Study of shell structure and order-to-chaos transition in warm rotating nuclei with the radioactive beams of SPES

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Warm rotating nuclei

- Fusion
- Neutron decay
- Rotation

**E2 strength**
- $|\alpha> = \sum \mu X_{\alpha}^{\mu} |\mu>
- Loss of selection rules

- Compound Nucleus
  - Chaos
  - $U \approx 8$ MeV

- Rotational Damping
  - Strongly interacting bands
  - $U = 1-5$ MeV

- Regular Bands
  - Mean field
  - $U < 1$ MeV

- WARM
- Very High Spin

- COLD
- Rotational bands
Collective rotations: de-excitation spectra

Analysis of quasi-continuum $\gamma - \gamma$ coincidence spectra with statistical and spectral shape analysis methods.

\[ N_{\text{path}} = \frac{N_{\text{eve}}}{\mu_2} \times \mu_1^2 - 1 \]

Fluctuation Analysis Method.
Band-mixing Calculations => decay flow simulation

\[ H(I) = H_{def} - \omega J_x + V_{SDI}^{residual} - \frac{J_z^2}{2\Gamma_{rot}} \]

\( n_b = \left[ \sum S_{if}^2 \right]^{-1} \)

168Yb

onset of damping

\( n_b = 2 \)

\( \varepsilon = 0.25 \)

I = 20-61 \( \hbar \)

400 levels

U \leq 2.5 MeV

A. Bracco et al. PRL76(1996) 4484
Main Results from the Analysis of Quasi-Continuum Rotational Spectra

Evidence for rotational damping

- Sensitivity to the residual interaction
- Collectivity with thermal energy
- Mass dependence
- Configuration dependence
- Measurement of Compound and Rotational Damping Width
- Superdeformation at finite temperature


- i) how large the damping width $\Gamma_{\text{rot}}$ is and how it changes with excitation energy and spin;
- ii) at which energy rotational damping sets in and how gradual is the process;
- iii) whether or not this process depends on the intrinsic nuclear configuration, therefore leading to different effects in connection with different quantum numbers of the shell-model states, such as the $K$-quantum number;
- iv) how high in excitation energy one has to go before a fully chaotic regime is reached.
Evidence for Rotational Damping
Importance of Residual Interaction

Band Mixing Calculations

\[ H = H_{\text{def}} - \omega J_x + V_{\text{res}} \]

Nilsson  Cranking  SDI inter.

\[ U_0 = 1 \text{ MeV} \]
\[ \Gamma_{\text{rot}} = 200 \text{ keV} \]

B. Herskind et al., PRL68(1992)3008
Sensitivity to Residual Interaction
Type of Interaction and Interaction Strength

Type of Interaction
Rotational Damping originates from high-multiple terms of two-body residual interaction

Interaction Strength
\[ \sqrt{\langle |V|^2 \rangle_{\text{SDI}}} = 20 \text{ keV} \]
\[ \sqrt{\langle |V|^2 \rangle_{\text{EXP}}} = 14 \text{ keV} \]
from discrete spectroscopy

M. Matsuo et al., NPA617,1 (1997)
Collectivity with Thermal Energy Fractional Doppler Shift Analysis

\[ \gamma - \gamma \text{ spectrum} \]

\[ \langle E_\gamma \rangle = 800 \text{ keV} \]

\[ (E_\gamma^1 - E_\gamma^2) \text{ keV} \]

\[ \text{Forward} \]

\[ \text{Backward} \]

\[ E_\gamma \text{ (keV)} \]

\[ 1000 \quad 1500 \]

\[ 0.0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \]

\[ F(\tau) \]

\[ E_\gamma \text{ (keV)} \]

\[ 500 \quad 700 \quad 900 \quad 1100 \quad 1300 \quad 1500 \]

\[ 164\text{Yb} \]

\[ Q_t = 7.6 \text{ eb} \]

\[ Q_t = 6.6 \text{ eb} \]

\[ Q_t = 5.5 \text{ eb} \]

\[ \text{Same Collectivity} \]

\[ Q_t = 5.5 \text{ eb} \]

\[ B(E2) = 200 \text{ W.u.} \]

\[ \text{yrast} \]

\[ \text{discrete exc. bands} \]

\[ \text{mixed exc. bands} \]

S. Frattini et al., PRL81(1998)2659
Configuration Dependence & Onset of Chaos
Persistence of selection Rules with Temperature:

Chaotic regime: $U \geq 2.5$ MeV

Smaller number of High-K states in the damping regime

Need for confirmation in other systems: egs. Hf nuclei

$^{136}\text{Te} + ^{48}\text{Ca} \rightarrow ^{180}\text{Hf} + 4n$

G. Benzoni et al., PLB 615 160-166 (2005)
Warm rotation in exotic systems

**Stable:** $^{48}\text{Ca}(\@ 215\text{MeV}) + ^{124}\text{Sn} \rightarrow ^{168}\text{Yb}(63\hbar) + 4n$

**SPES:** $^{132}\text{Sn}(\@ 560\text{MeV}) + ^{48}\text{Ca} \rightarrow ^{176}\text{Yb}(76\hbar) + 4n$

Stable beams: fission limits the maximum angular momentum of the nucleus

N-rich beams: fission barrier increases with N

population of larger angular momenta

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**Swiatecki-Myers**

- RIB
- Stable

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Spin and temperature dependence of $\Gamma_{\text{rot}}$

Stable: $^{48}\text{Ca}(\text{at } 215\text{MeV}) + ^{124}\text{Sn} \rightarrow ^{168}\text{Yb}(63\hbar) + 4n$

SPES: $^{132}\text{Sn}(\text{at } 560\text{MeV}) + ^{48}\text{Ca} \rightarrow ^{176}\text{Yb}(76\hbar) + 4n$

$\gamma$-flow

$E1/E2$
Rotational Damping: I and T dependence
Γ_{rot} and Γ_{μ} from γ-γ spectra

E2 strength

|α>

Γ_{rot}

Δω_{0}

Γ_{μ}

I-2

fine structure of rotational damping

Γ_{narrow} ≈ 2Γ_{μ}

Γ_{wide} ≈ √2Γ_{rot}

I = 40, 41 h
levels 11-100

S. Leoni et al., PRL93(2004)022501
F. Stephens et al., PRL88(2002)142501
M. Matsuo et al., PLB465(1999)1
Shell effects dependence

\[ \Delta \omega = \sqrt{(\Delta \omega_0^N)^2 + (\Delta \omega_0^P)^2} \]

for \( U \leq 2 \text{ MeV} \)

\[ \Gamma_{\text{rot}} = 2(2\Delta \omega_0) \]

\( \Gamma_{\text{rot}} \) depends on 2 contributions: \( P \) and \( N \). Accessing nuclei on an isotopic chain will help define the 2 contributions.

So far MASS dependence has been addressed

\[ \Gamma_{\text{rot}} \propto I A^{-5/2} \epsilon^{-1} \]

\[ U_0 \propto A^{-2/3} \]

**comparative study**

\[ A=110 \quad 114\text{Te} \quad \epsilon \approx 0.25 \]

\[ A=160 \quad 164\text{Yb} \quad \epsilon \approx 0.25 \]

**168\text{Yb} \quad I=40\text{h}, U=2\text{MeV}**

highly aligned orbits

no highly aligned orbits

neutron

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Rotational Damping: I and T dependence

γb isotopes

\[ \Gamma_{\text{rot}} = 2(2\Delta \omega_0) \]
\[ \Delta \omega_0 = \sqrt{(\Delta \omega_0^N)^2 + (\Delta \omega_0^P)^2} \]

Need for n-rich beams

\[ ^{132}\text{Sn} + ^{48}\text{Ca} \rightarrow ^{176}\text{Yb} + 4n \]
\[ ^{130}\text{Sn} + ^{48}\text{Ca} \rightarrow ^{174}\text{Yb} + 4n \]

Expected increase of \( \Gamma_{\text{rot}} \) (~25%) with N number, mainly driven by neutrons

M. Matsuo et al., PLB465(1999)1
Proposed reactions

\[ \Gamma_{\text{rot}} \] dependence on T, I and N

- \( ^{132}\text{Sn} + ^{48}\text{Ca} \rightarrow ^{176}\text{Yb} + 4n \)
- \( ^{130}\text{Sn} + ^{48}\text{Ca} \rightarrow ^{174}\text{Yb} + 4n \)

Order-to-chaos transition

- \( ^{136}\text{Te} + ^{48}\text{Ca} \rightarrow ^{180}\text{Hf} + 4n \)

Beam intensities \( \approx 10^8 \) pps

One order of magnitude less than presently available with stable beams,

- 1 pnA, i.e. \( \approx 10^9 \) pps.

\[ E_{\text{beam}} \approx 5 \text{ MeV/u} \]

\[ I \approx 70 \text{ h} \]

\[ U \approx 2 \text{ MeV} \]
Experimental array

Need for a $4\pi \gamma$ array:

*Ge Ball (AGATA/GALILEO) + LaBr$_3$ scintillators*

High-efficiency array could compensate low beam intensities
Conclusions

- Fusion-evaporation reactions induced by n-rich beams of SPES:
  - Higher fission barrier
  - Chance to reach larger angular momenta and internal energies

- Study of warm rotating nuclei with n-rich beams of SPES:
  - $\Gamma_{rot}$ dependence on Temperature/Spin
  - $\Gamma_{rot}$ dependence on neutron number
  - Order-to-chaos transition

- Requirements: $E_{beam} \sim 5$ MeV/u

$^{168-176}$Yb chain

- $^{\text{BEAM} \sim 10^9 \text{ pps}}$

- $4\pi\gamma$ array: AGATA + LaBr$_3$
  - Improved efficiency compensate lower I$_{beam}$

Proposed reactions:

\begin{align*}
^{132}\text{Sn} + ^{48}\text{Ca} & \rightarrow ^{176}\text{Yb} + 4\text{n} \\
^{130}\text{Sn} + ^{48}\text{Ca} & \rightarrow ^{174}\text{Yb} + 4\text{n} \\
^{136}\text{Te} + ^{48}\text{Ca} & \rightarrow ^{180}\text{Hf} + 4\text{n}
\end{align*}

Feasible at 1st operation of SPES