Spectroscopy of SHE

Voyage to superheavy elements

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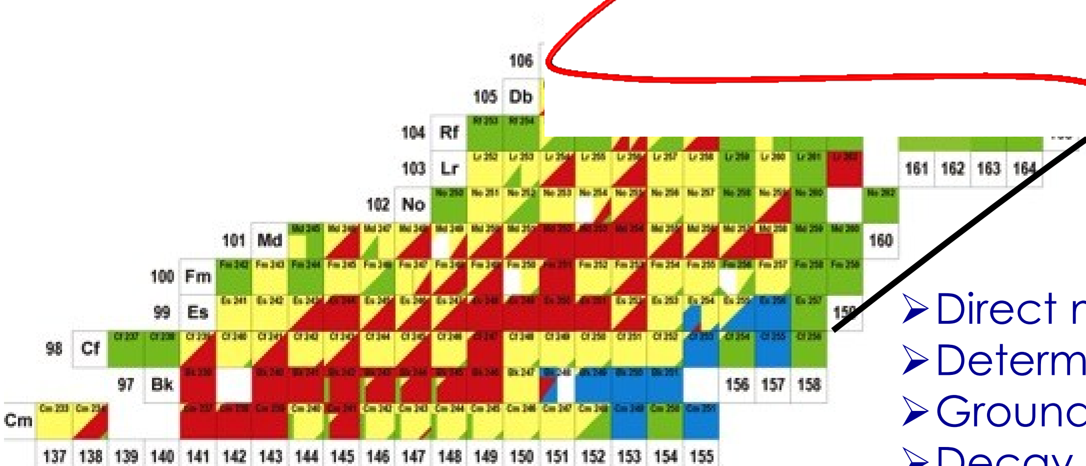
CEA Sacly

ECOS 2014

DUSAN PETRICIC

What we can learn from spectroscopy of SHE

- Learn about underlyi
- Lear about nuclear f
- Self consistent calcul prediction of propertie

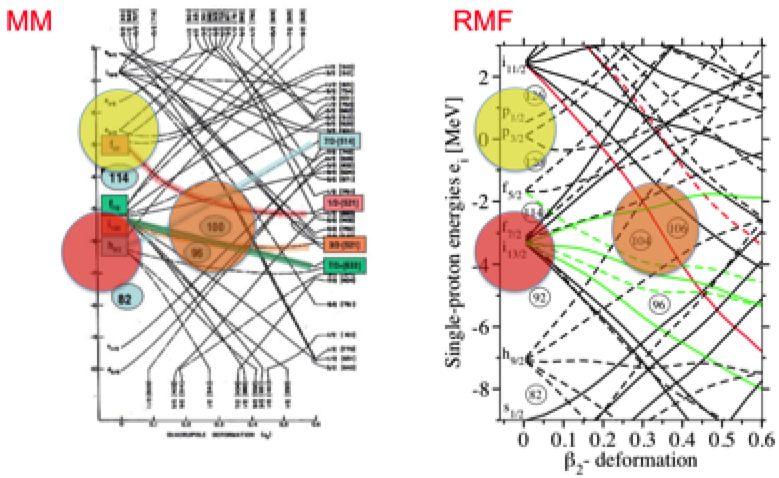


Observables

- Direct mass measurements
- Determination of rotational properties
- Ground state properties
- Decay properties nuclear structure
- Reaction mechanism

Motivation: Constraining theory

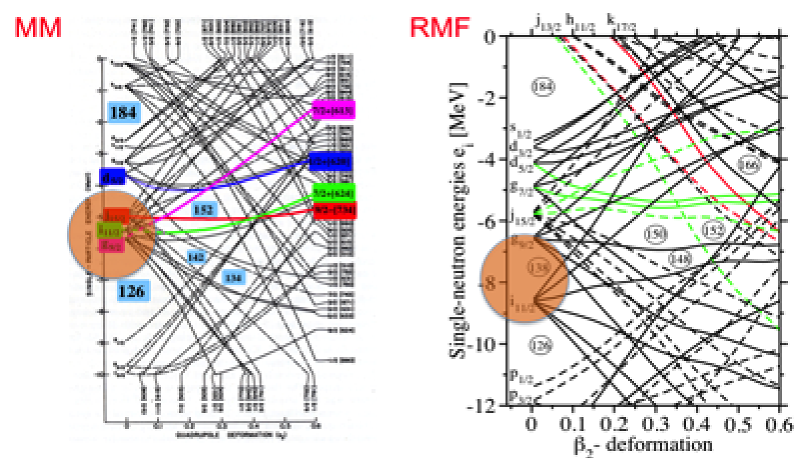
Nilsson Diagram: Protons



- Microscopic-Macroscopic models based on a liquid drop model (Z=114)
- Relativistic mean field models (Z=120,126)
- Hartree-Fock-Bogoliubov –Skyrme or Gogny Interaction (z=120,126)

- Differences in single-particle structure reflected in the shell gaps for both spherical and deformed systems

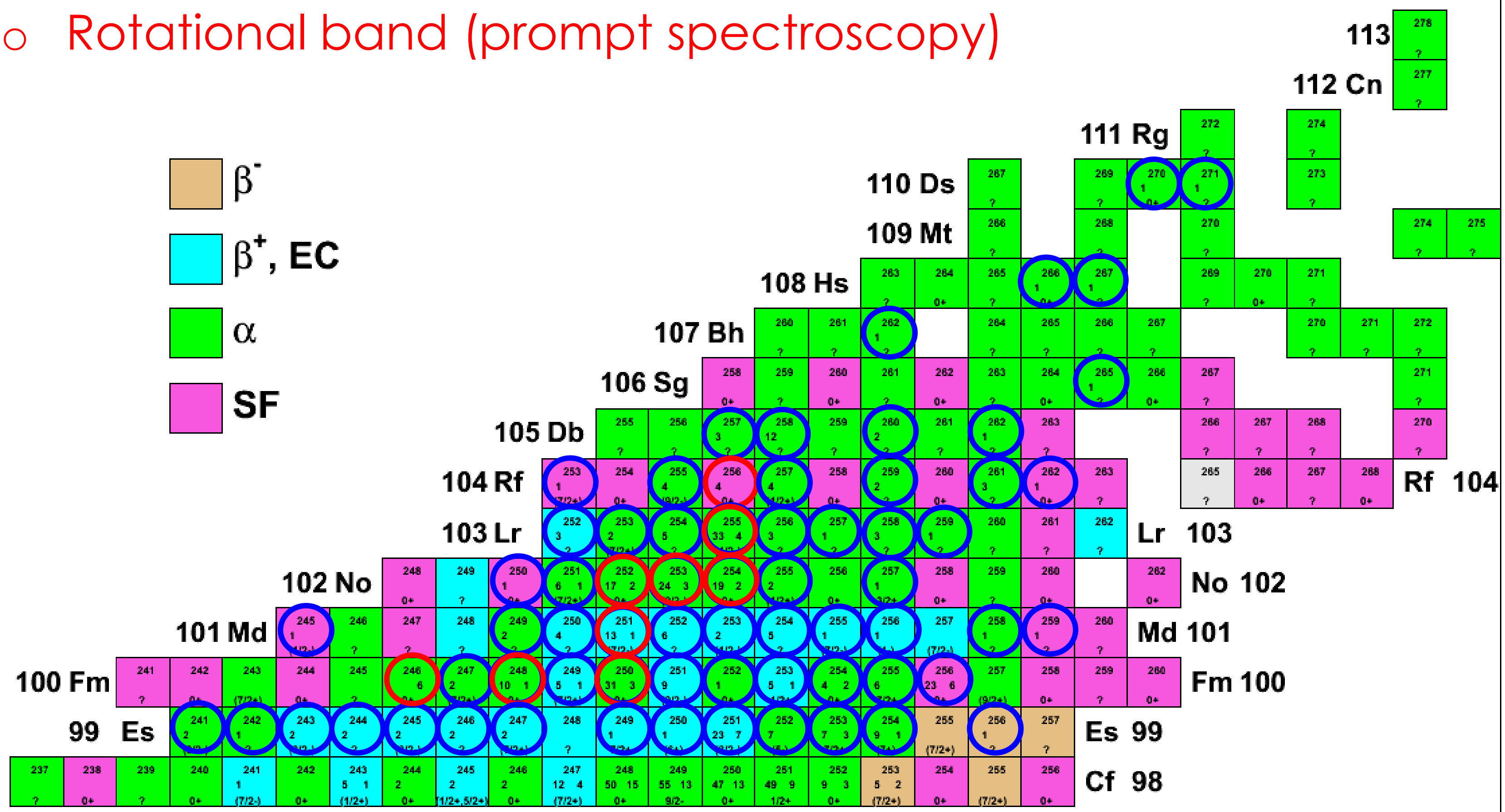
Nilsson Diagram: Neutrons



Similar differences seen for neutron level structure

VHE Status

- At least an excited states known
- Rotational band (prompt spectroscopy)



Courtesy of Ch.Theisen

Methods and limits

- In–beam spectroscopy using RDT & RT technique

  →recent achievements 10 nb @ z=104 (^{256}Rf) @JYFL

  →SAGE spectrometer allowing γ/e^- spectroscopy

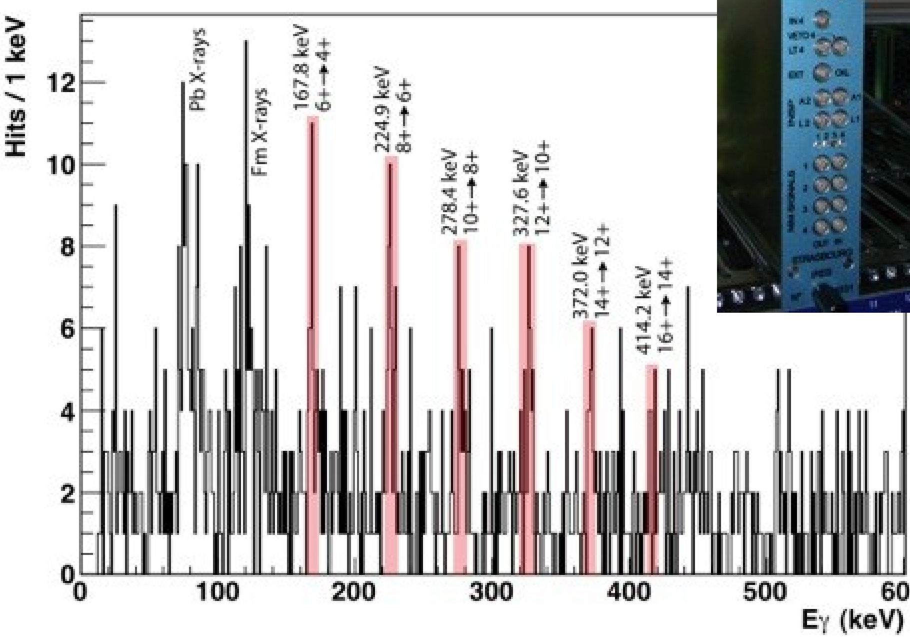
Bottleneck: Target position arrays limiting beam intensities environ 10 pnA

→ a factor 100 below the intensities for synthesis

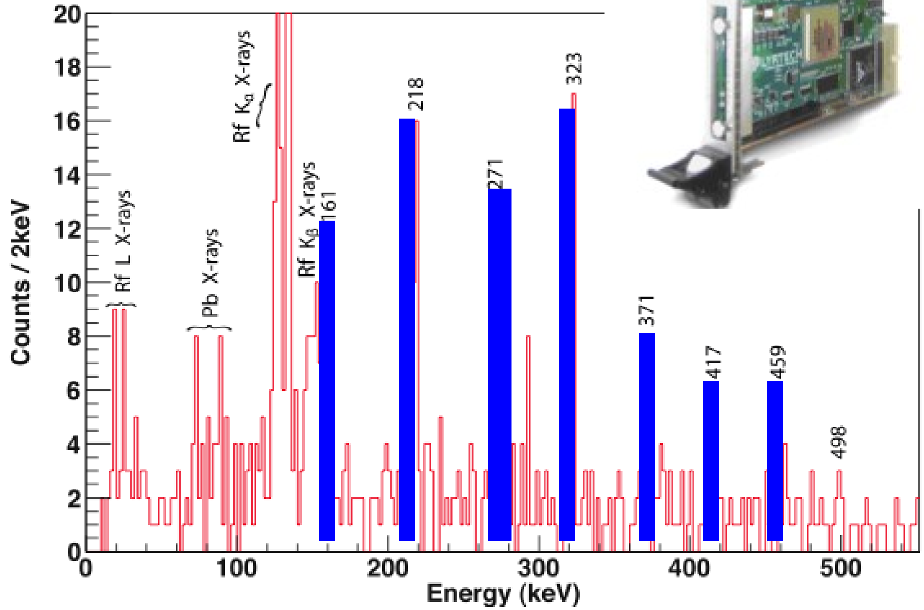
Current limit for in-beam spectroscopy

$^{208}Pb(^{40}Ar,2n)^{246}Fm$
up to 71 pnA, 40 kHz
σ=11 nb

J. Piot et al., Phys. Rev. C 85, 041301 (2012)



$^{208}Pb(^{50}Ti,2n)^{256}Rf$
up to 45 pnA, 50 kHz
σ=15 nb



P.T. Greenlees et al., Phys. Rev. Lett. 109 (2012) 012501

Methods and limits

- **Decay spectroscopy :** energies and ordering of single particle states can be obtained from the spectroscopy of odd-mass nuclei and K-isomeric states.

  → details studies are feasible up to Z=110

  →systematic nuclear structure study of odd-mass nuclei

→position of deformed shell gaps in region z=100 and N=152 are not well reproduced by modern mean-field theories

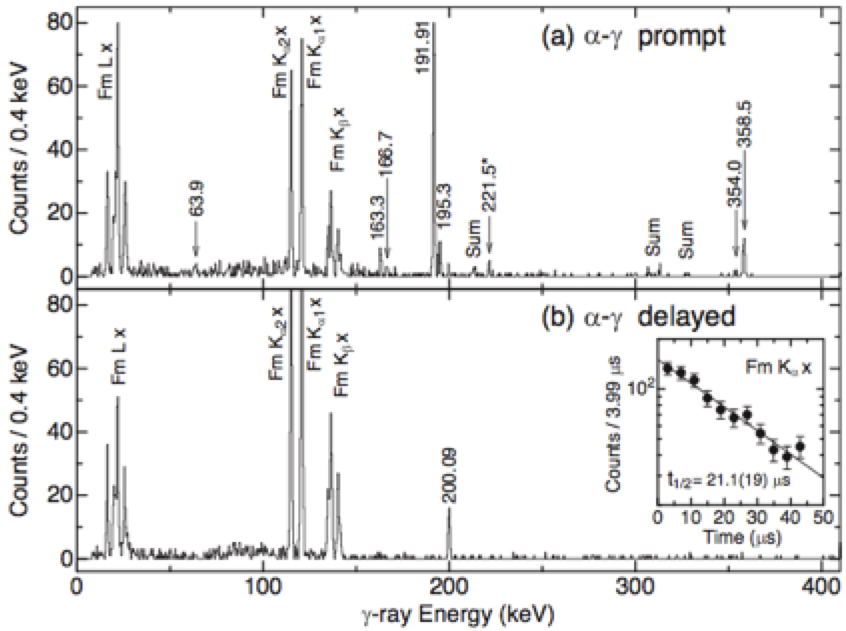
Bottleneck: limited counting rate

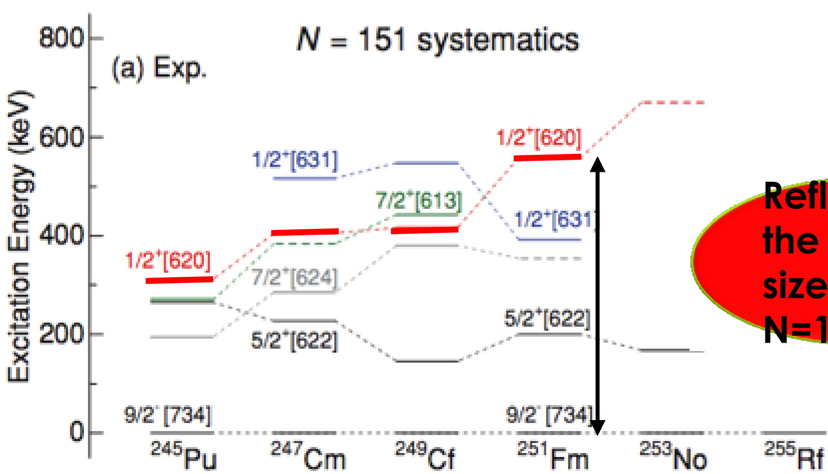
→ Needs a beam intensity increase by at least one order of magnitude is essential

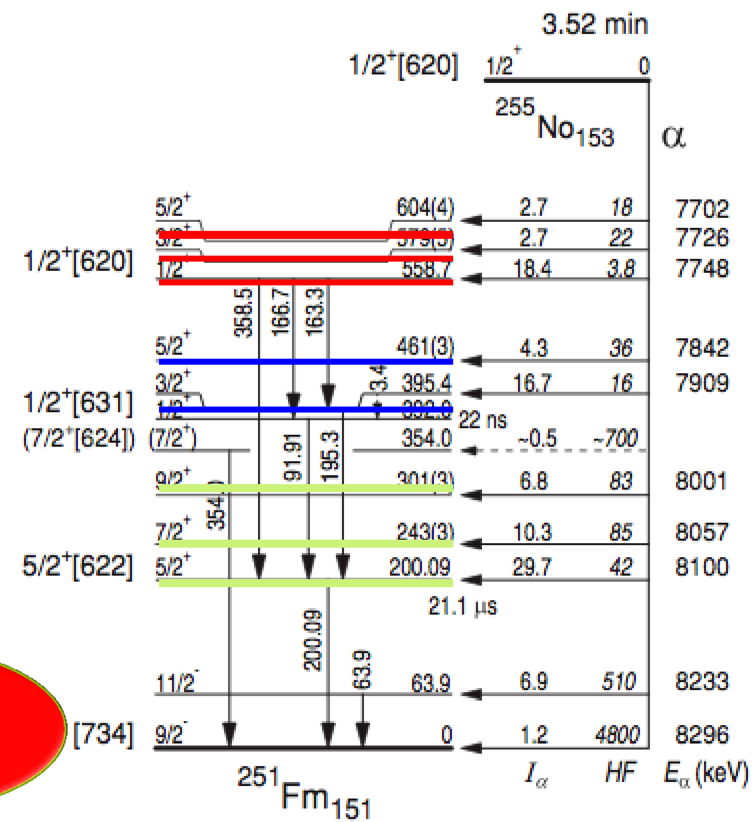
Decay spectroscopy: position of N=152 gap

No $^{248}Cm(^{12}C,5n)^{255}No$, I_{beam}=270 pnA, σ~600 nb

M. Asai et al., Phys. Rev. C 83 (2011) 014315



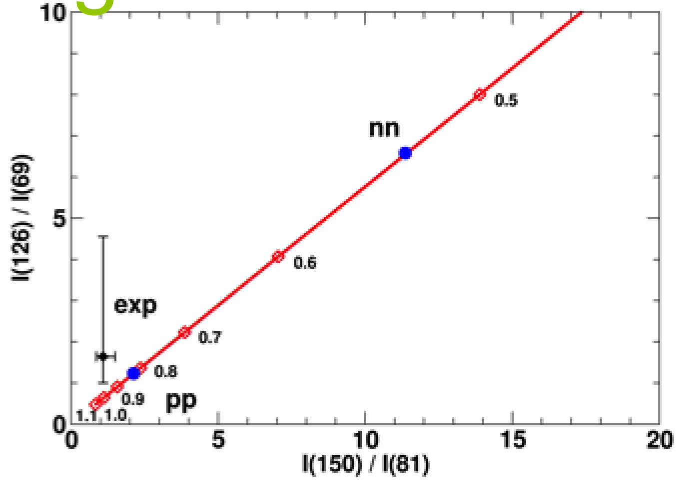




Reflects the size of the N=152 gap

➢ **N=152 gap energy increases with the atomic number**

High-K isomers in ^{254}No



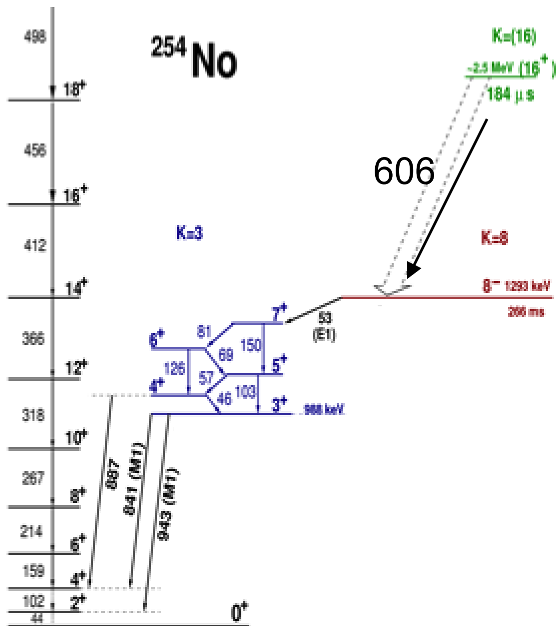
3$^+$: 2 quasiproton state 7/2-[514] ⊗ 1/2-[521]

8$^-$: 2 quasiproton state 7/2-[514] ⊗ 9/2+[624]

or

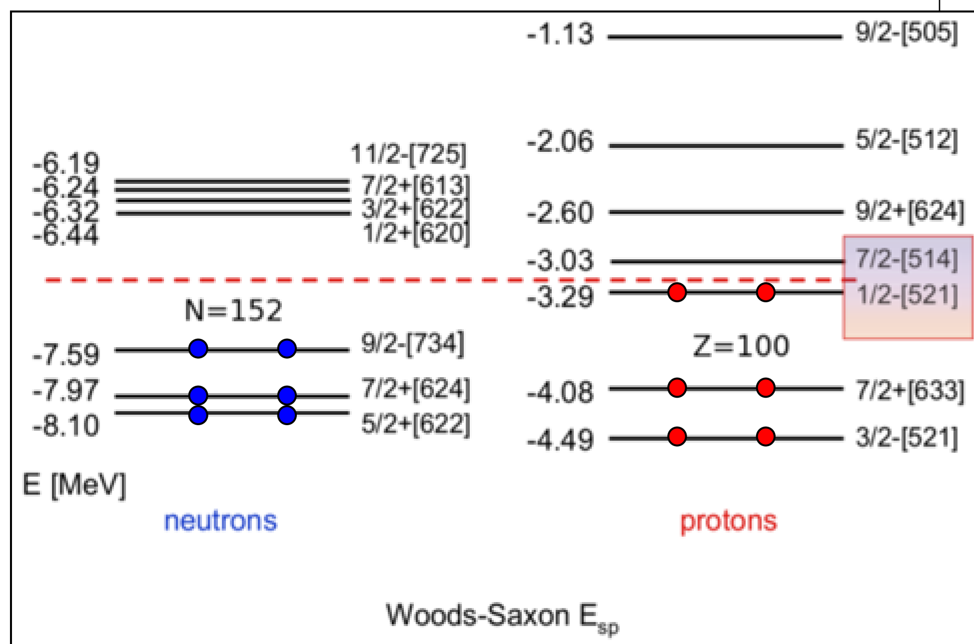
2 quasineutron state 9/2-[734] ⊗ 7/2+[613]

(and 7/2+[624] ⊗ 9/2-[734])

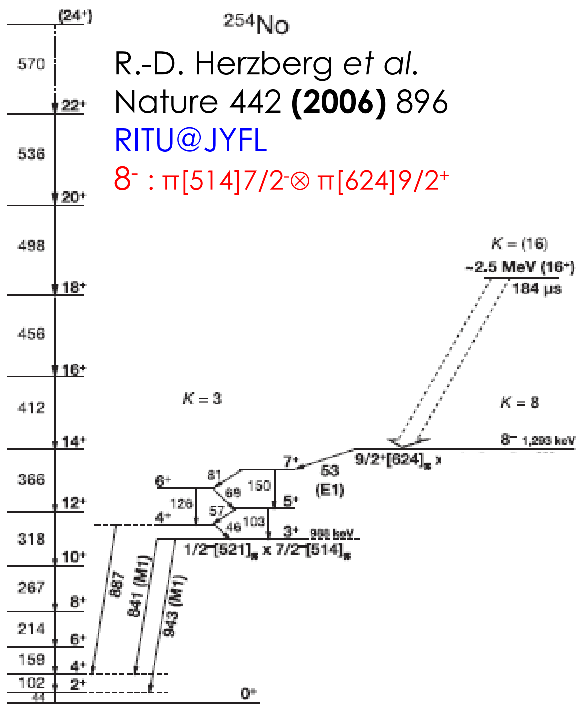


R.-D. Herzberg et al. Nature 442, 896 (2006)

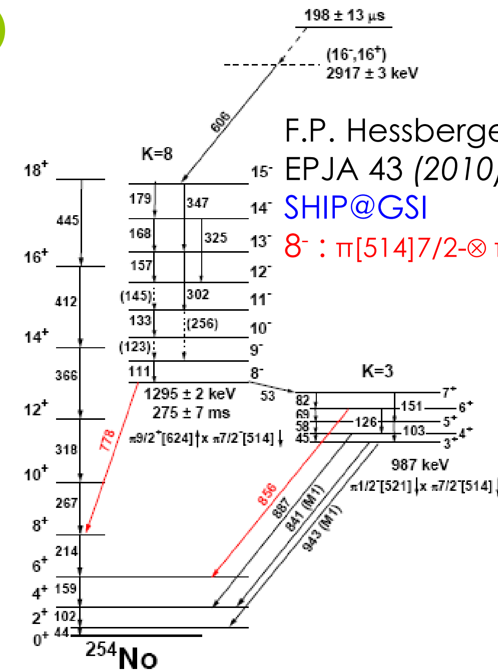
S. Tandel et al., Phys. Rev. Lett. 97 (2006) 082502



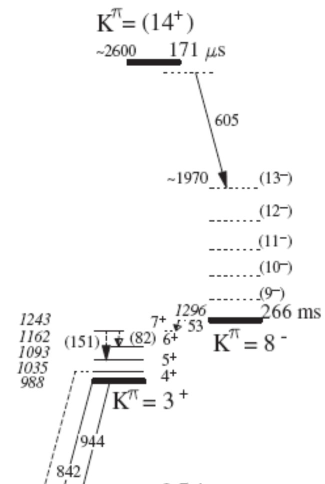
K isomerism in ^{254}No



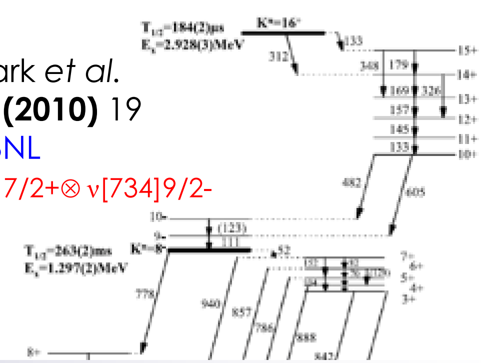
R.-D. Herzberg *et al.*
Nature 442 **(2006)** 896
RITU@JYFL
8^{-} : π[514]7/2^{-}⊗ π[624]9/2^{+}



F.P. Hessberger *et al.*
EPJA 43 *(2010)* 55
SHIP@GSI
8^{-} : π[514]7/2-⊗ π[624]9/2+



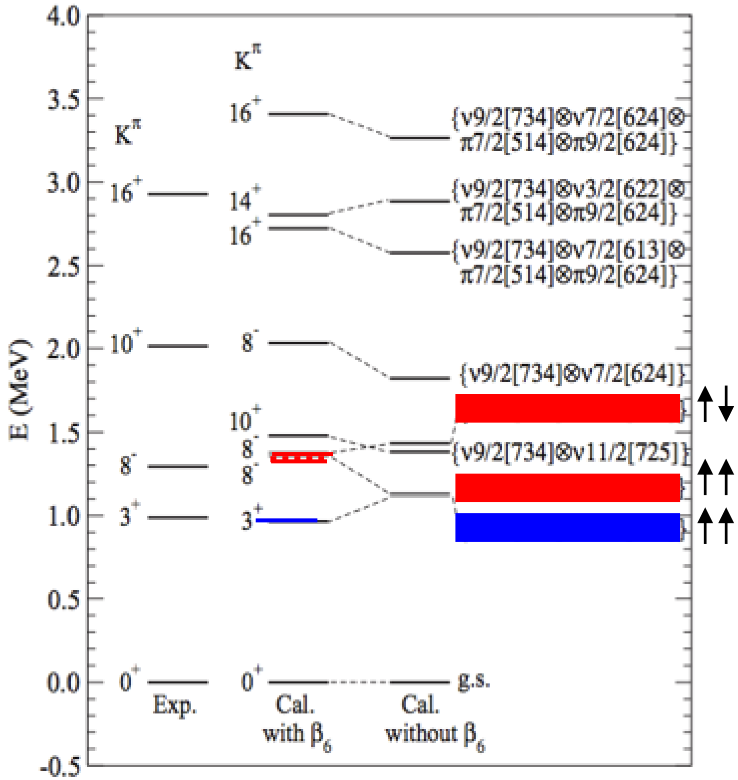
S.K. Tandel *et al.*
PLR 97 **(2006)** 082502
FMA@ANL
8^{-} : π[514]7/2-⊗ π[624]9/2+



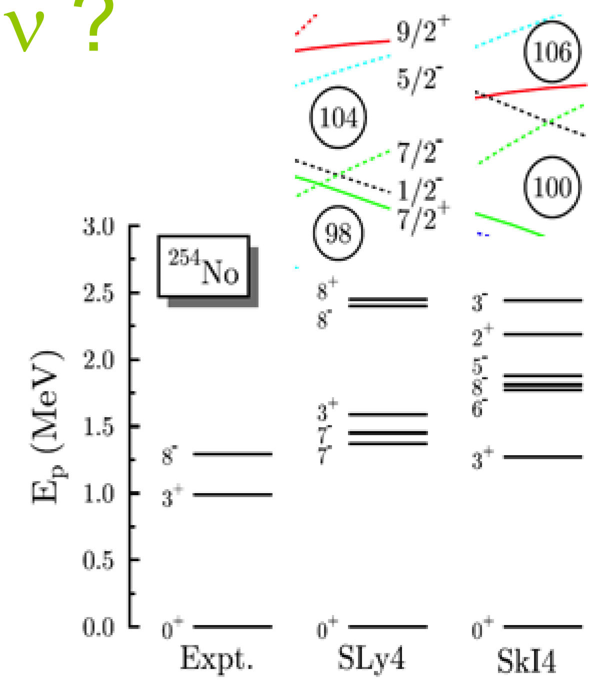
R.M. Clark *et al.*
PLB 690 **(2010)** 19
BGS@LBNL
8^{-} : ν[613]7/2+⊗ ν[734]9/2-

no agreement concerning an 2qp K isomer at ~1,3 MeV

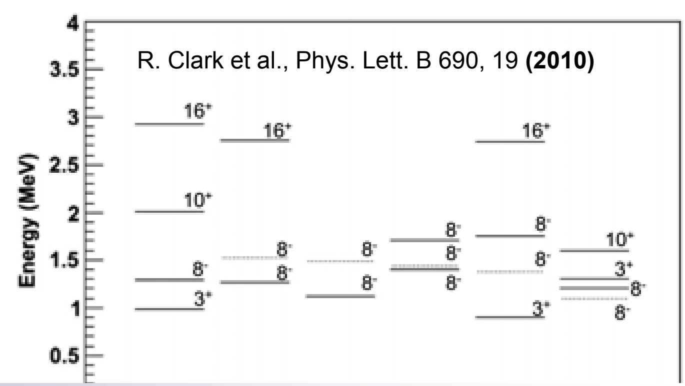
Theory: 8^- state, 2-π or 2-ν ?



H.L. Liu, F. R. Xu, P.M. Walker and C.A. Bertulani, Phys. Rev. C 83 **(2011)** 011303(R)



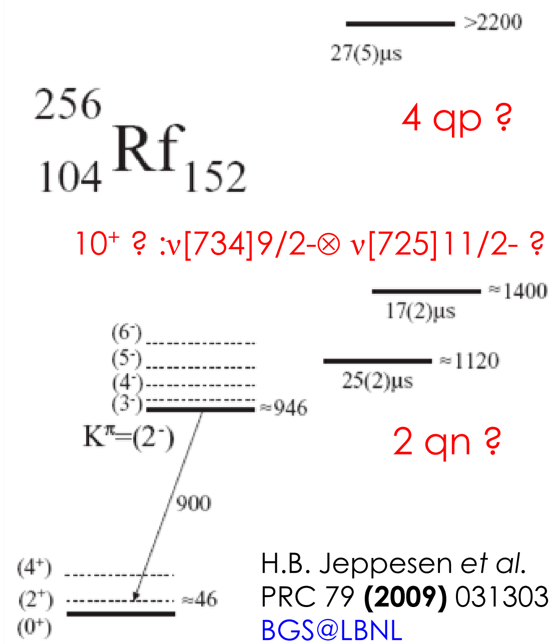
P-H Heenen, from http://nuclear1.paisley.ac.uk/SHEworkshop



Including higher order deformation strengthens the N=152 and Z=100 gaps

More experimental data are needed to solve the discrepancies

K isomerism in ^{256}Rf

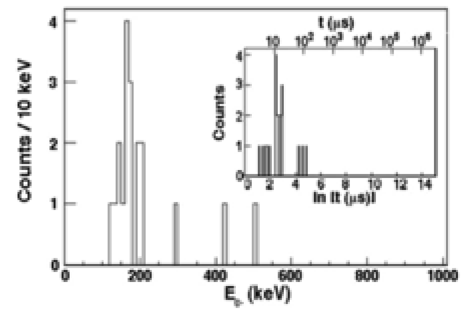


4 qp ?

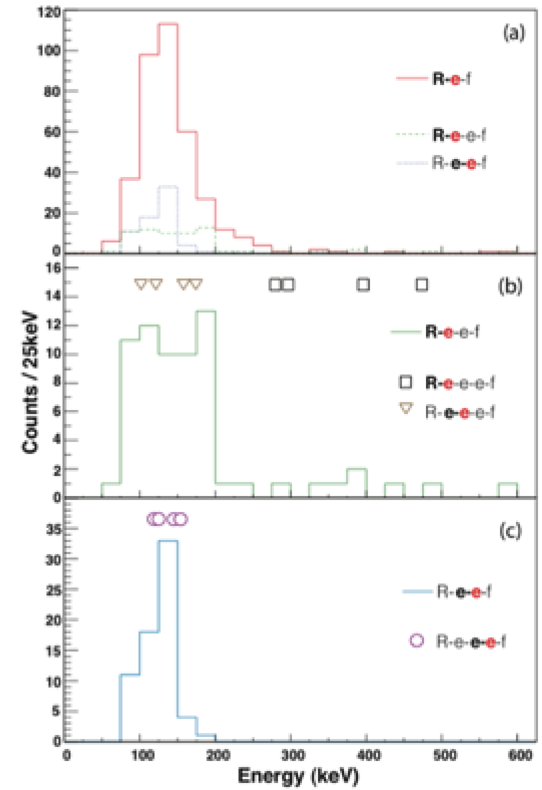
10^+ ? :ν[734]9/2-⊗ ν[725]11/2- ?

2 qn ?

H.B. Jeppesen *et al.*
PRC 79 **(2009)** 031303
BGS@LBNL



A.P. Robinson *et al.*
PRC 83 **(2011)** 064311
FMA@ANL
Only one isomer 17(5) μs 4qp ?



From P.T.Greenlees lecture 2014

Observed decays **BGS**

Chain	No. Events	$T_{1/2}$ (Parent-Daughter)
R-F	5400	6.67(9) ms
R-e-F	985 (18%)	25(2) μs
R-e-e-F	147 [illegible]	[illegible]
R-e-e-e-F	7 ([illegible]	[illegible]

Observed decays **ANL**

Chain	No. Events	$T_{1/2}$ (Parent-Daughter)
R-F	1322	6.9(4) ms

Observed decays **JYFL**

Chain	No. Events	$T_{1/2}$ (Parent-Daughter)
R-F	2210	6.9(2) ms
R-e-F	382 (17%)	23 μs
[illegible]	[illegible]	μs
[illegible]	[illegible]	μs

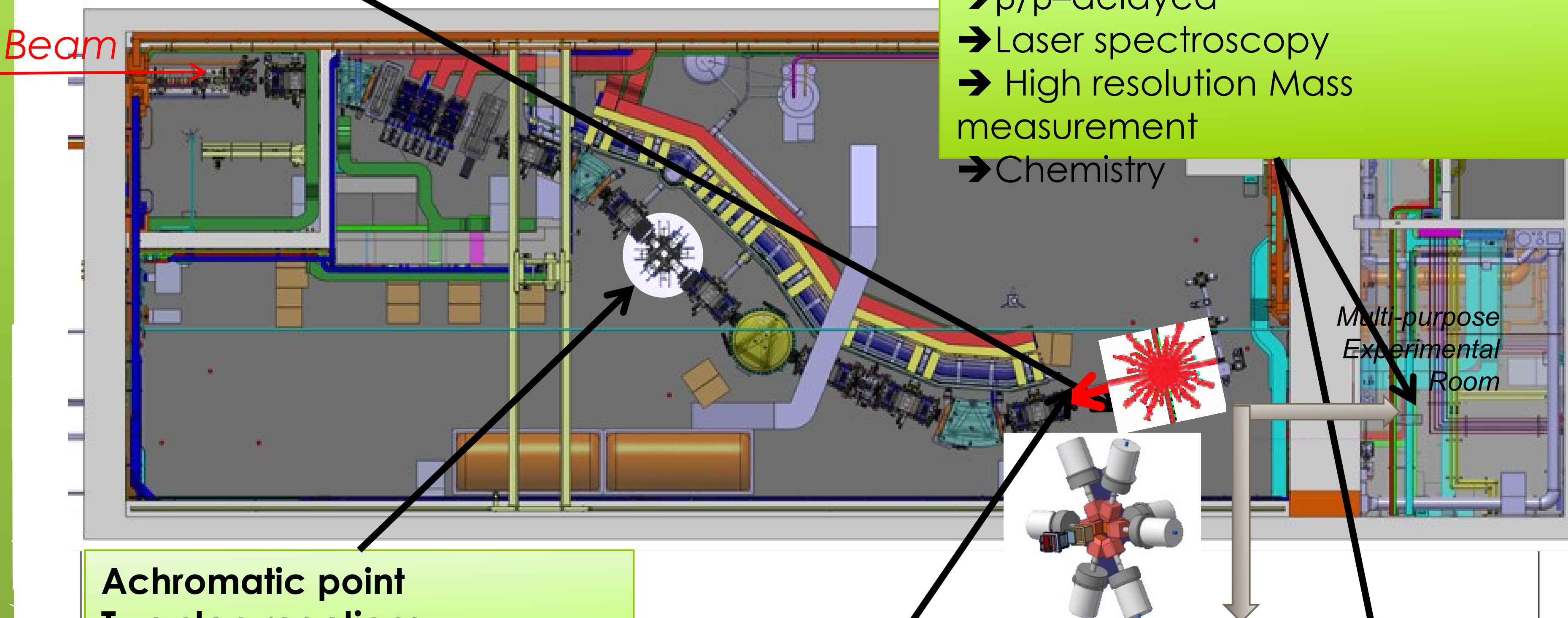
Experimental differences difficult to reconcile
→ **An order of magnitude in statistics is required**

S3 and LINAG @ GANIL

Experimental Techniques

Final focal plane
Selection & Identification
➔Time of flight + Energy
➔ A measurement

Converging mode
Gas catcher + Laser ionisation +
Mass Resolution by Time-of-flight
➔β/β–delayed
➔Laser spectroscopy
➔ High resolution Mass measurement
➔Chemistry



Achromatic point
Two step reactions
➔Transfer+Fusion (transfer)

Specific Modes
➔ Ion-ion collision : **FISIC**

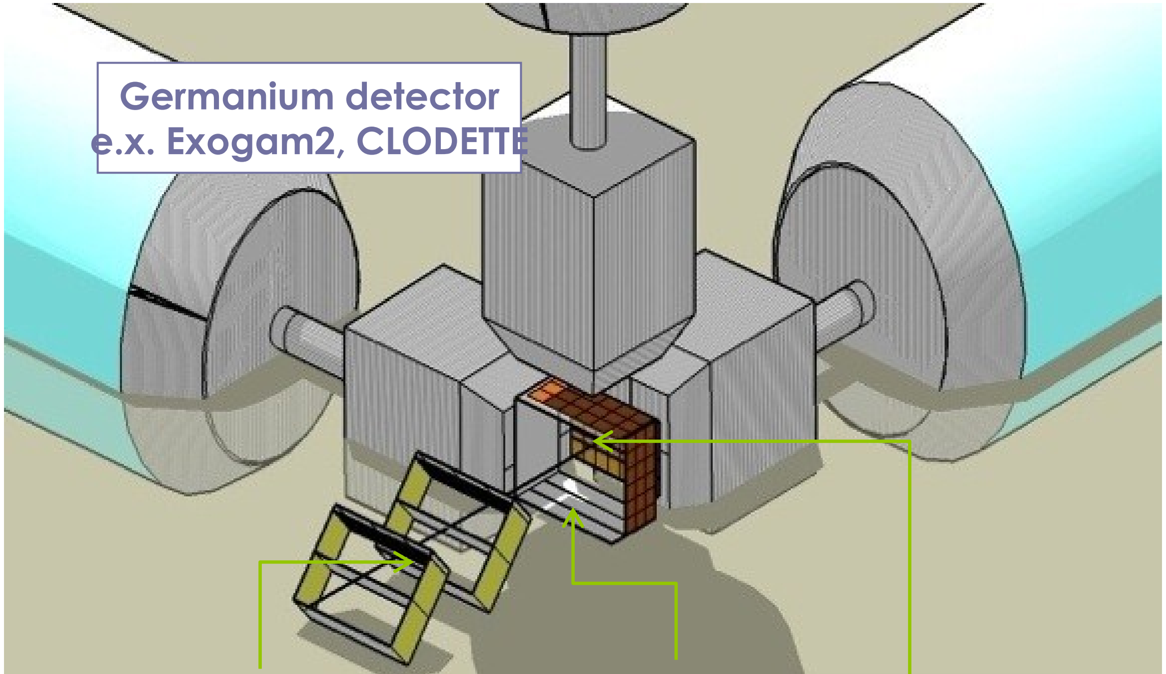
Mass dispersive mode
Delayed spectroscopy
➔ p, α, γ, e- decay

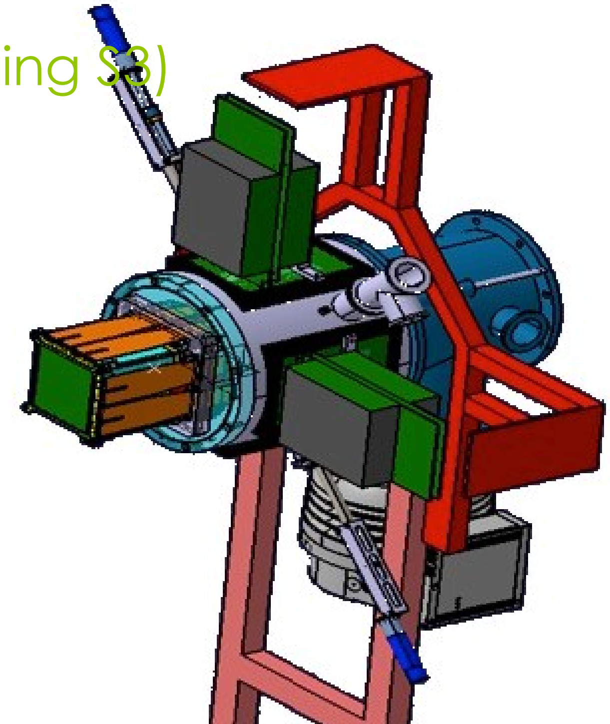
DESIR

S^3 room three weeks ago

SIRIUS

(Spectroscopy & Identification of Rare Ions Using S3)





Time of flight + tracking detector

- Large size (200x150 mm^2)
- Time Resolution < 1ns
- Position resolution = 1mm
- Very low thickness

Tunnel detector for escaped e^- and α

- Conversion electrons FWHM <5 keV
- Escaped alpha FWHM 15 keV

Implantation detector (HI, α and e^- decay)

- Large detector size 10x10cm^2
- High resolution FWHM
- **Ability to detect large> 50MeV pulse Followed (≈ 10µs) by a weak (<15MeV) pulse.**
- No Dead time

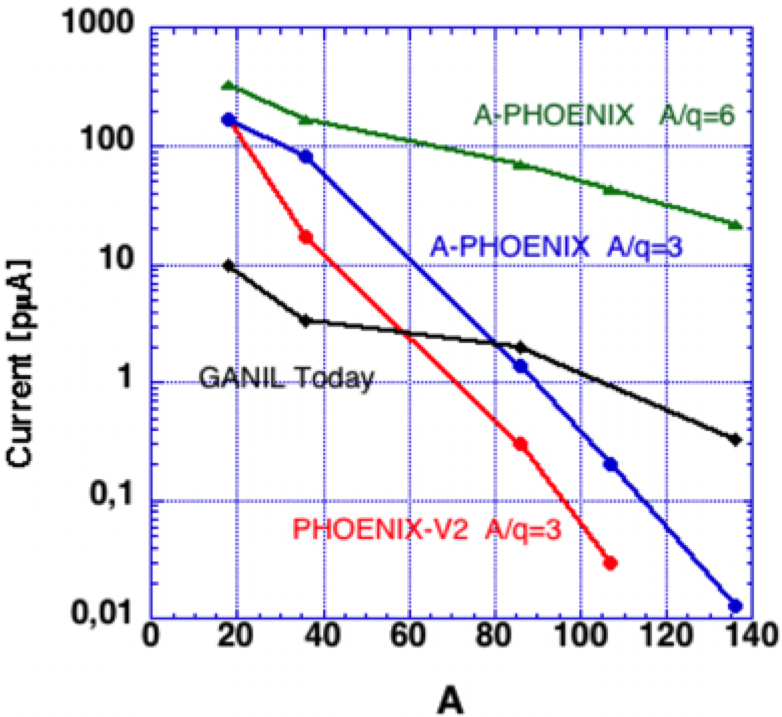
R&D is ending ➔ Construction phase could start

Search for the funds !

SPIRAL2 day1

Very high intensity beams with:

- Phoenix V3 source A/q=3 RFQ



Rate summary vs GSI UNILAC

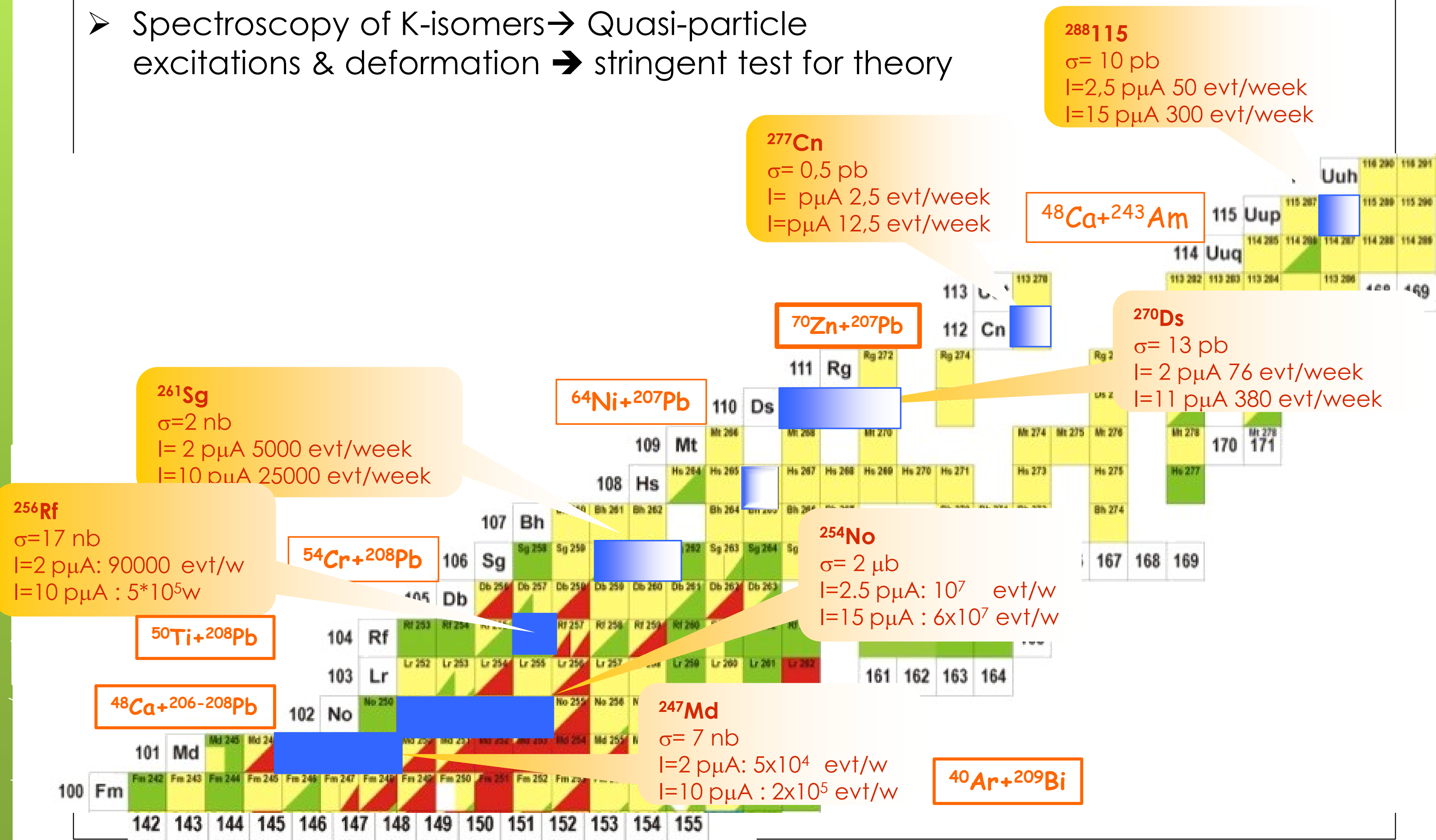
× 2-4 [A/Q=3, Phoenix V3]

× 15-20 [A/Q=6, SC source]

Ions	Intensity (pμA) Phoenix V2 PHOENiX V3
^{4}He	850
^{18}O	216
^{19}F	28,6
^{36}Ar	17.5
^{40}Ar	2.9
^{32}S	7.3
^{36}S	4.6/9
^{40}Ca	3/5
^{48}Ca	1.25/2.5
^{58}Ni	1.1/2
^{50}Ti	1/2
^{54}Cr	1/2
^{84}Kr	0
^{139}Xe	0
^{238}U	0

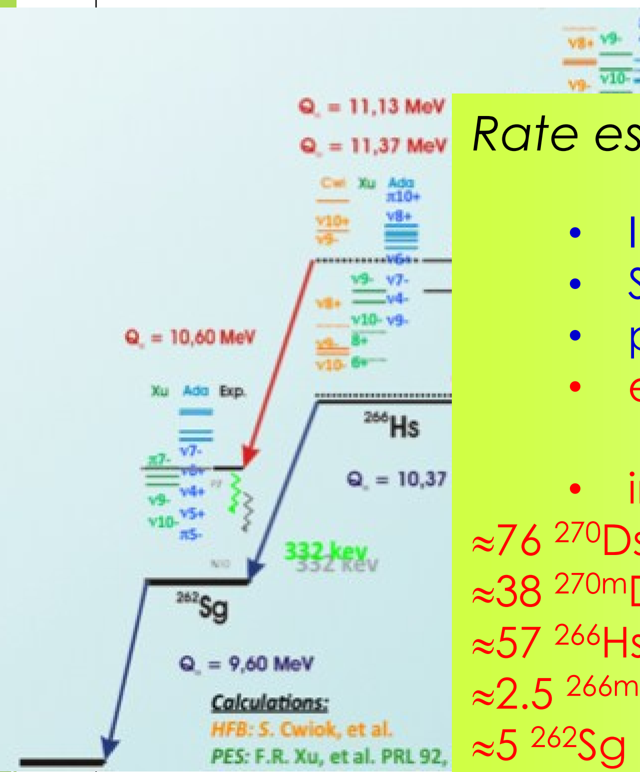
S^3 first day experiment and beyond

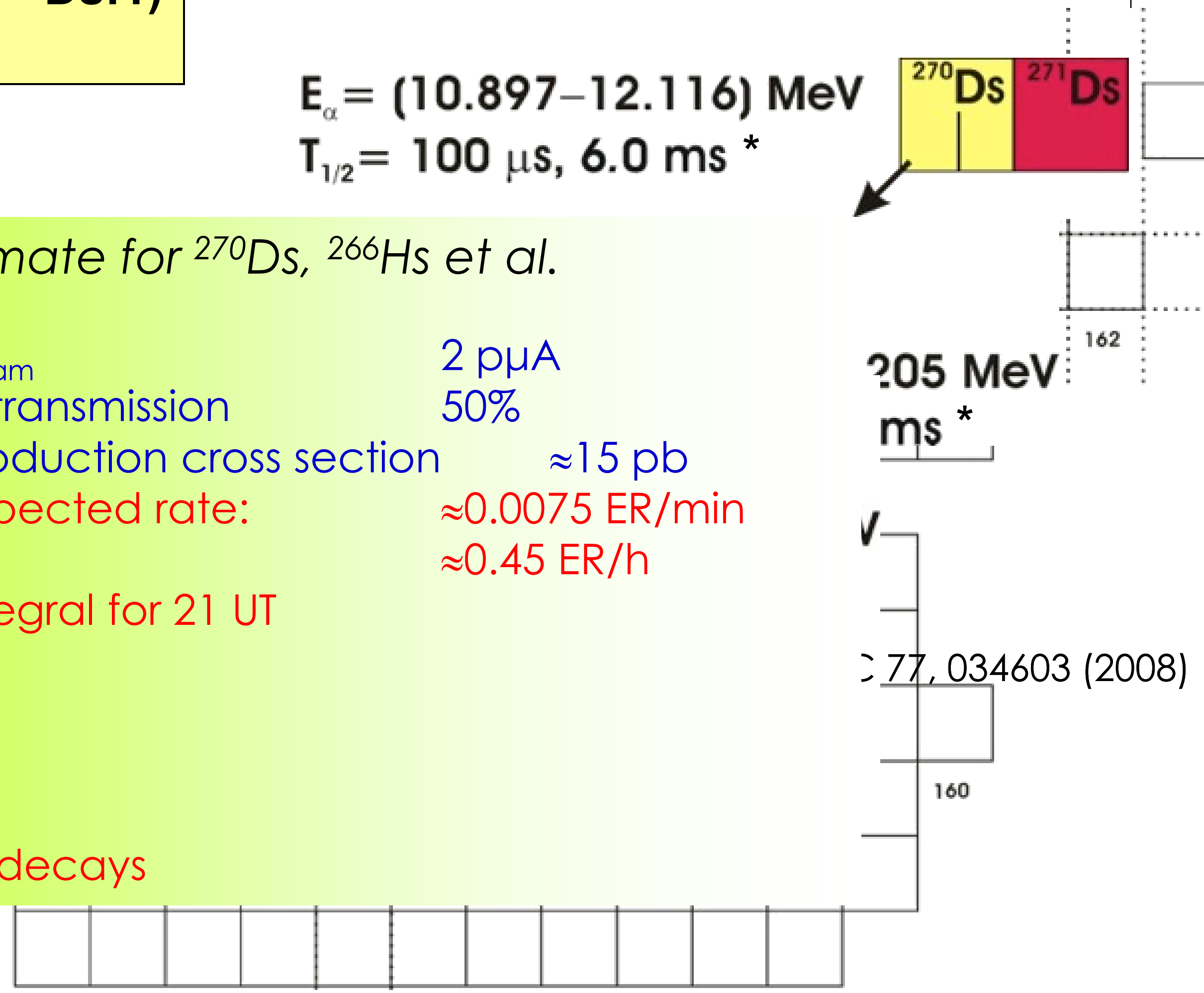
- Spectroscopy of K-isomers→ Quasi-particle excitations & deformation ➔ stringent test for theory



K- Isomers in ^{270}Ds & its decay ^{266}Hs @ GSI

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





Rate estimate for ^{270}Ds, ^{266}Hs et al.

- I_{beam} 2 pμA
- S^3 transmission 50%
- production cross section ≈15 pb
- expected rate: ≈0.0075 ER/min
  ≈0.45 ER/h
- integral for 21 UT

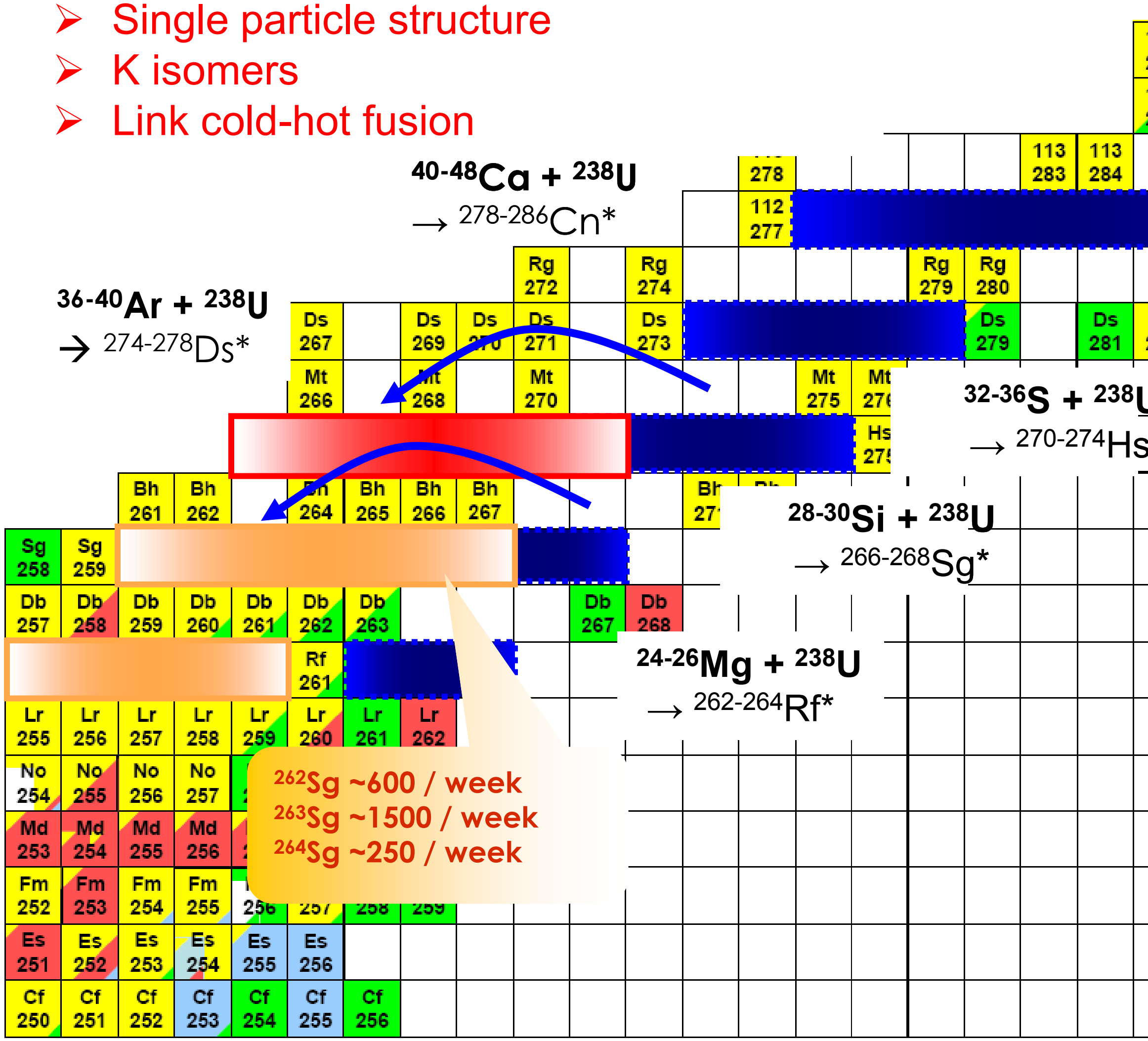
≈76 ^{270}Ds
≈38 ^{270m}Ds
≈57 ^{266}Hs
≈2.5 ^{266m}Hs
≈5 ^{262}Sg a-decays

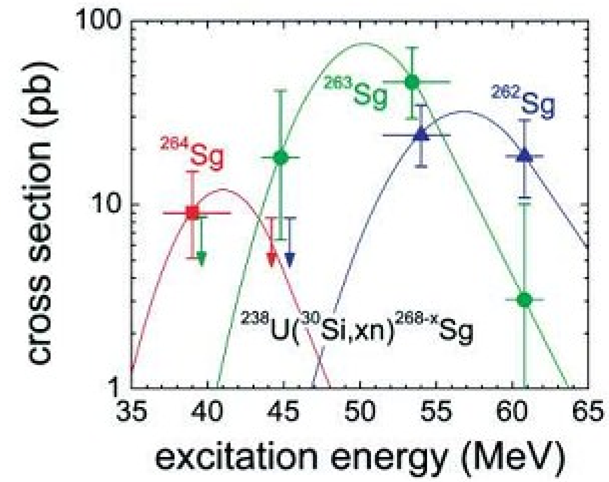
* $T_{1/2}$ from *S. Hofmann et al., Eur. Phys. J. A 10, 5 (2001)*

Courtesy of Dieter Ackermann

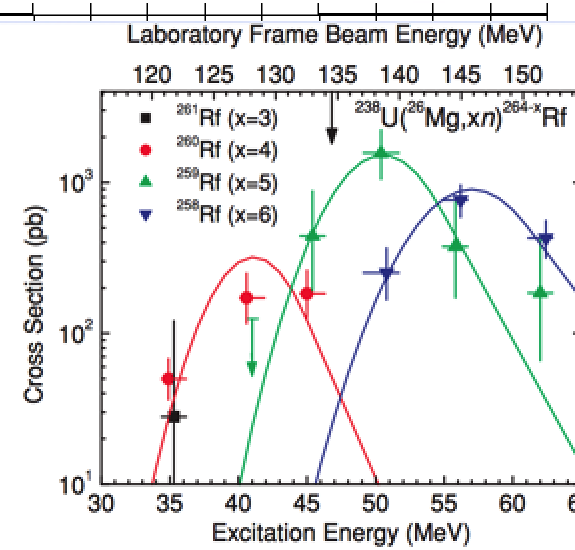
After Day 1 : reactions with U targets

- Reaction mechanism
- Single particle structure
- K isomers
- Link cold-hot fusion





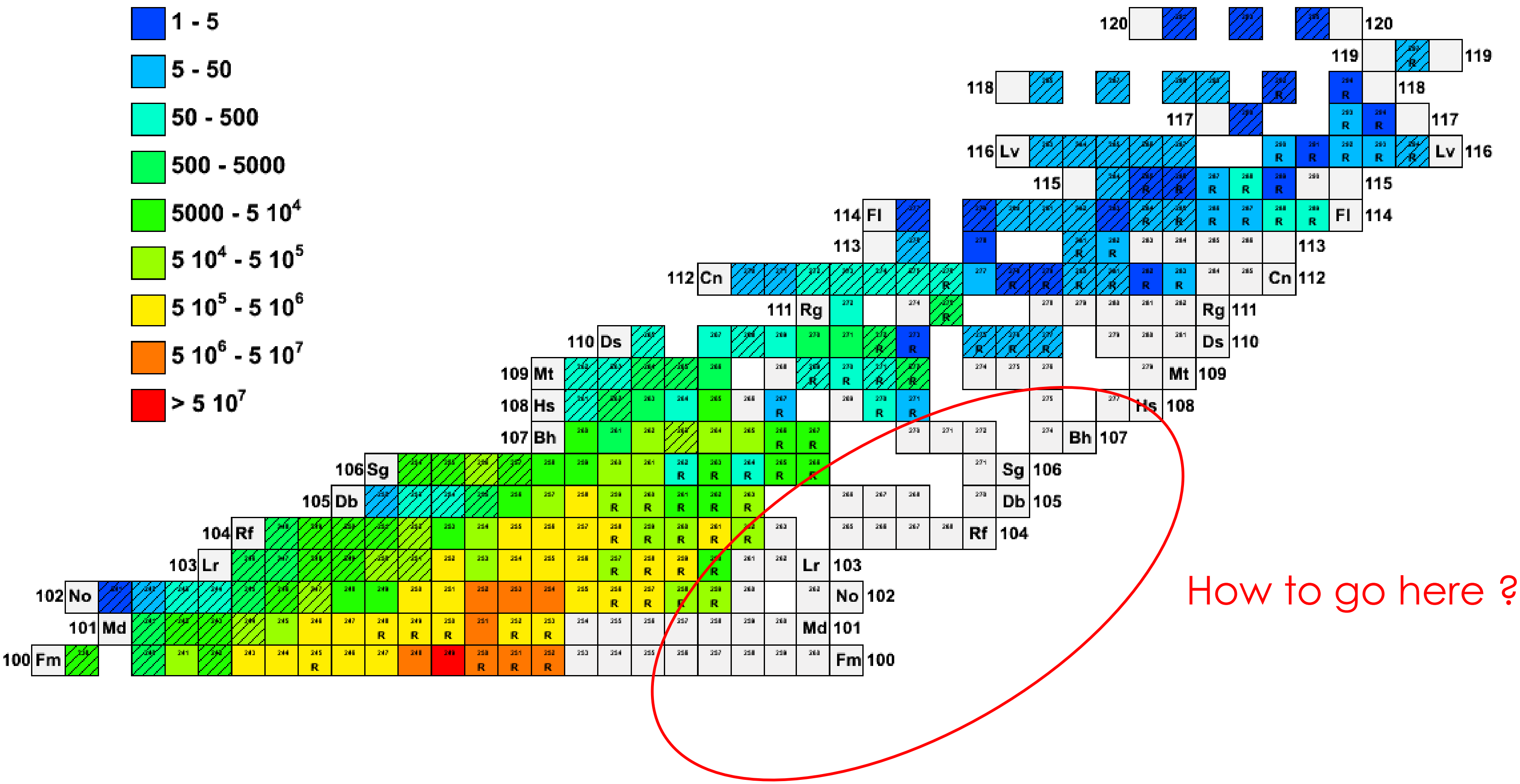
J.M.Gates et al.,, PRC 77, 034603 (2008)



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

Two weeks experiment; RFQ 1/6

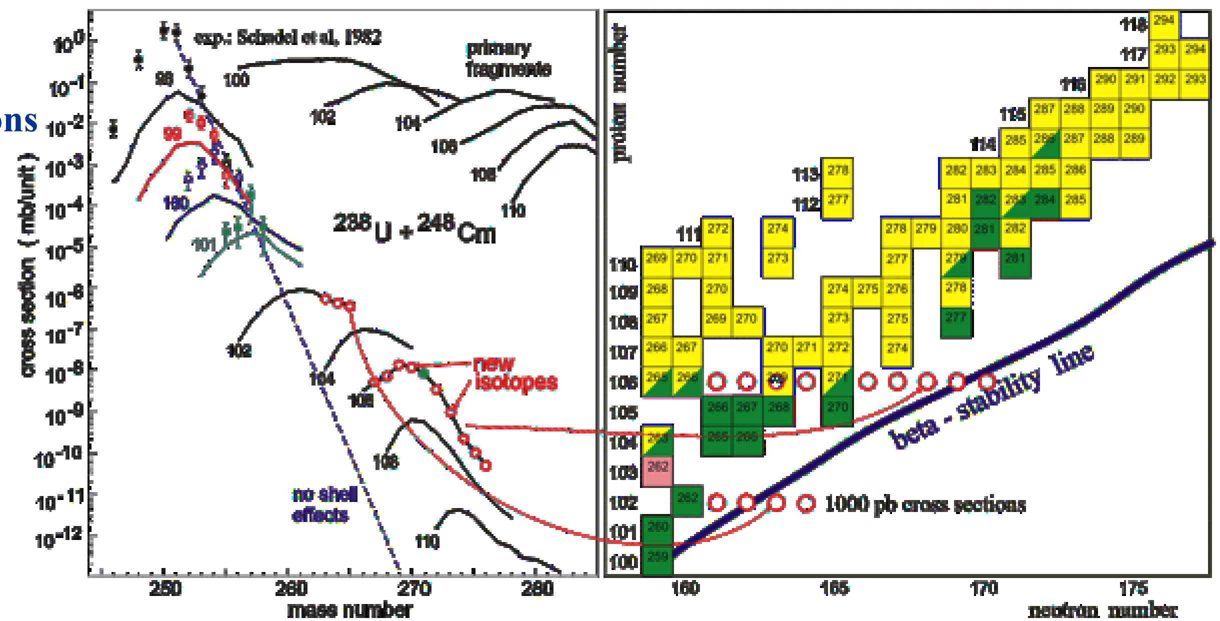
Spectroscopy up to Z=114 ?



The limits of fusion-evaporation reactions

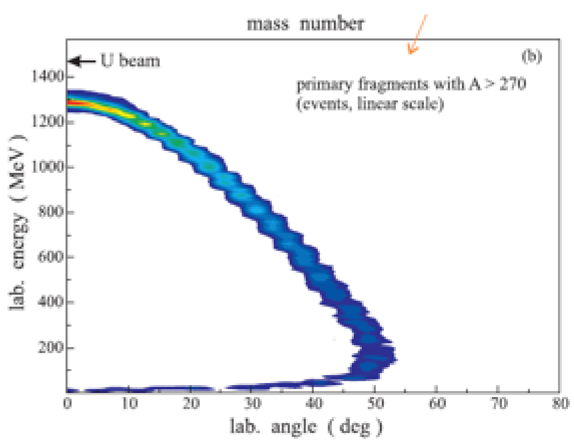
Using multi-nucleon transfer reactions ?

- **Multi-nucleon transfer reactions can be used for synthesis of neutron enriched long-living**
- **U-like beams are needed**
- **Actinide targets**
- **Lage acceptance spectromter**



Zagrebaiev, Greiner, PRC 78 (2008) 034610

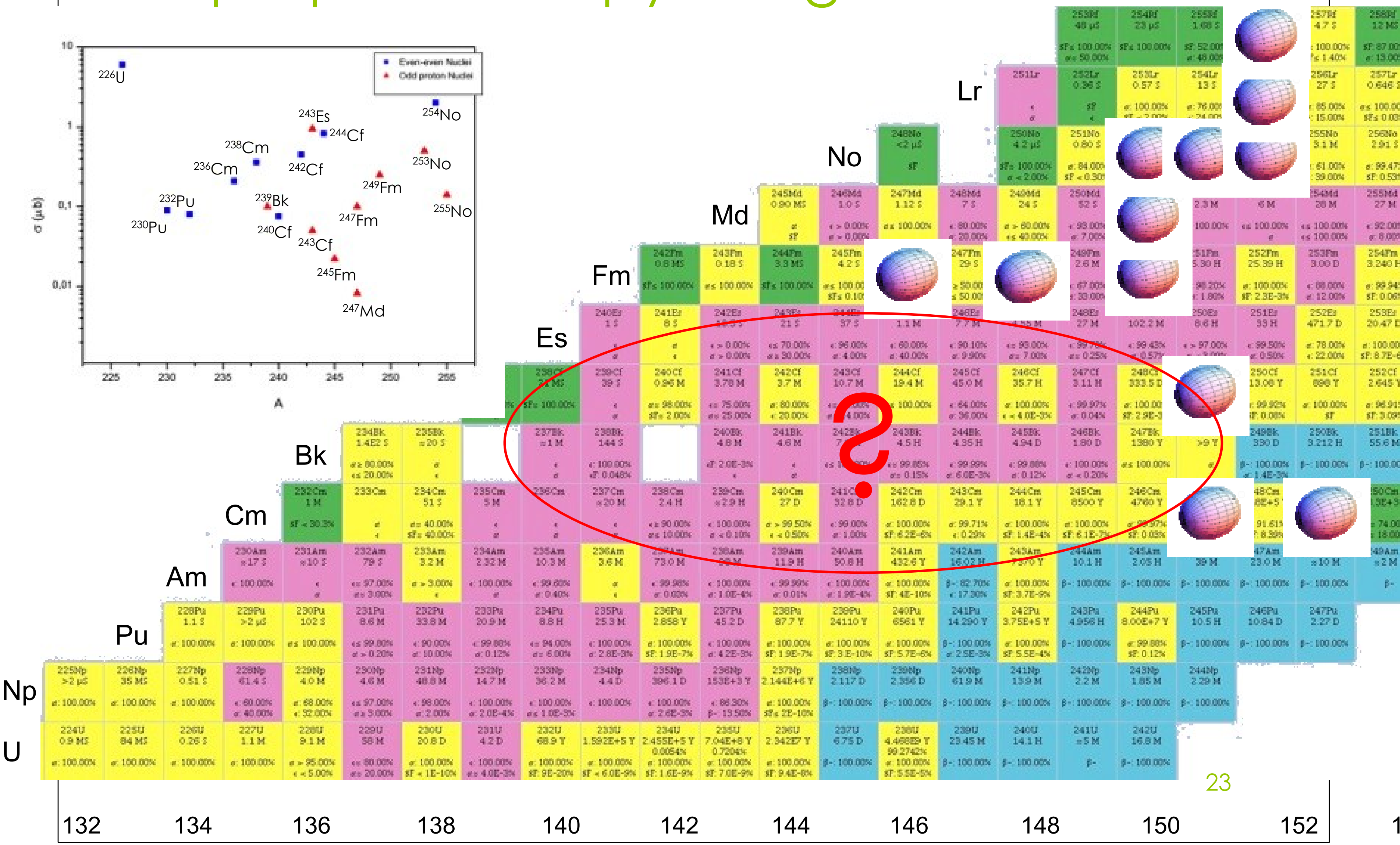
$^{238}U + ^{248}Cm$ @ 750 MeV



Still cross section near zero degree !!!

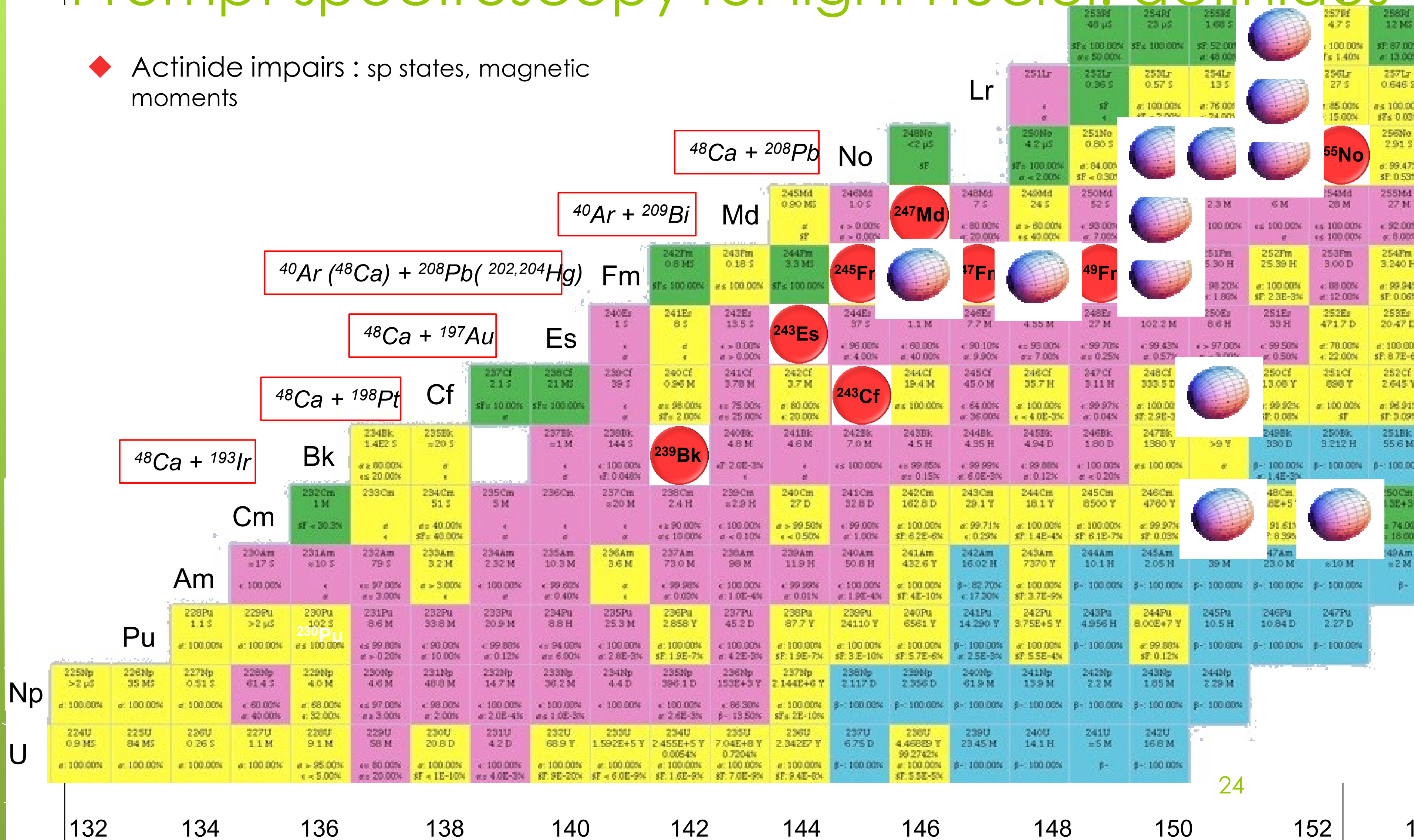
Zagrebaev, Greiner, PRC 83 (2011) 044618

Prompt spectroscopy for light nuclei: actinides



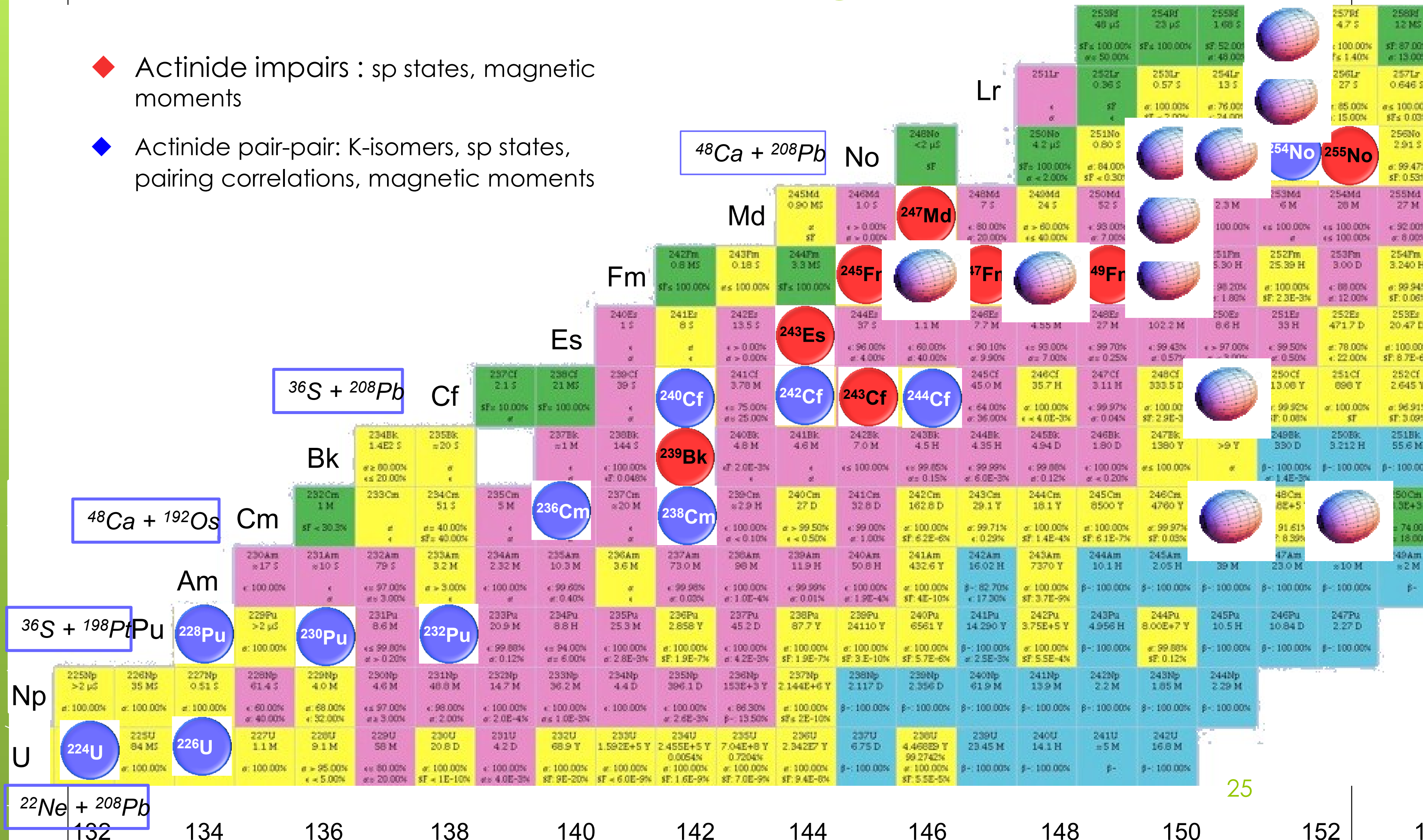
Prompt spectroscopy for light nuclei: actinides

- Actinide impairs : sp states, magnetic moments

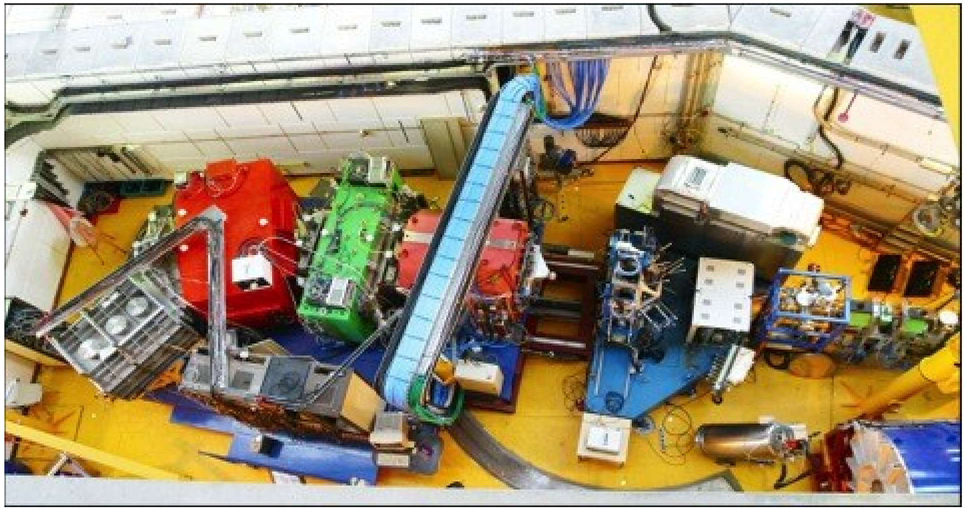


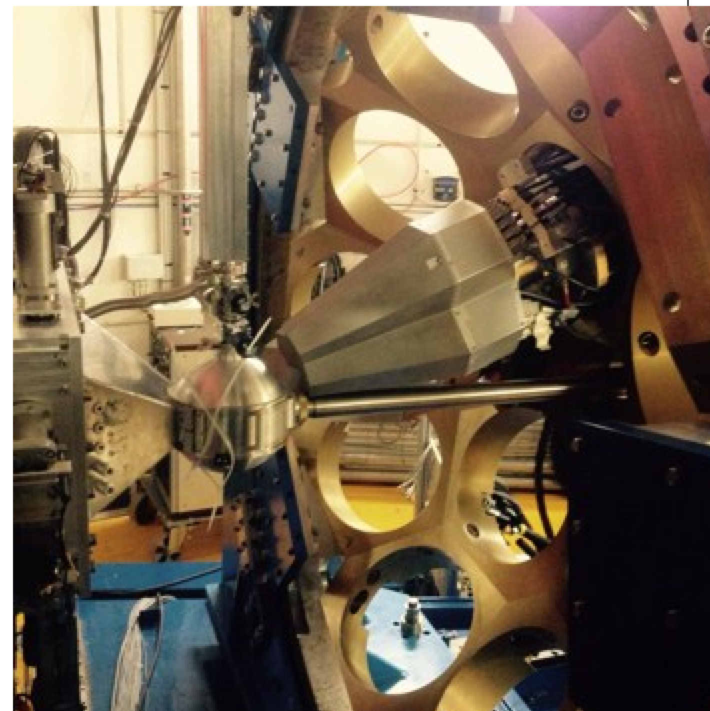
Prompt spectroscopy for light nuclei: actinides

- Actinide impairs : sp states, magnetic moments
- Actinide pair-pair: K-isomers, sp states, pairing correlations, magnetic moments



VAMOS gas filled separator





Large acceptance Ω ~ 60 msr
→Large transmission expected for
fusion-evaporation reactions

EXOGAM2, AGATA
→Gamma spectroscopy, high efficiency

MUSETT
→Focal plane detection, RDT

Competitors for the very high intensity facilities

Present generation facilities (intensities around 1pµA) : Berkely, Dubna, GSI, Riken, IMP/Lanzhou

S^3 does better for light ions, and slightly better (x2) for heavy ones

Next Generation

Dubna and the SHE Factory

➔ SC ion source

➔ Very high intensity cyclotron : 10-20pµA

➔ 1st experiments foreseen in 2016

GSI HLI

➔ 28GHz ion source and A/q=6 injector

➔ new continuous wave Superconducting LINAC

➔ Construction should start in 2015

➔ Not funded

SC ion source and associated RFQ are required to compete with the next generation facilities

Summary

- Availability of a high charge state ions source, the A/q=6-7 line, actinide targets and a state of the art detection system

- Availability of VSMOS-GFS from 2017 coupling with AGATA

- GANIL and Spiral2 phase 2 provide opportunities to study alternative production schemes of yet unknown isotopes;

  →MNT and fusion–evaporation reactions using stable or neutron reach beams