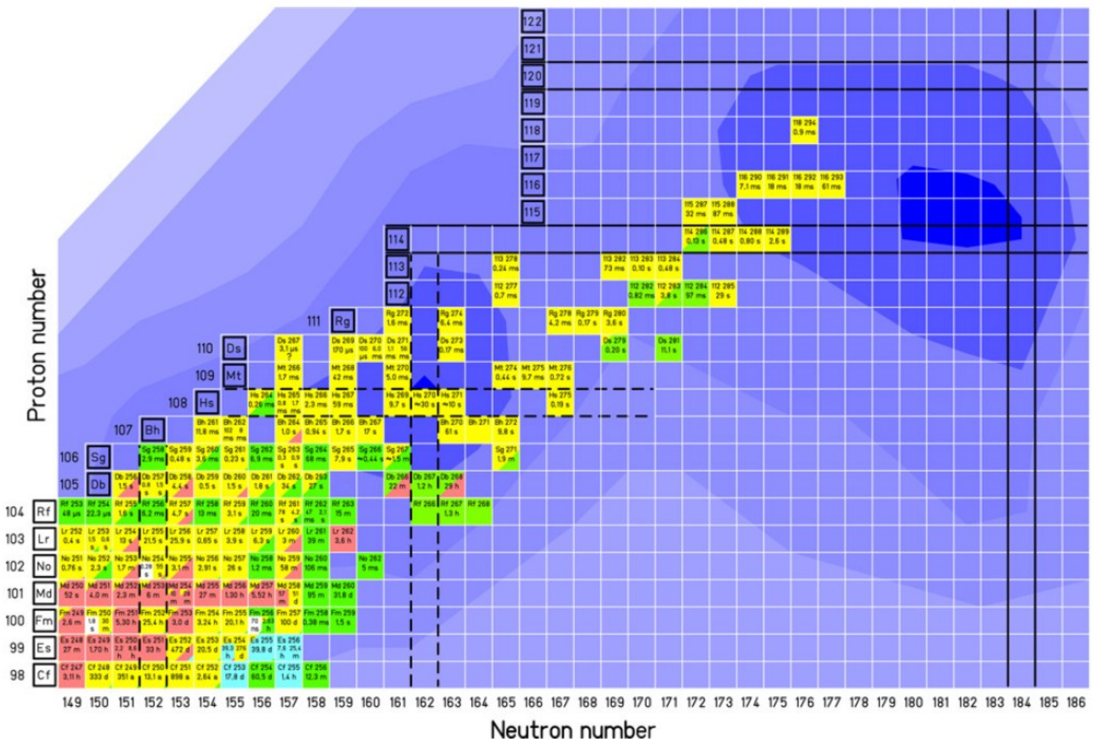
J.M.Gates et al., PRC 77, 034603 (2008)



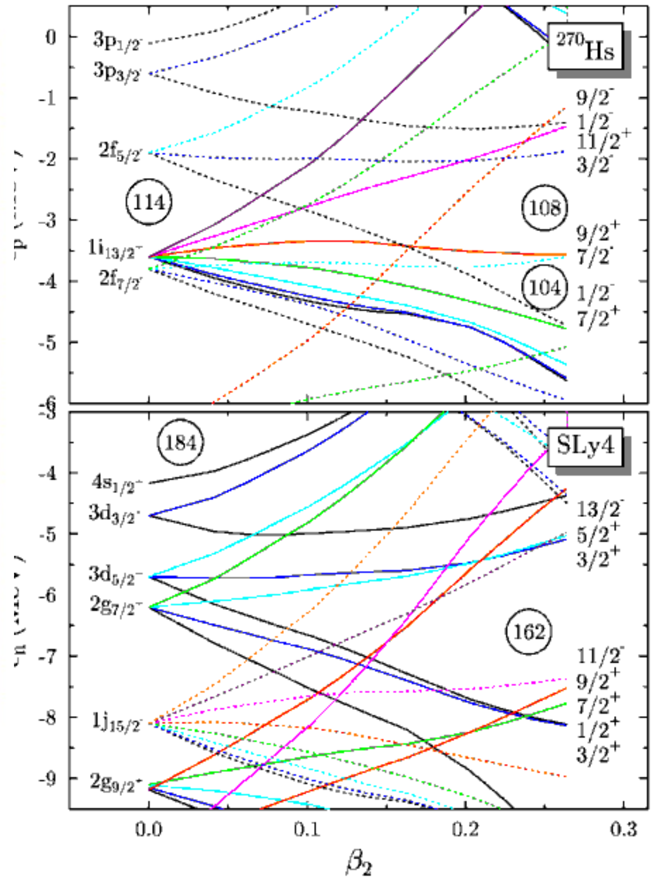
K.E.Gregorich et al., PRC 74, 044611 (2006)

Toward ^{270}Hs doubly magic deformed

- K-isomers; single particles from spectroscopy of odd nuclei
- Need highest production; need RFQ 1/6



S. Hofmann, Prog. Part. Nucl. Phys. 62 (2009) 337343

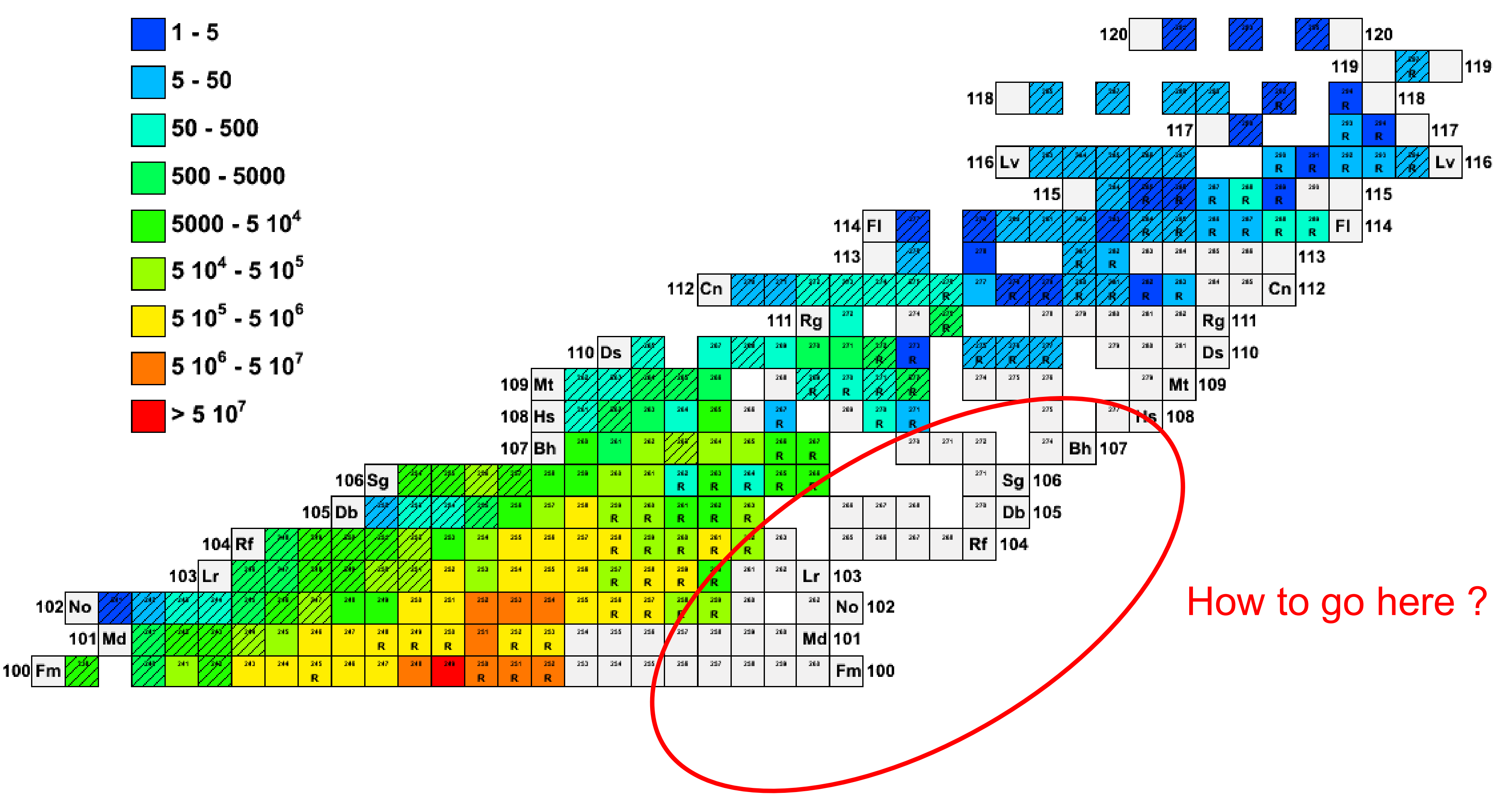


M. Bender, Priv. Com.

LINAG et S3

Two weeks experiment; RFQ 1/6

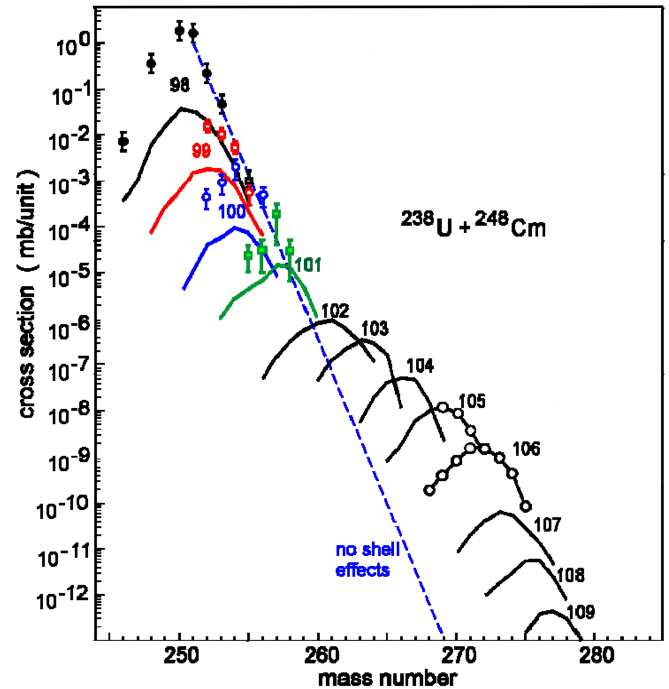
Spectroscopy up to Z=114 ?



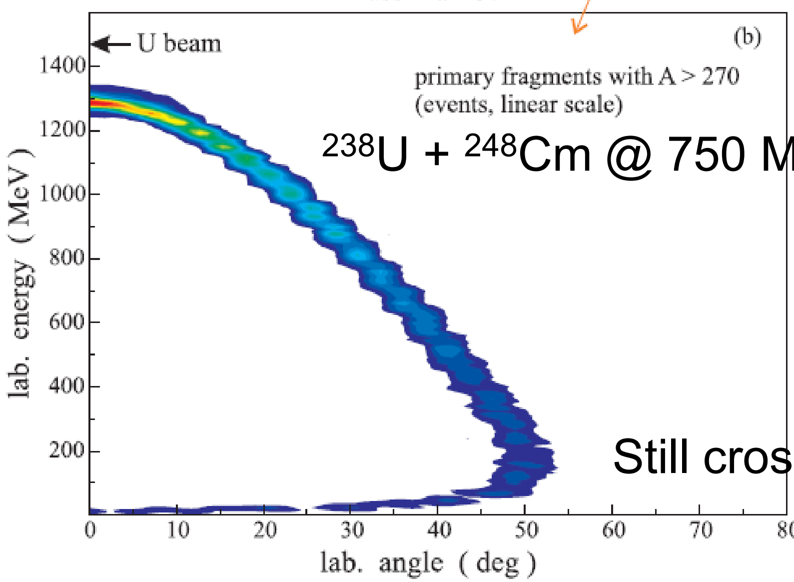
The limits of fusion-evaporation reactions

- Using multinucleon transfer reactions ?

$^{238}U + ^{248}Cm$ @ 800 MeV
Zagrebaiev, Greiner, PRC 78 (2008) 034610



mass number



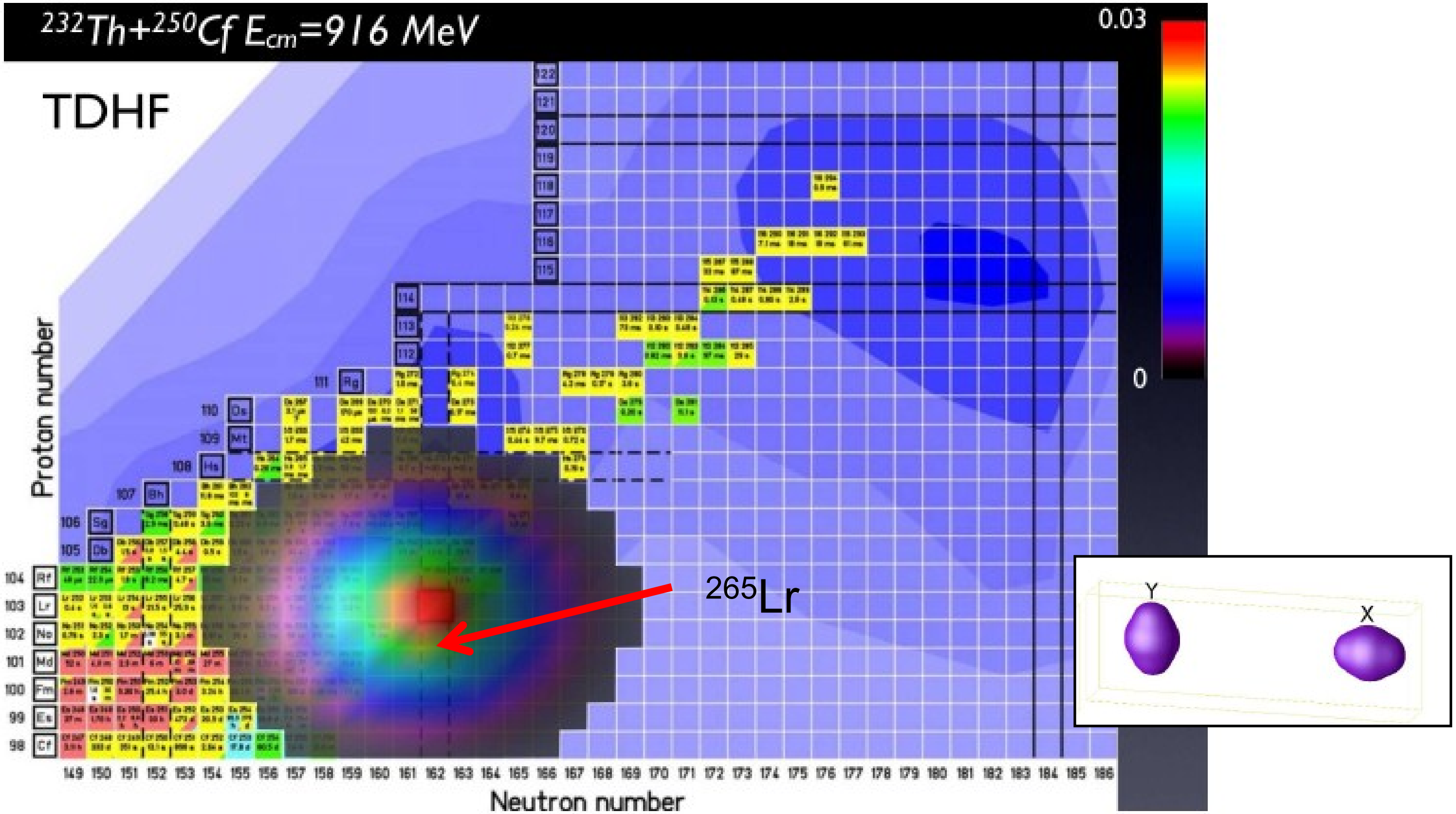
$^{238}U + ^{248}Cm$ @ 750 MeV

Still cross section near zero degree !!!

Zagrebaev, Greiner, PRC 83 (2011) 044618

Actinide collisions & TDHF

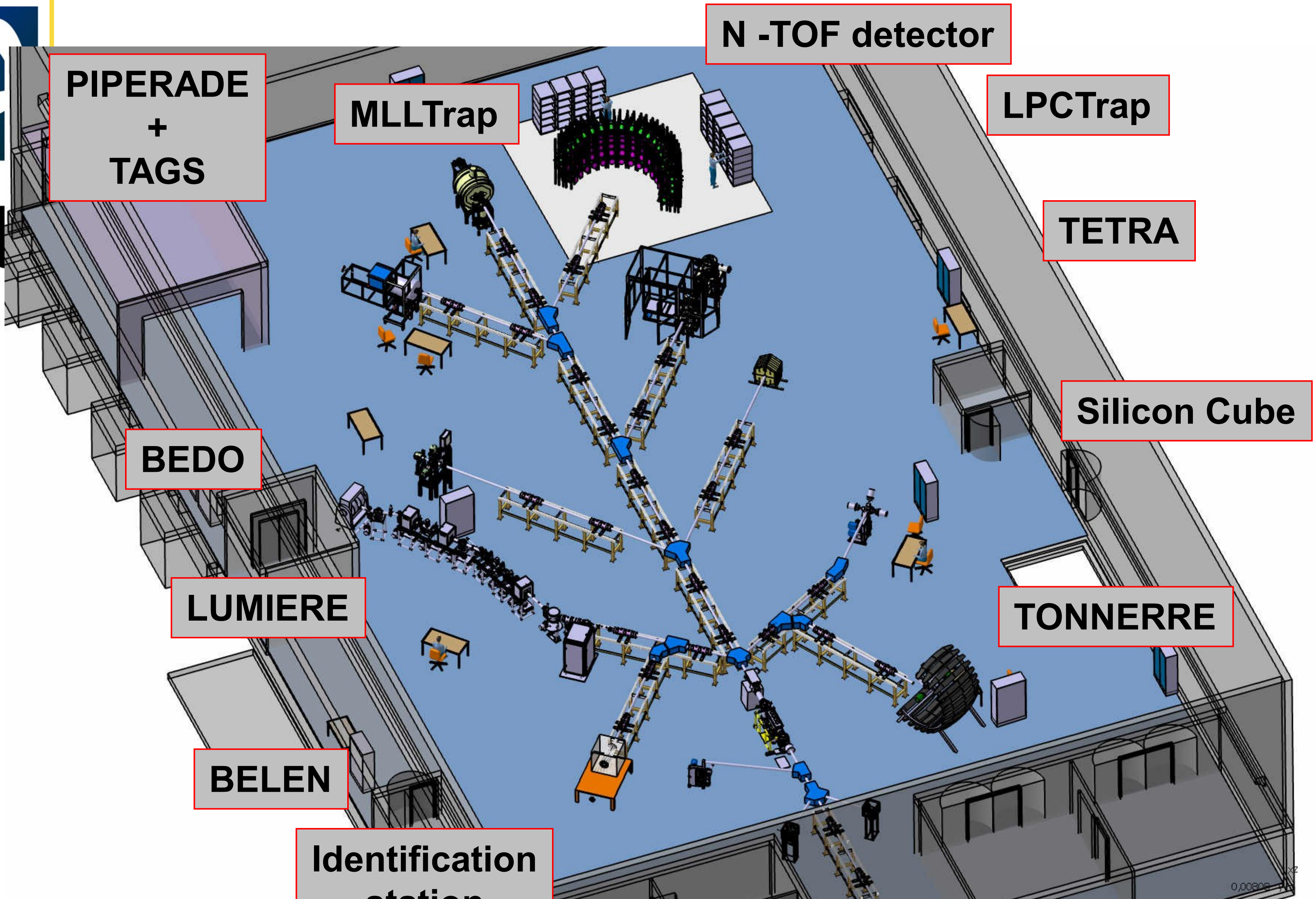
C. Simenel, C. Golabek and D.J. Kedziora
Eur. Phys. J. web of conference 17, 09002 (2011).



TDHF probability distribution for the heavy fragment produced in ^{232}Th+^{250}Cf central collision in the *xy* configuration.

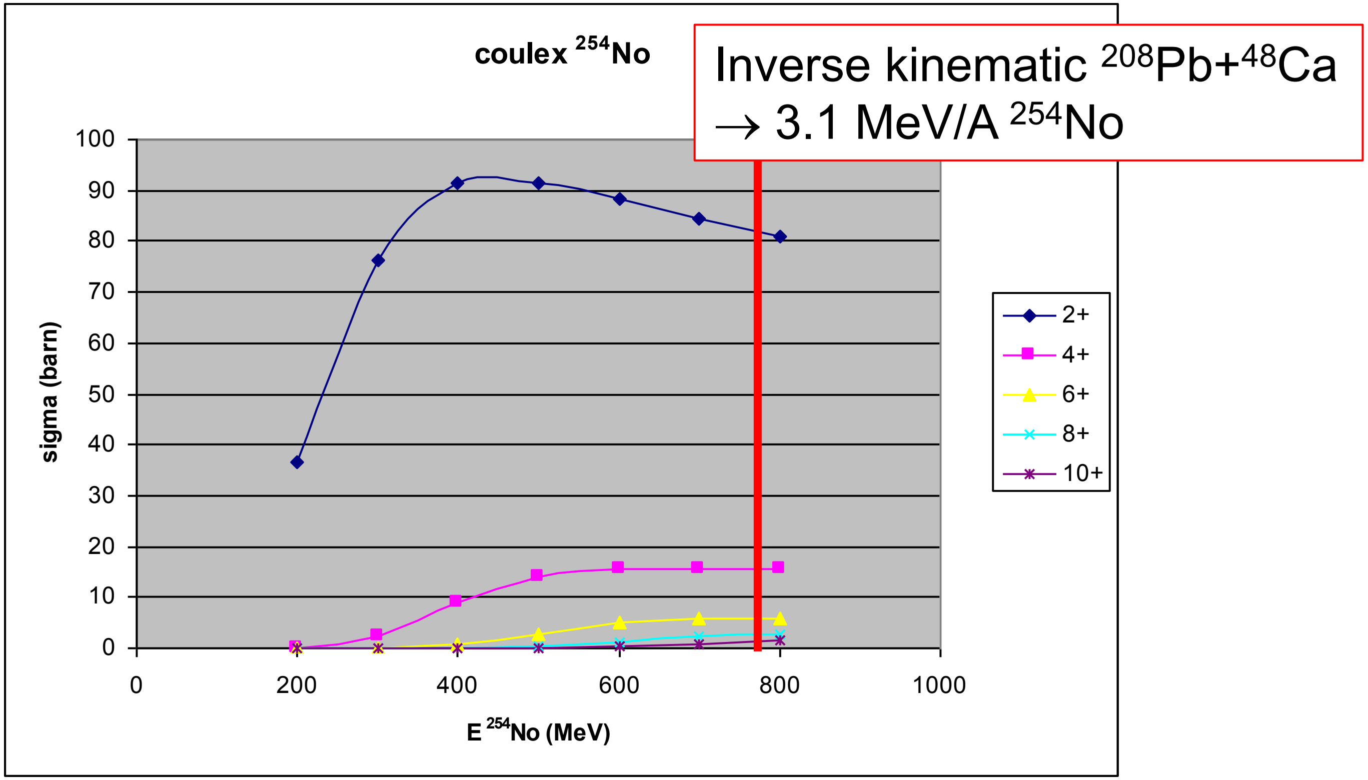
Cross-sections needed !!!

Other techniques with S3



Other techniques with S3

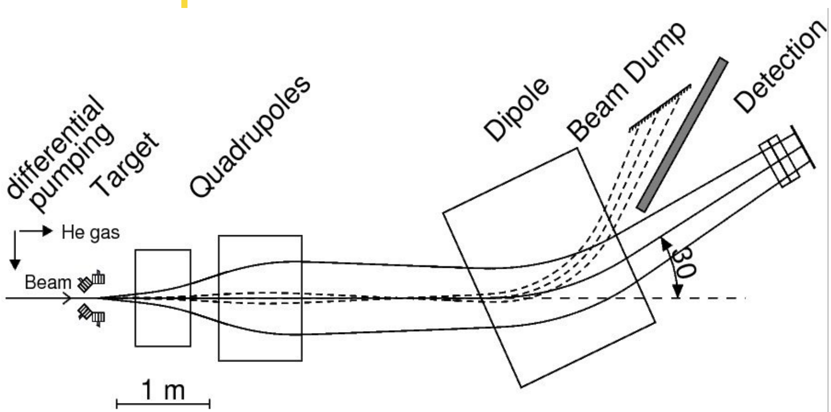
- Coulex ?



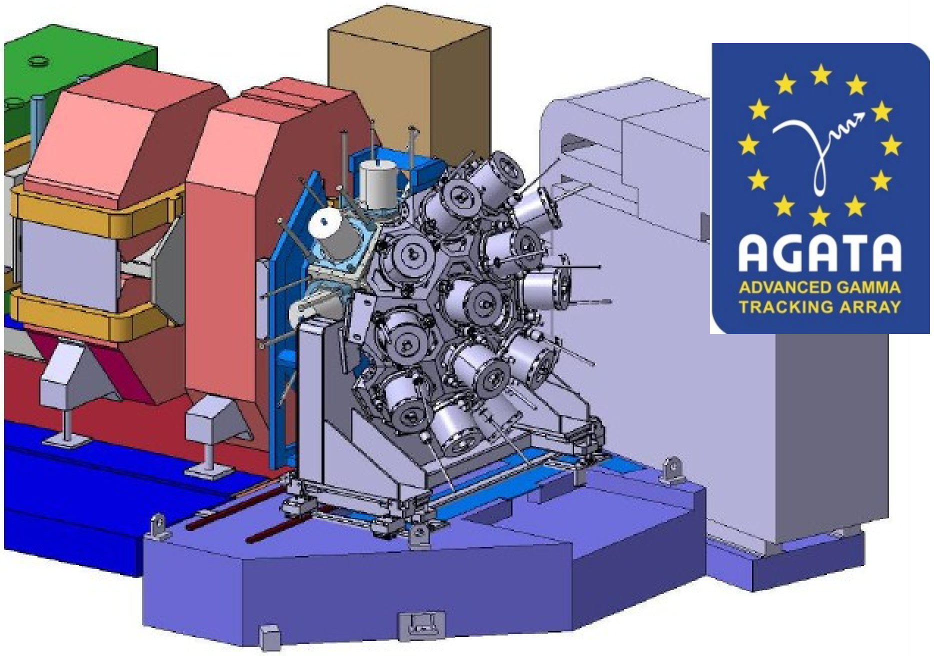
- transfer reaction ?

Less highest intensity : prompt γ-ray spectroscopy

- Prompt gamma-ray spectroscopy
- Max ~ few 10 pnA already achievable
- Need digital electronics
- Need for a zero degree separator with room around target
  - RITU + SAGE
  - VAMOS Gas-Filled, Agata +/- Exogam 2



C. Schmitt *et al.*, NIMA 621 (2010) 558
95% transmission for $^{40}Ca+^{150}Sm$



40 Agata crystals+ 8 Exo Clover ϵ > 20 %

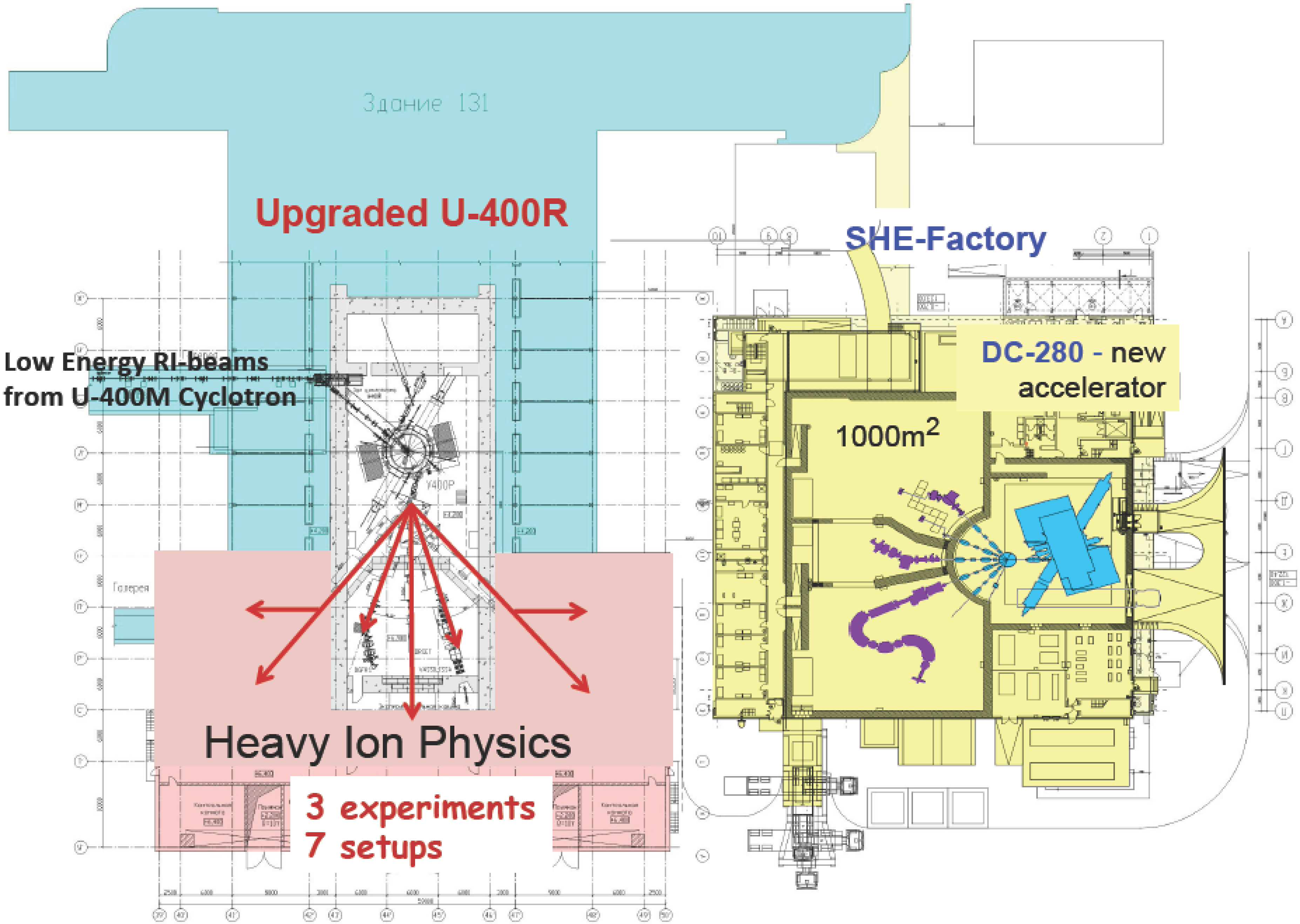
Other projects in Europe : Dubna SHE

Irfu

ACCELERATORS

Beam parameters	HI-Physics U-400R	SHE-Factory DC-280
Projectiles	Stable and RIB ($T_{1/2}$ > 0.1s)	Stable only
Projectile masses	4He – 238U	40Ar – 86Kr
Energy range	0.5 – 27.0 MeV/n	5 – 8 MeV/n
Energy resolution	0.5%	1.5%
Beam intensity (for 48Ca)	2.5 pμA	10-20 pμA
SHE-research program	≤30%	~100%
Registered decay chains of SHN (per year)	120 (now **30**)	**3000 - 5000**
State of readiness	75%	In course of design

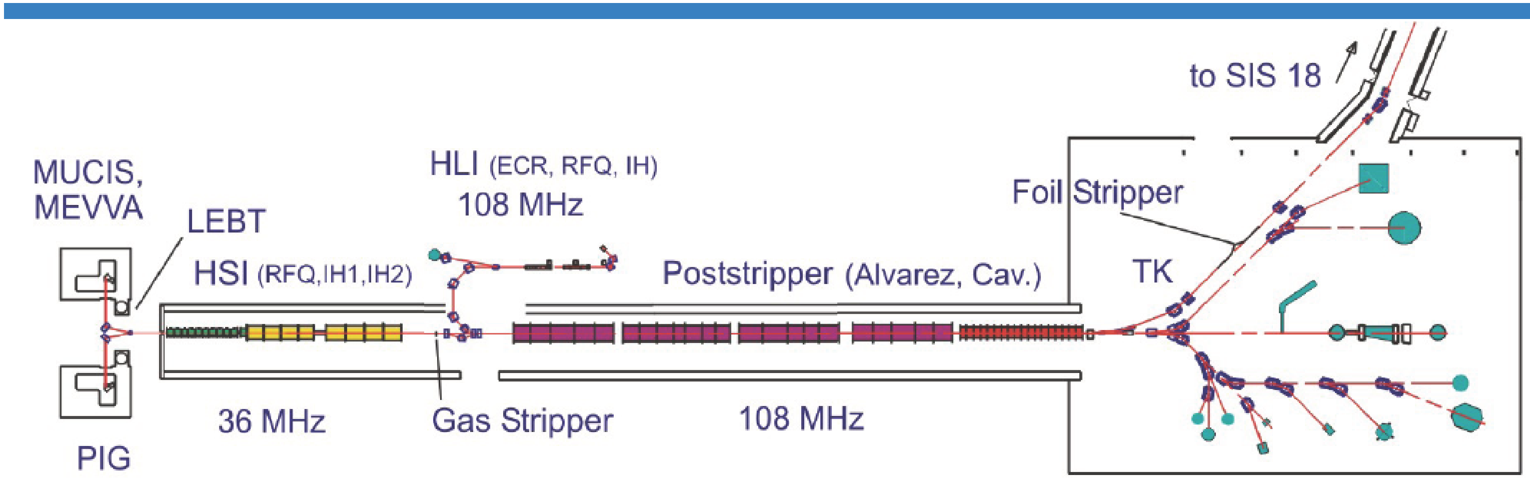
From Yuri Oganessian, FUSHE 2012



Yuri Oganessian. "Synthesis of SH-nuclei" FUSHE 2012, May14, 2012, Weilrod, Germany

Other projects in Europe : GSI

Overview/High duty factor upgrade



	Luminosity gain
• New RFQ: Duty cycle 25 -> 40%	x 1.6
• New MS-ECRIS: higher beam currents and	
• LEBT for new MS-ECRIS at HLI	x 5.0
• cw-linac	
– 100% duty cycle	x 2.5
– independent operation	x 2.0
	x 40

Conclusions

- Very active topics
- New accelerators / spectrometers : great opportunities for the field
- Perspectives with Linag + S3 and around

- High beam intensities : great results expected in a near future but
  - Still need to produce differently and better : reaction mechanisms, multinucleon transfer
  - Need LINAG with RFQ 1/6 to be competitive

- Challenges
  - Highest beam intensities : targets (actinides), rejection, power dissipation
  - “Total” spectroscopy : efficiency, resolution, dead time
  - Reliability
  - Prompt spectroscopy with highest beam intensity (Agata, Exogam2, SAGE, …)
  - Production techniques : multinucleon transfer around zero degree ?
  - Radioactive beams (chances in a decent future ?)
  - Theory