Heavy element spectroscopy
(focus on interplay between collective and single-particle motions)

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Outline

- Motivation

- Experimental techniques

- Structure of N=150 & N=151 isotones

- Detailed spectroscopy of $^{251}$Fm in Dubna

- Conclusion & perspectives
The heaviest nuclei owe their stability against spontaneous fission to quantum shell effects.
Available spectroscopic data

Comparison to theory

Single particle energies extracted from experimental energies in $^{247,249}$Bk, $^{251}$Es & $^{247}$Cm, $^{251}$Cf

Issues:
Wrong ordering
Wrong gaps
Missed degeneracies
Experimental challenge

Unreacted beam
Scattered beam
Transfer: beamlike
Transfer: targetlike
Coulex
Quasi-fission
Fusion - Fission
Fusion & Survival of
the nucleus of interest:
\( \sigma \sim 1-1000 \text{ nb} \)

For \( \sigma = 100 \text{ nb}, A_{\text{target}} \sim 200 \)
\( \Rightarrow \sim 1 \text{ ER/s per mg/cm}^2 \) and per \( \mu A \) of beam on target

\( \Rightarrow \) Need to select the needle in the hay stack!
Gas-jet Transport

$^{248}\text{Cm}(^{13}\text{C},4\text{n})^{257}\text{No}$ @ JAEA, Japan

In-flight separation

FLNR - JINR, Dubna

GSI - Darmstadt

Vassilissa

Separator for Heavy Ion reaction Products

University of Jyväskylä, Finland

Argonne National Laboratory
Argonne Tandem Linear Accelerator System (ATLAS)

other gas-filled devices: BGS, TASCA
Decay spectroscopy

\[ ^{250}\text{Fm} \]


\[ T_{1/2} = 1.92(5) \text{s} \]

\[ \text{Beam} \]

\[ \text{Filter} \]

\[ \text{ToF} \]

\[ \text{Recoils} \]

\[ \gamma \]

Recoil energy, \( \alpha \), electrons

Decay spectroscopy

\[ E^*, j^\pi, \tau \]

\[ Z, A \]

\[ \beta, \epsilon \]

Fission

\[ \alpha_1 \]

\[ \alpha_2 \]

\[ Z-2, A-4 \]
Prompt spectroscopy

Identification:
ToF + Energy & Decay

$\gamma$ and/or electron det.

Filter

Recoils

$\gamma, e^-$

isomer

$A_Z X$

$^{250}$Fm

Low-lying structures in N=150 isotones

\[ B(M1)/B(E2) \]
\[ E^*(8^-) \]
\[ \downarrow \]
\[ 7/2^+ [624] \nu \otimes 9/2^- [734] \nu \]

\[ \Delta j = \Delta l = 3 \]

Woods Saxon \( E_{sp} \)

\[ \begin{array}{c|c|c}
N=152 & \lambda & Z=100 \\
-7.00 & 9/2^- [734] & 7/2^+ [624] \, 5/2^+ [622] \\
-7.57 & 5/2^+ [622] & 3/2^- [521] \, 1/2^+ [613] \\
-8.07 & 1/2^+ [613] & \ \\
-8.54 & 5/2^+ [642] & \ \\
-9.04 & 7/2^- [734] & \ \\
\end{array} \]

SHELS@Dubna

VASSILISSA (Energy filter) ➞ SHELS (velocity filter)

Gain in transmission, especially for asymmetric reactions

GABRIELA@SHELS

Intense beam

Rotating target

8° magnet

Concrete wall

ToF

Focal plane

Triggerless detector array

Fission

ICE

γ

α
Spectroscopy of $^{251}\text{Fm}$

$^{248}\text{Cm}(^{12}\text{C},5\text{n})^{255}\text{No}$, gas-jet & rotating wheel $\alpha$–$\gamma$ detection

Spectroscopy of $^{251}_{\text{Fm}}$

$^{48}_{\text{Ca}} + ^{209}_{\text{Bi}} \rightarrow ^{257}_{\text{Lr}} \rightarrow ^{255}_{\text{Lr}} + 2n \xrightarrow{15\%} ^{255}_{\text{No}}$

$\sigma \sim 400 \text{ nb, } E_{\text{beam}} = 220 \text{ MeV mid-target}$

K. Rezynkina, PhD thesis (2016)
Spectroscopy of $^{251}$Fm

$\delta(E3/M2) = 0.76^{+0.20}_{-0.19}$

$T_{1/2} = 23.7 \pm 1.1\mu$s

$B(E3) = 18(6)$ W.u
$B(M2) = 3.0(6) \times 10^{-3}$ W.u
particle-vibration coupling


K. Rezynkina, PhD thesis (2016) and article in prep.
Comparison to theory

QRPA + GOGNY  I. Deloncle and S. Peru, private comm.

⇒ Inclusion of particle-phonon coupling is necessary to describe states in the region around $^{254}\text{No}$
2\(^+\) energies

« The energy gaps (closed shells or subshells) influence the values of moments of inertia and thus of \(E^{2+}\) of nuclei by weakening the pairing correlations, to which moments of inertia are very sensitive. »

2+ energies

![Graph showing 2+ energies](image)
Conclusion

- Presence of a low-lying octupole vibrational mode in nuclei around $^{254}\text{No}$ which affects excitation energies, transition strengths and possibly (?) moments of inertia and masses

- Care needs to be taken when comparing experimental & theoretical sp energies...

- Clear need for beyond-mean-field theoretical calculations in e-e but also o-e isotopes

- Importance of conversion electron spectroscopy to determine multipolarities & mixing ratios

- Can we measure the E1 rates out of the octupole-vibrational bands ? And would that be useful ?

- Can we trace the influence of the phonon in odd Z nuclei ($^{249}\text{Es}$, $^{251}\text{Md}$, $^{253}\text{Lr}$...?)
$N=152$ gap

