Microscopic description of shape coexistence/mixing phenomena as large-amplitude collective motions

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Outline

Atomic nuclei exhibit different shapes depending on the numbers of protons and neutrons, the excitation energies, or angular momentum. Shape coexistence phenomena, in which an excited band with a shape different from the shape in the ground band exists close to the ground band, are widely observed all over the nuclear chart. Since the nuclear deformation is in general sensitive to the nuclear structure, the description of these shape coexistence phenomena can be a touchstone for nuclear structure models. In this study, we mainly study the oblate-prolate shape coexistence/mixing as large-amplitude collective motions in the low-lying states of proton-rich Se-Kr isotopes on the basis of the adiabatic self-consistent collective coordinate (ASCC) method.

Collaborators:
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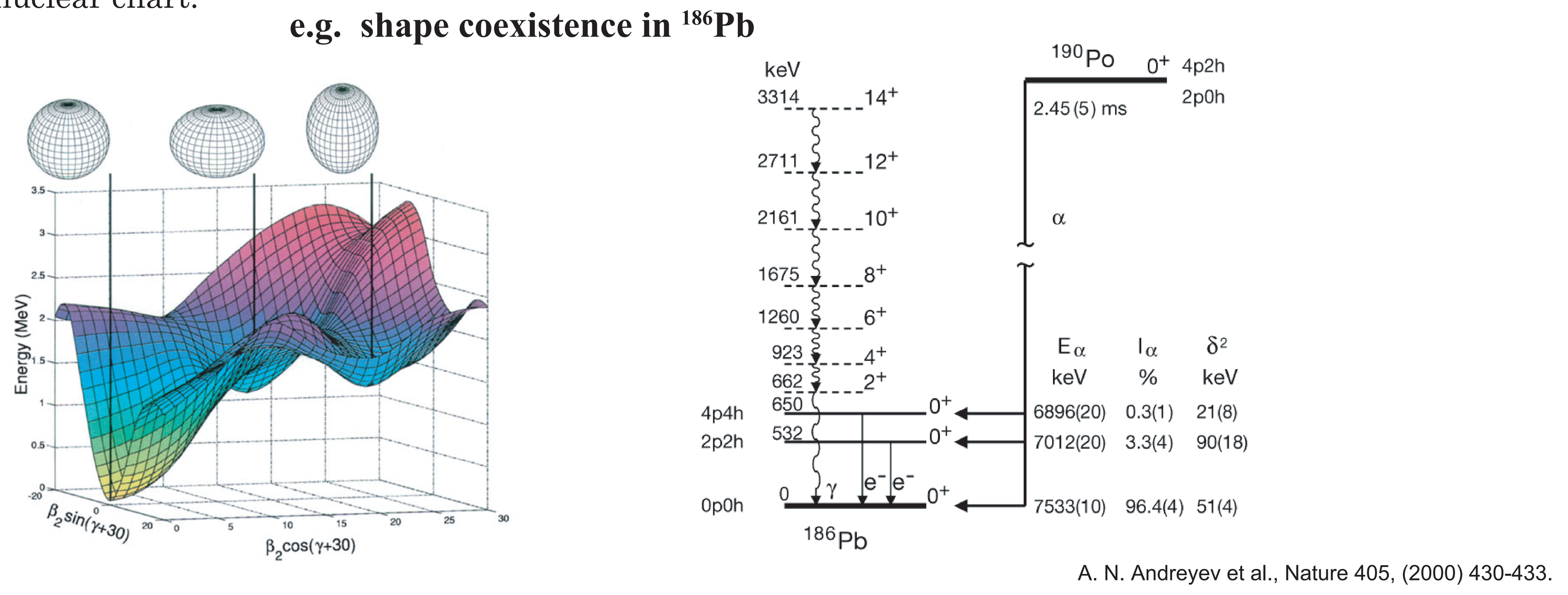
Shape coexistence phenomena

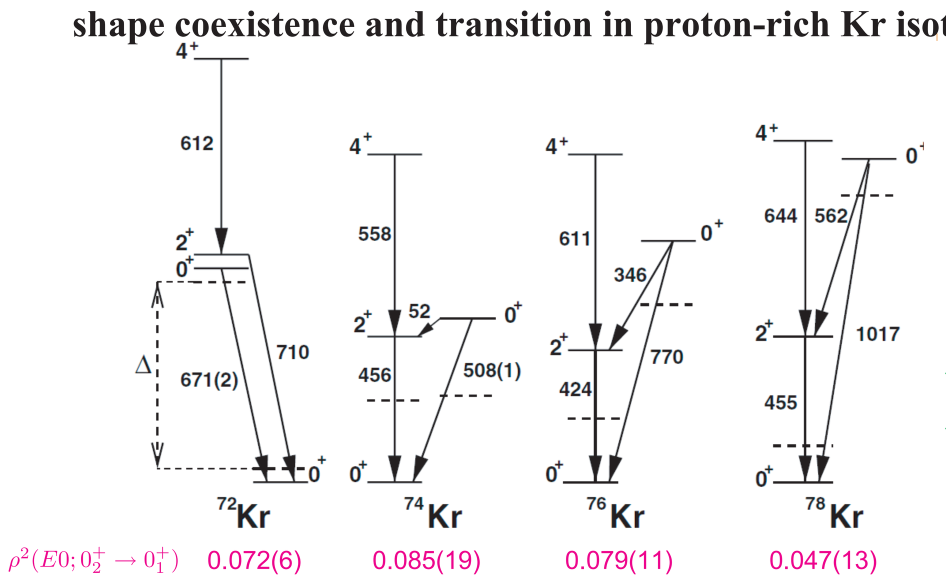
Atomic nuclei exhibit different shapes depending on the numbers of protons and neutrons, the excitation energies, or angular momentum. Shape coexistence phenomena, in which an excited band with a shape different from the shape in the ground band exists close to the ground band, are widely observed all over the nuclear chart.

e.g. shape coexistence in ^{186}Pb



A. N. Andreyev et al., Nature 405, (2000) 430-433.

shape coexistence and transition in proton-rich Kr isotopes

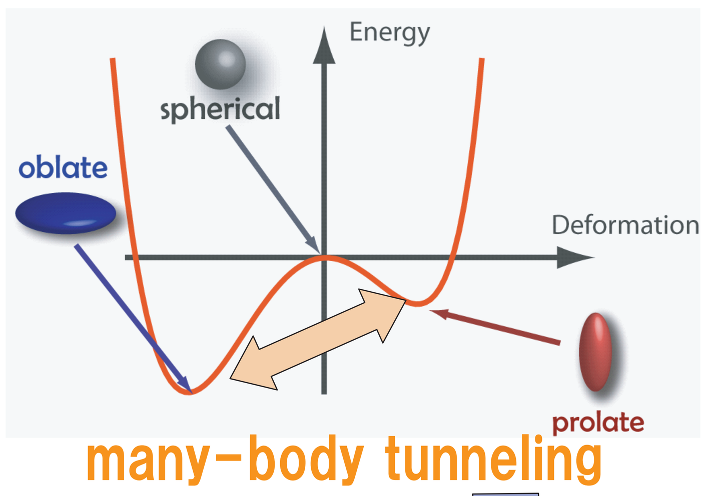


C. Chandler et al. PRC 56 (1997) 2924.
E. Bouchex et al., PRL 90 (2003) 082502.

Appearance of a low-lying excited 0+ state is one of typical experimental indications of the shape coexistence.

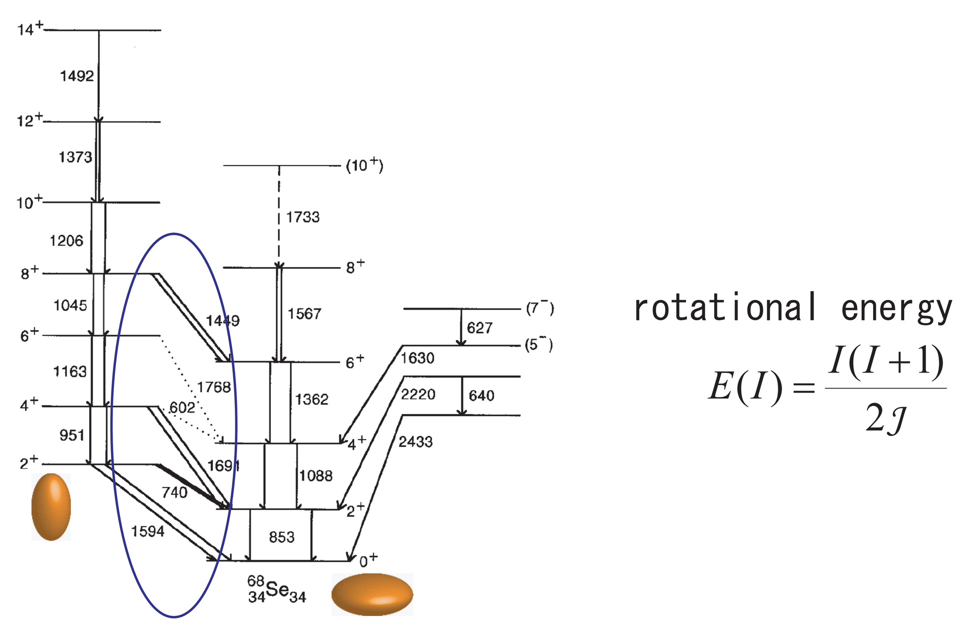
- Low-lying excited 0+ states
- Irregularities of the excitation spectra
- Systematics of the excited 0+ energies and E0 transition strengths

Tunneling effects and shape mixing



From the mean-field viewpoint, shape coexistence indicates that there are two equilibrium points in the mean-field potential.
The nucleus is a quantum many-body system: Different shapes are mixed by the tunneling effect through the potential barrier between the minima.

Large-amplitude collective motion

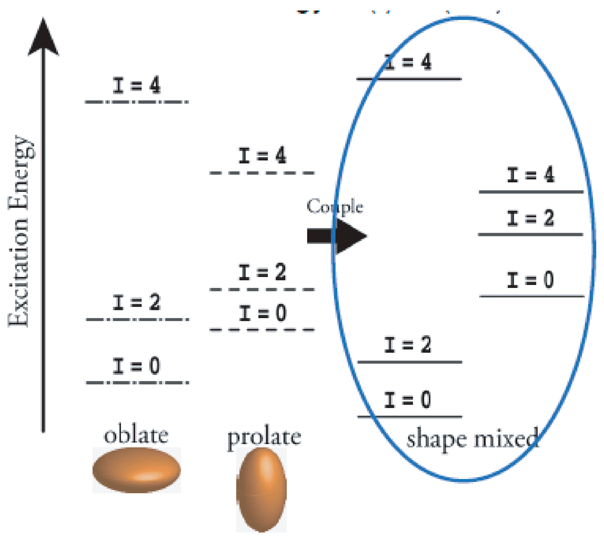


S.M. Fischer et al., Phys. Rev. Lett. 84, (2000) 4064.

EM transition caused by shape mixing

rotational energy

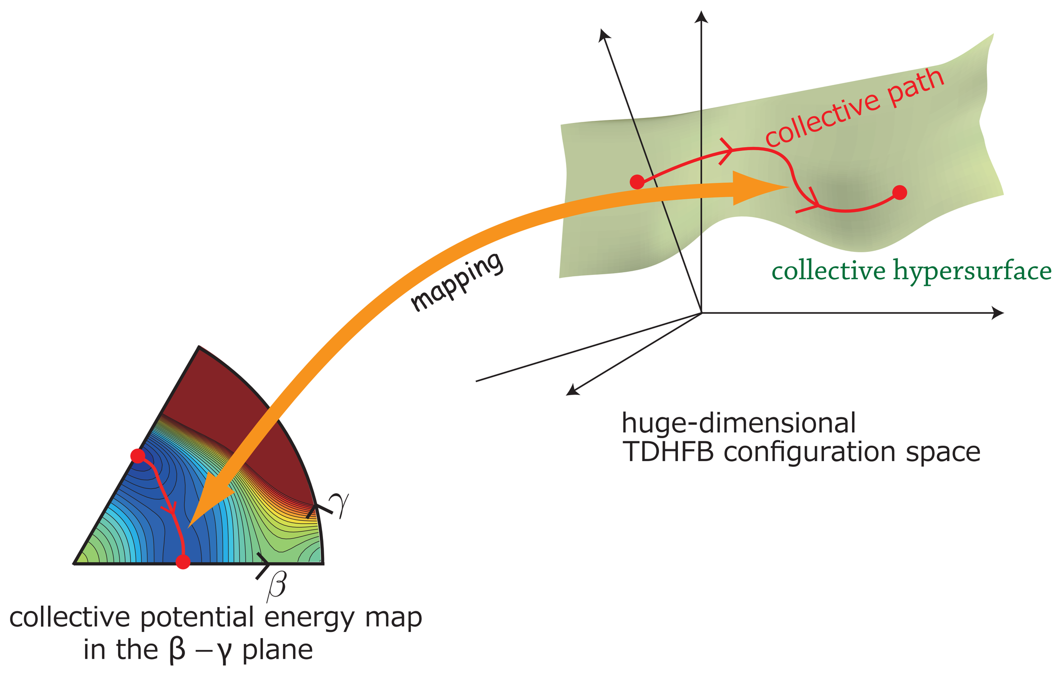
$$E(I) = \frac{I(I+1)}{2\mathcal{J}}$$



deviation from the regular rotational spectra

Microscopic approach to large-amplitude collective motions

The construction of a microscopic theory of large-amplitude collective motions is a long-standing open problem in nuclear structure physics.
In this work, we attempt to construct a microscopic theory of large-amplitude collective motions on the basis of the adiabatic self-consistent collective coordinate(ASCC) method.



The ASCC method is based on the time-dependent Hartree-Fock-Bogoliubov (TDHFB) method and an adiabatic solution of the SCC method formulated by Marumori et al, with which we can extract the optimal collective path (collective submanifold), maximally decoupled from non-collective degrees of freedom, in the large-dimensional TDHFB phase space.

T. Marumori et al., Prog. Theor. Phys. 64 (1980), 1294
M. Matsuo et al., Prog. Theor. Phys. 103 (2000) 959.
N. Hinohara et al., Prog. Theor. Phys. 117, 451 (2007).

Adiabatic Self-consistent Collective Coordinate method

The one-dimensional (1D) ASCC method, in which we assume one collective coordinate, was applied to the shape coexistence/ mixing in proton-rich Se and Kr isotopes and gave successful results. Now we are going to extend the 1D ASCC method to the two-dimensional version. N. Hinohara et al., Prog. Theor. Phys. 119, 59 (2008); Phys. Rev. C 80, 014305 (2009).

As a first step toward the full 2D ASCC method, in this study, we solve the two-dimensional ASCC approximately and determine microscopically the three vibrational and three rotational inertial functions and the collective potential in the five-dimensional quadrupole collective Hamiltonian: we solve the constrained Hartree-Fock-Bogoliubov (CHFB) equation and the "local" QRPA (LQRPA) equations at each point on the β − γ plane.

→ Constrained HFB + Local QRPA method

5D Quadrupole Collective Hamiltonian (General Bohr-Mottelson Hamiltonian)

A. Bohr, Mat. Fys. Medd. Dan. Vid. Selsk. 26, No. 14 (1952).
A. Bohr and B. R. Mottelson, Mat. Fys. Medd. Dan. Vid. Selsk. 27, No. 16 (1953).

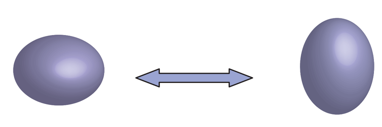
$$H = T_{\rm vib} + T_{\rm rot} + V(\beta,\gamma)$$

Collective potential

vibrational energy:

$$T_{\rm vib} = \frac{1}{2} D_{\beta\beta}(\beta,\gamma)\dot\beta^2 + D_{\beta\gamma}(\beta,\gamma)\dot\beta\dot\gamma + \frac{1}{2} D_{\gamma\gamma}(\beta,\gamma)\dot\gamma^2$$

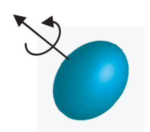
vibrational inertial mass



rotational energy:

$$T_{\rm rot} = \sum_{k=1}^{3} \frac{1}{2}\mathcal{J}_k \omega_k^2$$

Moment of inertia



quantization

Local QRPA (LQRPA) mass

One of the most important features of our method is that the inertial masses obtained with our method contain the contribution from the residual interaction unlike the widely-used cranking masses.

Collective Schrödinger equation

$$\left[\hat T_{\rm vib}(\beta,\gamma) + \hat T_{\rm rot}(\beta,\gamma) + V(\beta,\gamma)\right]\Psi_{IM\alpha}(\beta,\gamma,\Omega) = E_{I,\alpha}\Psi_{IM\alpha}(\beta,\gamma,\Omega)$$

$\Omega = (\theta_1,\theta_2,\theta_3)$: Euler angles

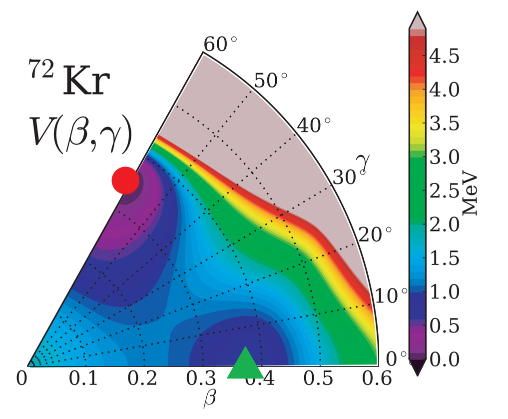
Collective wave function

$$\Psi_{IM\alpha}(\beta,\gamma,\Omega) = \sum_{K:{\rm even}} \Phi_{IK\alpha}(\beta,\gamma)\langle\Omega|IMK\rangle$$

Application of the CHFB+LQRPA method to 72Kr

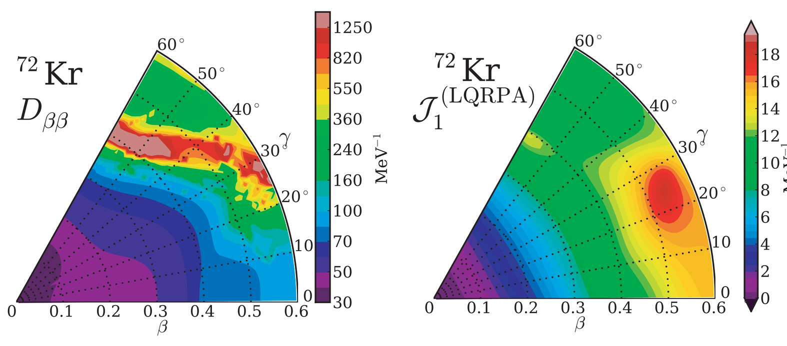
KS & N. Hinohara, arXiv:1006.3694

Collective potential



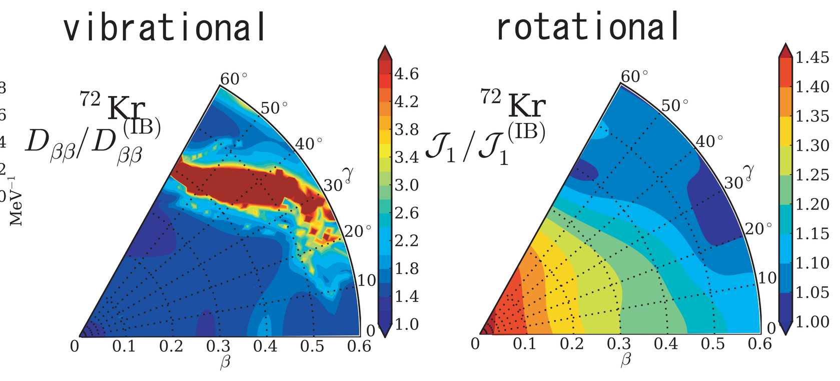
●:the absolute minimum
▲:the 2nd lowest minimum

Local QRPA masses

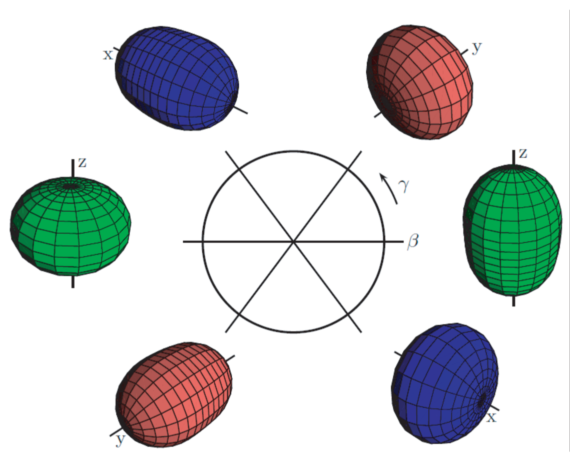


Strong dependence on (β, γ)

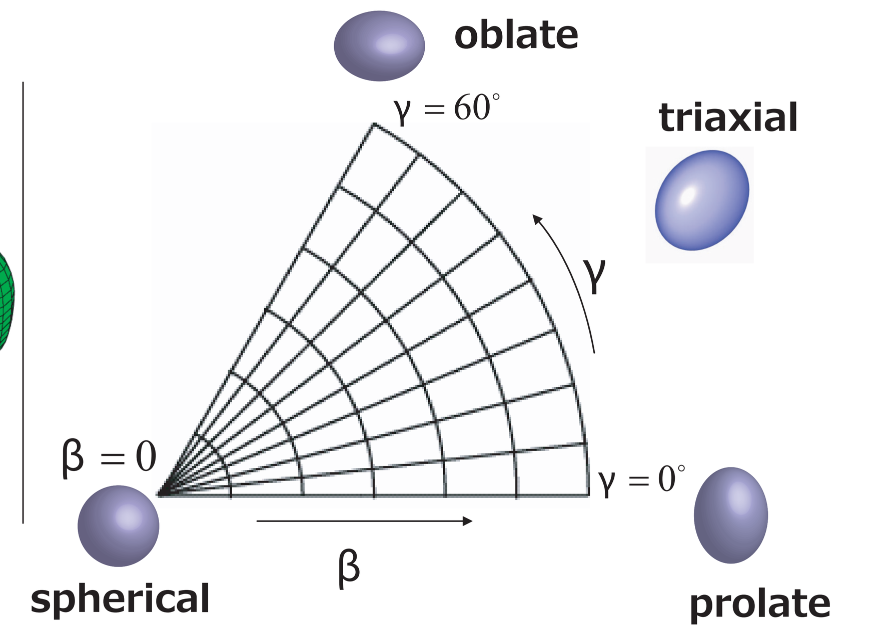
Effects of residual interaction



The residual interaction increases the inertial masses



taken from L. Fortunato, Eur. Phys. J. A 26 (2005) 1.



β − γ plane

Summary

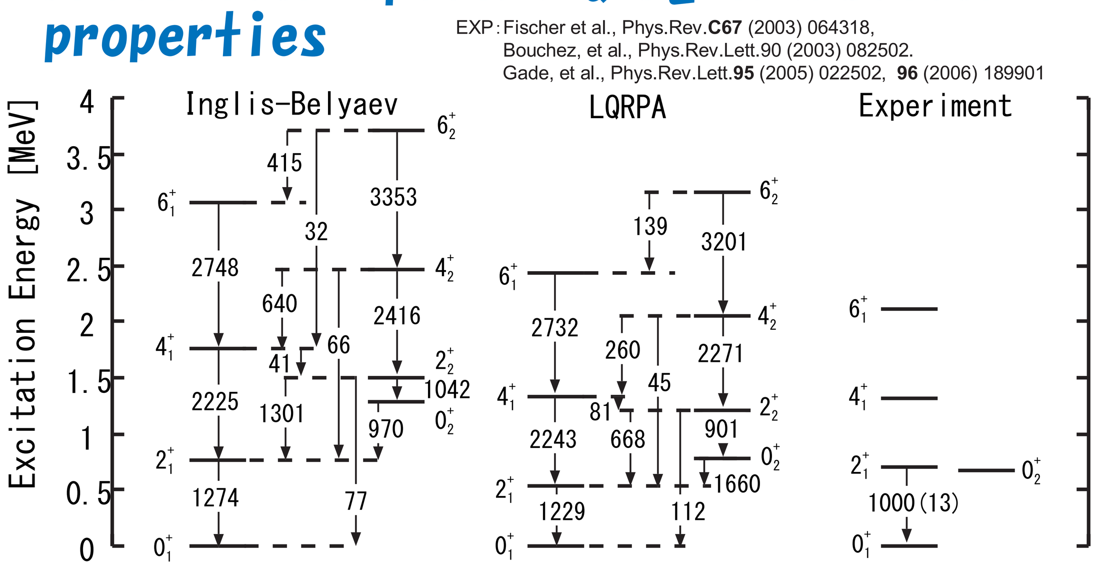
- We have developed a new method to determine microscopically the 5D quadrupole Hamiltonian on the basis of ASCC method for the description of large-amplitude collective motions in atomic nuclei
- Numerical results for proton-rich Kr isotopes show that the rotational motion plays an important role for the growth of the deformation.

Outlook

- Fully self-consistent calculation: We are going to extend the CHFB+LQRPA method, an approximate version of the two-dimensional ASCC method, to the fully self-consistent version.
- Realistic interaction: We are going to adapt a more realistic interaction like Skyrme interaction, which is one of the standard interactions in modern nuclear structure physics, based on the density functional theory

Excitation Spectra & E2-transition properties

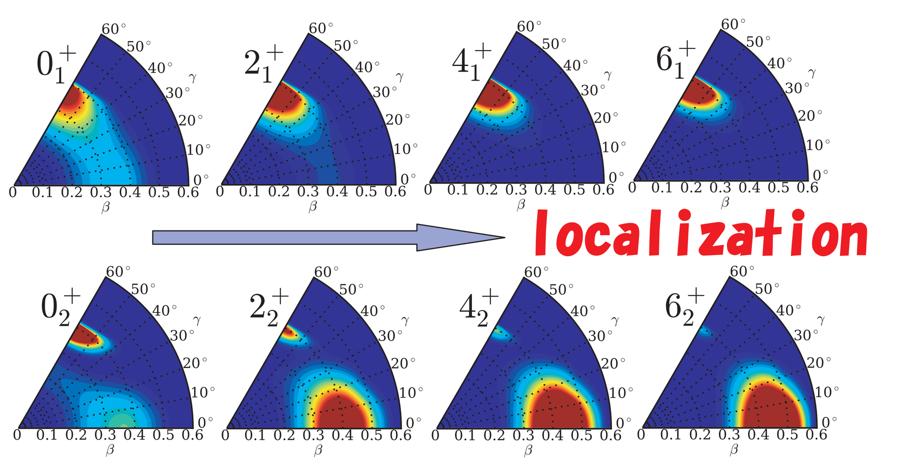
EXP: Fischer et al., Phys.Rev.C67 (2003) 064318, Bouchez, et al., Phys.Rev.Lett.90 (2003) 082502. Gade, et al., Phys.Rev.Lett.95 (2005) 022502, 96 (2006) 189901



The numbers on arrows show $B(E2)$ values in units of $e^2{\rm fm}^4$.

Collective wave functions squared (probability densities)

$\beta^4 \sum_K |\Phi_{IKk}(\beta,\gamma)|^2$



Rotation hinders shape mixing