Low-lying excitations in neutron-rich nuclei: Deformation and pairing

Niigata Univ.
Kenichi Yoshida
Structure of mid-shell medium-heavy nuclei
A challenge for microscopic theory
maximum # of valence nucleons
imbalanced neutrons/protons
Evolution of collective modes
explored by EURICA
decay-spectroscopic studies
Gamma vibration

A well-established collective vibration

✓ Systematically appears in the even-even deformed nuclei

✓ Low-frequency quadrupole vibration along the γ direction

✓ Soft mode of the triaxial deformation

sensitive to the shell structures
classical picture not applicable

How about in neutron-rich deformed nuclei?

universality of emergence of the collective mode across the nuclear chart
Exploring the quadrupole collectivity around $^{170}_{66}$Dy$_{104}$

Middle of the major shells between $^{132}$Sn and $^{208}$Pb

✓ Effect of neutron excess on the occurrence of γ-vibration
✓ Shell structure in neutron-rich medium-heavy nuclei

Decay spectroscopy at RIKEN RIBF

H. Watanabe et al., PLB760(2016)641
P.-A. Söderström et al., PLB762(2016)404

$^{172}\text{Dy}_{106}$

Long-lived isomeric state

Ground-state rotational band

Possible gamma band

Sudden decrease in the excitation energy at $N=106$
Nuclear DFT for collective vibration with Skyrme + pairing energy-density functional $\mathcal{E}[\rho, \tilde{\rho}](r)$

Hartree-Fock-Bogoliubov (HFB) like equation in coordinate space

\[
\begin{pmatrix}
  h^q(r\sigma) - \chi^q \\
  \tilde{h}^q(r\sigma) - (h(r\sigma) - \chi^q)
\end{pmatrix}
\begin{pmatrix}
  \varphi^q_{1,\alpha}(r\sigma) \\
  \varphi^q_{2,\alpha}(r\sigma)
\end{pmatrix} = E_{\alpha}
\begin{pmatrix}
  \varphi^q_{1,\alpha}(r\sigma) \\
  \varphi^q_{2,\alpha}(r\sigma)
\end{pmatrix}
\]

\(q = \nu, \pi\)

"s.p." Hamiltonian and pair potential:

\[
h^q = \frac{\delta \mathcal{E}}{\delta \rho^q}, \quad \tilde{h}^q = \frac{\delta \mathcal{E}}{\delta \tilde{\rho}^q}
\]

Response to the weak external field $\hat{F}$: $v^{\text{ext}}(r)e^{-i\omega t}$

\[
\delta \rho_i(r) = \int dr' \chi^i_{0}(r, r') \left[ \frac{\delta^2 \mathcal{E}}{\delta \rho_j \delta \rho_k} \delta \rho_k(r') + v^{\text{ext}}_j(r') \right]
\]

QRPA: $[H, \Gamma^\dagger_\lambda] |\Psi_0\rangle = \omega_\lambda \Gamma^\dagger_\lambda |\Psi_0\rangle$

$|\Psi_\lambda\rangle = \Gamma^\dagger_\lambda |\Psi_0\rangle = \sum_{\alpha\beta} [X^\lambda_{\alpha\beta} a^\dagger_\alpha a^\dagger_\beta - Y^\lambda_{\alpha\beta} a_\alpha a_\beta] |\Psi_0\rangle$

Collective mode = coherent superposition of 2qp excitations

Transition matrix elements: $\langle \Psi_\lambda | \hat{F} | \Psi_0 \rangle = \int dr \delta \rho(r; \omega_\lambda) v^{\text{ext}}(r)$
Single-particle energies in $^{172}$Dy
Gamma-vibration in the neutron-rich Dy isotopes

KY, H. Watanabe, PTEP (in press.)

H. Watanabe et al., PLB760(2016)641
P.-A. Söderström et al., PLB762(2016)404
Microscopic structure of the $\gamma$-vibration: isotopic dependence

@N=102

$\Delta N = 0 \text{ or } 2, \Delta n_3 = 0, \Delta \Lambda = \Delta \Omega = 2$
Microscopic structure of the γ-vibration: isotopic dependence

\[ \langle \Psi_\lambda | \hat{F} | \Psi_0 \rangle = \int \! \! \! \! dr \, \delta \rho (r; \omega_\lambda) v_{\text{ext}}(r) \]

\[ \delta \rho_i (r) = \int \! \! \! \! dr' \, \chi_{ij0} (r, r') \left[ \delta^2 E \delta \rho_j \delta \rho_k \delta \rho_k (r') + v_{\text{ext}}j (r') \right] \]

\[ h_q = \delta E \delta \tilde{\rho}_q, \tilde{h}_q = \delta E \delta \tilde{\rho}_q \]

\[ h_q (r_\sigma) - \lambda_q \tilde{h}_q (r_\sigma) = (h (r_\sigma) - \lambda) (\phi_q 1, \alpha (r_\sigma) \phi_q 2, \alpha (r_\sigma)) = \tilde{E}_\alpha (\phi_q 1, \alpha (r_\sigma) \phi_q 2, \alpha (r_\sigma)) \]

\[ \Delta N = 0 \text{ or } 2, \Delta n_3 = 0, \Delta \Lambda = \Delta \Omega = 2 \]

\[ @N=104 \]
Microscopic structure of the $\gamma$-vibration: isotopic dependence

\[\begin{align*}
\text{Energy (MeV)} & \quad \text{Strength (fm}^4) \\
\text{protons} & \quad \text{neutrons}
\end{align*}\]

$\Delta N = 0$ or $2$, $\Delta n_3 = 0$, $\Delta \Lambda = \Delta \Omega = 2$

$N = 106$
Microscopic structure of the $\gamma$-vibration: isotopic dependence

$\Delta N = 0$ or 2, $\Delta n_3 = 0$, $\Delta \Lambda = \Delta \Omega = 2$

$\langle \Psi_\lambda \vert \hat{F} \vert \Psi_0 \rangle = \int dr \delta \rho(r; \omega_\lambda) v_{\text{ext}}(r)$

$\delta \rho_i(r) = \int dr' \chi_{ij}(r, r') \left[ \delta^2 \delta \rho_j \delta \rho_k \delta \rho_k(r') + v_{\text{ext}}(r') \right]$
Strong collectivity of the $\gamma$-vibration around N=108-110

Isotopic dependence is governed by the 2qp excitations near the Fermi level.

2qp matrix elements constructing the $\gamma$-vib.

$$\langle i | \hat{F}^q_{\lambda K} | 0 \rangle = \sum_{\alpha \beta} M^q_{\alpha \beta}$$

SkM*

cumulative ME

$$\sum_{E_{2qp} < E'} M^q_{\alpha \beta}$$
Enhancement in the transition strength

The γ-vib. in these nuclei are strongly collective.
Similar isotopic dependence in the neighbouring nuclei

Deformation parameter

QRPA frequency (MeV)

less contributions of protons
β-decay properties of the neutron-rich rare-earth nuclei

systematic and microscopic description of β-decay half-life now available

spin-isospin response calculations (GT and F)
Microscopic description of the nuclear $\beta$-decay

equivalent-exchange mode of excitation

= superposition of 2qp excitations of a proton and a neutron

\[
\hat{O}_i^\dagger = \sum_{\alpha\beta} X_{\alpha\beta}^i \hat{a}_{\alpha,\nu}^{\dagger} \hat{a}_{\beta,\pi}^{\dagger} - Y_{\alpha\beta}^i \hat{a}_{\beta,\pi}^{\dagger} \hat{a}_{\alpha,\nu}^{\dagger}
\]

\[
\frac{1}{T_{1/2}} = \frac{(g_A/g_V)^2_{\text{eff}}}{D} \sum_K \sum_{E_i^* < Q_\beta} f(Z, Q_\beta - E_i^*) |\langle i | \hat{F}_K^- | 0 \rangle|^2
\]

\[
Q_\beta - E_i^* \simeq \Delta M_{n-H} - \omega_i + \lambda_\nu + \lambda_\pi = \Delta M_{n-H} - E_{T,i}
\]

J. Engel et al., PRC60(1999)014302

low-lying GT states are decisive for the half-life
Roles of pairing on beta-decay

- Sensitive to shell structure and pairing/deformation (both $T=0$ and $T=1$)
- $V^T=0 = f \cdot V^T=1$

- Distortion of Fermi surfaces
- $V_{\text{pn-pair}}$

- Phase-space factor

- $E_\beta$: Energy of emitted beta particle

- $E^*$: Excitation energy wrt daughter nucleus

- GT strength

- W/ pn-pairing
  - W/ like-particle pairing and/or deformation

- W/ o pn-pairing
  - W/ like-particle pairing and/or deformation

- W/ o like-particle pairing and/or deformation
Single-particle energies
Low-lying GT states in $^{152}$Nd

$^{152}$Nd

$\nu[532]3/2 \otimes \pi[532]5/2$

 Allowed-unhindered (au) transition

$w/ T=0$ pairing ($f=1.0$)

$w/o T=0$ pairing

$\nu[532]3/2 \otimes \pi[532]5/2$

Neutron single-particle energy (MeV)

Deformation parameter $\beta$
Low-lying GT states in $^{154}$Nd

Deformation parameter $\beta$

Neutron single-particle energy (MeV)

$^{154}$Nd

Particle

$\nu[523]5/2 \otimes \pi[532]5/2$

Hole

$\nu[523]3/2 \otimes \pi[532]5/2$
Low-lying GT states in $^{156}$Nd

Deformation parameter $\beta$

Neutron single-particle energy (MeV)

$\nu[532]3/2 \otimes \pi[532]5/2$

$\nu[523]5/2 \otimes \pi[532]5/2$

$\nu[521]3/2 \otimes \pi[532]5/2$
Low-lying GT states in $^{158}$Nd

Neutron single-particle energy (MeV)

Allowed-unhindered (au) transition

$\nu[532]3/2 \otimes \pi[532]5/2$

$\nu[523]5/2 \otimes \pi[523]7/2$

$\nu[521]3/2 \otimes \pi[532]5/2$

$\nu[523]5/2 \otimes \pi[532]5/2$
GT-strength distribution in $^{158}$Nd

Most of the strengths are concentrated in the GR region. Collectivity of the low-lying states relevant to the $\beta$-decay is quite weak.
Summary

Low-lying modes of excitation in medium-heavy neutron-rich nuclei are described microscopically in a framework of the Skyrme-EDF based QRPA.

neutron-rich rare-earth nuclei: heaviest neutron-rich nuclei with spectroscopic studies been made

isotopic trend in the $\gamma$-vibration and $\beta$-decay properties are well reproduced

shell structure of the medium-heavy neutron-rich nuclei are reasonably described

stronger collectivity of the $\gamma$-vib. around $^{174-176}$Dy is predicted

deformation and $T=1$ pairing correlations lead to fragmentation of the GT states

$T=0$ pairing interaction should be investigated in more detail

The EDF-based deformed QRPA is a promising tool to investigate/predict the excitation modes of excitation in exotic nuclei.
Highly deformed toward $N=72$ in the neutron-rich Zr isotopes

$B(E2 : 2^+_1 \rightarrow 0^+_0) = \frac{Q_0^2}{16\pi}$

F. Browne et al., PLB750 (2015) 448
T. Sumikama et al., PRL106 (2011) 202501

A. Blazkiewski et al., PRC71 (2005) 054321
Deformation effect on GT strength distributions

SLy4 spherical deformed ($\beta=0.40$) Fragmentation of strengths

$^{98}$Zr $^{100}$Zr

$\Gamma=0.1 \text{ MeV}$
Beta-decay half-lives of Zr isotopes w/ $T=0$ pairing int.

- Strength of $T=0$ pairing determined at $N=60$
- **SLy4**
  - reproduces well the observed isotopic dependence with $T=0$ pairing
  - Effect of the $T=0$ pairing is small beyond $N=68$
- **SkM***
  - gives a strong deformed gap at $N=64$
- Deformed gap at $N=72$
  - pairing correlations inactive

(Lorusso, Nishimura+ 2015)