Decay spectroscopy in the rutherfordium region (Z = 104) at SHIP

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Transuranium nuclei

Region accessible by present technique
Production rate 1 - 10 event / week

Region accessible for nuclear spectroscopy
10 – 1000 nuclei / hour

Two examples for the decay spectroscopy
- Alpha-gamma decay spectroscopy
- Study of isotopes undergoing via EC
SHIP separator

Velocity filter optimized for fusion-evaporation reactions


Efficiency ~40 %
Flight time ~ 1-2 μs

Very powerful beam
$^{54}$Cr ~ 720 pA

Bi$_2$O$_3$, PbS target – 450 μg/cm$^2$
Rotating wheel – 31 cm diameter

Back detector
PSSD
Ge-Clover
<table>
<thead>
<tr>
<th>Element</th>
<th>Mass Number</th>
<th>Decay Mode</th>
<th>Half-Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ds</td>
<td>267</td>
<td>Alpha</td>
<td>1.7 ms</td>
</tr>
<tr>
<td>Mt</td>
<td>269</td>
<td>Alpha</td>
<td>10.24 s</td>
</tr>
<tr>
<td>Hs</td>
<td>270</td>
<td>Alpha</td>
<td>8.01 s</td>
</tr>
<tr>
<td>Bh</td>
<td>271</td>
<td>Alpha</td>
<td>20.9 s</td>
</tr>
<tr>
<td>Sg</td>
<td>269</td>
<td>Gamma</td>
<td>1.9 ms</td>
</tr>
<tr>
<td>Db</td>
<td>267</td>
<td>Gamma</td>
<td>10.24 s</td>
</tr>
<tr>
<td>Rf</td>
<td>259</td>
<td>Gamma</td>
<td>3.6 h</td>
</tr>
<tr>
<td>Lr</td>
<td>255</td>
<td>Gamma</td>
<td>3.6 h</td>
</tr>
<tr>
<td>No</td>
<td>259</td>
<td>Gamma</td>
<td>1.9 ms</td>
</tr>
<tr>
<td>Md</td>
<td>249</td>
<td>Gamma</td>
<td>1.9 ms</td>
</tr>
<tr>
<td>Fm</td>
<td>243</td>
<td>Alpha</td>
<td>0.18 s</td>
</tr>
</tbody>
</table>

**CLASSICAL TOOL: ALPHA - GAMMA DECAY**

**$^{259}$Sg AND $^{255}$Rf**
alpha decay of $^{259}$Sg

Fusion-evaporation reaction $^{54}$Cr$+^{206}$Pb$\rightarrow^{259}$Sg + 1n  $I(^{54}$Cr$^{8+}) = 720$pnA

1 week of beamtime 750 nuclei of $^{259}$Sg  (assuming $b_\alpha\approx97\%$)

9610 keV  $T_{1/2} = 402\pm56$ ms

9550 keV  $T_{1/2} = 226\pm27$ ms
alpha decay of $^{259}$Sg

New long-lived isomeric state in $^{259}$Sg exists due to the 11/2$^-[725]$ and 1/2$^+[620]$ nilsson levels known in lighter N=153 isotones.
New isomer in $^{255}$Rf

$\alpha$ decays populating short-lived isomeric state in $^{255}$Rf de-exciting by emission of CEs

New short-lived (50 ± 17) µs isomeric state in $^{255}$Rf at ≈ 135 keV assigned as 5/2+[622] state similarly to lighter N=151 isotones.
N=153 and 151 isotones systematics

Significant change of the g.s. configuration for N=153 isotones from 1/2+[620] to 11/2-[725].

Possible explanation by phonon-particle interaction suggested already for $^{249}$Cf in 1975 - possible mixing with $\{9/2-[734]+2\}^{5/2+}$.

… another new isomer in $^{255}$Rf

Fusion-evaporation reaction $^{50}$Ti$+^{207}$Pb $\rightarrow$ $^{255}$Rf + 2n $\sim$1300 events

Besides its fission properties (see the poster by Pavol Mošať) we aimed at

delayed coincidences of ER-CE-SF/$\alpha$
And another new isomer in $^{255}\text{Rf}$

Fusion-evaporation reaction $^{50}\text{Ti} + ^{207}\text{Pb} \rightarrow ^{255}\text{Rf} + 2\text{n}$ \hspace{1cm} \sim 1300$ events

It seems we have a new high-spin $K$ (multi-qp isomer) isomer(s) at $\sim 1$ MeV exc. energy.

Besides it's fission properties (see the poster by Pavol Mošať) we aimed at delayed coincidences of ER-CE-SF/$\alpha$.

Several ten events of CE with energy up to the 900 keV; some in coincidence with $\gamma$ up to the 600 keV.
EC IN HEAVIEST NUCLEI

258Db AND 257Rf
EC identified via CE-X-ray coincidences

- Production in $^{50}\text{Ti} + ^{209}\text{Bi} \rightarrow ^{258}\text{Db} + 1\text{n}$
- 8.5 days of beamtime, $\approx 3000$ nuclei of $^{258}\text{Db}$
- Delayed CE-$\alpha$/SF coincidences ($\Delta T < 50$ ms) resembled Rf X-rays.

- Production in $^{50}\text{Ti} + ^{209}\text{Bi} \rightarrow ^{258}\text{Db} + 1\text{n}$
- 8.5 days of beamtime, $\approx 3000$ nuclei of $^{258}\text{Db}$
- Delayed CE-$\alpha$/SF coincidences ($\Delta T < 50$ ms) resembled Rf X-rays.

First confirmation of EC decay for $^{258}\text{Db}$; Direct Z identification of fissions via X rays. Precise $Q_\alpha$ value for $^{258}\text{Rf}$.

Gate at Fm X rays allowed very sensitive selection; almost pure $^{258}\text{Rf}$
Beta-decay studies $^{257}$Rf

Search for an EC decay in $^{257}$Rf by looking at delayed CE(+X-ray) - $\alpha$ correlations.

$CE(+X$-ray$)$ from de-excitation cascade in $^{257}$Lr

Direct production $^{257}$Rf (populated low and high-spin state)

Indirect production $^{257}$Rf from $^{261}$Sg (populated low spin state)

Despite of limited statistics indication new isomer in $^{257}$Lr assigned as 1/2-[521]

F.P. Heßberger, EPJ Web of Conferences 131, 02005 (2016)

30. 5. 2019
NSD Venice, 13.5. – 17.5.2019
Uncertain g.s. configuration for most of the Lr isotopes and completely missing data on excited levels. There are not almost any new data available in last 10 years.
ANOTHER EC DECAY STUDY... ²⁵⁴Md
EC of $^{254}\text{Md}$ to $^{254}\text{Fm}$

$^{254}\text{Md}$ (produced via EC of $^{254}\text{No}$ in $^{48}\text{Ca}+^{208}\text{Pb}$) decays to $^{254}\text{Fm}$

Old case – observed in 1970 by Fields et al.

Only very basic data are available

Suggested 1- and 3- long-lived states

$\gamma$s in coinc. with CE up to 600 keV and Fm X-rays

A. Broniš, Project of PhD Thesis

CE with high energy $\gamma$ transitions up to 700 keV and Fm X rays

Populated state at 1200 – 1400 keV (considering bind. energy)
EC of $^{254}$Md to $^{254}$Fm

649 and 694 keV $\gamma$ lines known from $\beta$- decay of $^{254m}$Es (2+ state)

The $\beta$- decay of $^{254m}$Es involves a transitions between low-spin states. Do we expect something similar for EC of $^{254}$Md is higher?
EC of $^{254}\text{Md}$ to $^{254}\text{Fm}$

We should expect low spin states in $^{254}\text{Md}$

$\pi 7/2-[514] \oplus \nu 1/2+[620] \ldots \ldots 3-$
$\pi 1/2-[521] \oplus \nu 1/2+[620] \ldots \ldots 1-$
$\pi 7/2-[514] \oplus \nu 3/2+[622] \ldots \ldots 2-$
$\pi 1/2-[521] \oplus \nu 3/2+[622] \ldots \ldots 2-$

$^{254}\text{Md}$

$^{254}\text{No}$

$^{254}\text{Md}$

EC/β+

EC/β+

$^{254}\text{Md}$

$^{254}\text{Fm}$

$^{254}\text{Md}$

$^{254}\text{Md}$

55% of all EC transitions goes well above known 2+ and 3+ states at $\approx 700$ keV

⇒ There are higher spin states populated than expected and thus also initial in $^{254}\text{Md}$

It seems, the ambiguity for available single particle levels is critical issue again
Conclusion

• Besides $\alpha$-decay studies the EC might provide interesting data (using delayed coincidences with CE+X-ray coincidences); see e.g. $^{258}\text{Db}$, $^{257}\text{Rf}$, $^{253,254}\text{Md}$…

It’s tricky, but possible.

• Level systematics above fermium remains very uncertain especially for isotopic chains $\Rightarrow$ it’s really difficult to predict and explain decay characteristics of heaviest isotopes.

• There is still lot of work for both – theory and experiment - in the region of heaviest nuclei.

Thank you