

The Study of Superheavy Elements at EURISOL

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Task 10
Superheavy Elements Sub-Task

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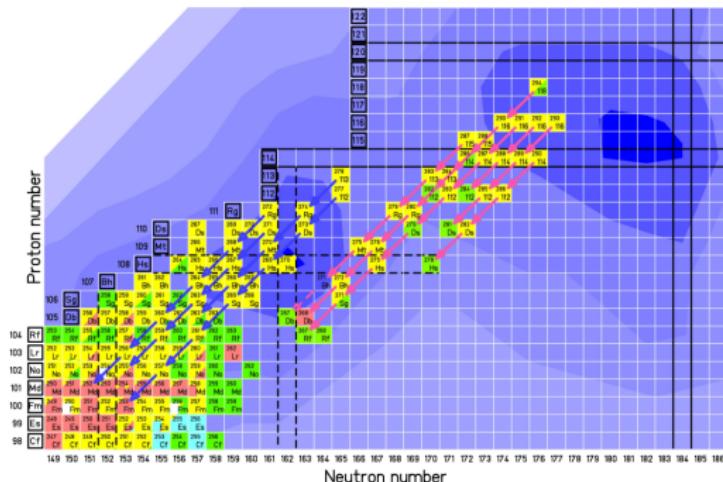
Krunoslav Subotic, INN Vinca

Outline

- 1 Motivation
- 2 Synthesis and Decay of Superheavy Elements
- 3 In-beam Spectroscopy
- 4 Optical Spectroscopy
- 5 Instrumentation



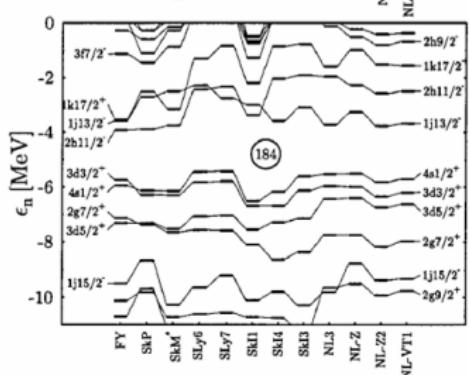
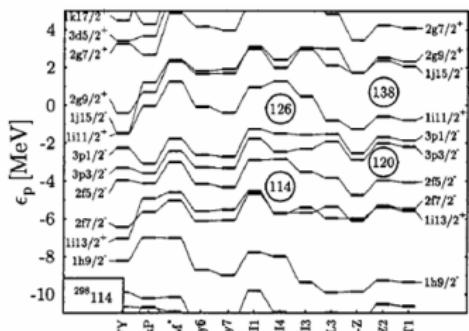
Spectroscopy of the heaviest elements



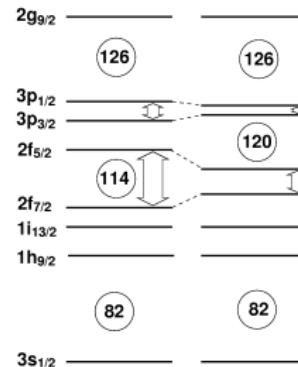
S. Hofmann, Nucl. Phys. News. Intl.

- Detailed structure studies of the heaviest nuclei
- Locate and determine properties of single-particle states
- Interplay of collective and single-particle degrees of freedom
- Role of isomerism - comparison to ground state
- Complementary approaches
- In-beam spectroscopy
- Decay spectroscopy
- Optical spectroscopy

Next Closed Shells?

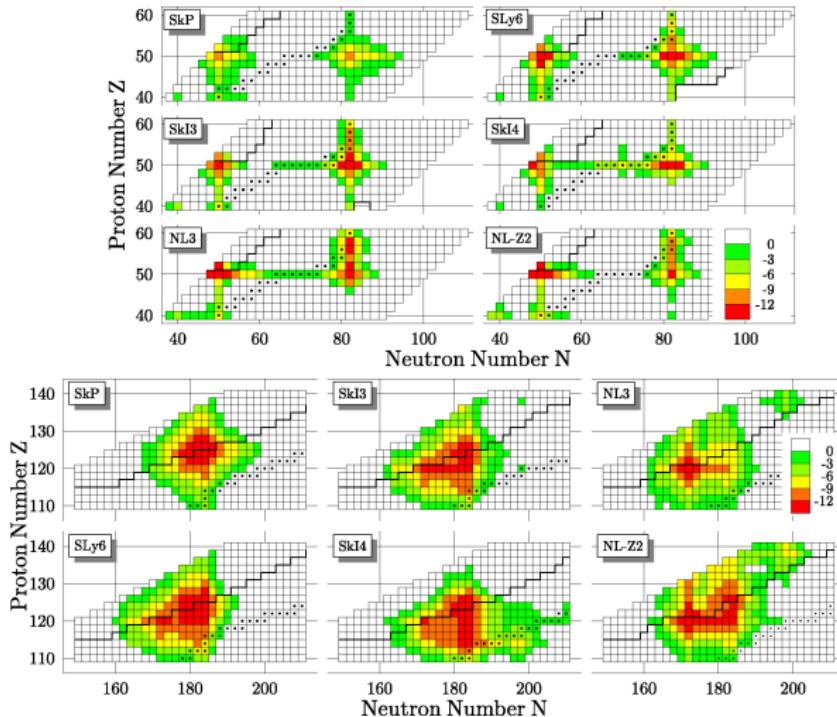


M. Bender et al., PRC60, 034304 (1999)



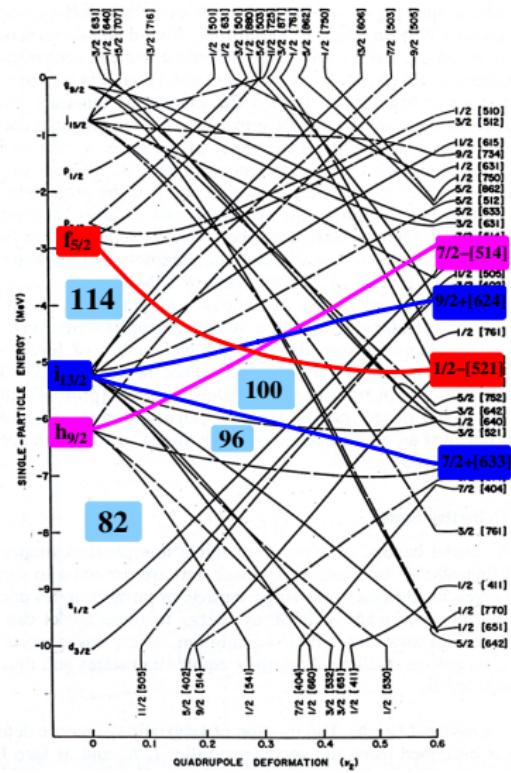
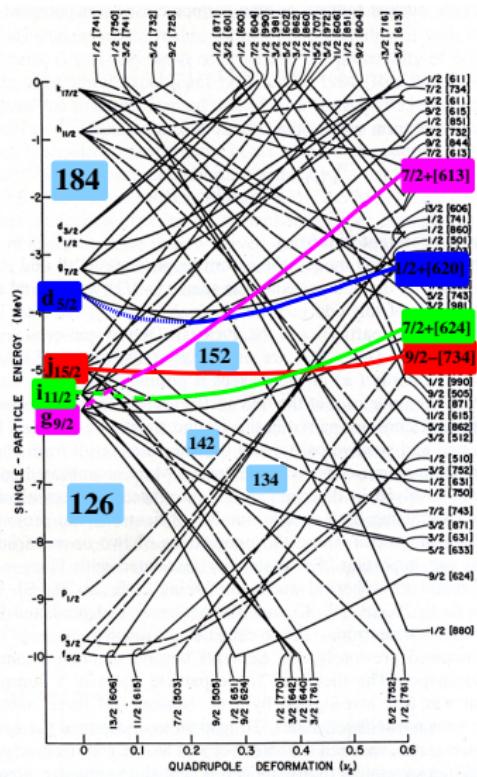
- Various models give different ordering and energies of single-particle states
- Leads to different predictions of shell gaps
- Expect broad regions of enhanced shell effects
- Obtain experimental data to constrain models and determine correct ordering

Extended Regions of Enhanced Shell Effects

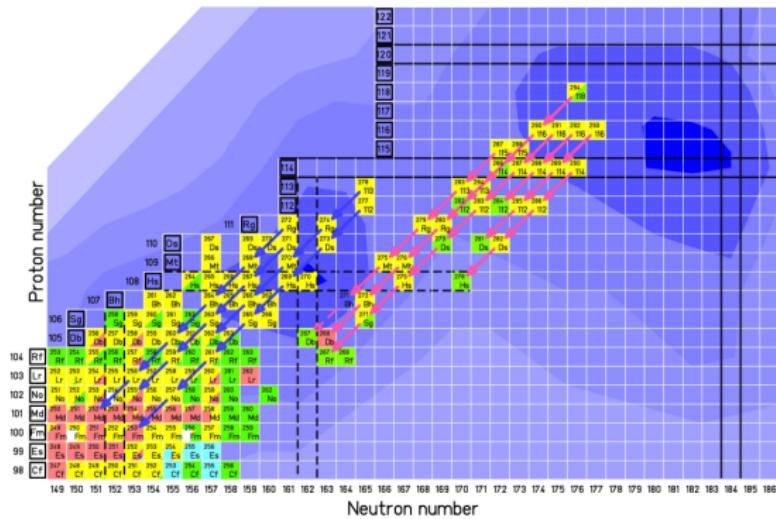


M. Bender, W. Nazarewicz, P.-G. Reinhard, PLB 515, 42 (2001)

Single-Particle Orbitals in Region of ^{254}No



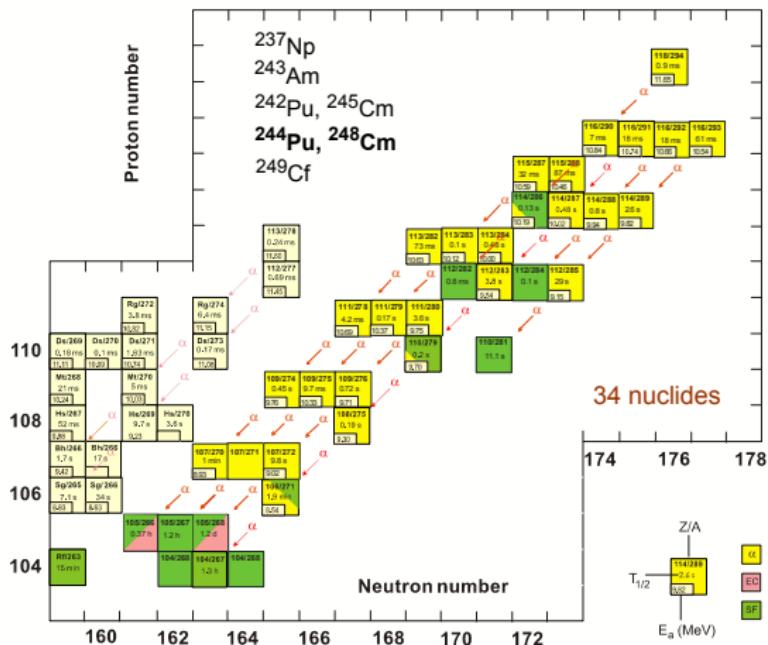
Synthesis and decay of the heaviest elements



S. Hofmann, Nucl. Phys. News. Intl.

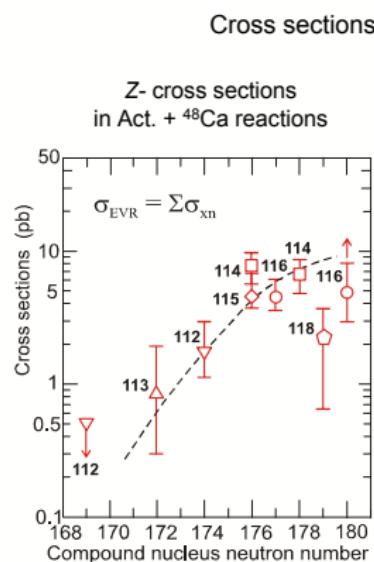
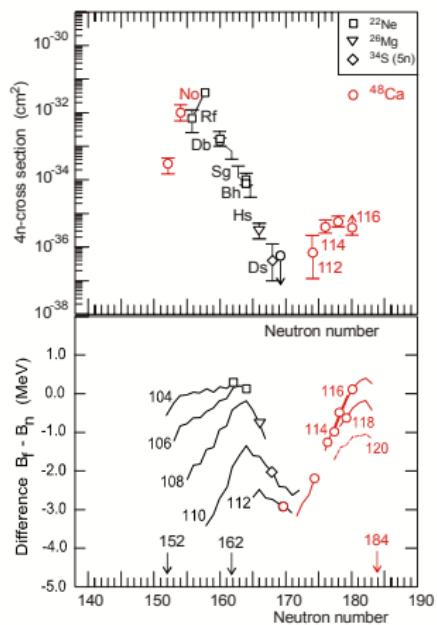
- Focal plane spectroscopy
- Highest Intensity Beams (^{132}Sn , $^{90,92}\text{Kr}$, (Rb, Sr) , ^{44}Ar)
- Below 10pb very difficult
- 100pnA / 10pb \rightarrow 1 event/week
- Produce more neutron-rich nuclei
- Push to $N=162$ or $N=184$
- Symmetric reactions?
Theoretical XS needed

“Hot” Fusion at Dubna



Yu. Ts. Oganessian, Presented at WAPHE06

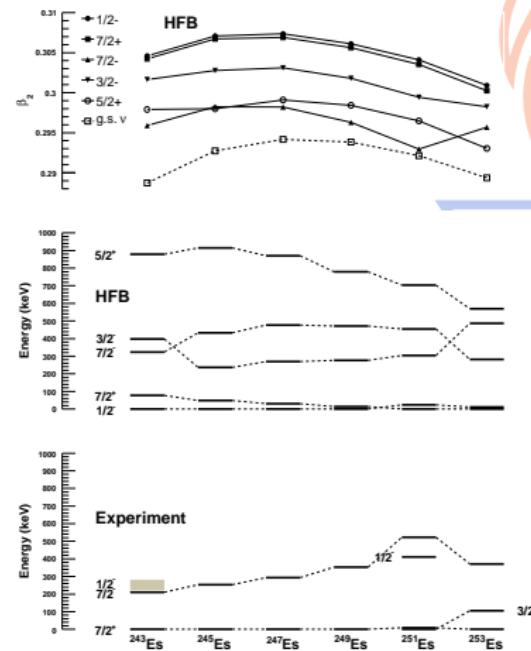
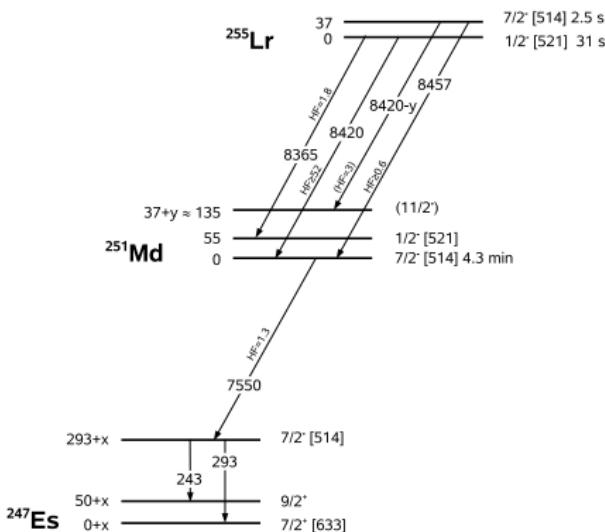
“Hot” Fusion Cross Sections



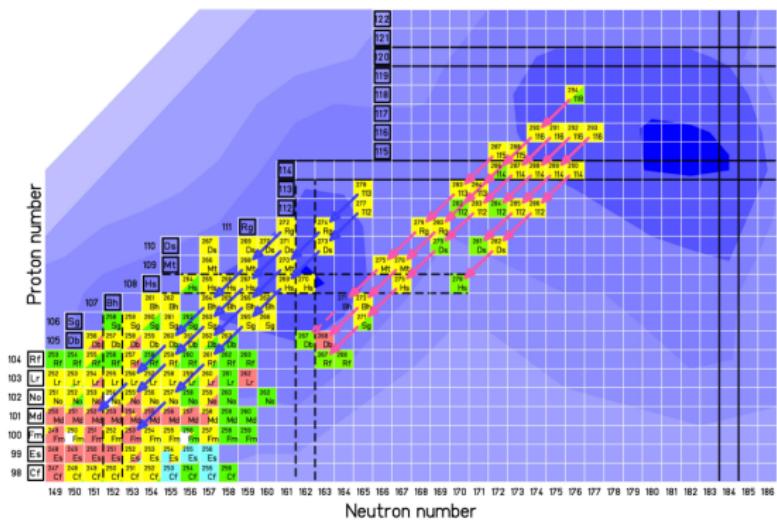
Yu. Ts. Oganessian, Presented at WAPHE06

Decay spectroscopy - ^{255}Lr

$^{48}\text{Ca} + ^{209}\text{Bi} \Rightarrow ^{255}\text{Lr} + 2\text{n}$, $\sigma \simeq 300 \text{ nb}$, GANIL and JYFL data
 A.Chatillon,Ch.Theisen,P.T.Greenlees et al., EPJA in print



Sample Reactions



S. Hofmann, Nucl. Phys. News. Intl.

Around N=162

- $^{132}\text{Sn} + ^{137}\text{Cs} \rightarrow ^{267}\text{Db}^*$
- $^{132}\text{Sn} + ^{132,134,136}\text{Xe} \rightarrow ^{264,266,268}\text{Rf}^*$
- $^{132}\text{Sn} + ^{138}\text{Ba} \rightarrow ^{270}\text{Sg}^*$
- $^{132}\text{Sn} + ^{139}\text{La} \rightarrow ^{271}\text{Bh}^*$
- $^{132}\text{Sn} + ^{140,142}\text{Ce} \rightarrow ^{272,274}\text{Hs}^*$
- $^{132}\text{Sn} + ^{142-150}\text{Nd} \rightarrow ^{274-282}\text{Ds}^*$
- $^{90,92}\text{Kr} + ^{181}\text{Ta} \rightarrow ^{271,273}\text{Mt}^*$
- $^{90,92}\text{Kr} + ^{186}\text{W} \rightarrow ^{276,278}\text{Ds}^*$
- $^{44}\text{Ar} + ^{232}\text{Th} \rightarrow ^{276}\text{Hs}^*$
- $^{44}\text{Ar} + ^{238}\text{U} \rightarrow ^{282}\text{Ds}^*$

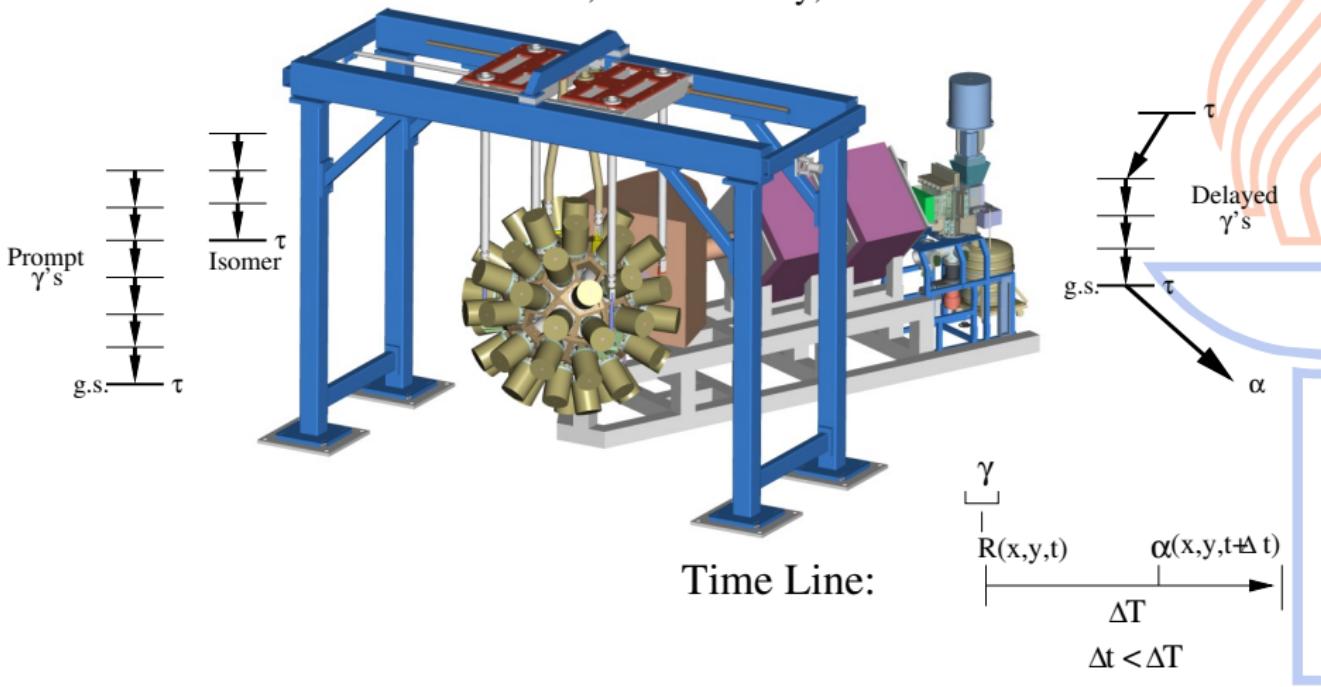
Towards N=184?

Difficult even with radioactive beams

- $^{90-95}\text{Kr} + ^{208}\text{Pb} \rightarrow ^{298-303}118^*$
- $^{132}\text{Sn} + ^{170}\text{Er} \rightarrow ^{302}118^*$
- $^{132}\text{Sn} + ^{176}\text{Yb} \rightarrow ^{308}120^*$

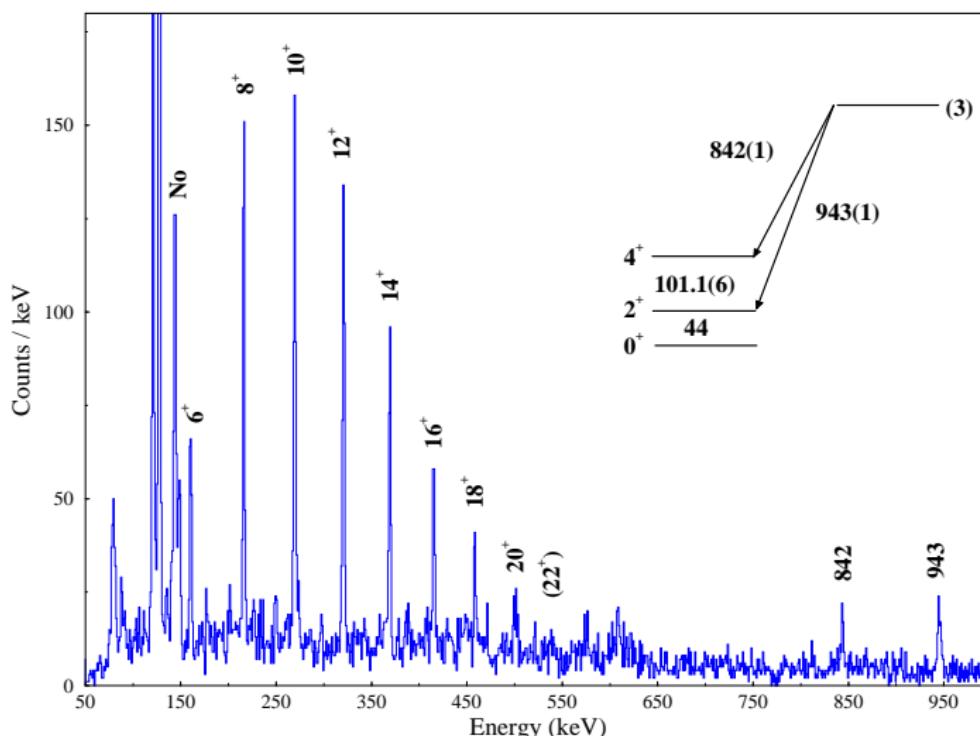
Principles of RDT

Tagging Techniques Recoil, Recoil–Decay, Isomer

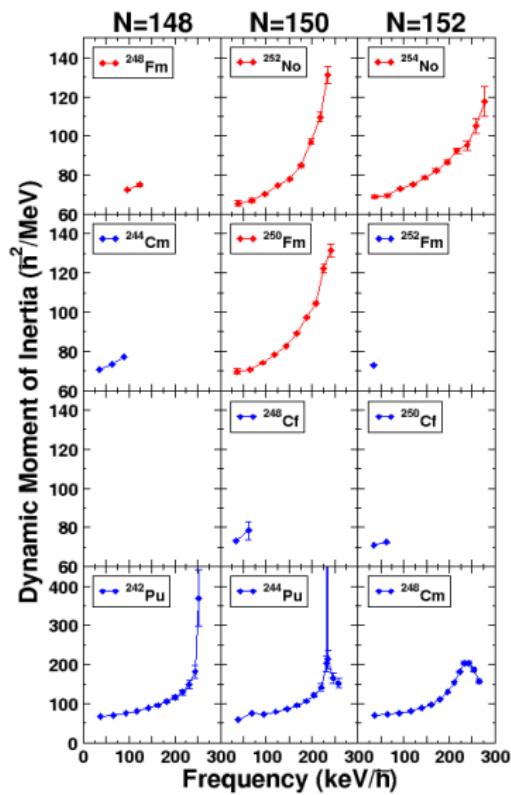


In-beam γ -ray Spectroscopy of ^{254}No

$^{48}\text{Ca} + ^{208}\text{Pb} \Rightarrow ^{254}\text{No} + 2\text{n}$, S. Eeckhaudt, P.T. Greenlees et al., EPJA **26**, 227 (2005)



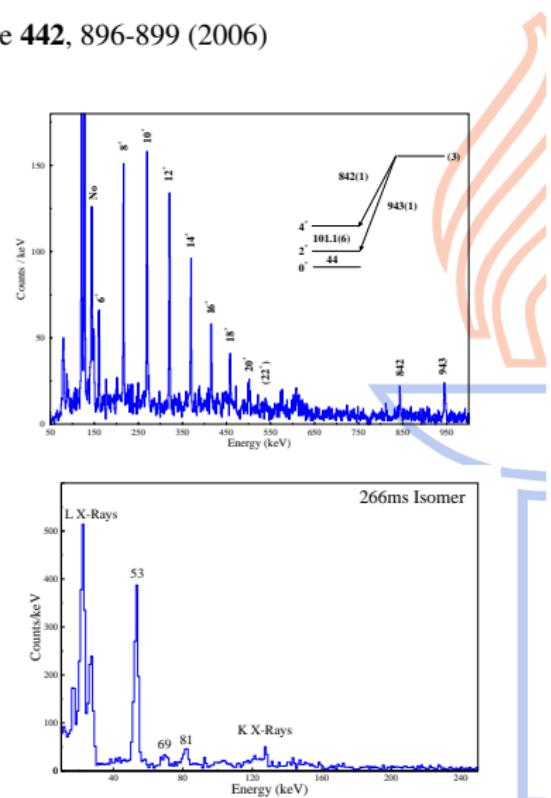
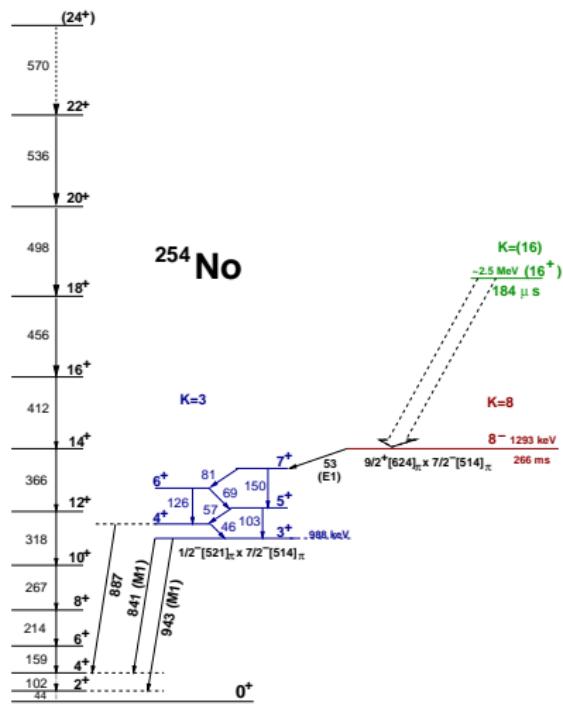
Moment of Inertia Systematics (Even-Even Nuclei)



- Confirmed deformed nature of nuclei around ^{254}No
- Showed fission barrier robust with spin ($> 20\hbar$)
- Faster alignment at $N=150$ compared to $N=152$ ($\pi i_{13/2}, \nu j_{15/2}$)
- Excellent testing ground for theory; e.g.
 - Duguet et al., NPA **679**, 427 (2001),
 - Bender et al., NPA **723**, 354 (2003),
 - Afanasjev et al., PRC **67**, 024309 (2003),
 - Egido and Robledo, PRL **85** 1198 (2000)

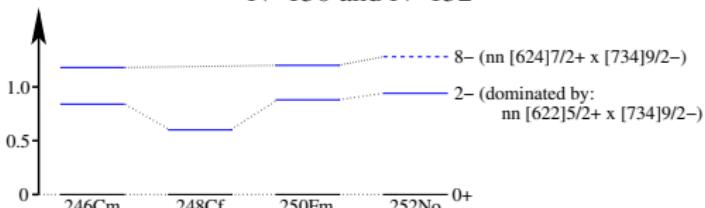
Structure and K-Isomerism in ^{254}No

R.-D. Herzberg, P.T. Greenlees et al., Nature **442**, 896-899 (2006)

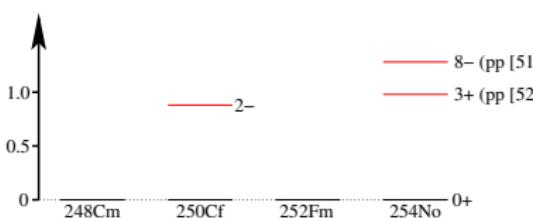
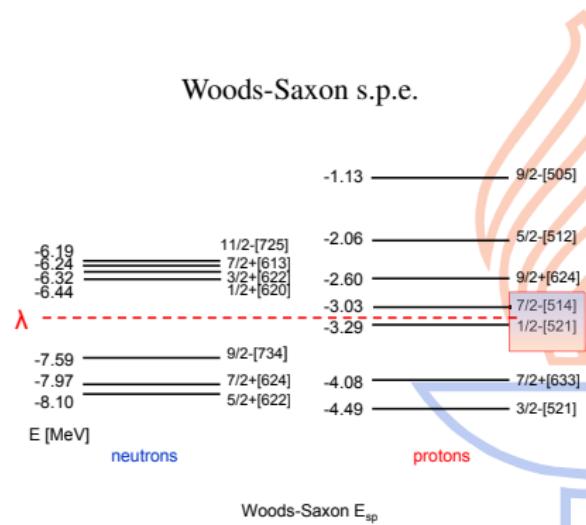


Systematics of 2 quasi-particle states

N=150 and N=152

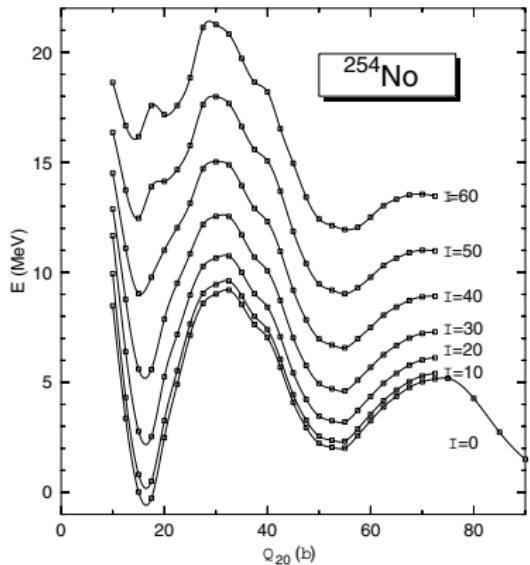


Woods-Saxon s.p.e.



Soloviev et al., Yad. Fiz. 54, 1232 (1991)
 ^{250}Cf 2⁻ - p[633]7/2⁺ \otimes p[521]3/2⁻ 72%

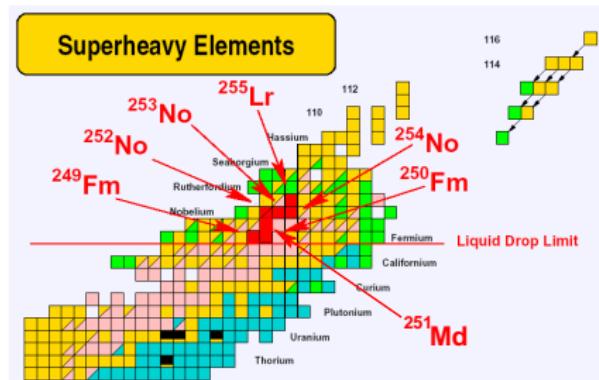
Higher spin and excitation energy?



- Excitation function narrow
- $^{92}\text{Kr} + ^{164}\text{Dy} \rightarrow ^{256}\text{No}^*$
- Access higher spin (SD??) states
- Produce more neutron-rich nuclei
- Required intensities may be lower

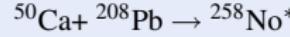
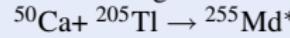
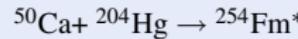
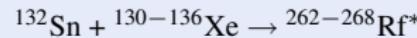
Egidio and Robledo, PRL85 (2000) 1198

Sample Reactions

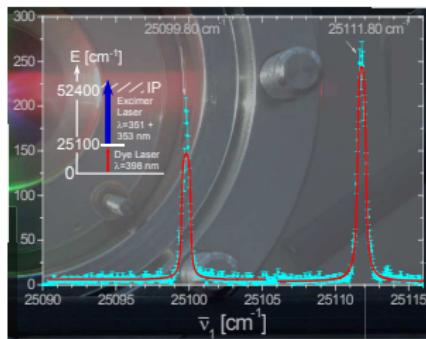
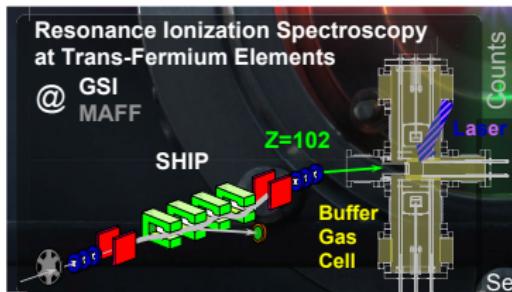


Around N=152

$^{90-96}\text{Kr} + ^{164}\text{Dy} \rightarrow ^{254-260}\text{No}^*$
Also Sr,Rb



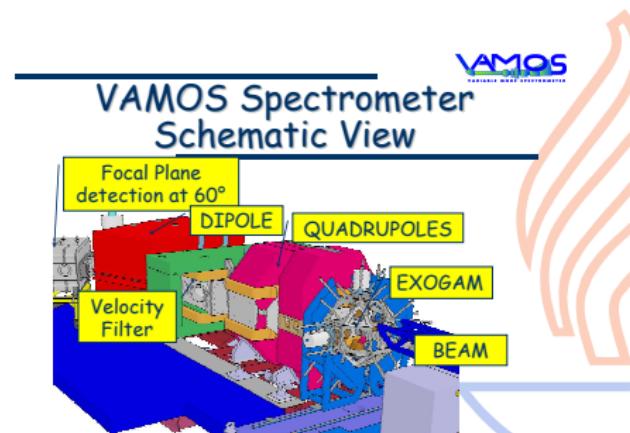
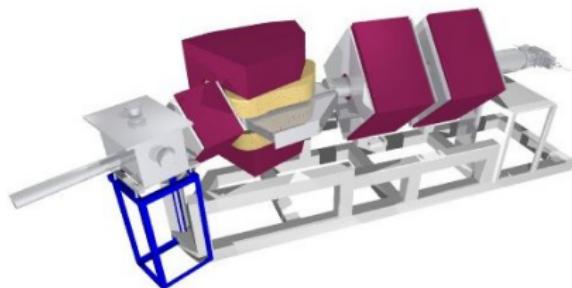
Optical spectroscopy of heaviest elements



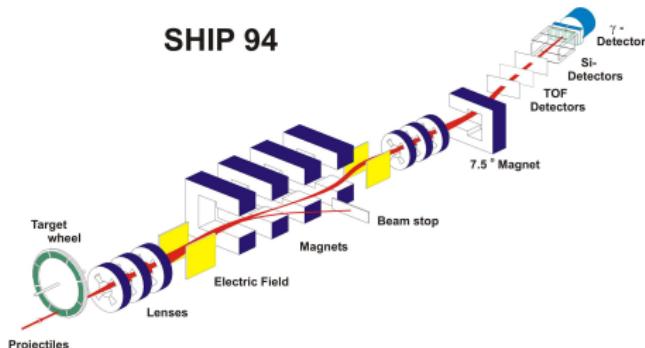
Sewtz et al., PRL90

- Sample of ^{255}Fm produced at ORNL
- Breeding of ^{255}Es from ^{246}Cm
- Sample transported to Germany (about 10^{11} atoms)
- Isotope Shift and Hyperfine Spectroscopy
- Next step ^{254}No (5 ions/s)
- Similar reactions as for decay/in-beam
- Heavily dependent on atomic theory

Recoil Separator?



SHIP 94

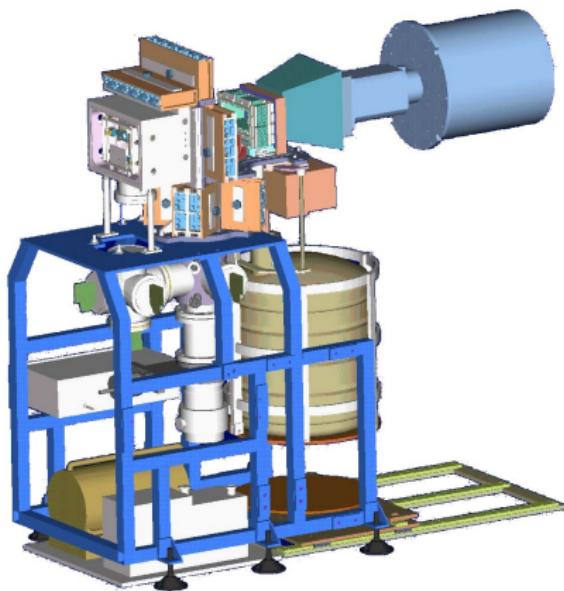


Instrumentation

Recoil Separator

- High Transmission
- High mass resolution not essential (but useful!)
- Excellent beam suppression
- Deal with both symmetric and asymmetric reactions
- Compact focal plane image size
- High granularity Si detectors
- As much Ge as possible at focal plane
- Possibility to measure conversion electrons at focal plane
- Problems: What to do with unreacted beam (target chamber and beam dump)?

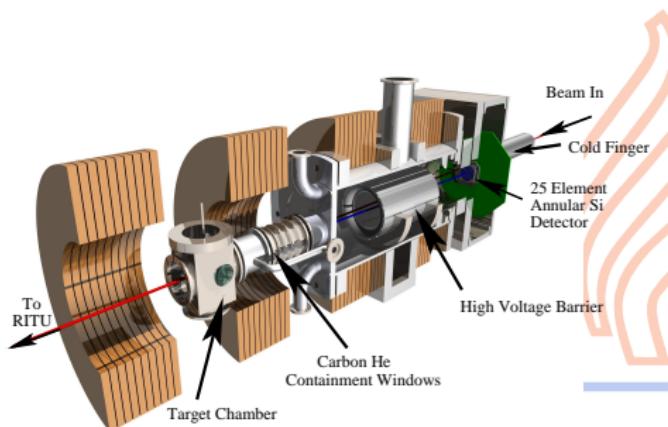
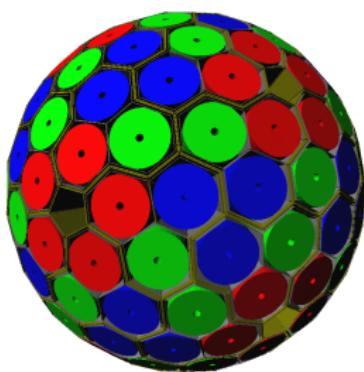
Instrumentation: Focal Plane starting point



- UK Universities + Daresbury
- $2 \times 60 \text{ mm} \times 40 \text{ mm}$ DSSSD
- $28 \times 28 \text{ mm} \times 28 \text{ mm}$ PIN Diodes
- 24×12 Segmented Planar Ge
- Compton-Suppressed 16-fold Segmented Clover Ge
- Position Sensitive MWPC
- Total Data Readout (TDR) Acquisition System

R.D.Page et al., NIM **B204**, 634 (2003)

Instrumentation: Gamma and Electron Spectroscopy



AGATA

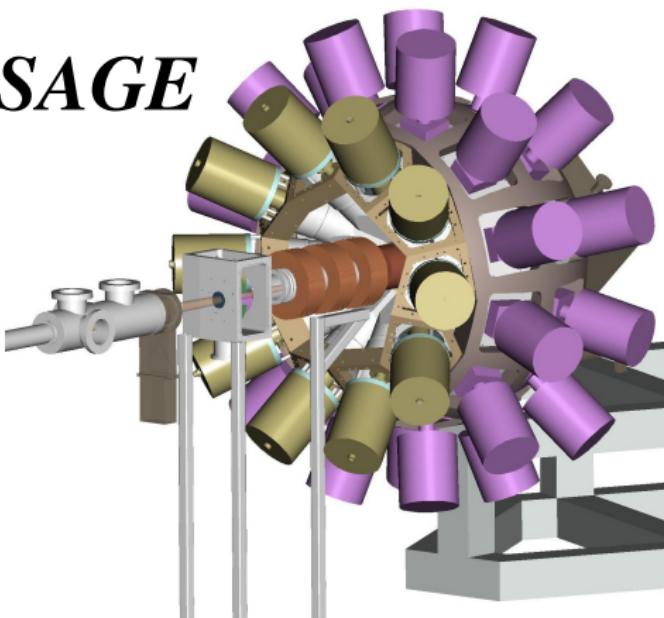
- Highly Efficient 40%
- High Count Rate Capability
- Alternatives necessary
- Combined electron spectroscopy

SACRED

- Highly Efficient > 10%
- High Count Rate Capability
- 1 keV intrinsic resolution
- Superconducting?

Instrumentation: Gamma and Electron Spectroscopy

SAGE



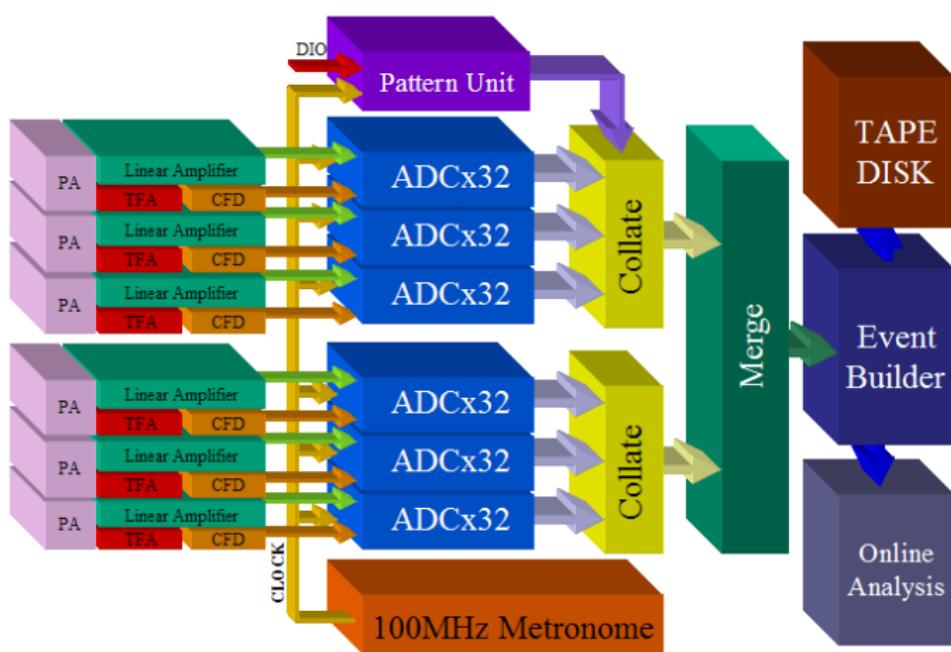
- Simultaneous Electron-Gamma Measurements
- Combine Digital Electronics with TDR
- Unique and Powerful Device for Spectroscopy of Heavy Nuclei



THE UNIVERSITY
of LIVERPOOL



Instrumentation: DAQ starting point



I.H.Lazarus et al., IEEE Trans. Nucl. Sci **48**, 567 (2001)

Instrumentation: Optical Spectroscopy

- Recoil Separator
- Buffer Gas Cell (UHV-set up) + optical resonator
- High repetition, high-power laser systems
- 1 kHz repetition rate, $> 353 \text{ mJ/pulse}$ @ 353nm
- PIPS detectors

Beam Requirements: All

- Around 5 MeV/u
- Narrow excitation functions
- Energy resolution better than 1%
- Reproducible, absolute energy measurement
- Emittance no worse than present stable beams ($5\pi\text{mm mrad}$ or better)
- Highest possible intensity!

Summary

The EURISOL Facility

- Offers a great opportunity to extend the study of SHE
- Access to nuclei which cannot be produced with stable beams
- New nuclear structure data at the upper extreme of the chart
- Input needed in cross-section calculations (beam selection)
- Recoil separator design needs manpower
- Radiation issues to be resolved
- Suppression of background and beam dumping