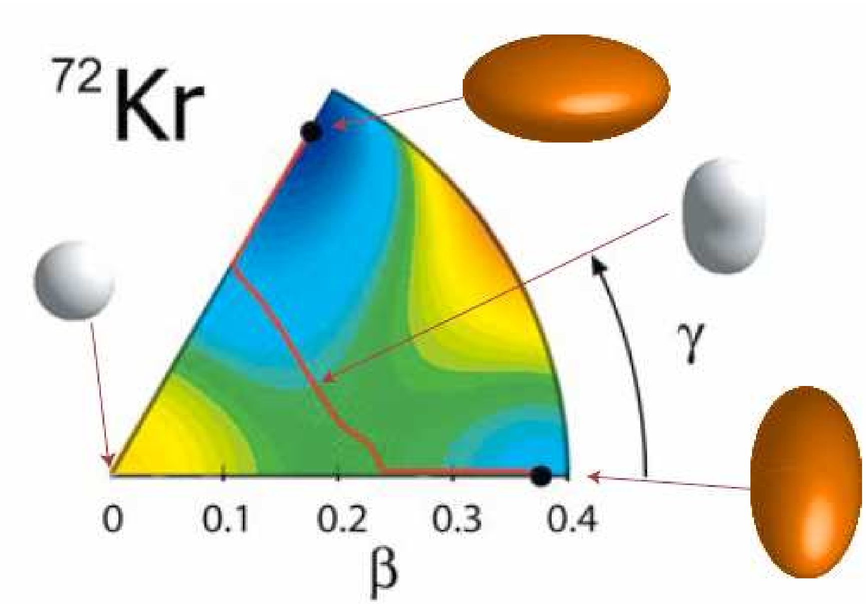
Application of the Adiabatic Self-Consistent Collective Coordinate (ASCC) Method to Shape Coexistence/ Mixing Phenomena



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Microscopic Description of Nuclear Large-Amplitude Collective Motion by Means of the Adiabatic Self-Consistent Collective Coordinate Method

The major part of this thesis will appear in Prog. Theor. Phys. Jan. 2008 within a few days

Sunny Field

Life lively grows

Hinohara Nobuo

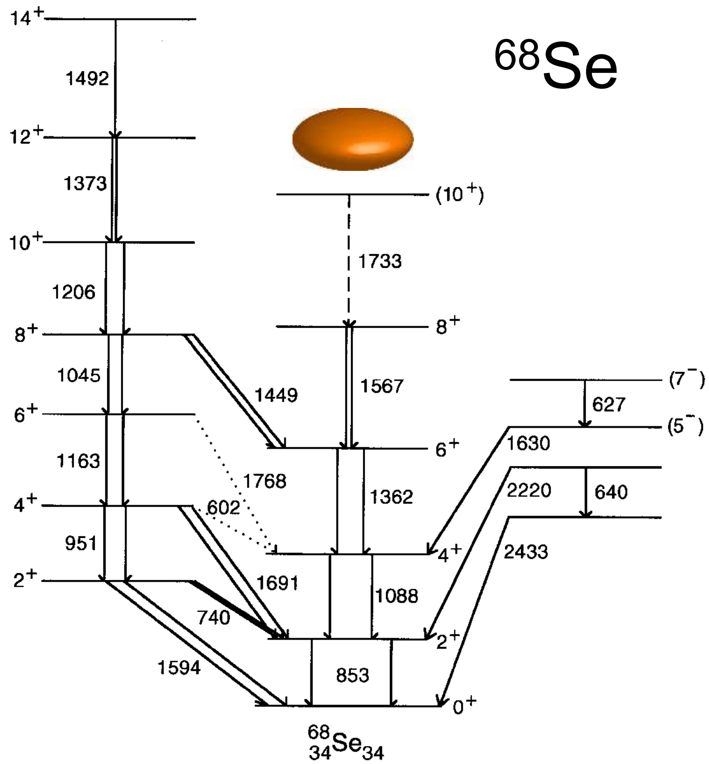
日野原　伸生

doctoral dissertation defense

2008.1.17

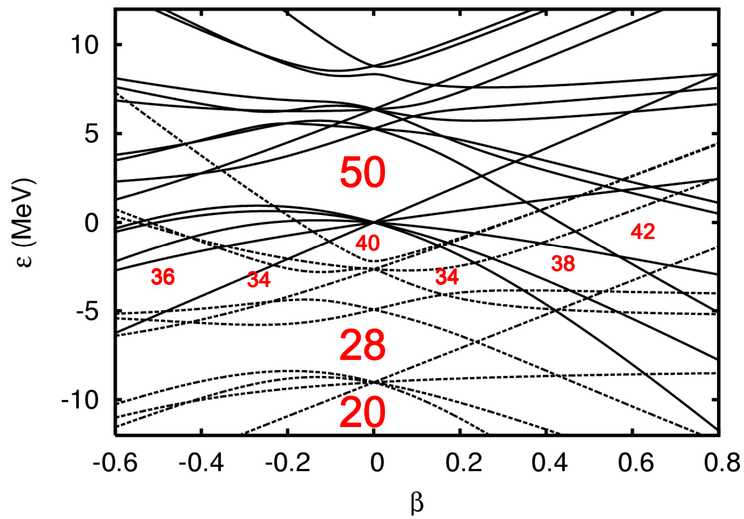
学位論文公聴会

Shape coexistence in N~Z~40 region



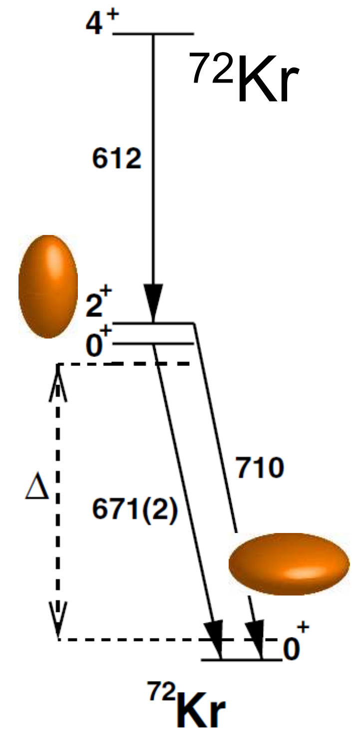
Fischer *et al.* Phys.Rev.**C67** (2003) 064318.

neutron single particle energy

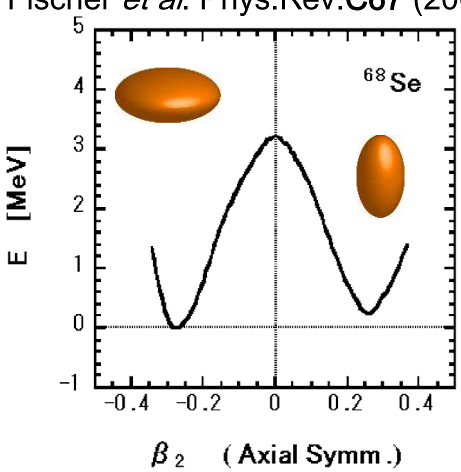


Z,N = 34,36 (oblate magic numbers)

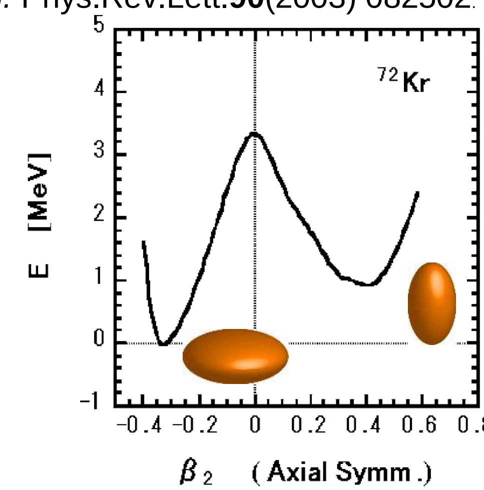
Z,N = 38 (prolate magic number)



Bouchez *et al.* Phys.Rev.Lett.**90**(2003) 082502.



- oblate-prolate shape coexistence
- oblate ground state
- shape coexistence/mixing

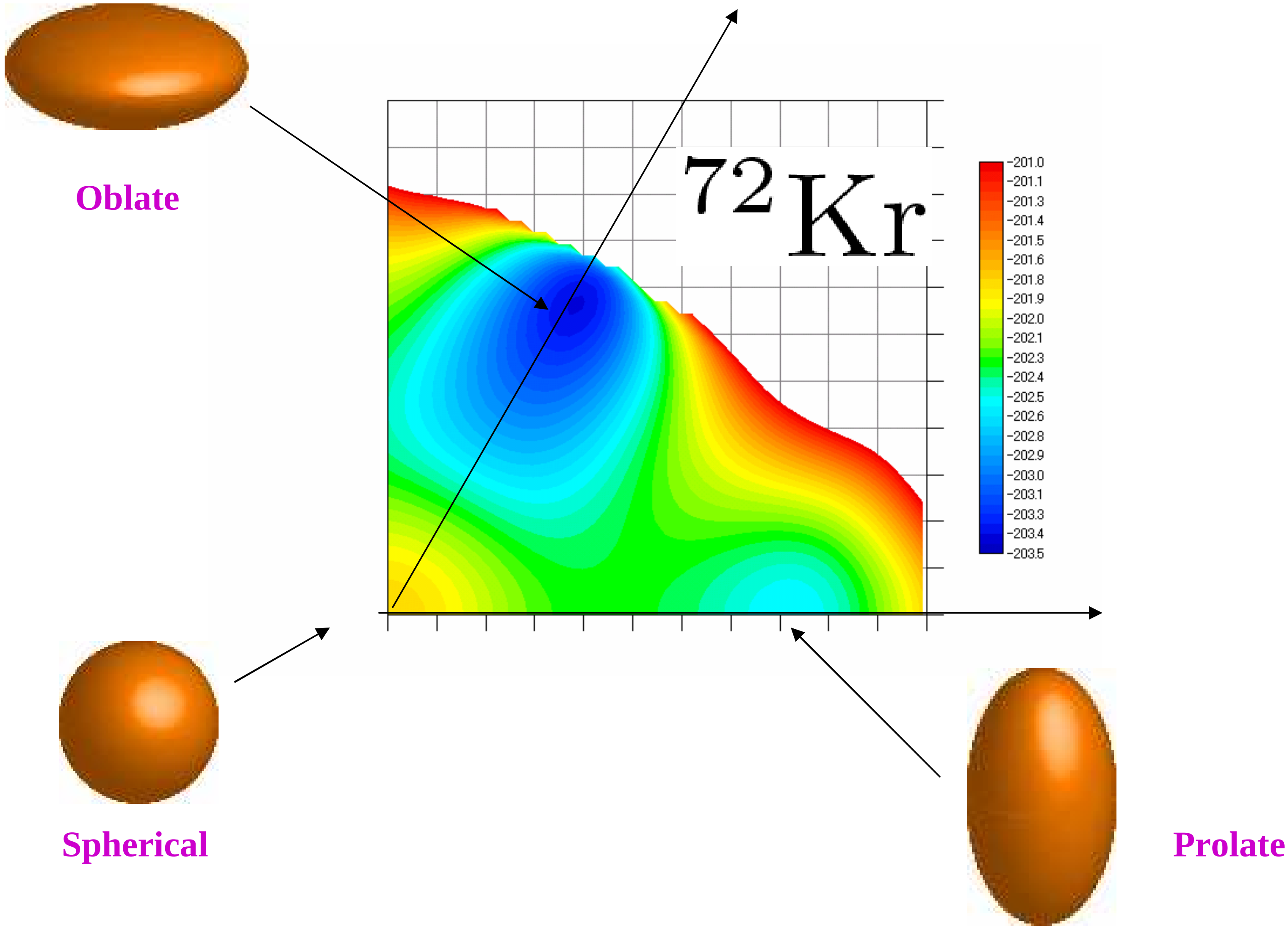


Skyrme-HFB: Yamagami *et al.* Nucl.Phys.**A693** (2001) 579.

Many-Body Tunneling between Different Vacua

Basic question

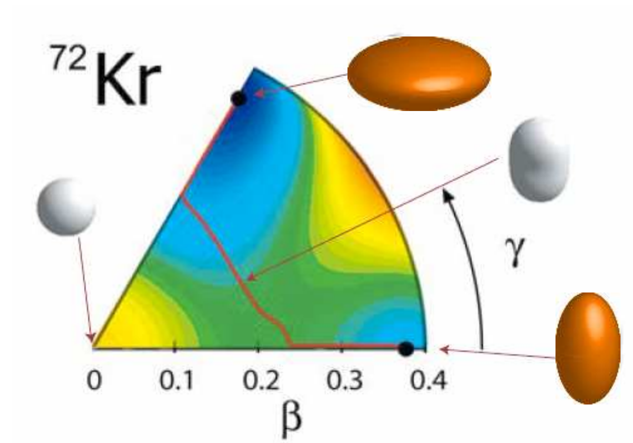
Why localization is possible for such a low barrier ?!



Main points

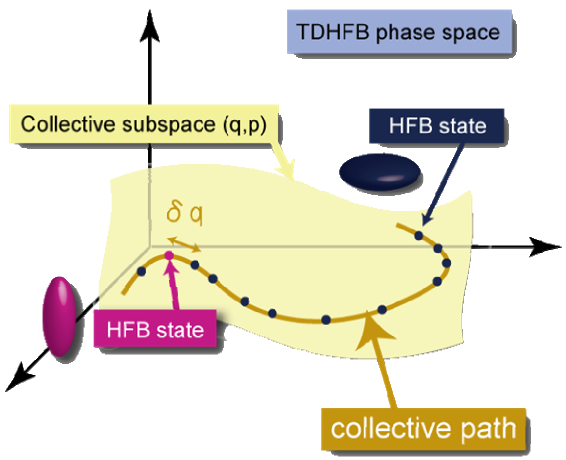
I am going to report the **first application** of
the microscopic theory of large amplitude collective motion,
based on the time-dependent mean-field (TDHFB) theory,
to real nuclear structure phenomena
in nuclei with superfluidity.

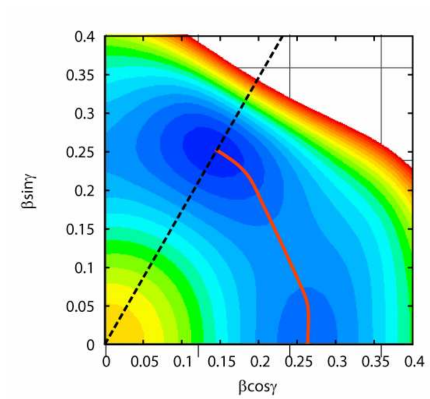
Coexistence/mixing of
oblate and prolate shapes
is a typical phenomenon of
large amplitude collective motion.

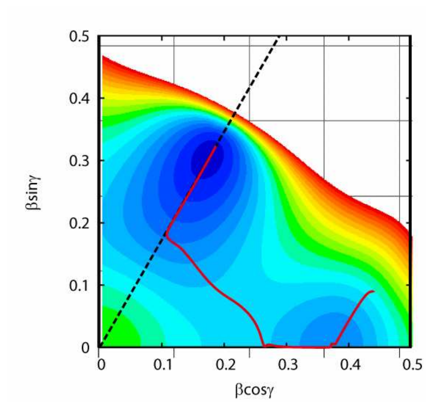


Main points

In contrast to the GCM, **collective coordinate and momentum are microscopically derived;** i.e., self-consistently extracted from huge-dimensional TDHFB phase space.

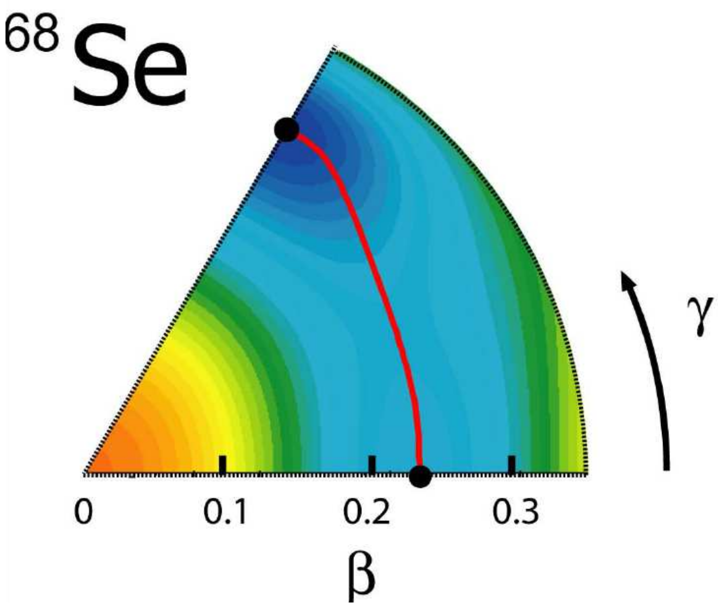


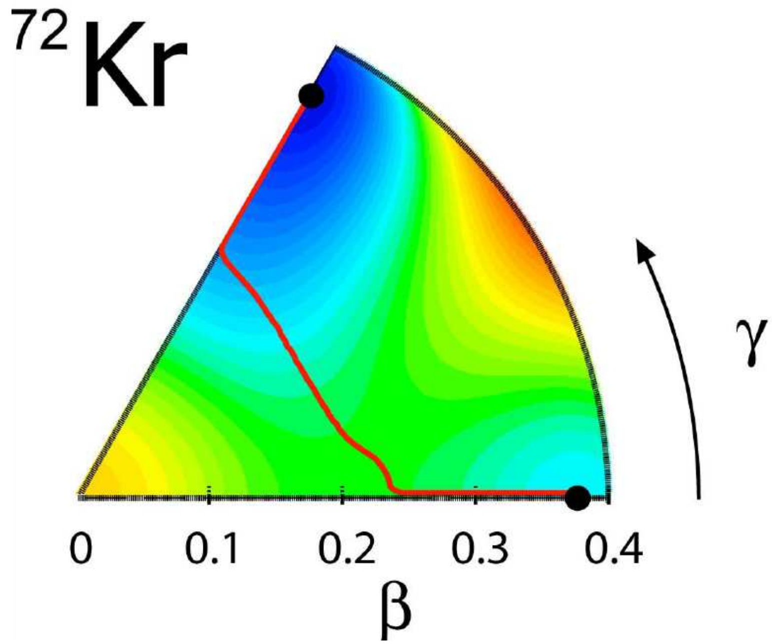




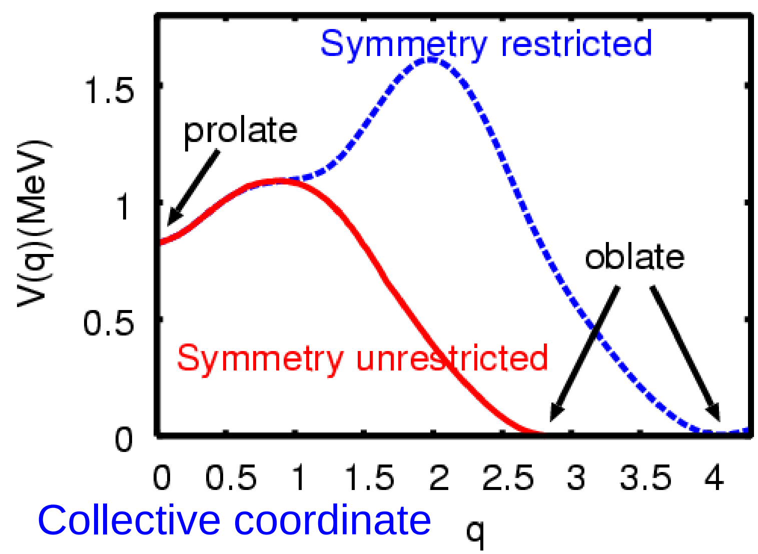
In ^{68}Se and ^{72}Kr, **the collective paths,** connecting the oblate and prolate minima, **run in the triaxially deformed region.**

Collective paths obtained by means of the ASCC method





Comparison with the axially symmetric path

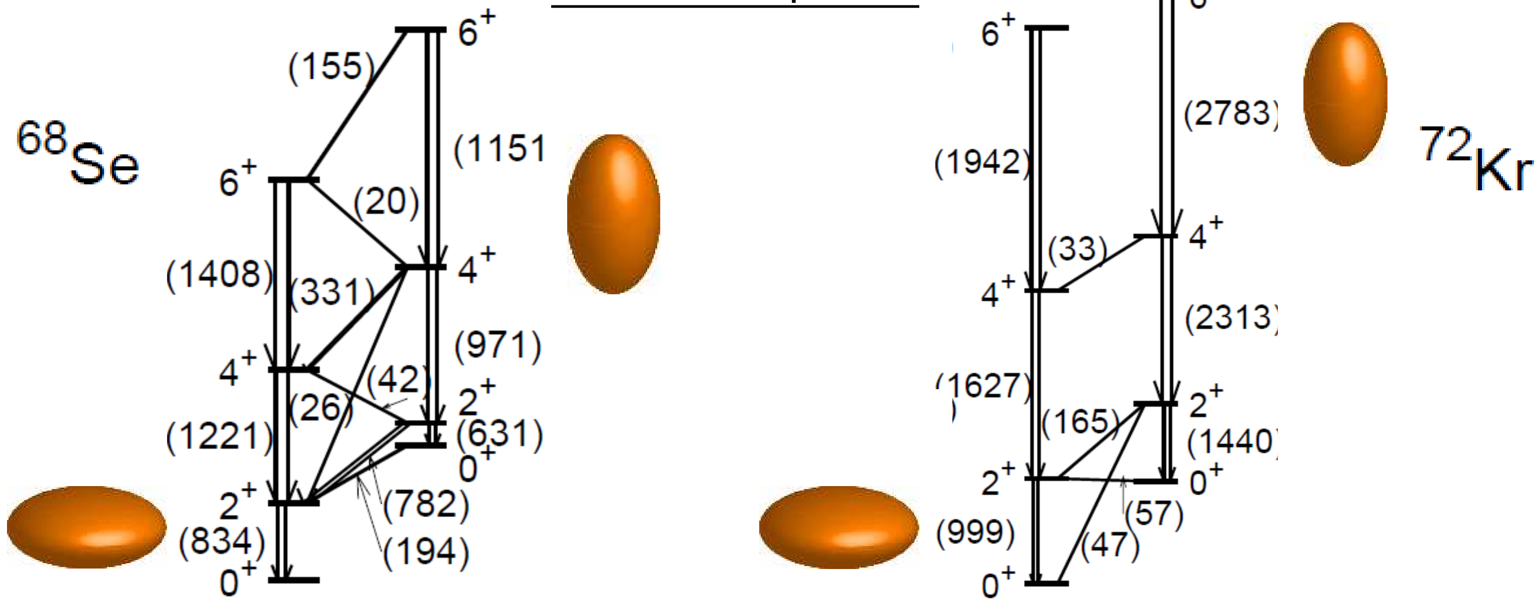


Main points

The collective Hamiltonian, derived microscopically, is quantized and excitation spectra, E2 transitions and quadrupole moments are evaluated for the first time.

The result indicates that the oblate and prolate shapes are strongly mixed at I=0, but the mixing rapidly decreases with increasing angular momentum.

Calculated spectra



After a long history (more than 30 years) , a way for wide applications of large-amplitude theory is now open.

$$\delta\langle\phi(q,p)|i\hbar\frac{\partial}{\partial t} - H|\phi(q,p)\rangle = 0.$$

SCC and quasiparticle SCC

Marumori-Maskawa-Sakata-Kuriyama, Yamamura, Matsuo, Shimizu-Takada, and many colleagues, reviewed in Prog. Theor. Phys. Supplement 141 (2001).

$$\begin{aligned} |\phi(q,p)\rangle &= e^{i\hat{G}(q,p)}|\phi_0\rangle \\ \hat{G}(q,p) &= \sum G_{mn}(\eta^*)^m\eta^n \\ \eta &= \frac{1}{\sqrt{2}}(q+ip) \end{aligned}$$

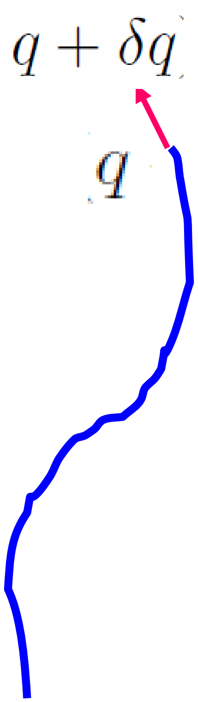
ATDHF and ATDHFB

Villars, Kerman-Koonin, Brink, Rowe-Bassermann, Baranger-Veneroni, Goeke-Reinhard, Bulgac-Klein-Walet, Giannoni-Quentin, Dobaczewski-Skalski and many colleagues, reviewed in G. Do Dang, A. Klein and N.R. Walet, Phys.

$$|\phi(q,p)\rangle = e^{ip\hat{Q}(q)}|\phi(q)\rangle$$

ASCC

Time dependent mean-field



time-dependent variational principle

$$\delta \langle \phi(q,p) | i\hbar \frac{\partial}{\partial t} - H | \phi(q,p) \rangle = 0.$$

collective coordinate q

collective momentum p

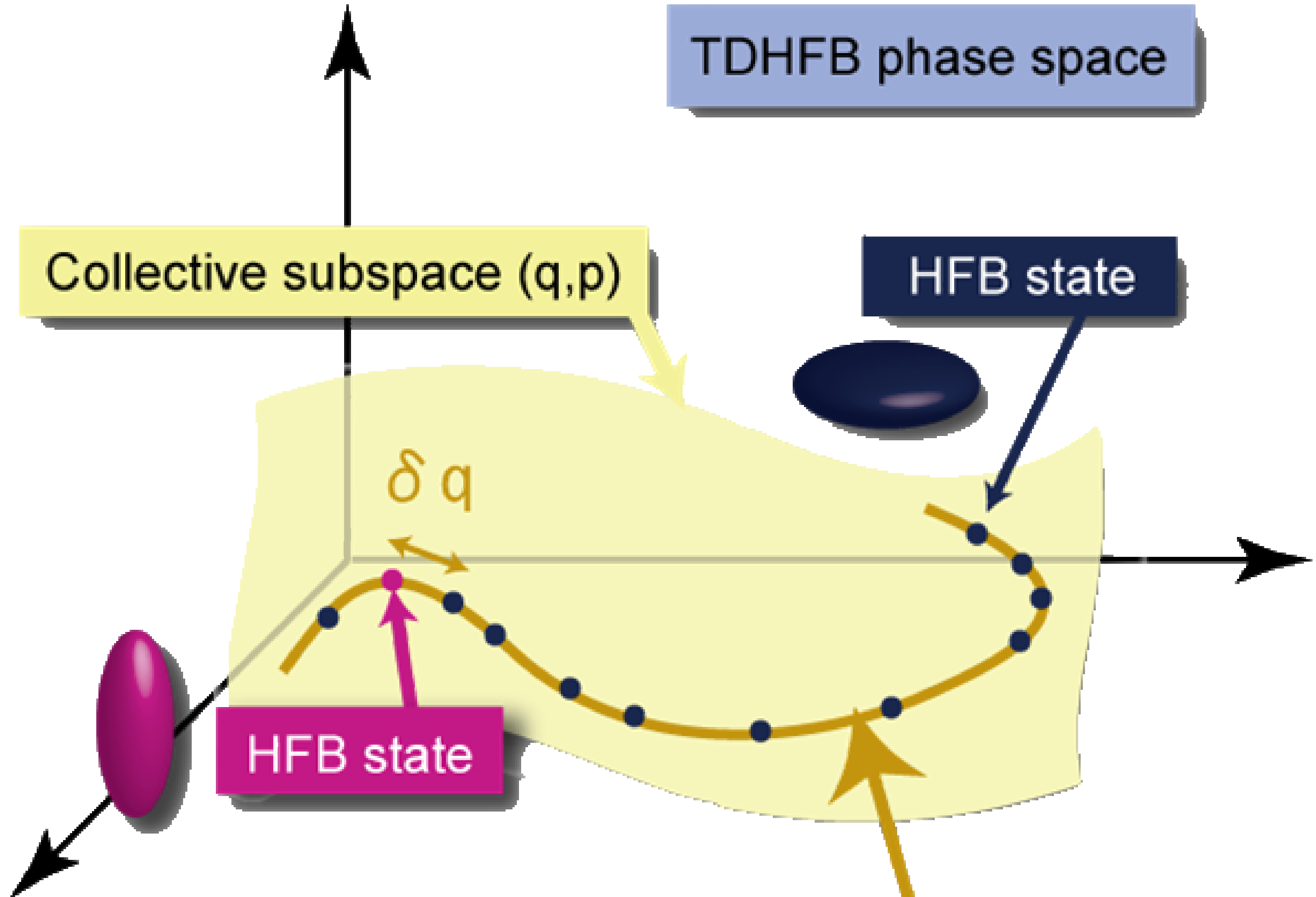
$$\frac{\partial}{\partial t} \Rightarrow \dot{q}\frac{\partial}{\partial q} + \dot{p}\frac{\partial}{\partial p}$$

$$|\phi(q,p)\rangle = e^{ip\hat{Q}(q)} |\phi(q)\rangle$$

Adiabatic expansion (ATDHFB)

$$|\phi(q+\delta q)\rangle = (1 - i\delta q \hat{P}(q)) |\phi(q)\rangle$$

Find an optimum direction at every point of q



$$\delta\langle\phi(q,p)|i\hbar\frac{\partial}{\partial t} - H|\phi(q,p)\rangle = 0.$$

$$|\phi(q,p)\rangle = e^{ip\hat{Q}(q)}|\phi(q)\rangle \qquad |\phi(q+\delta q)\rangle = (1 - i\delta q\hat{P}(q))|\phi(q)\rangle$$

ASCC Basic Equations

Moving-frame HFB equation (from 0-th order in p)

moving-frame Hamiltonian

$$\delta \langle \phi(q) | \hat{H}_M(q) | \phi(q) \rangle = 0 \qquad \hat{H}_M(q) = \hat{H} - \lambda(q)\hat{N} \boxed{- \frac{\partial V}{\partial q}\hat{Q}(q)}$$

Not included in HFB

Local harmonic equations (moving-frame QRPA equations)

$$\delta \langle \phi(q) | [\hat{H}_M(q), \hat{Q}(q)] - \frac{1}{i}B(q)\hat{P}(q) | \phi(q) \rangle = 0$$

(from 1st-order in p)

$$\delta \langle \phi(q) | [\hat{H}_M(q), \frac{1}{i}\hat{P}(q)] - C(q)\hat{Q}(q) \boxed{- \frac{\partial \lambda}{\partial q}\hat{N}}$$

(from 2nd-order in p)

$$\boxed{- \frac{1}{2B(q)}[[\hat{H}_M(q), (\hat{H} - \lambda(q)\hat{N})_{aa,\, a^\dagger a^\dagger \text{ part}}], \hat{Q}(q)]} | \phi(q) \rangle = 0$$

Terms not included in QRPA

$$C(q) = \frac{\partial^2 V}{\partial q^2} + \boxed{\frac{1}{2B(q)}\frac{\partial B}{\partial q}\frac{\partial V}{\partial q}}$$

$$\hat{P}(q) | \phi(q) \rangle = i\frac{\partial}{\partial q} | \phi(q) \rangle$$

Collective Hamiltonian

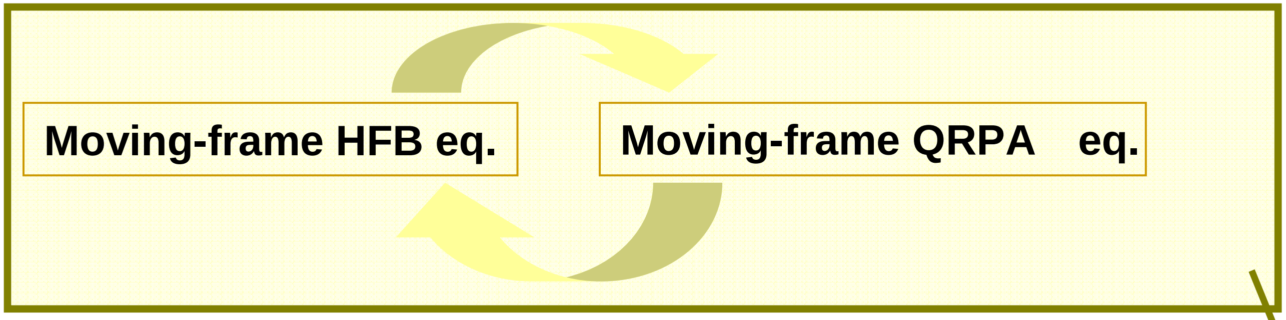
$$\begin{aligned} \mathcal{H}(q,p,N) &= \langle \phi(q,p,N) | \hat{H} | \phi(q,p,N) \rangle \\ &= V(q) + \frac{1}{2}B(q)p^2 + \lambda(q)n \end{aligned}$$

Canonical variable conditions

$$\begin{cases} \langle \phi(q) | [\hat{Q}(q), \hat{P}(q)] | \phi(q) \rangle = i \\ \langle \phi(q) | [\hat{\Theta}(q), \hat{N}] | \phi(q) \rangle = i \end{cases}$$

Basic Scheme of the ASCC method (1)

1st Step: Solve ASCC equations and find collective path.



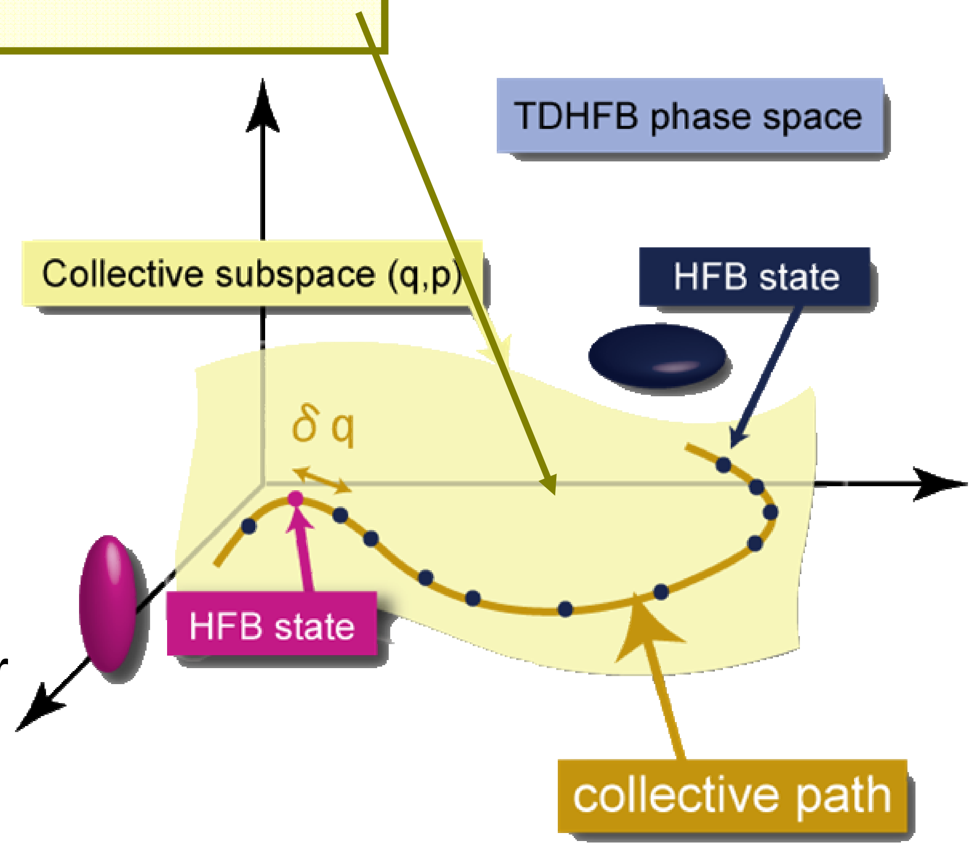
Double iteration for each q

$$\mathcal{H}(q,p,\mathbf{I}) = \frac{1}{2}\boxed{B(q)}p^2 + \boxed{V(q)} + \sum_{i=1}^{3}\frac{I_i^2}{2\boxed{\mathcal{J}_i(q)}}$$

collective mass

collective potential

Thouless-Valatin Moment of Inertia for moving-frame Hamiltonian



An important remark

The ASCC method was proposed in

M. Matsuo, T. Nakatsukasa and K. Matsuyanagi ,
Prog. Theor. Phys. 103 (2000) 959.

Quite recently, it was found that its basic equations are invariant against gauge transformations associated with pairing correlations.

$$|\phi(q,p,\varphi,n)\rangle = e^{-i\varphi\tilde{N}} e^{ip\hat{Q}(q)} e^{in\hat{\Theta}(q)} |\phi(q)\rangle$$

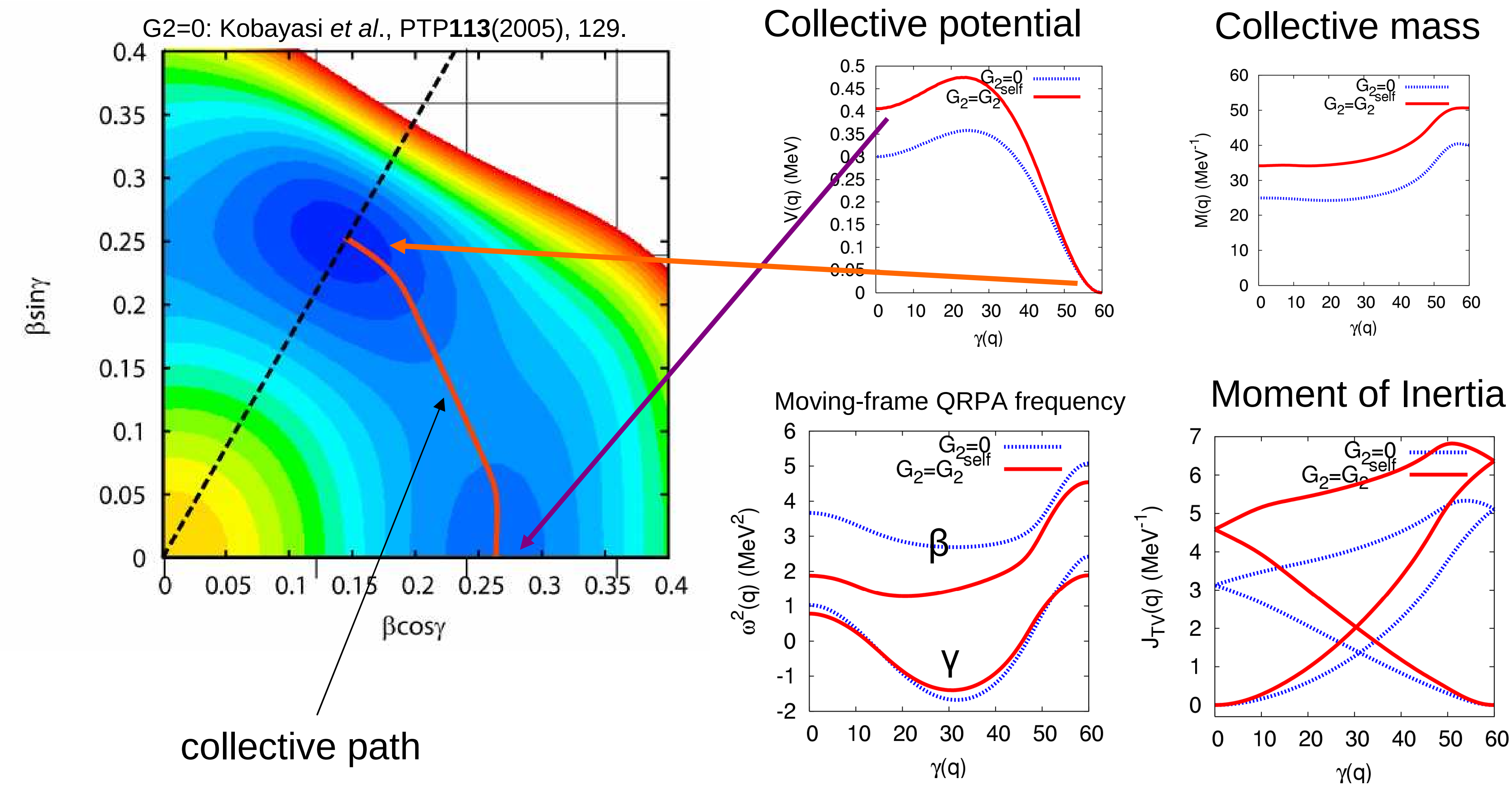
Gauge invariant ASCC method.

Choosing an appropriate gauge fixing condition, numerical instabilities encountered previously are now completely removed.

N. Hinohara et al., Prog. Theor. Phys. 117 (2007) 451

Collective path in ^{68}Se

P0+P2+QQ interaction



- Triaxial deformation connects two local minima
- **Enhancement of the collective mass and MoI by the quadrupole pairing**

⇧

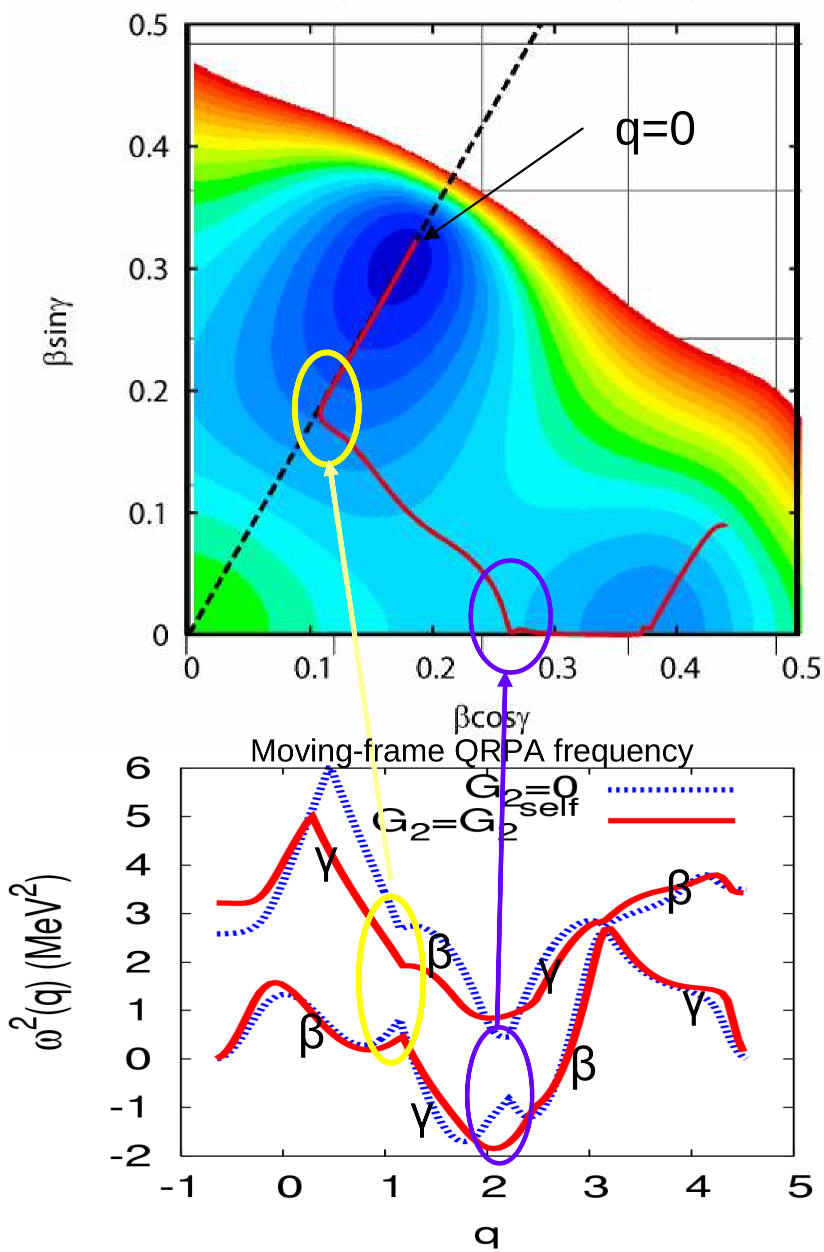
due to the time-odd pair field

Prog.Theor.Phys.115(2006)567.

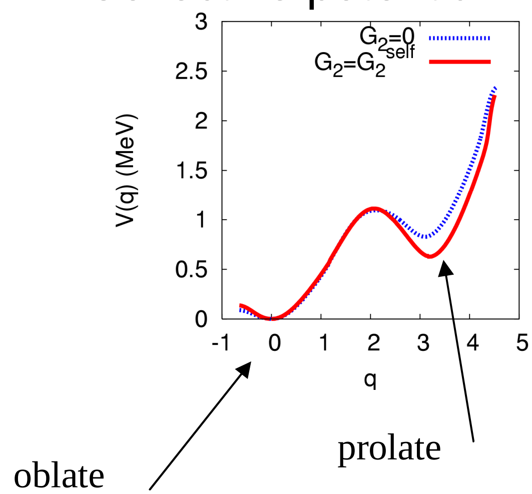
Collective path in ^{72}Kr

P0+P2+QQ interaction

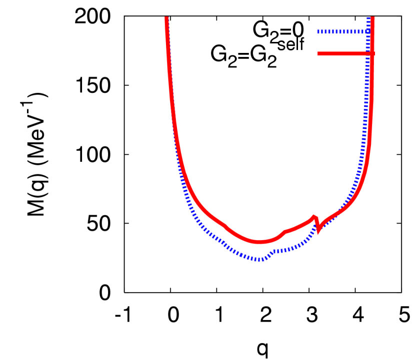
G2=0: Kobayasi *et al.*, PTP**113**(2005), 129.



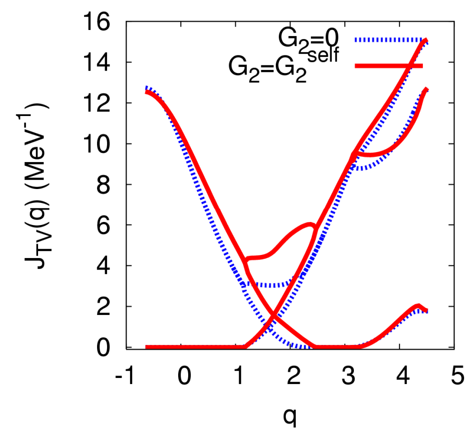
Collective potential



Collective mass



Moment of Inertia



- **Dynamical symmetry breaking of the path**
- Triaxial degrees of freedom: important
- Enhancement of the collective mass and MoI by the quadrupole pairing

Basic Scheme of the ASCC Method (2)

2nd Step: Requantize the collective Hamiltonian.

$$p \to \frac{\hbar}{i}\frac{\partial}{\partial q}, \quad I_i \to \hat{I}_i,$$

Collective wave function

vibrational wave functions

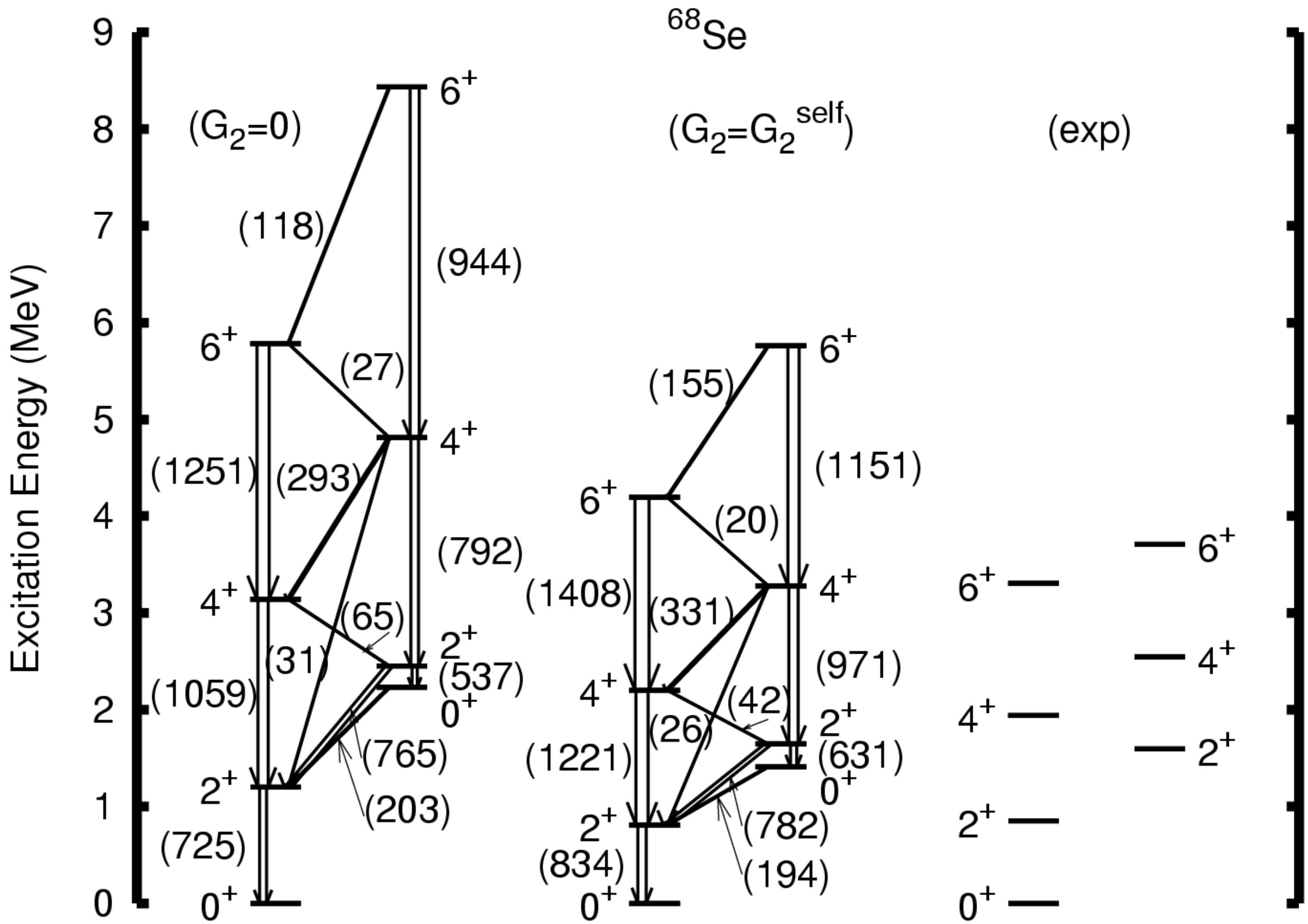
$$\Psi_{IMk}(q,\Omega) = \sum_{K=-I}^{I} \Phi'_{IKk}(q)\sqrt{\frac{2I+1}{8\pi^2}}\mathscr{D}^{I}_{MK}(\Omega)$$
$$= \sum_{K=0}^{I} \Phi_{IKk}(q)\,\langle\Omega|IMK\rangle\,.$$

rotational wave functions

Collective Schrodinger eq.

$$\left(-\frac{1}{2}\frac{\partial^2}{\partial q^2} + \sum_{i=1}^{3}\frac{\hat{I}_i^2}{2\mathcal{J}_i(q)} + V(q)\right)\Psi_{IMk}(q,\Omega) = E_{I,k}\Psi_{IMk}(q,\Omega)$$

Excitation spectra of ^{68}Se



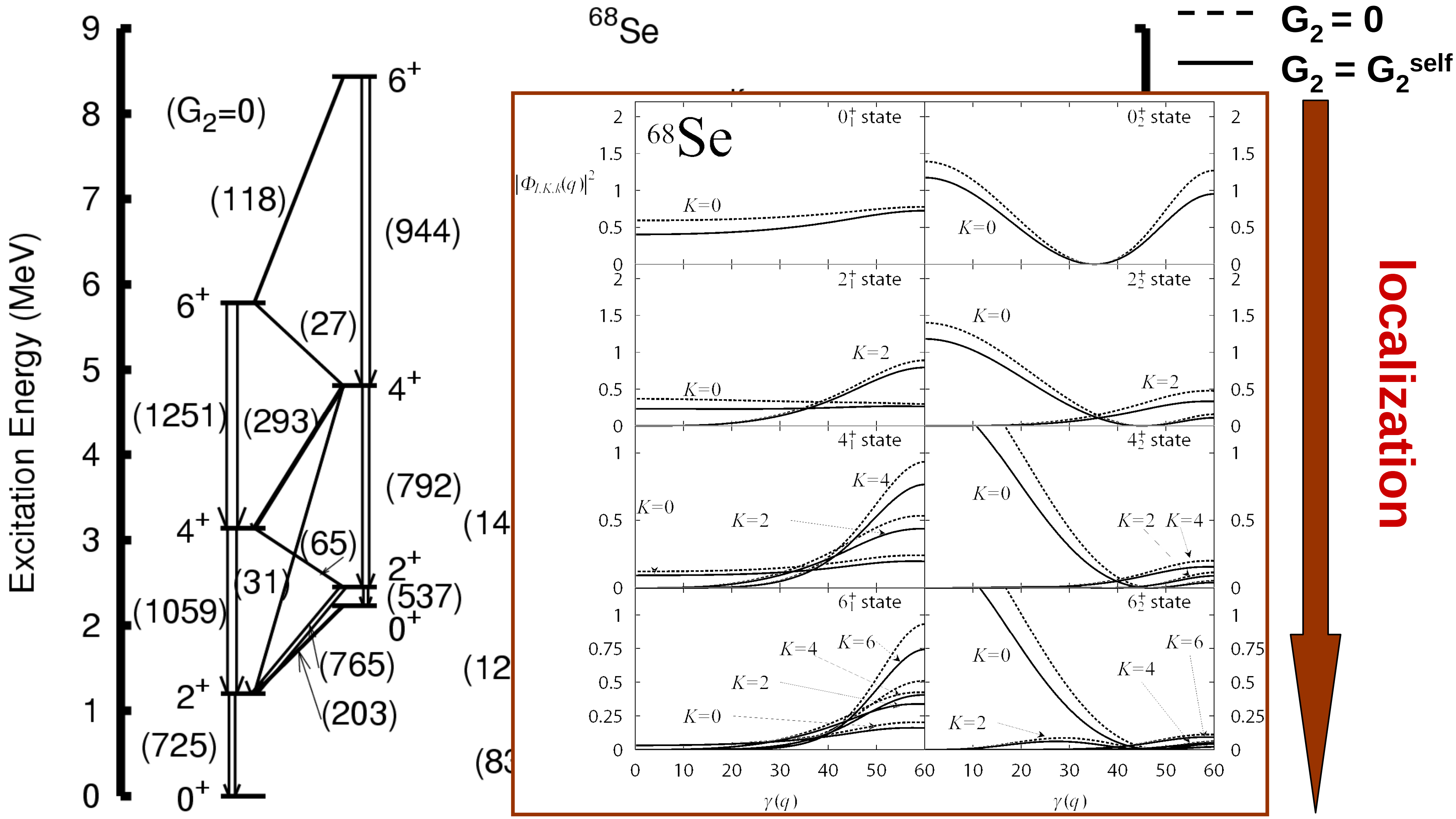
- two rotational bands
- 0_2^+ state
- quadrupole pairing lowers ex.energy

( ) …B(E2) e^2 fm^4

effective charge: e_{pol} = 0.904

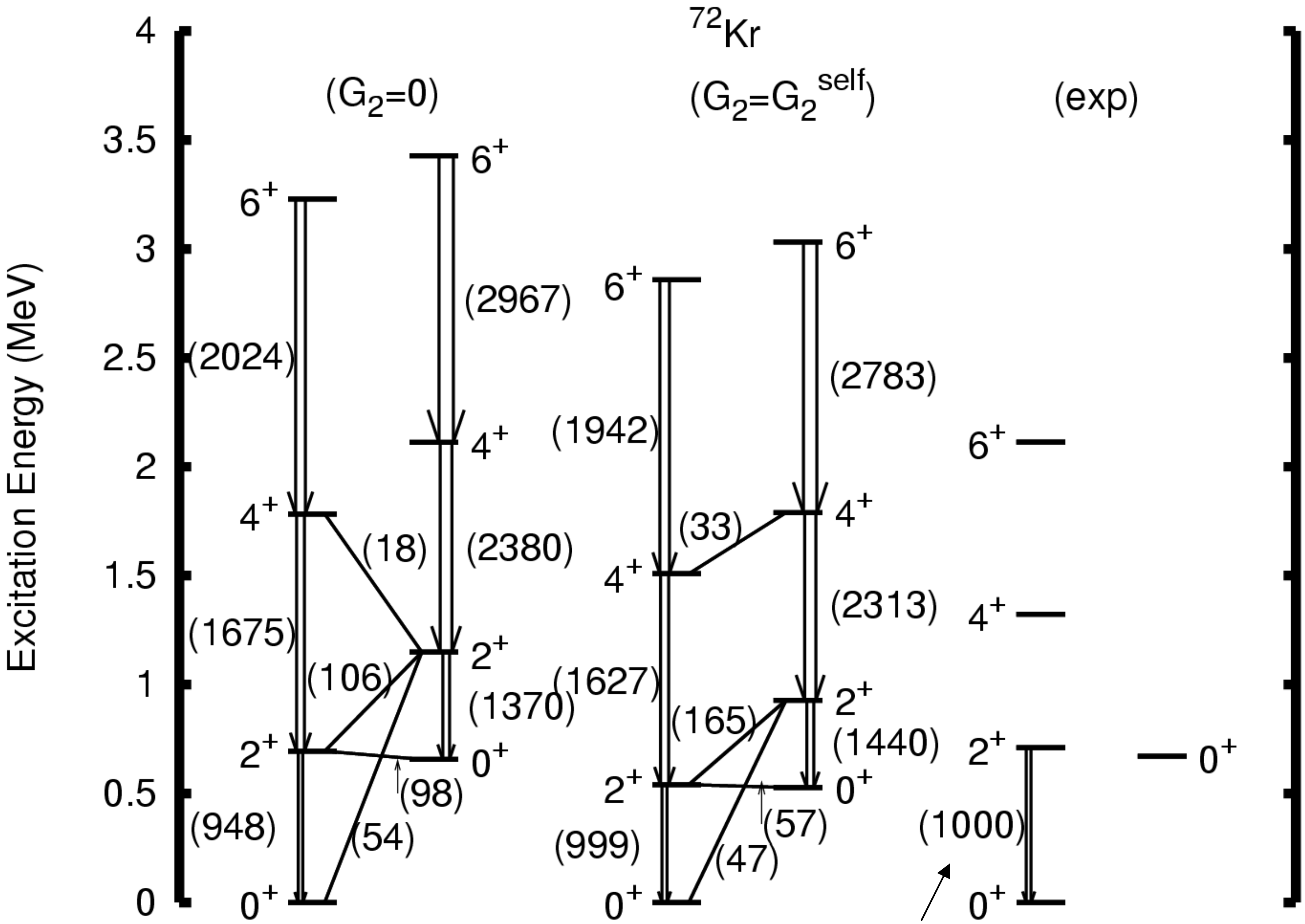
EXP：Fischer et al., Phys.Rev.**C67** (2003) 064318.

Collective wave functions in ^{68}Se



- I = 0: oblate and prolate shapes are strongly mixed via triaxial degree of freedom
- ground band: mixing of different K components、excited band: K=0 dominant
- oblate-prolate mixing: strong in 0^+ states, decreases as angular momentum increases

Excitation Spectra of ^{72}Kr



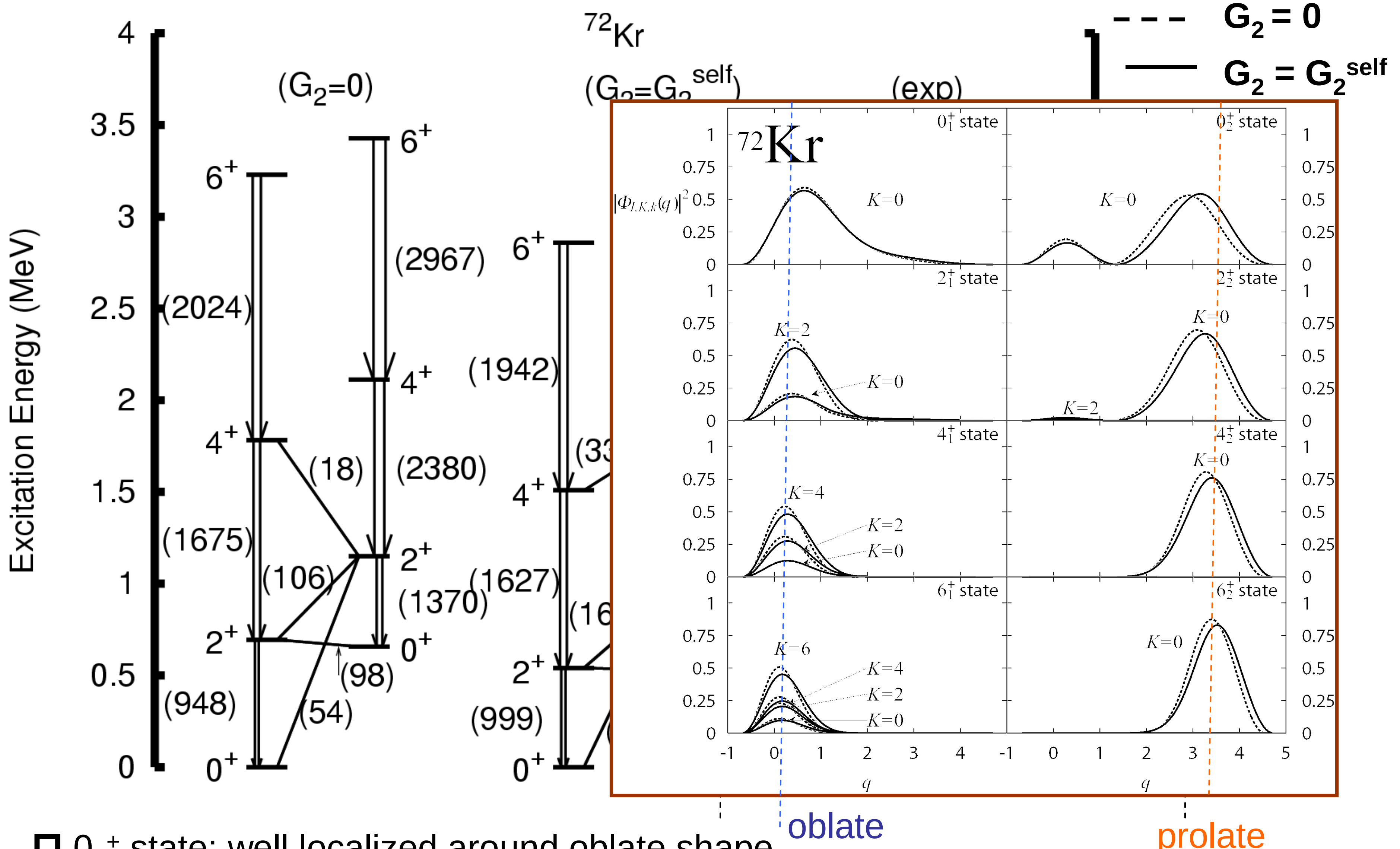
effective charge is adjusted to this value

( ) …B(E2) e^2 fm^4

- two rotational bands
- small inter-band B(E2): shape mixing rather weak

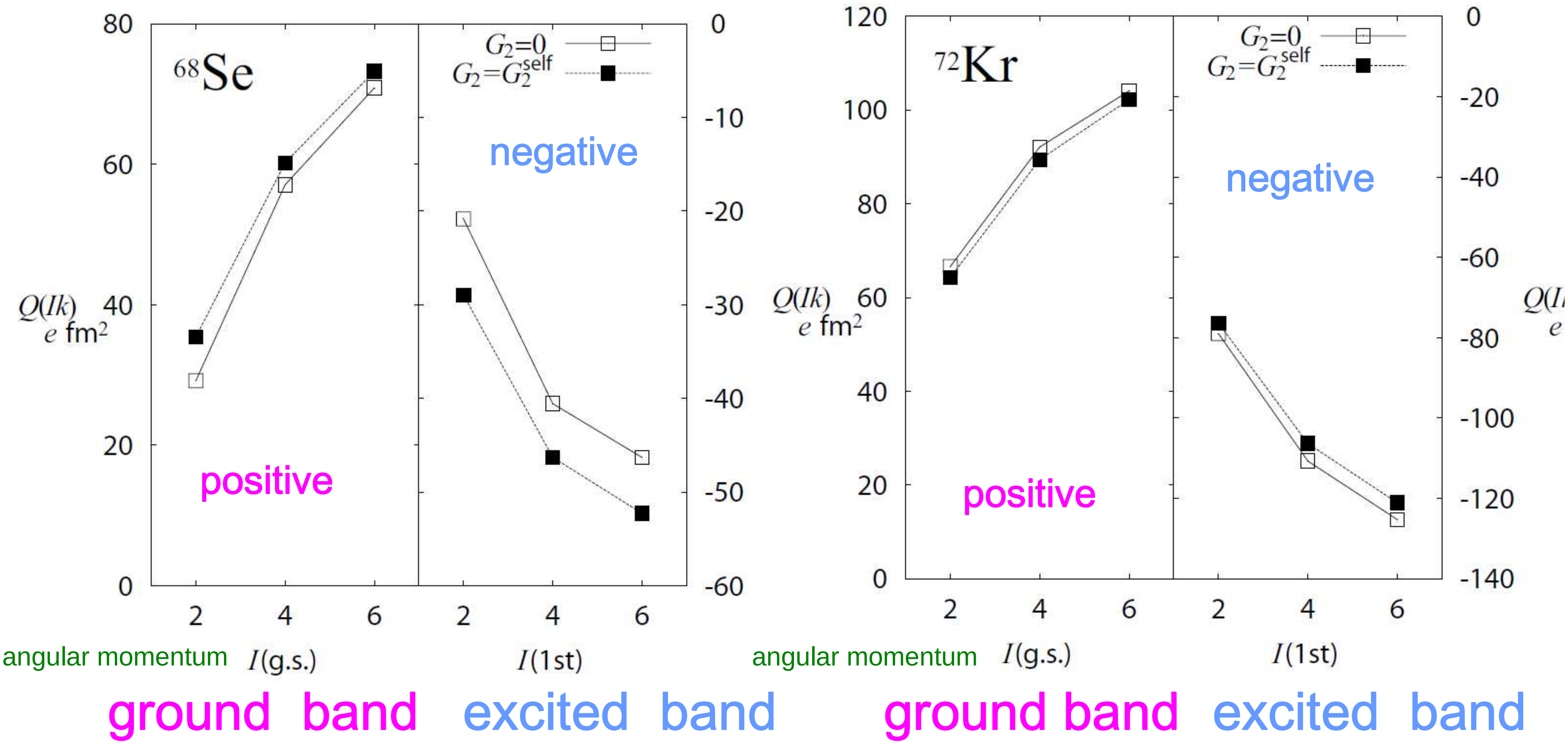
EXP：Fischer et al., Phys.Rev.**C67** (2003) 064318, Bouchez, et al., Phys.Rev.Lett.90 (2003) 082502.
Gade, et al., Phys.Rev.Lett.**95** (2005) 022502, **96** (2006) 189901

Collective wave functions in ^{72}Kr



- 0_1^+ state: well localized around oblate shape
- 0_2^+ state: weak oblate-prolate shape mixing
- other states: well defined shape character

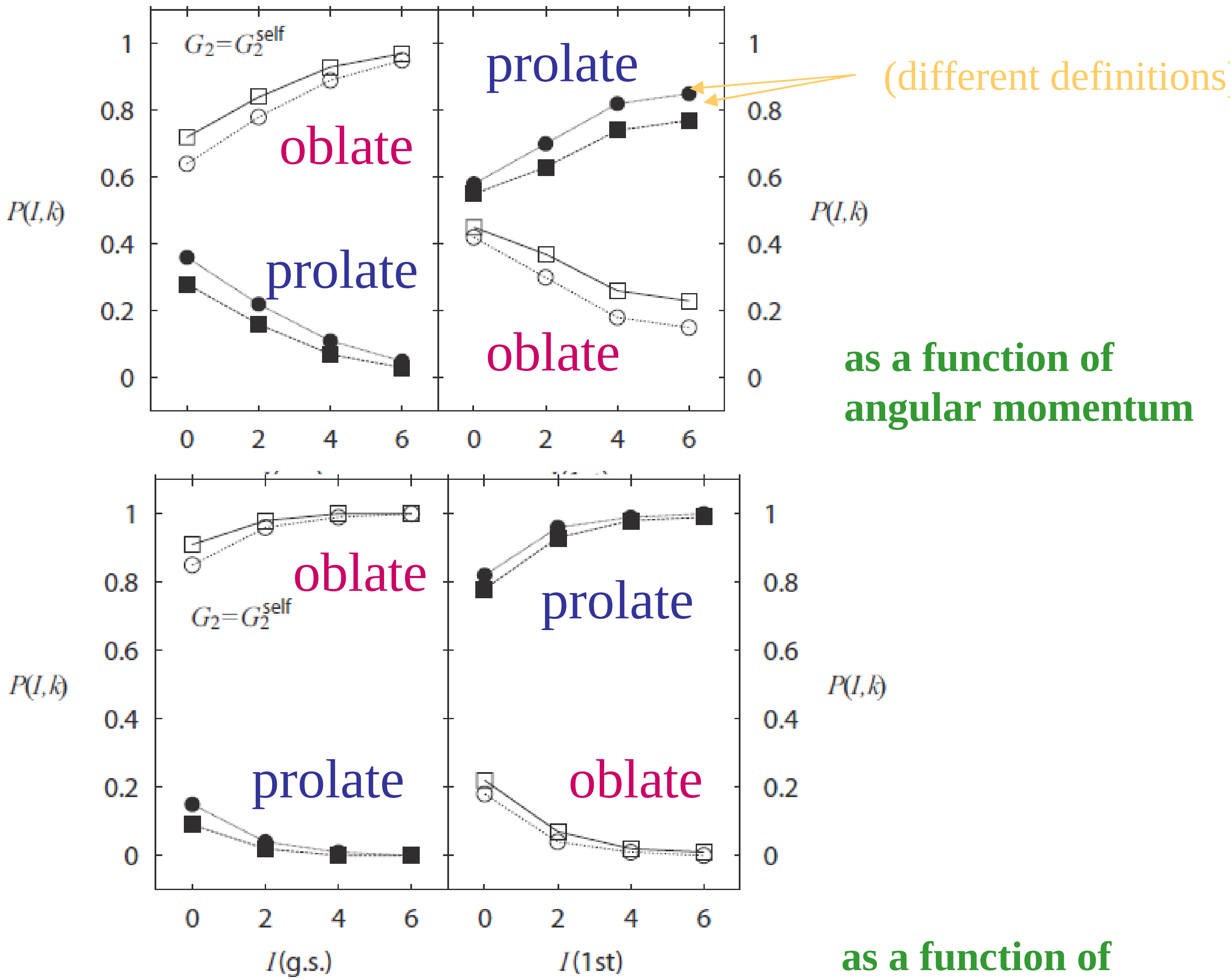
Spectroscopic quadrupole moments



Probabilities of the Oblate and Prolate Components

^{68}Se

^{72}Kr



ground band excited band

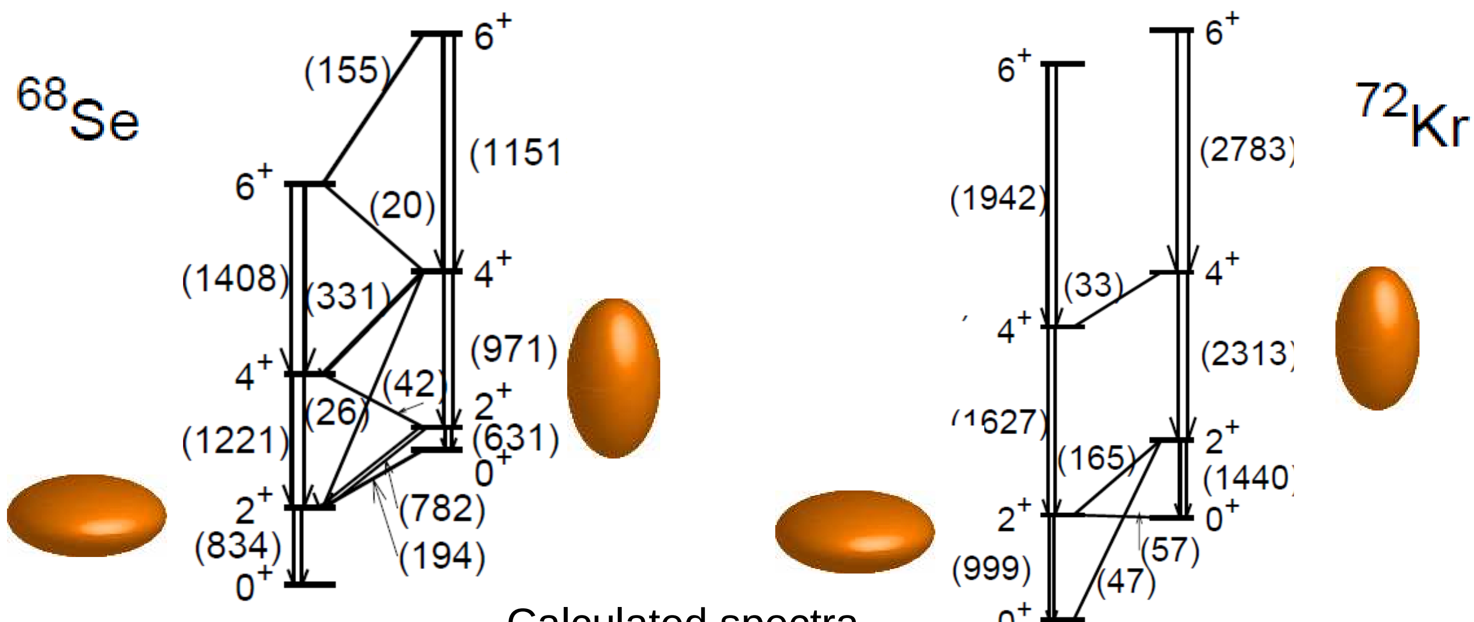
as a function of angular momentum

as a function of angular momentum

Summary

For the first time, excitation spectra and E2 properties were evaluated quantizing the collective Hamiltonian derived by the ASCC method

The result indicates interesting properties of the oblate-prolate shape mixing dynamics, like decline of mixing with increasing angular momentum.



Calculated spectra

Wide applications can be envisaged in the coming years