Study of shape evolution around A~100

Ground state deformation from HFB calculations

Rich variety of nuclear shapes

- Rapid variations with (Z,N)
- Oblate and prolate minima → shape coexistence

HFB+GCM(GOA) calculations with Gogny D1S force, J.P. Delaroche et al., PRC 81 (2008)
Motivation

- Evolution of the $2^+_1$ excitation energy as a function of neutron number in the $A \sim 100$ region.

- Experimental evidence of shape transition at $N=58-60$.

- Experimental measurements of lifetime to determine transition strengths ($B(E2)$).
The experimental procedure involves the use of a multi-detector setup for fission fragment detection. The setup includes VAMOS and Agata detectors. For VAMOS, the settings are as follows:

- **VAMOS Settings:**
  - 20° rotation
  - Magnetic rigidity $B_p (Mv/q) = 1.1$

The target nucleus is $^{247}_{96}$Cm, and the beam is $^{238}_{92}$U. The intermediate compound nucleus is $^{9}_{4}$Be. The detectors used are Agata, which consists of 35 detectors.
Experimental Procedure

MWPC: Multi-Wire Proportional Counter
MWPPAC: Multi-Wire Parallel Plate Avalanche Counter
DC: Drift Chamber
IC: Ionization Chamber
D: Dipole

Plunger: few ps-100 ps
FATIMA: ~50 ps

VAMOS Settings:
20° rotation
Magnetic rigidity Bp (Mv/q): 1.1

24-LaBr₃ (FATIMA)
Agata (35 detectors)
AGATA is an array composed of high-purity segmented germanium detectors.

**Strength of the array:**
- Determine the interaction point of $\gamma$ ray by comparing it to the measured signal shapes.
- Reconstruct the path of a Compton scattered $\gamma$ ray inside the array.

35 AGATA detectors were used in the present work.

Each AGATA crystal is composed of 36-fold segments.

AGATA project aims at reaching a $4\pi$ solid angle.
Raw Data File

Crystal Producer
- Data replay (amplitudes, time,..)

Preprocessing Filter
- Calibrated energy and time Spectra, cross-talk corrections

PSA Filter
- Pulse Shape Analysis

Post-PSA Filter
- Recalibration, neutron damage correction,

Tracking

Merge

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Cross talk correction

- Electronic cross talk effects are observed in segmented Ge detectors.
- Cross talk correction allows to recover the sum of hit energies.

a) $^{60}$Co peaks for sum of all multiplicities

b) Energy difference between absolute and measured energy vs segment multiplicities

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• Interaction of neutrons with Ge crystals induces lattice defects.

• Lattice defects are more susceptible to trap holes than electrons.

• Neutron damage correction is possible from the knowledge of the interaction position and corrects for the deficiency of the charge collection.
Vamos Analysis

MWPC: Multi-Wire Proportional Counter
MWPPAC: Multi-Wire Parallel Plate Avalanche Counter
DC: Drift Chamber
IC: Ionization Chamber
D: Dipole

MWPC 238\textsuperscript{U} 24-LaBr_3 Agata

Fission fragments
MWPC: Multi-Wire Proportional Counter
MWPPAC: Multi-Wire Parallel Plate Avalanche Counter
DC: Drift Chamber
IC: Ionization Chamber
D: Dipole

Mass separation

Mass distribution
Which isotopes are accessible?

Strongest channel
Recoil Distance Doppler Shift method

\[ E_{\gamma} = E_{\gamma} \frac{\sqrt{1-\beta^2}}{1-\beta \cos \theta} \]

- \( E_{\gamma} \): before doppler correction
- \( E_{\gamma_0} \): after doppler correction
- \( \beta = v/c \)
- \( \theta \): angle between recoil and \( \gamma \)

**Diagram:**

- **Left line:** \( \gamma \) emitted before the degrader.
- **Right line:** \( \gamma \) emitted after the degrader.

**Graphs:**

- **a)** \( \cos \theta \) vs \( E_{\gamma} \)
- **b)** \( \cos \theta \) vs \( E_{\gamma_0} \)
Differential Decay Curve Method (DDCM)

$^{104}\text{Mo}$

DDCM (singles)

Counts

$\gamma$ keV

450 µm

780 µm

1170 µm

1755 µm

shifted

un-shifted
Differential Decay Curve Method (DDCM)

\[ Q_{ij}(x) = \frac{I_{ij}^u(x)}{I_{ij}^u(x) + I_{ij}^s(x)} \]
Differential Decay Curve Method (DDCM)

\[ Q_{ij}(x) = \frac{I_{ij}^u(x)}{I_{ij}^u(x) + I_{ij}^s(x)} \]

\[ \tau_i(x) = -\left[v \frac{dQ_{ij}(x)}{dx}\right]^{-1} [Q_{ij}(x) - b_{ij} \sum_h \alpha_{hi} Q_{hi}(x)] \]
Differential Decay Curve Method (DDCM)

\[ T(4^+_1) = 35.4(11) \text{ ps} \]
$^{104}\text{Mo}$

DDCM (singles)

- $450 \mu\text{m}$
- $780 \mu\text{m}$
- $1170 \mu\text{m}$
- $1755 \mu\text{m}$

DDCM ($\gamma-\gamma$)

- $450 \mu\text{m}$
- $780 \mu\text{m}$
- $1170 \mu\text{m}$
- $1755 \mu\text{m}$

**Results**

- $\tau (4^+_1) = 35.4(11) \text{ ps}$
- $\tau (4^+_1) = 41(5) \text{ ps}$
Comparison of AGATA vs EXOGAM for $^{98}\text{Zr}$

AGATA

- 155 um
- $^{98}\text{Zr} (4^+_1)$
- $^{98}\text{Zr} (6^+_1)$
- 265 um
- 450 um
- 780 um
- 1755 um

EXOGAM

- 265 um
- $^{98}\text{Zr} (2^-_1)$
- 1223 keV

Counts

P. Singh et al., PHYSICAL REVIEW LETTERS 121, 192501 (2018)
Limits of observation ($^{104}$Zr)

$\tau (4^+_1) = < 90 \text{ ps}$

$T (6^+_1) = 7.7(5) \text{ ps}$
Limits of observation ($^{104}$Zr)

\[ \tau (4^+_1) = < 90 \text{ ps} \]

Possible side-feeding from $4^-$ state

\[ T (6^+_1) = 7.7(5) \text{ ps} \]
Transition Strength

\[ B(E2, 4^+_1 \rightarrow 6^+_1) e_b^2 \]

\[ B(E2, 4^+_1 \rightarrow 8^+_1) e_b^2 \]

\[ 98 \text{Zr} \quad 100 \text{Zr} \quad 102 \text{Zr} \quad 104 \text{Zr} \quad 106 \text{Zr} \]

\[ 0 \quad 0.5 \quad 1 \quad 1.5 \quad 2 \quad 2.5 \quad 3 \]

\[ 100 \text{Mo} \quad 102 \text{Mo} \quad 104 \text{Mo} \quad 106 \text{Mo} \quad 108 \text{Mo} \]

\[ 0 \quad 0.5 \quad 1 \quad 1.5 \quad 2 \quad 2.5 \quad 3 \]
Transition Strength

\[ B(E2; 4^+_1 \rightarrow 6^+_1) e^2 b^2 \]

\[ B(E2; 6^+_1 \rightarrow 8^+_1) e^2 b^2 \]

exp - experimental

5DCH - 5DCh model

Zr

Mo

preliminary
Transition Strength

Work in Progress!
Conclusion

- Fusion-Fission Experiment with AGATA & VAMOS

- Confirmation of Previous lifetime
  \[ 4^+_1 \, ^{98}\text{Zr}, \ 4^+_1 \, ^{102,104}\text{Mo}, \ 6^+_1 \, ^{98,100}\text{Zr}, \ 6^+_1 \, ^{106}\text{Mo} \]

- New lifetimes in \( 4^+_1 \) & \( 6^+_1 \) \( ^{104}\text{Zr}, \ ^{104}\text{Mo} \)

- Potential in Ru, Pd, Sr …

- B(E2) measurements are an important ingredient for Coulomb excitation measurements performed at CARIBU (\( ^{104,106}\text{Mo}, \ ^{110}\text{Ru}, \) planned \( ^{100}\text{Zr}, ^{112}\text{Ru} \)).

- Work in progress!
THANK YOU