Spectroscopy of Very Heavy Elements

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Fréjus, France

What is the link?




Outline

Outline

SHE Workshop UWS Paisley

- **What is the structure of the superheavy elements?**
- **How can the study of transfermium nuclei inform the structure of the superheavy elements?**
- What is predictive power of theory for the transfemium nuclei and the superheavies? Are extrapolations reliable?
- What are experimental uncertainties? What data can be safely used by theorists to benchmark modern density functionals?
- What new experimental data are needed? Is there any guidance from theory in that respect?
- What are the crucial questions regarding the structure of the transfermium nuclei?

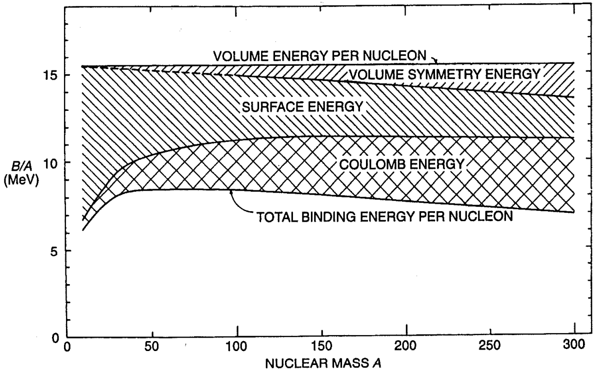
http://nuclear1.paisley.ac.uk/SHEworkshop/

- **Ultimate goal of the work addressed here: To confront theoretical predictions of the structure of heavy nuclei with spectroscopic experimental data of the highest quality**

What is a Superheavy Element?

Reminder - Nuclear Binding Energy:

$$B = a_{volume}A - a_{surface}A^{2/3} - \frac{1}{2}a_{symmetry}\frac{(N-Z)^2}{A} - \frac{3}{5}\frac{Z^2e^2}{4\pi\epsilon_0 R_C} \quad (1)$$

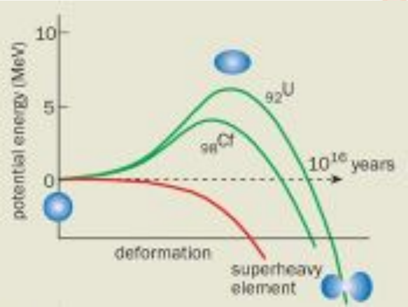


What is a Superheavy Element?

Liquid Drop Model and Fission Barrier:

$$E(d) = E_C(d) + E_S(d) = a_C \frac{Z^2}{A^{1/3}} \left(\frac{E_C(d)}{\overset{0}{E}_C} \right) + a_S \left(1 - \kappa_S \left(\frac{(N-Z)}{A} \right)^2 \right) A^{2/3} \left(\frac{E_S(d)}{\overset{0}{E}_S} \right) \quad (2)$$

- $\overset{0}{E}_C$,$\overset{0}{E}_S$ - spherical shape
- Calculate for a sequence of nuclear shapes
- e.g. Expansion of nuclear radius in spherical harmonics
- $R(\theta, \phi) = c(\beta_\lambda) R_0 \left[1 + \sum_{\lambda=2}^{\lambda_{max}} \beta_\lambda Y_{\lambda 0}(\theta, \phi) \right]$



What is a Superheavy Element?

Fissility Parameter and Barrier Height

- Competition of Coulomb repulsion and surface tension
- Fissility Parameter, $x = \frac{E_C^0}{2E_S^0}$
- Barrier Height, $E_{barrier} = \frac{98}{15}\frac{(1-x)^3}{(1+2x)^2}E_S^0$
- Superheavy Element - $E_{barrier} = 0, x > 1$
- Fuzzy definition - depends on parameterisation

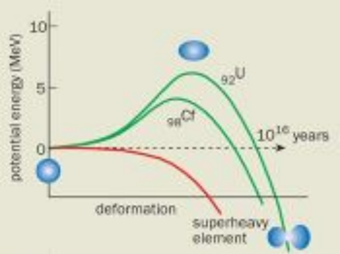


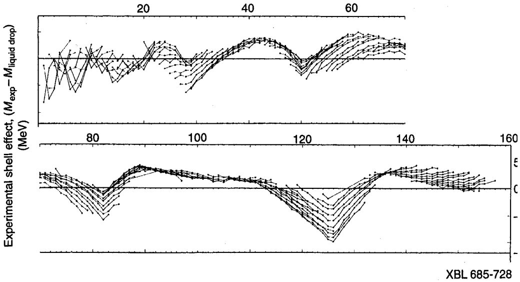
Table 4.1. *Height of fission barriers and β_2 (a_2) deformations at the top*
the barrier calculated in the liquid-drop model using a third-order expansio
for different values of the fissility parameter x.

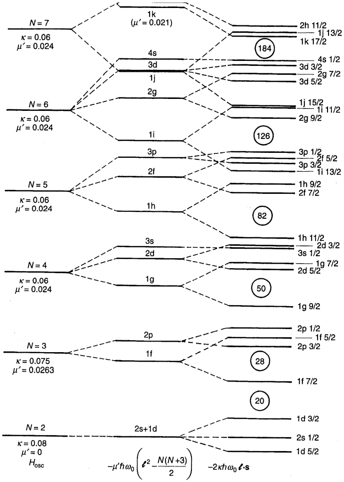
	Z^2/A	x	E_{barr} (MeV)	a_2^{barr}	β_2^{barr}
$^{209}_{83}$Bi	32.96	0.700	17.9	0.88	1.40
$^{232}_{90}$Th	34.91	0.753	9.7	0.69	1.09
$^{238}_{92}$U	35.56	0.769	7.8	0.64	1.01
$^{242}_{94}$Pu	36.51	0.787	6.0	0.58	0.92
$^{254}_{100}$Fm	39.37	0.841	2.4	0.41	0.65
$^{294}_{110}$X	41.16	0.912	0.4	0.22	0.35

What is a Superheavy Element?

Enhanced Stability - Shell Effects

- Nucleus not simply a liquid drop
- Evidence e.g. from masses
- Enhanced stability at 2,8,20,28,50,82,(126)
- Confining potential - gaps in energy level spectrum
- Reproduction of Magic Numbers - l^2 and $l.s$ terms

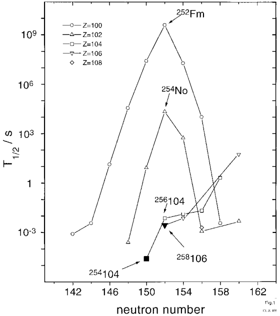


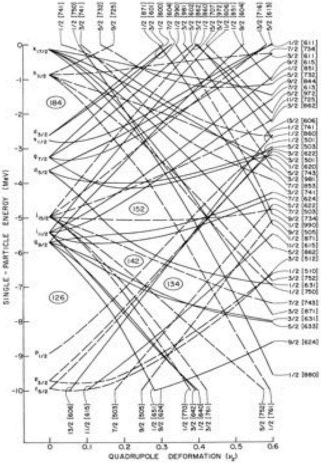


What is a Superheavy Element?

Enhanced Stability - Shell Effects

- Majority of nuclei not spherical
- Effect of deformation?
- Deformed shell gaps
- Enhanced stability e.g. at N=142,152





What is a Superheavy Element?

Enhanced Stability - Shell Effects

- Strutinsky Method
- $E = E_{LDM} + E_{SHELL}$
- $E_{SHELL} = \sum_{i=1}^{A} \epsilon_i(\delta) - \widetilde{E}_{SHELL}$
- Calculate Potential Energy Surface

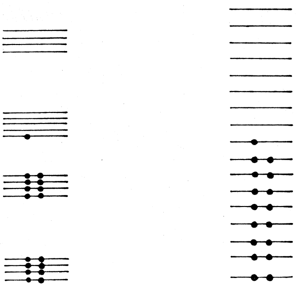
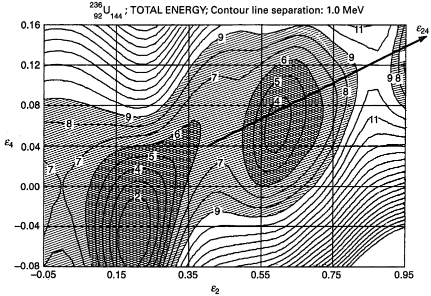
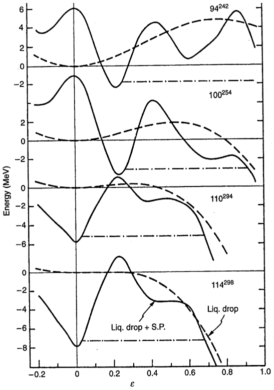


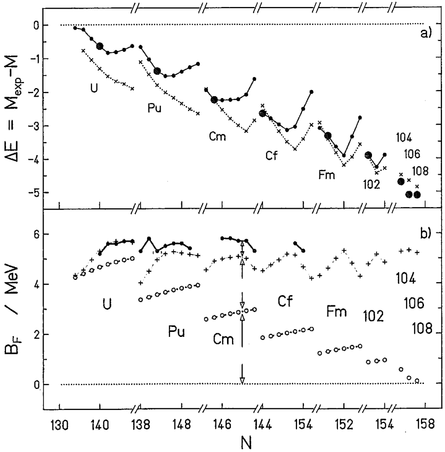
FIG. 8. Schematic diagram of Strutinsky shell-correction method illustrating the difference between bunched energy levels and a smooth level ordering. In practical calculations actual energy levels are used.



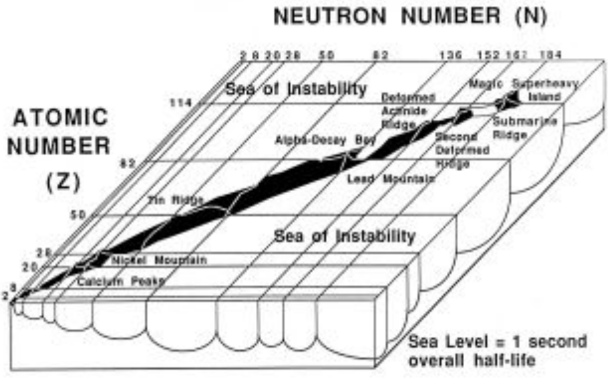
What is a Superheavy Element?

Back to the Fission Barrier





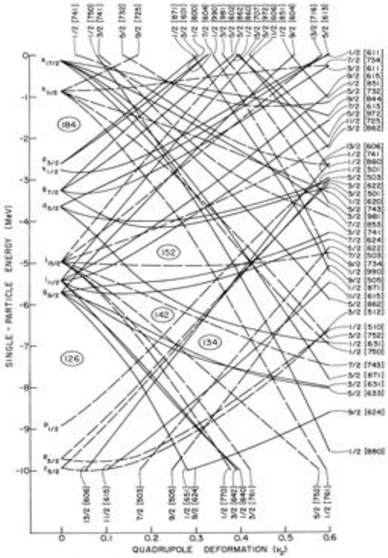
The Island of Stability

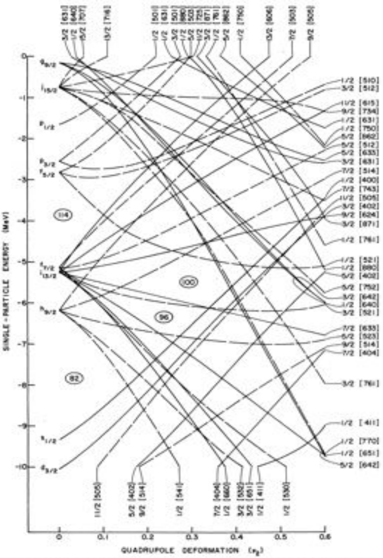


An allegorical representation of the stability of nuclei showing a peninsula of known stable or nearly stable nuclei and a ridge of relatively stable nuclei around Z = 108 and N = 162 and a predicted Magic Superheavy Island around Z = 114 and N = 184.

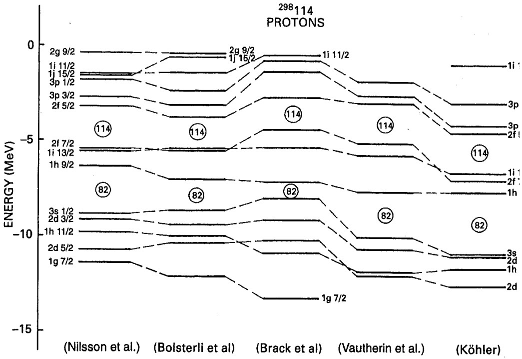
The Seaborg Archive, LBL

Next Spherical Shell Gap?





Next Closed Shells? Where is the Island?



Extrapolation with Mass

- Gap at Z=114 sensitive to spin-orbit strength
- Splitting of $f_{5/2}$ and $f_{7/2}$
- Differences in level ordering/spacing
- Large uncertainties in extrapolation

Next Closed Shells? Where is the Island?

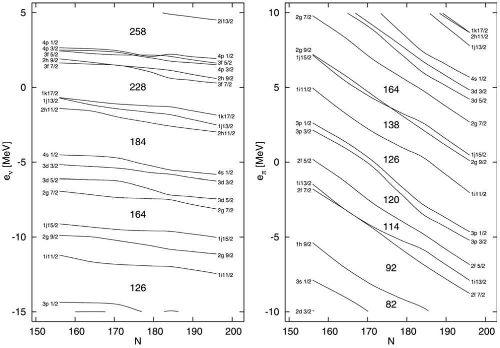


Fig. 37. The Gogny neutron and proton single-particle levels for $Z = 114$ as functions of the neutron number N.

Extrapolation with Mass

- Proton shell gaps change with N
- Z=114,120 only for neutron-deficient isotopes?
- Evolution of shell structure
- c.f. light neutron-rich nuclei

Sensitivity to Deformation

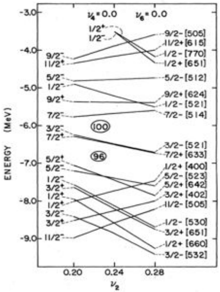


FIG. 8. Actinide proton single-particle levels as a function of ν_2; $\nu_4=0.0$, $\nu_6=0.0$.

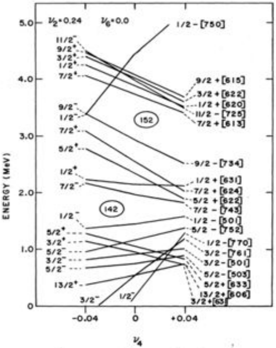


FIG. 6. Actinide neutron single-particle levels as a function of ν_4; $\nu_2=0.24$, $\nu_6=0.0$.

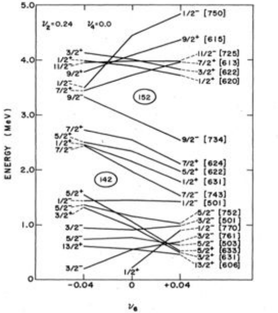
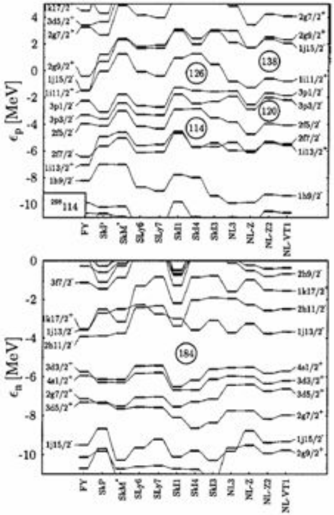


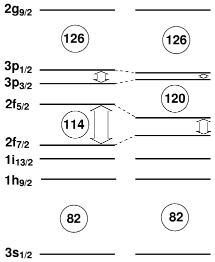
FIG. 7. Actinide neutron single-particle levels as a function of ν_6; $\nu_2=0.24$, $\nu_4=0.0$.

R.R. Chasman et al., Rev. Mod. Phys. **49**, 833 (1977)

Next Closed Shells? Where is the Island?



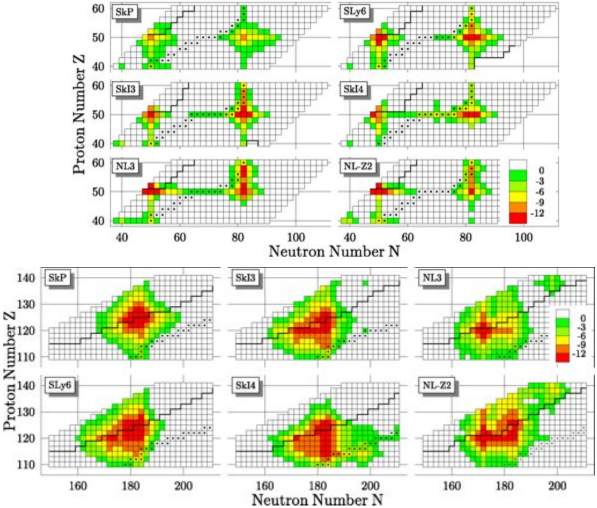
M. Bender et al., PRC60, 034304 (1999)



Self-Consistent Theories

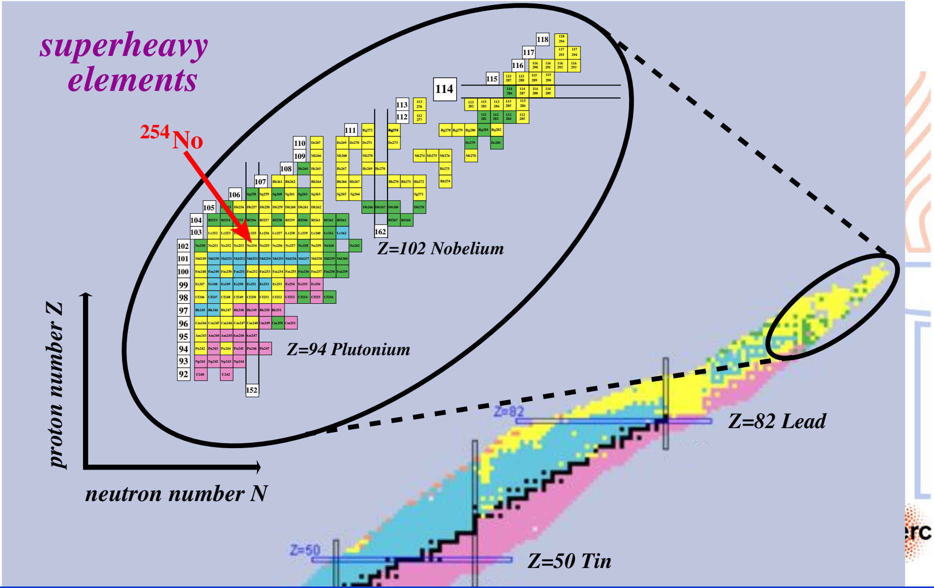
- Calculations based on realistic effective nucleon-nucleon interaction
- e.g. Skyrme
- Allows results to be traced back to interaction
- Difficult in Macroscopic-Microscopic calculations
- Need experimental data to determine correct ordering
- Will provide better predictions of properties of SHE

How big is the Island?

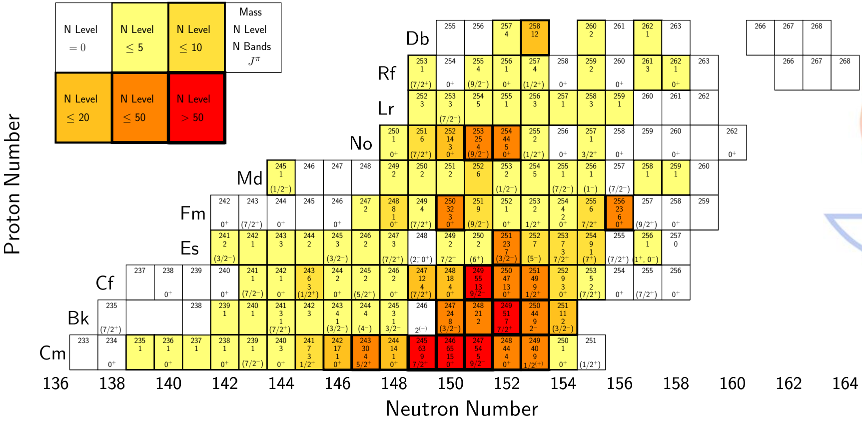


M. Bender, W. Nazarewicz, P.-G. Reinhard, PLB 515, 42 (2001)

What is the structure of SHE?

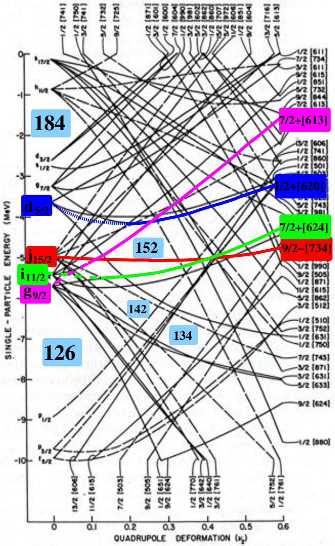


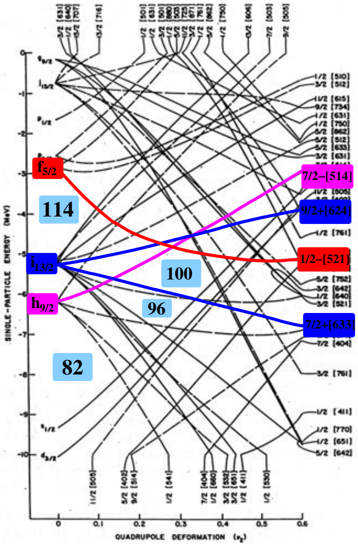
Knowledge of the Region



R.-D.Herzberg and P.T.Greenlees, Prog. Part. Nuc. Phys. 61, 674 (2008)

What is the structure of SHE?

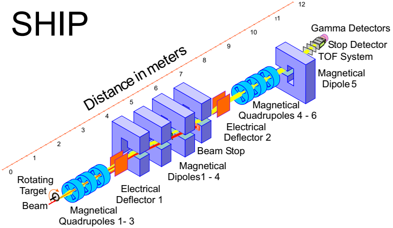


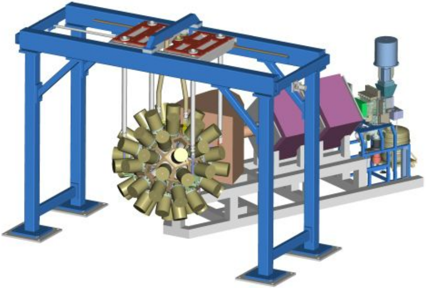


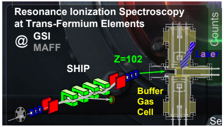
Outline

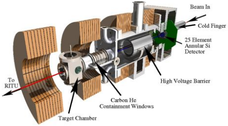
Experimental Approaches

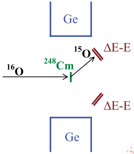
SHIP







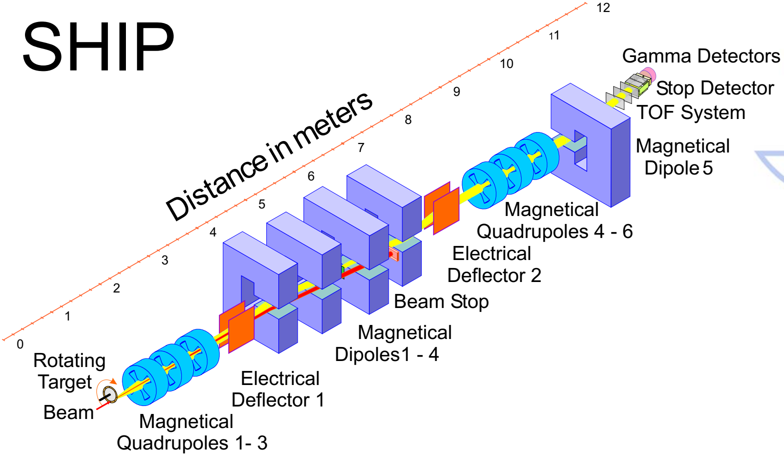




Recoil Separators - Velocity Filters

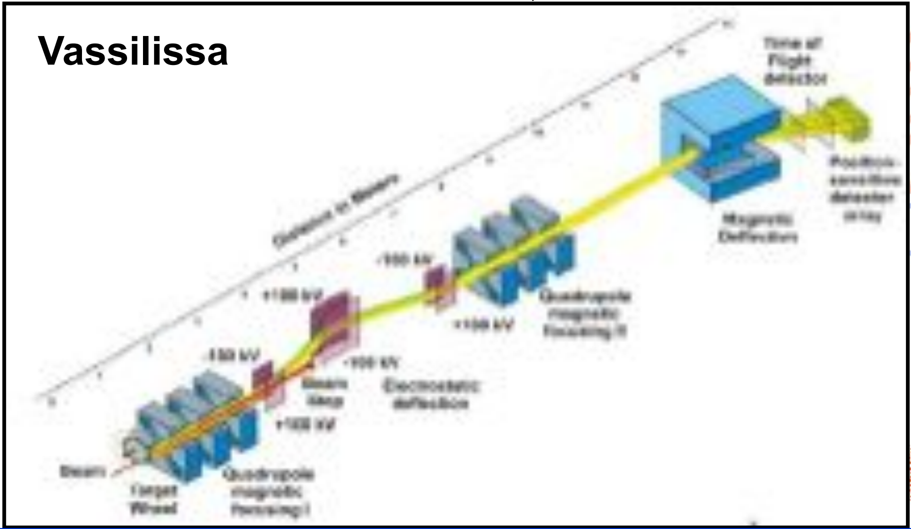
$$F_B = qvB, \; F_{el} = qE \quad (3)$$

$$F_{tot} = (F_B - F_{el}) = q(vB - E) \rightarrow F_{tot} = 0 \quad \text{for} \quad v = -E/B \quad (4)$$



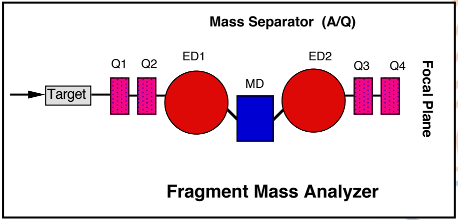
Recoil Separators - Velocity Filters

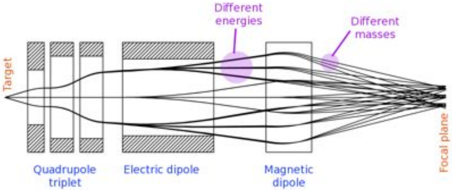
FLNR - JINR, Dubna



Recoil Separators - Mass Spectrometers

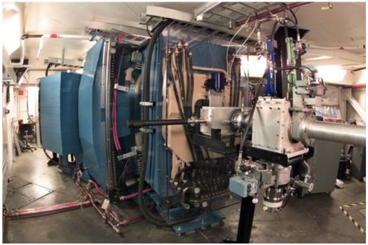
Argonne National Laboratory
Argonne Tandem Linear Accelerator System (ATLAS)



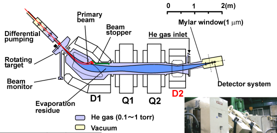


Recoil Separators - Gas-Filled Separators

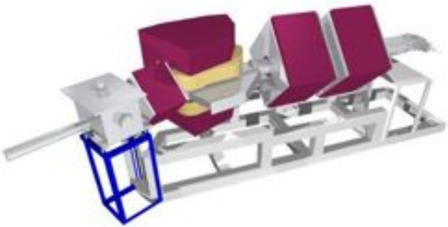
$$B\rho = \frac{mv}{q_{ave}} = \frac{mv}{[(v/v_0)eZ^{1/3}]} = \frac{0.0227A}{Z^{1/3}}\ \mathrm{Tm}, \qquad (5)$$



RIKEN GARIS(Gas-filled Recoil Ion Separator)



Magnification	X	-0.76
	Y	-1.99
Dispersion		0.97 cm/%
Total length		5760 mm
Acceptance	Δθ	± 68 mrad
	Δϕ	± 57 mrad
	ΔΩ	12.2 msr



Decay Spectroscopy

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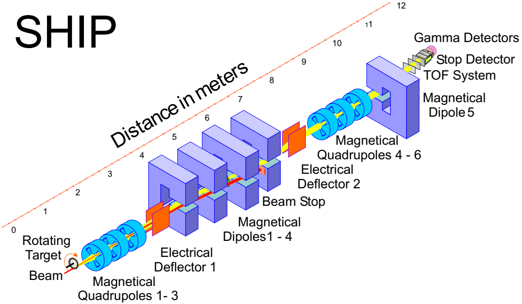
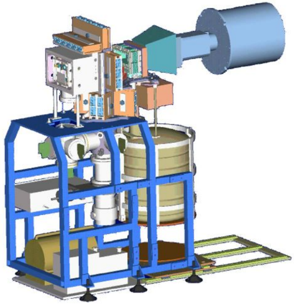
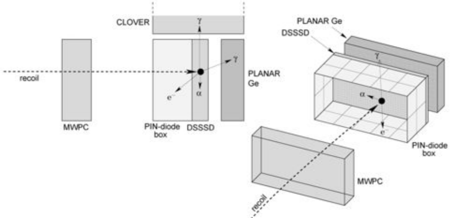
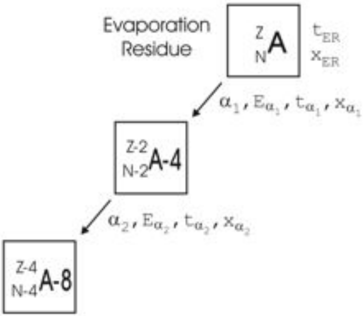






- Alpha-Gamma/Electron Coincidences
- Excitation energies, spins, parities
- High beam intensities (pμA)
- Clean environment

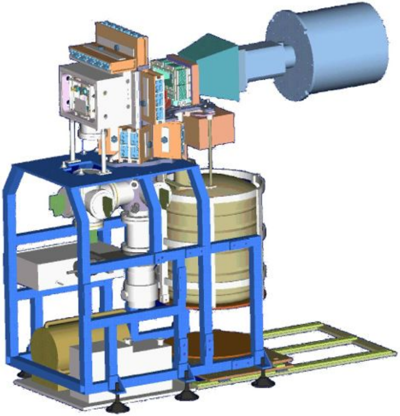
Genetic Correlations



S.Antalic, Thesis 2005

- Search for pairs of events at same x,y position
- Search time Δt
- Based on assumption that paired events follow each other in time
- $P_{acc}=Tr_1r_2r_3\Delta t_{1,2}\Delta t_{2,3}$

The GREAT Spectrometer



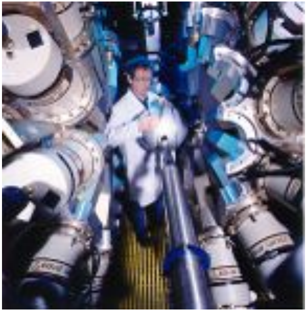
- UK Universities + Daresbury
- 2 × 60 mm × 40 mm DSSSD
- 28 × 28 mm × 28 mm PIN Diodes
- 24 × 12 Segmented Planar Ge
- Compton-Suppressed 16-fold Segmented Clover Ge
- Position Sensitive MWPC
- Total Data Readout (TDR) Acquisition System

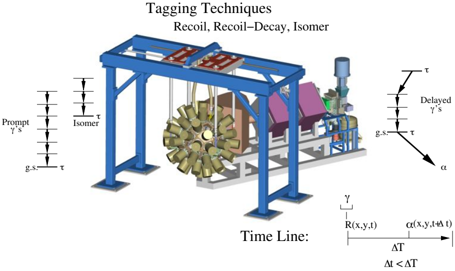
R.D.Page et al., NIM **B204**, 634 (2003)

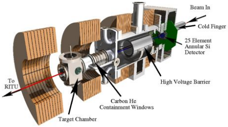
In-beam Spectroscopy

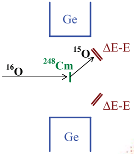
Observables

- Excitation energies, spins, parities
- Moments of Inertia, Alignments

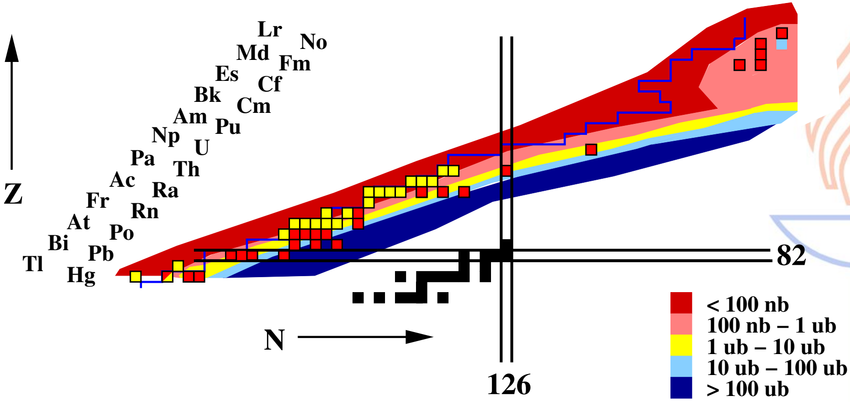








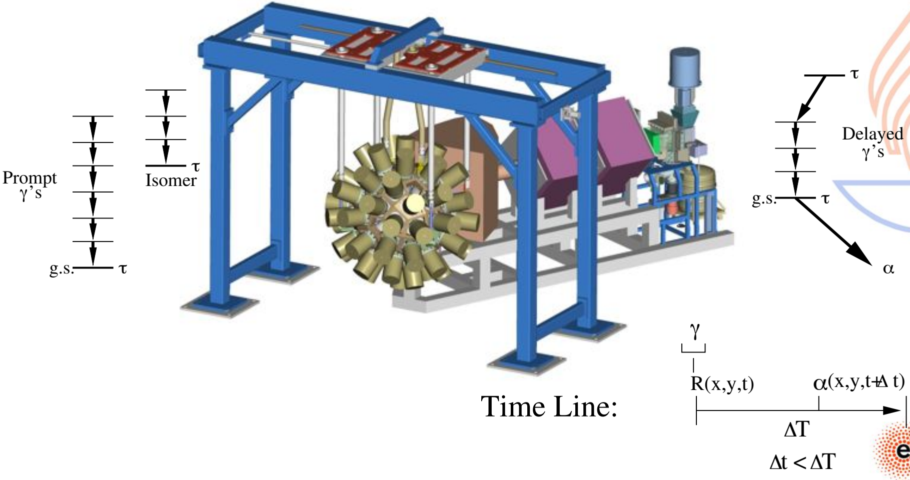
Cross Sections



Principles of Recoil-Decay Tagging

Tagging Techniques

Recoil, Recoil–Decay, Isomer



Recoil-Decay Tagging

Z. Phys. A – Atomic Nuclei 325, 197–202 (1986)

Zeitschrift für Physik A
Atomic Nuclei
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Evidence for Nuclear Shape Coexistence in ^{180}Hg

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Received August 4, 1986

The γ decay in the radiative fusion reaction ^{90}Zr + ^{90}Zr → ^{180}Hg + $x\gamma$ has been observed in an array of NaI detectors. States up to 6^+ in the yrast sequence of ^{180}Hg are tentatively assigned and suggest the coexistence of weakly oblate and strongly prolate nuclear shapes. The difference in potential energy between the two inferred shapes has dropped to about 200 keV, continuing the downward trend observed in the heavier even isotopes $^{188-182}$Hg.

Volume 168B, number 1,2 PHYSICS LETTERS 27 February 1986

GAMMA-SPECTROSCOPIC INVESTIGATIONS IN THE RADIATIVE FUSION REACTION ^{90}Zr + ^{90}Zr

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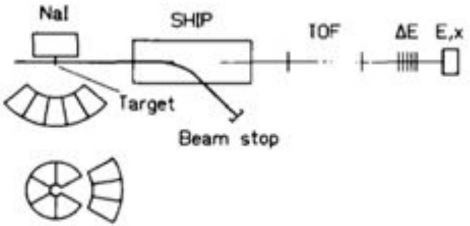
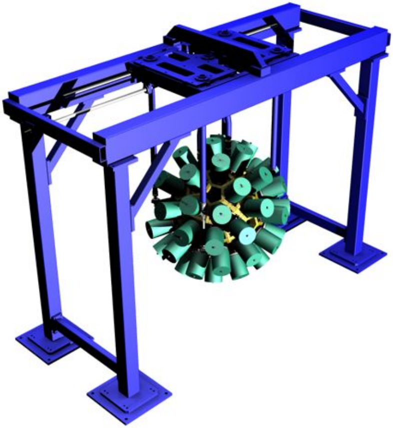
Received 3 July 1985

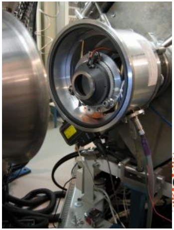
The γ rays emitted in the radiative fusion reaction ^{90}Zr + ^{90}Zr → ^{180}Hg + $x\gamma$ were measured. No indication was found for a specific direct capture process associated with a high-energy γ ray. The shape of the observed γ spectrum is compatible with a statistical deexcitation of the compound nucleus.



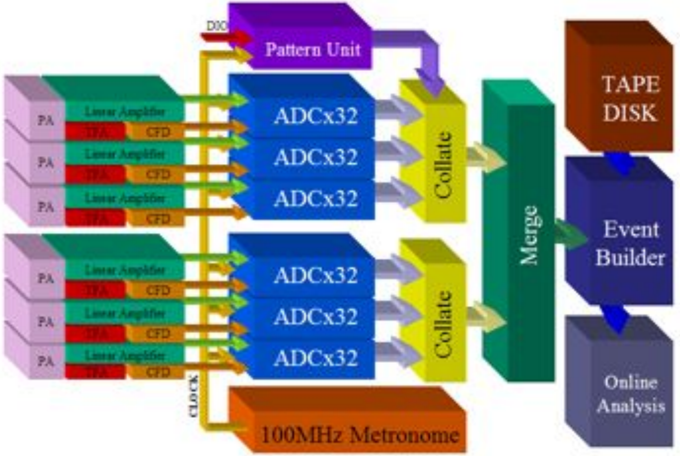
The JUROGAM Germanium Array



- 43 Phase I and GASP-type Ge detectors - EUROBALL and U.K.-France loan pool
- Total Photopeak Efficiency 4.2% @ 1.3 MeV
- Much improved (x10) γ-γ efficiency
- Software Compton suppression
- Autofill system built by University of York, part of GREAT
- Target chamber built by IReS Strasbourg, allows use of rotating target wheel
- Modified EUROGAM support structure

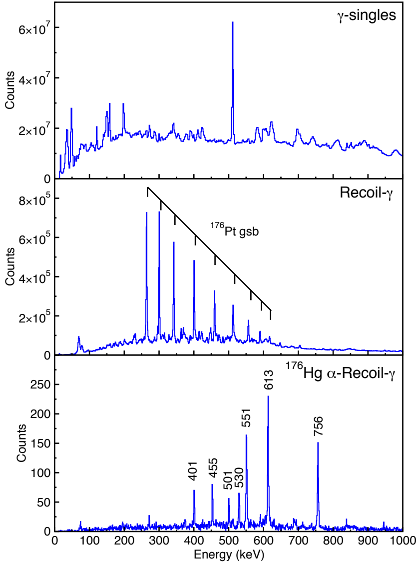


Anatomy of Total Data Readout (TDR)



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

In-beam Spectroscopy: Recoil-Decay Tagging



- Typical beam intensity: 6.25×10^{10} pps
- Total Gamma Ray Counting Rate: >1 MHz
- 10 nb - 3 reactions/hour
- 1 in 10^9 selectivity

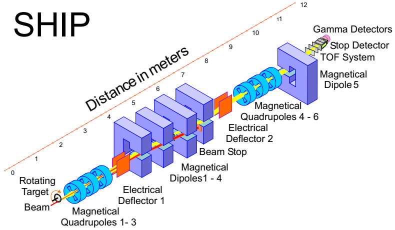
Experimental Data

- Is the data reliable?
- Do we get the full picture?
- Favoured (α, β) decays connect states of similar structure
- Coincidence techniques give multipolarities (spin/parity changes)
- Very few reliable measurements of ground-state spins/parities
- Did we really see the ground state?
- Transfer reactions powerful tool - limited number of cases
- Complemented by in-beam studies (MoI, $B(M1)/B(E2)$, g_K, etc)
- K-isomers also give valuable information on location of s.p. states

Outline

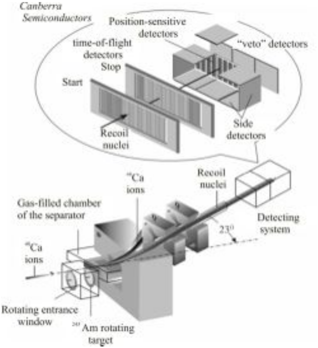
Centres for study of SHE

GSI

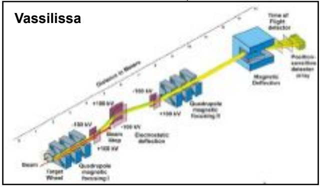


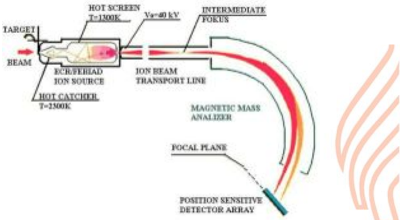
- Renowned centre of SHE research
- New elements 107-112 (Bh-Cn)
- SHIP/TASCA
- Synthesis/Structure/Chemistry
- Intensities pμA range
- Radioactive Targets

FLNR



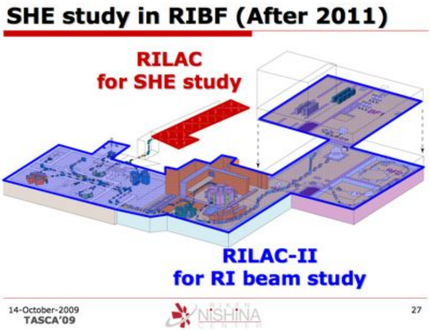
FLNR - JINR, Dubna

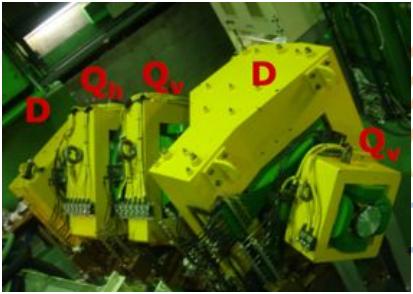




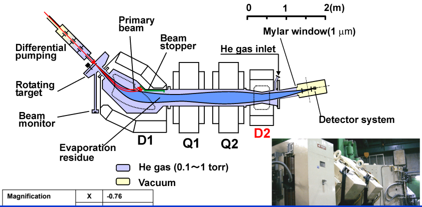
- Renowned centre of SHE research
- Large number of new elements (recently 114-118)
- GFRS/Vassilissa/MASHA
- Synthesis/Structure/Chemistry
- Intensities pμA range
- Radioactive Targets
- New dedicated facility under construction

RIKEN



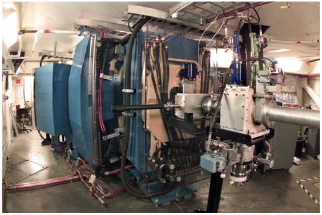


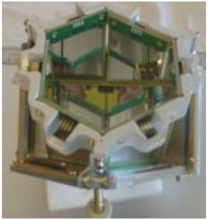
RIKEN GARIS(Gas-filled Recoil Ion Separator)



- GARIS/GARIS2
- Synthesis/Structure/Chemistry
- Recently been studying 113
- Intensities pμA range
- Radioactive Targets
- New dedicated facility for SHE

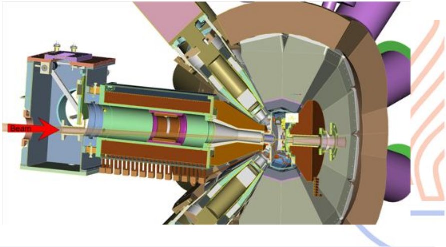
Lawrence Berkeley Laboratory

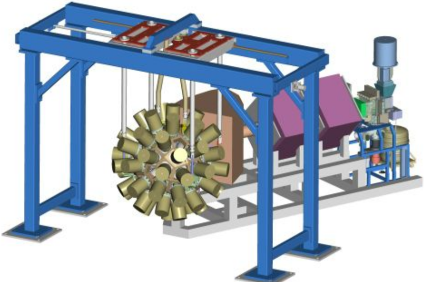




- Historical centre of SHE research
- 88 inch cyclotron/BGS
- Synthesis/Structure/Chemistry
- Intensities 0.4pμA range
- Radioactive Targets
- Recently hosted GRETINA

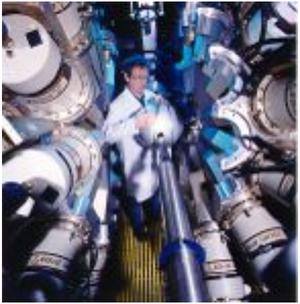
JYFL

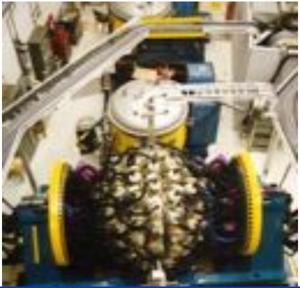


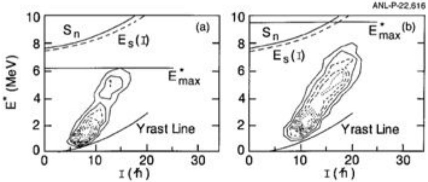


- JGII/RITU/GREAT/SAGE
- Structure
- Specialist in in-beam work
- Intensities 0.1pμA range
- Electron spectroscopy unique
- New Mass Spectrometer MARA

ANL

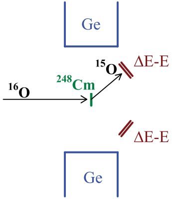


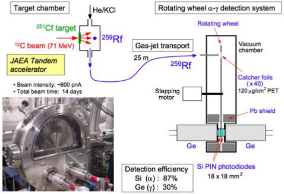




- GS/FMA
- Structure
- In-beam and decay spectroscopy
- Intensities 0.4pμA range
- Entry distribution measurements unique
- Intensity Upgrade
- Digitised GS
- Plans for new GFS

JAEA Tokai





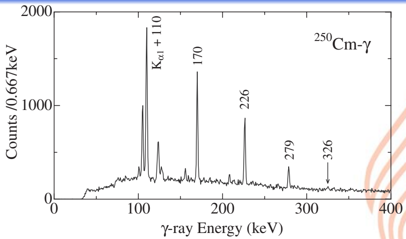
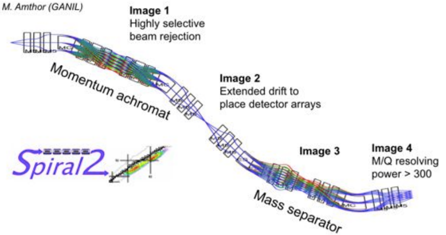
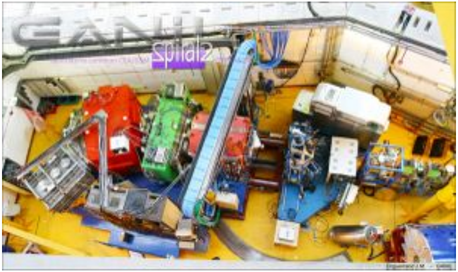


Fig. 2. γ-ray spectrum of ^{250}Cm, obtained by setting the gate on [16] indicated by the enclosed area in Fig. 1.

- Tandem/Booster
- Structure/Chemistry
- In-beam and decay spectroscopy
- Intensities 0.4pμA range
- Radioactive Targets
- Transfer Reactions

GANIL





- LISE/VAMOS/EXOGAM
- Structure
- In-beam and decay spectroscopy
- Intensities 0.4pμA range
- VAMOS tested in GF mode
- S^3/LINAG under development