New results on the decay spectroscopy of $^{254}$No with GABRIELA @ SHELS

Group: Du noyau aux étoiles, IPHC / University of Strasbourg
Speaker: Margaux Forge, 2nd year PhD Student
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2. **Experimental Set up**

3. **Results from** $^{208}$Pb + $^{48}$Ca $\rightarrow$ $^{254}$No + 2n reaction

4. **Super-Deformation in** $^{254}$No?

5. **Conclusion**
Motivation

Motivation

Very-Heavy Nuclei Area

Reaching $^{254}\text{No}$

Nobelium: $^{254}_{102}\text{No}_{152}$

fusion evaporation reaction

Nobelium: $^{254}_{102}$No$_{152}$

Reaching $^{254}$No

fusion evaporation reaction
Nobelium: $^{254}_{102}$No$_{152}$

fusion evaporation reaction

$^{48}$Ca + $^{208}$Pb
Reaching $^{254}$No

Nobelium: $^{254}_{102}$No$_{152}$

$^{48}$Ca + $^{208}$Pb $\rightarrow$ $^{254}$No + 2n

fusion evaporation reaction
Reaching $^{254}$No

Nobelium: $^{254}_{102}$No$_{152}$

Fig. 2: Neutron single particle energies for VHE [Dudek]
J. Dudek et al., private communication.
Past experiments & disagreements

JYFL
University of Jyväskylä
Institute of Physics [1]
2006
Past experiments & disagreements

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LBNL
Lawrence Berkeley National Laboratory [3]
2010

254\text{No}^{152}
Past experiments & disagreements

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Society for Heavy Ion Research [4]
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254\(^{\text{No}}\)
102\(^{\text{No}}\)
152

Past experiments & disagreements

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Past experiments & disagreements

Two isomers:

1. A Short-lived isomer:
   a. Excitation energy at ~2900 keV ? ~2600 keV ?
   b. Configuration assignment at 16+ ? 14+ ?
   c. Different decay scheme
   d. Nature of the state as \{\pi^2 (8^-), \nu^2 (8^-)\} 16^+ ? \{\pi^2 (8^-), \nu^2 (6^-)\} 14^+ ?

2. A Long-lived isomer:
   a. Configuration assignment at 8-
   b. Nature of the state as \(\pi 7/2^- [514] \otimes \pi 9/2^+ [624] \) ? \(\nu 7/2^+ [613] \otimes \nu 9/2^- [734] \) ?

\[K^\pi = (14^+) \quad \text{171 \mu s}\]

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Separator SHELS (JINR-IN2P3 collaboration) from existing VASSILISSA separator

SHELS [5]
Super-Heavy Elements Separator

Beam $^{48}\text{Ca}$

$^{208}\text{Pb}$ Target

Separator

Recoil $^{254}\text{No}$

• Separator SHELS (JINR-IN2P3 collaboration) from existing VASSILISSA separator
• Time of Flight (2 MCP)

GABRIELA @ SHELS

- Separator SHELS (JINR-IN2P3 collaboration) from existing VASSILISSA separator
- Time of Flight (2 MCP)
- Implantation detector (1 DSSD 128x128, 100.4 x 100.4 mm²)

SHELLS [5]
Super-Heavy Elements Separator

GABRIELA [6][7]
Gamma Alpha Beta Recoil Investigations with the Electromagnetic Analyzer

Beam $^{48}$Ca
$^{208}$Pb Target

Separator

Recoil $^{254}$No

ToF

DSSD

GABRIELA @ SHELS

- Separator SHELS (JINR-IN2P3 collaboration) from existing VASSILISSA separator
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208Pb
Beam 48Ca

Target

Separator

Recoil 254No

ToF

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- High Pure Germanium detectors (4 monocrystals + CLODETTE clover)

**SHELS [5]**
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Beam $^{48}$Ca

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Tunnel

DSSD

CLOVER

HPGe detectors

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GABRIELA @ SHELS

- Separator SHELS (JINR-IN2P3 collaboration) from existing VASSILISSA separator
- Time of Flight (2 MCP)
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Efficiency largely improved

SHELS [5]
Super-Heavy Elements Separator

GABRIELA [6][7]
Gamma Alpha Beta Recoil Investigations with the Electromagnetic Analyzer

208Pb
Target
Beam $^{48}$Ca

Separator

Recoil $^{254}$No

ToF

Tunnel

DSSD

CLOVER

HPGe detectors

Genetic Correlations (Time + Space)

Example with a schematic nuclear structure

Example with a schematic nuclear structure

Isomers

Ground State

Beam $^{48}\text{Ca}$

Target

Recoil $^{254}\text{No}$

$^{208}\text{Pb}$ ($^{48}\text{Ca, 2n}$) $^{254}\text{No}$ reaction

Flight time

$^{208}\text{Pb}$

$^{208}\text{Pb}$

New results on the decay spectroscopy of $^{254}\text{No}$
Genetic Correlations (Time + Space)

**Example with a schematic nuclear structure**

- **208Pb** target
- Beam **48Ca**
- **208Pb (48Ca, 2n) 254No reaction**
- Implantation: \( E_r, X_r, Y_r \)
- Flight time
- **Recoil**
- Excited Recoil
- **Recoil (254No)**
  - Isomers
  - Ground State

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21/09/2021
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Genetic Correlations (Time + Space)

Example with a schematic nuclear structure

$^{208}$Pb ($^{48}$Ca, 2n) $^{254}$No reaction

$^{208}$Pb (Target) -> Beam $^{48}$Ca

Recoil $^{254}$No

Flight time

Isomer decay ($E_i, X_i = X_f, Y_i = Y_f$)

Implantation ($E_r, X_r, Y_r$)

Excited Recoil

Recoil ($^{254}$No)

Decay

Isomers

Ground State

example with a schematic nuclear structure

Ground State

Isomers

Decay
Genetic Correlations (Time + Space)

Beam $^{48}$Ca

Target

$^{208}$Pb

Recoil $^{254}$No

$^{208}$Pb ($^{48}$Ca, 2n) $^{254}$No reaction

Flight time

Excited Recoil

$e^-/\gamma$

$e^-/\gamma$

Implantation ($E_r, X_r, Y_r$)

Isomer decay ($E_i, X_i = X_r, Y_i = Y_r$)

Groud state decay

Recoil ($^{254}$No)

Example with a schematic nuclear structure

Isomers

Decay

Ground State

Example with a schematic nuclear structure
Genetic Correlations (Time + Space)

Example with a schematic nuclear structure

$^{208}\text{Pb}$ (48Ca, 2n) $^{254}\text{No}$ reaction

$^{208}\text{Pb}$ Target

Beam $^{48}\text{Ca}$

Recoil $^{254}\text{No}$

Flight time

Implantation $(E_r, X_r, Y_r)$

Isomer decay $(E_i, X_i = X_r, Y_i = Y_r)$

Ground state decay $(E_a, X_a = X_r, Y_a = Y_r)$

$\alpha$-decay

$\alpha$

$^{250}\text{Fm}$

(Fission)

$e^+/\gamma$

$e^-/\gamma$

$^{254}\text{No}$ reaction

Ground state decay

Isomers

Decay

Recoil

Example with a schematic nuclear structure
Genetic Correlations (Time + Space)

208Pb Target

Beam 48Ca

Recoil 254No

208Pb (48Ca, 2n) 254No reaction

Example with a schematic nuclear structure

Recoil (254No)

Decay

Isomers

Ground State

To 250Fm

(Fission)

Genetic correlations

Flight time

Implantation (E_i, X_i, Y_i)

Isomer decay (E_i = X_i, Y_i = Y_r)

Ground state decay (E_a = X_a = X_r, Y_a = Y_r)

α-decay

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1. Scientific context
2. Experimental Set up
3. Results from $^{208}\text{Pb} + ^{48}\text{Ca} \rightarrow ^{254}\text{No} + 2\text{n reaction}$
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208\(^{\text{Pb}}\) (48\(^{\text{Ca}}\), 2n) \(^{254}\text{No}\) reaction

- October 2019 (2 years ago)
- 3 weeks of beamtime

- 208\(^{\text{Pb}}\) Target (99.99% pure)
- 233\(\mu\)g/cm\(^2\) 1.5 \(\mu\)m Titanium backing

- 48\(^{\text{Ca}}\) beam
- Intensity = 300 – 400\(\text{pnA}\)
- Beam Energy = 225 – 228 MeV

- Calibration in \(\alpha\) and \(e^+\): \(^{164}\text{Dy(48Ca,xn)}^{212-xn}\text{Rn reaction}\)
  \[\gamma : \text{133Ba and 152Eu sources}\]

- Initial purpose of the experiment:
  Fission branch of ground state and isomers
Experiment’s parameters

$^{208}\text{Pb} (^{48}\text{Ca}, 2n) ^{254}\text{No}$ reaction

- October 2019 (2 years ago)
- 3 weeks of beamtime
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- Initial purpose of the experiment:
  Fission branch of ground state and isomers

**Parameters** used for data analyze:

1. With BGO (Anti-Compton detector)
2. With / Without Add Back for the CLOVER detector
3. Correlations:

![Diagram showing Recoil, Isomers decay, $\alpha$-decay, $R$, $E_{\text{DSSD}}$, $\gamma$, $E_{\text{tunnel/DSSD}}$ and Coincidences]
Energy – Lifetime correlation graph

Recoil

First particle in DSSD (e or α)

Log₂(T_Particle - T_Recoil)

Energy of the particle (in keV)

10³

10²

10

1
• More than 1 million $\alpha$ from $^{254}$No identified
Energy – Lifetime correlation graph

- More than 1 million $\alpha$ from $^{254}$No identified
- $6.6 \times 10^5$ electrons from long-lived isomer

Energy: 8083 keV
Lifetime: 51s (25.6 ($\mu$s) in log2)

Recoil
First particle in DSSD (e or $\alpha$)

Energy of the particle (in keV)

Log2(T Part - T Recoil)

- 4.2 s
- 2 ms

Electrons from long-lived isomer
Energy – Lifetime correlation graph

• More than 1 million $\alpha$ from $^{254}$No identified
• $6.6 \times 10^5$ electrons from long-lived isomer
• $1.2 \times 10^4$ electrons from short-lived isomer

Electrons from long-lived isomer

Electrons from short-lived isomer

Recoil
First particle in DSSD (e or $\alpha$)

Energy: 8083 keV
Lifetime: 51s (25.6 ($\mu$s) in log2)

$\alpha$ from $^{254}$No

Pile-up
Energy – Lifetime correlation graph

- More than 1 million $\alpha$ from $^{254}$No identified
- 6.6 x 10^5 electrons from long-lived isomer
- 1.2 x 10^4 electrons from short-lived isomer

HIGH STATISTICS
AND
QUALITY DATA!

- 4.2 s
  - Electrons from long-lived isomer
- 2 ms
  - Electrons from short-lived isomer
- 2 us
  - Pile-up

Energy: 8083 keV
Lifetime: 51 s (25.6 (µs) in log2)

$\alpha$ from $^{254}$No
Coincidence Gammas (long-lived isomer)

Energy electron VS coincidence gamma (5us) in correlation R-E2_dssd/G-A

Coincidence Gammas

Recoil Coincidence of $\gamma$ with long-lived isomer ($\alpha$-decay)
Coincidence Gammas (long-lived isomer)

Different rotational band transition
X-Rays
Same rotational band transition
New gammas

$E_x = 1.297(2)$ MeV
$T_{1/2} = 263(2)$ ms
$K^\pi = 8^-$

Coincidence Gammas (short-lived isomer)

Energy electron VS coincidence gamma (5us) in correlation R-E1_dssd/G-A

Energy G1

25/29 111 133 156 178 278 300 312 319 326 482 606

Recoil

Coincidence of \( \gamma \) with short-lived isomer (\( \alpha \)-decay)
Coincidence Gammas (short-lived isomer)

- Different rotational band transition
- X-Rays
- Same rotational band transition
- New gammas

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The last decay scheme from LBNL

Analyse ongoing

The new decay scheme

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Decay scheme

Analyze on going

The new decay scheme

GM splitting energy: 216 keV

The last decay scheme from LBNL

T_{1/2}=184(2)\mu s
E_{x}=2.928(3)\text{MeV}

T_{1/2}=263(2)\text{ms}
E_{x}=1.297(2)\text{MeV}
1. Scientific context

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Coincidence of $e^-_{\text{Tunnel}} / e^-_{\text{DSSD}}$ – Long-lived isomer

*Electron_coincE2_tunnel* Entries 30422 Mean 734.2 Std Dev 76.97

Energy of the conversion electron (in keV)
Coincidence of $e^{-}_{\text{Tunnel}} / e^{-}_{\text{DSSD}}$ – Long-lived isomer

Energy of the conversion electron (in keV)

$K_{842}$
Coincidence of $e^-_{\text{Tunnel}} / e^-_{\text{DSSD}}$ – Long-lived isomer
Coincidence of $e^-_{Tunnel} / e^-_{DSSD}$ – Long-lived isomer

$K_{887}$, $K_{842}$, $K_{943}$
2 solutions to this super conversion:

- The existing 887keV is a very highly converted transition (M4 or more)…
  ...But its lifetime doesn’t fit…

- Contribution from an E0 transition…
  ...Interpreted as a pure E0 transition from 0+ state to Ground State!
New potential decay scheme

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New potential decay scheme

Super-deformed State?

~ 885 keV
From 2000

Fission barriers for different spin values

Egido & Robledo predicted a SD well at around 2MeV.

Comparison with theory

From 2000

**Fission barriers for different spin values**

Delaroche results: prediction of a SD state at around 1MeV.

From 2006

**Excitation energy from SD state in different nuclei**

Egido & Robledo predicted a SD well at around 2MeV.

~2MeV

~1MeV

Egido & Robledo predicted a SD well at around 2MeV.

Delaroche results: prediction of a SD state at around 1MeV.


Comparison with theory in IPHC

From 2021
Shell models calculations + mean field theory

Preliminary!

D. Dao & F. Nowacki shell model calculations reproduce 8-long-lived isomer / 3+ state (interpretation in discussion)

J. Dudek calculations on going

Excitation energy (keV)

254No

0+ 1296
7+ 1243
6+ 1161
5+ 1091
4+ 1033
3+ 987

254No

0+ 372
8+ 1371
7+ 1296
6+ 1161
5+ 1091
4+ 1033
3+ 987

GCM (15 states)

EXP

Preliminary!

Talk on “Generator Coordinate Method with effective nuclear Shell Model interaction s and Applications” on Wednesday 29th October in Colloque GANIL at 11:45am
Conclusion

• The study of the long-lived isomer decay has revealed new states in $^{254}$No.

• In particular, a super-deformed state (calculation ongoing…)

• We need theoretical calculations (expected soon) which can explain why we are able to populate the SD state.

• Analysis ongoing concerning the short-lived isomer…
Collaborators

**IN2P3**: O. Dorvaux, A. Lopez-Martens, K. Kessaci, K. Hauschild, B. J. P. Gall, Z. Asfari, R. Chakma


**GANIL**: J. Piot

Thank you for your attention!
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A. G. Popeko et al., NIM B 376, 140-146 (2016).


Duc Dao presentation for Colloque GANIL 2021