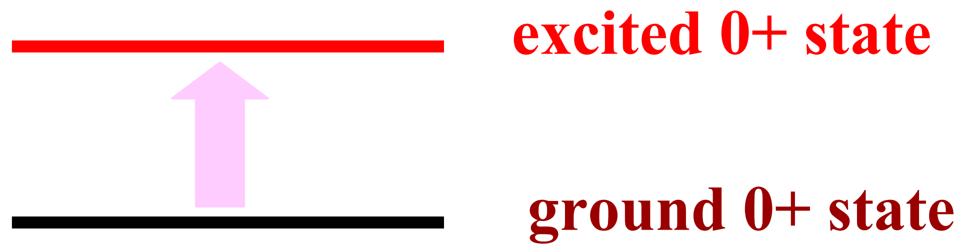
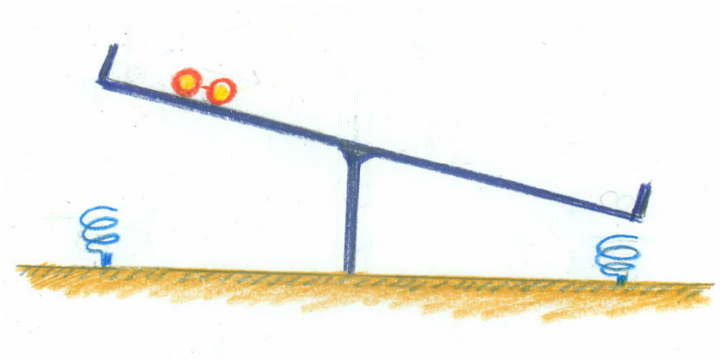
Nature of excited 0+ states in deformed neutron-rich nuclei



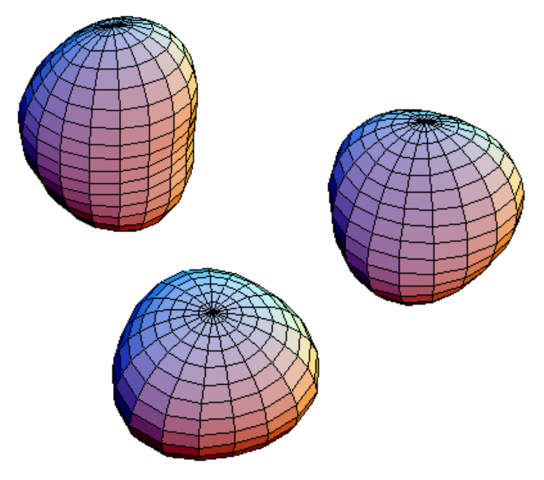
K. Yoshida, M. Yamagami, and K. Matsuyanagi

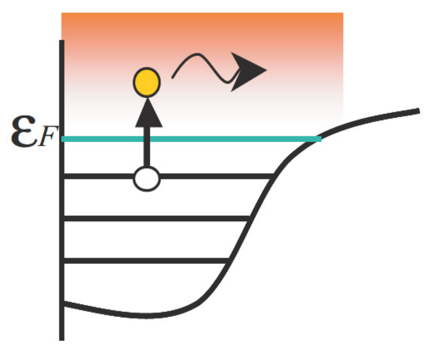


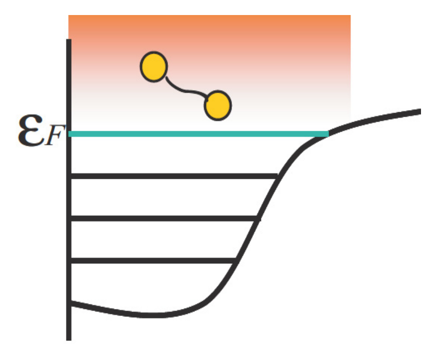
Microscopic Approach to Collective Phenomena in Unstable Nuclei

Can we expect new types of collective excitation modes to emerge under the new situation of (deformed) shell structure and pairing correlations in unstable nuclei ???

Let us discuss mechanism of generating collectivity (coherence) in weakly bound systems over from the basics.







Neutron-rich nuclei as a unique and new fermion many-body system

New environment

New degrees of freedom

Neutron skins
Di-neutron

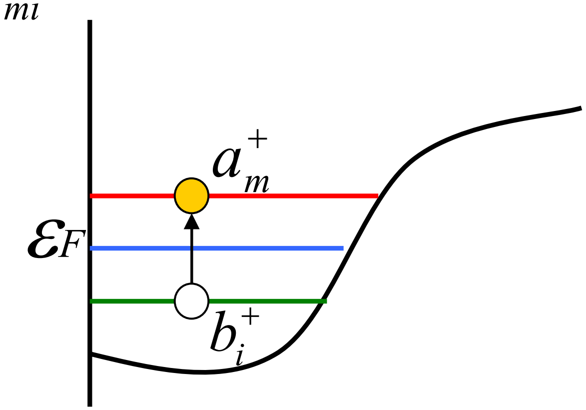
New types of correlation

Continuum coupling
Pairing correlations
Deformations

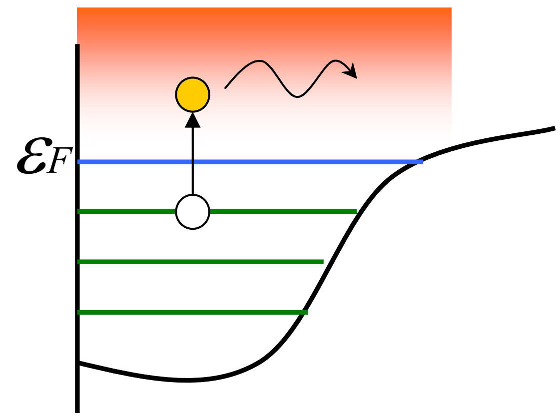
Unique single-particle and collective motions

Collective vibrations ~superposition of particle-hole excitations

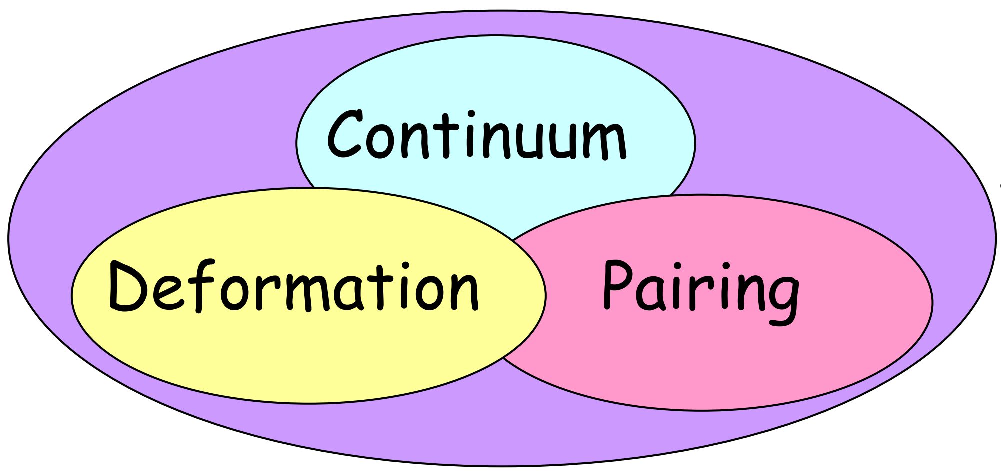
$$|\,\mathrm{vib.}\rangle = \sum_{mi} X_{mi} a_m^+ b_i^+ - Y_{mi} b_i a_m \left|\mathrm{gr.}\right\rangle$$

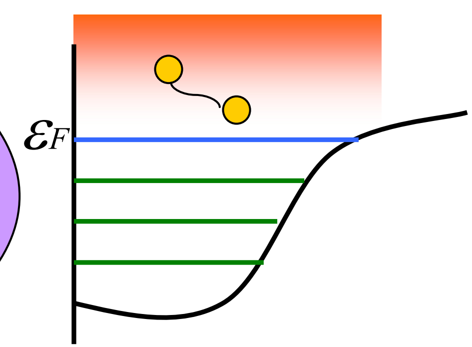


Stable nuclei



Drip-line nuclei





Mechanism for generation of collective modes under the new environment ?

Deformed HFB calculation

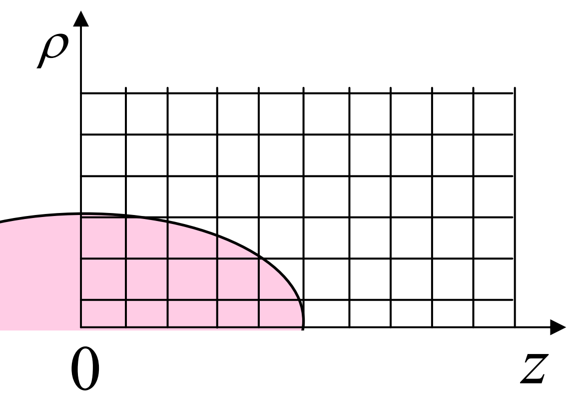
Mean-field Deformed Woods-Saxon potential

$$V(\rho,z)=V_{\mathrm{WS}}f+V_{\mathrm{SO}}\nabla f\cdot(\sigma\times\mathbf{p})$$

$$f(\rho,z)=(1+\exp[(r-R(\theta))/a])^{-1},\quad r^2=\rho^2+z^2$$

Pair-field Self-consistent pairing

$$\Delta(\rho,z)=\frac{V_0}{2}\left(1-\frac{\rho(\mathbf{r})}{\rho_0}\right)$$



Directly solve HFB eq. in coordinate-space mesh-representation

H.O. basis $\not\Longrightarrow$ Spatially extended structure

The equation of motion $[\hat{H}', \hat{O}_\lambda^+] \left| \Psi_0^{\mathrm{RPA}} \right\rangle = \hbar\omega_\lambda \hat{O}_\lambda^+ \left| \Psi_0^{\mathrm{RPA}} \right\rangle$

$\Downarrow$

The QRPA equation in the matrix formulation

$$\sum_{\gamma\delta} \begin{pmatrix} A_{\alpha\beta\gamma\delta} & B_{\alpha\beta\gamma\delta} \\ B_{\alpha\beta\gamma\delta} & A_{\alpha\beta\gamma\delta} \end{pmatrix} \begin{pmatrix} X_{\gamma\delta}^{\lambda} \\ Y_{\gamma\delta}^{\lambda} \end{pmatrix} = \hbar\omega_\lambda \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} X_{\alpha\beta}^{\lambda} \\ Y_{\alpha\beta}^{\lambda} \end{pmatrix}$$

Residual interaction

p-h channel $v_{\mathrm{ph}}(\mathbf{r}, \mathbf{r}') = [t_0(1 + x_o P_\sigma) + \frac{t_3}{6}(1 + x_3 P_\sigma)\rho(\mathbf{r})]\delta(\mathbf{r} - \mathbf{r}')$

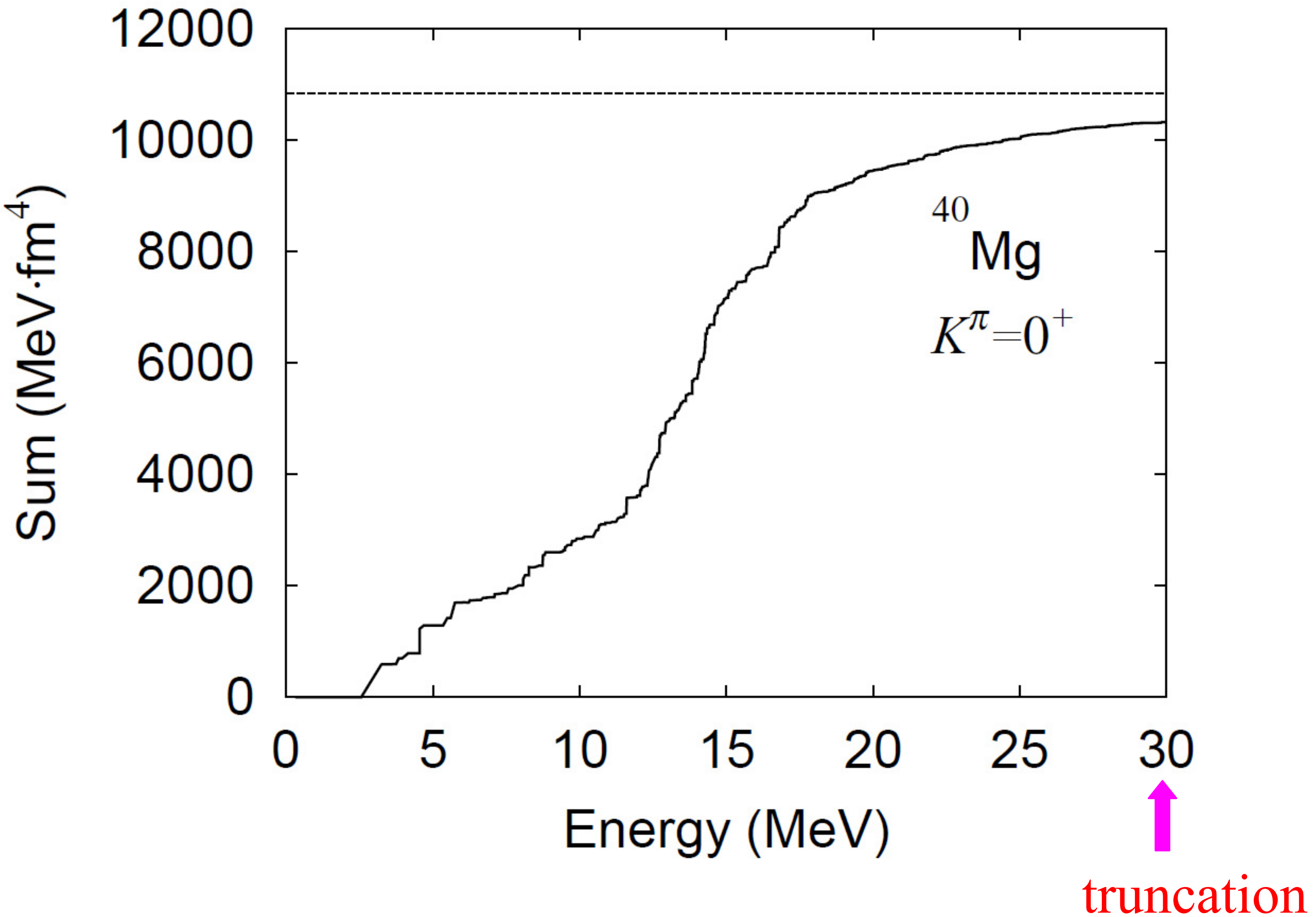
p-p channel $v_{\mathrm{pp}}(\mathbf{r}, \mathbf{r}') = V_0 \left(1 - \frac{\rho(\mathbf{r})}{\rho_0}\right) \delta(\mathbf{r} - \mathbf{r}')$

Spurious (Nambu-Goldstone) modes are properly removed.

$v \rightarrow f \cdot v$

Rotation, Pair rotation, Center-of-mass motion

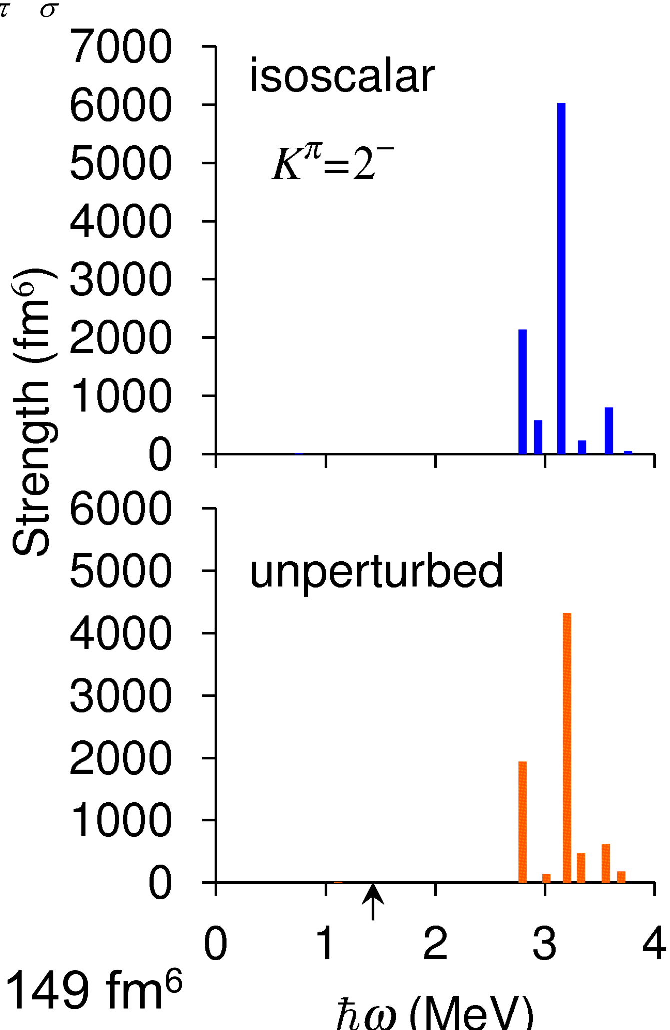
Test of sum rule



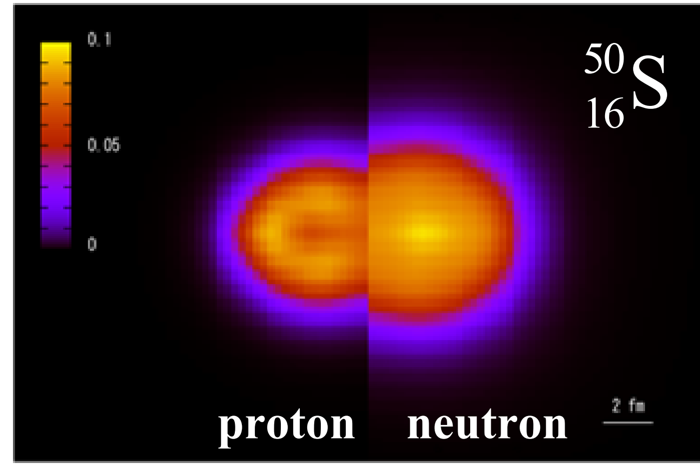
Octupole excitations on superdeformed state in sulfur isotopes close to the neutron drip line

$$\left|\left\langle \Psi_\lambda^{\mathrm{RPA}} \left| \hat{Q}_{32}^{\mathrm{IS}} \right| \Psi_0^{\mathrm{RPA}} \right\rangle\right|^2$$

$$\hat{Q}_{32}^{\mathrm{IS}} = \sum_{\nu,\pi} \sum_{\sigma} \int d\mathbf{r} r^3 Y_{32} \psi^+(\mathbf{r},\sigma)\psi(\mathbf{r},\sigma)$$



1W.u.=149 fm^6



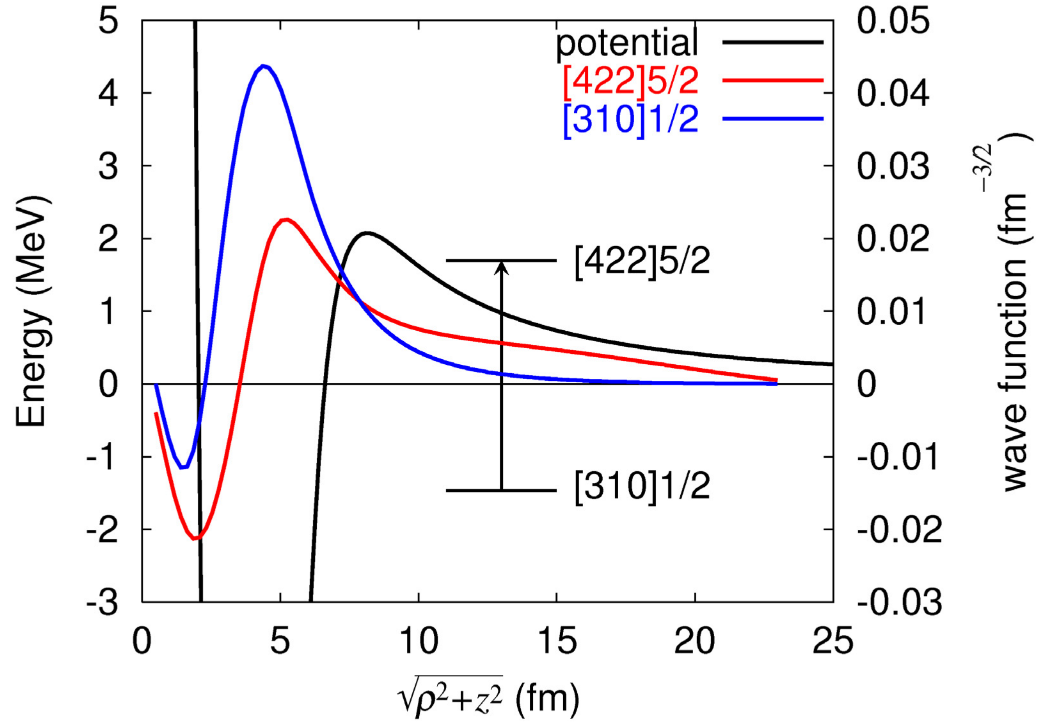
Deformed RPA
without pairing

K.Yoshida *et al.*, PTP113 (2005) 1251

Single-particle excitation to the resonance

Single-particle excitation from weakly bound to resonant state

$$X_{mi} \approx 0.97$$

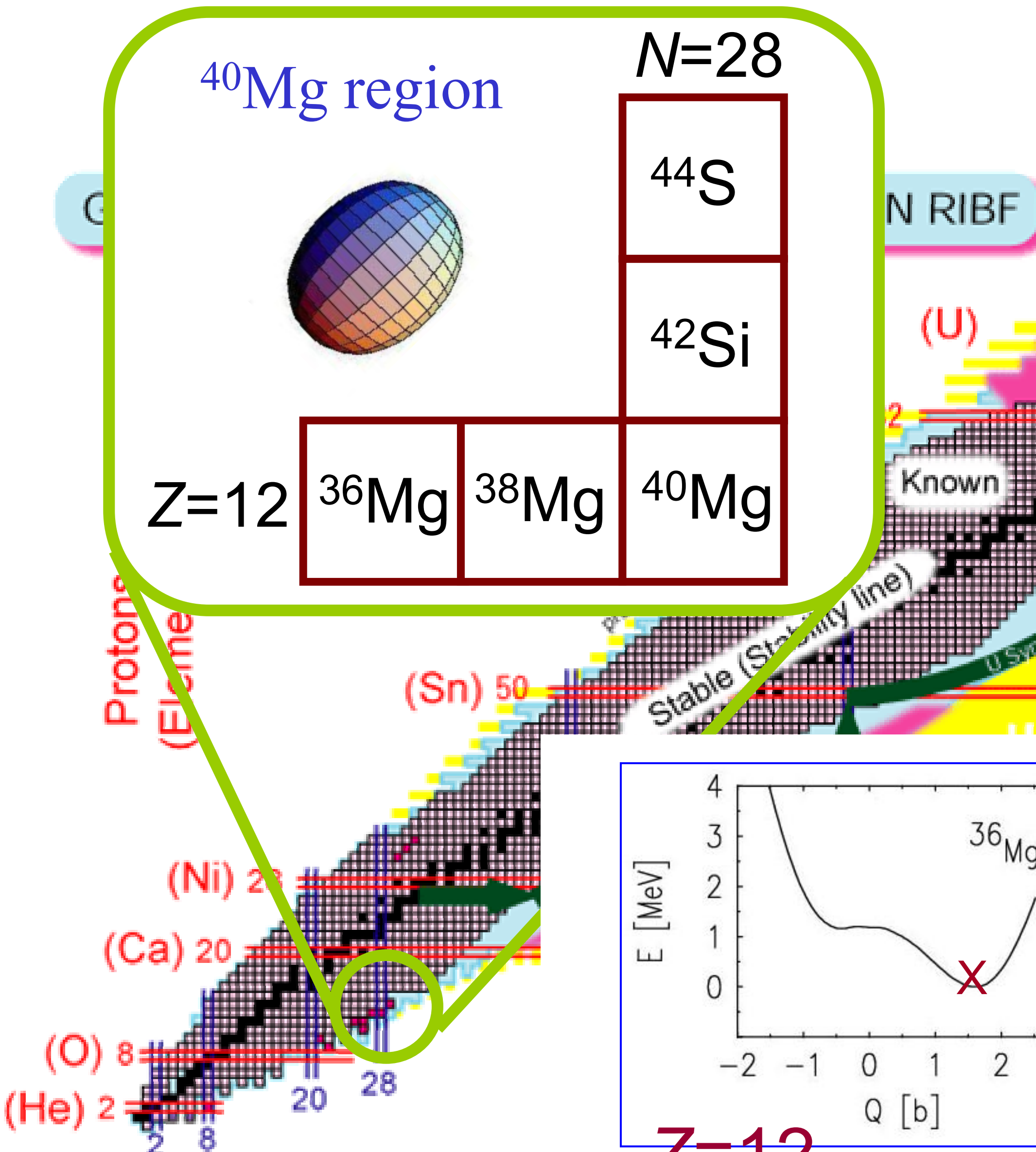


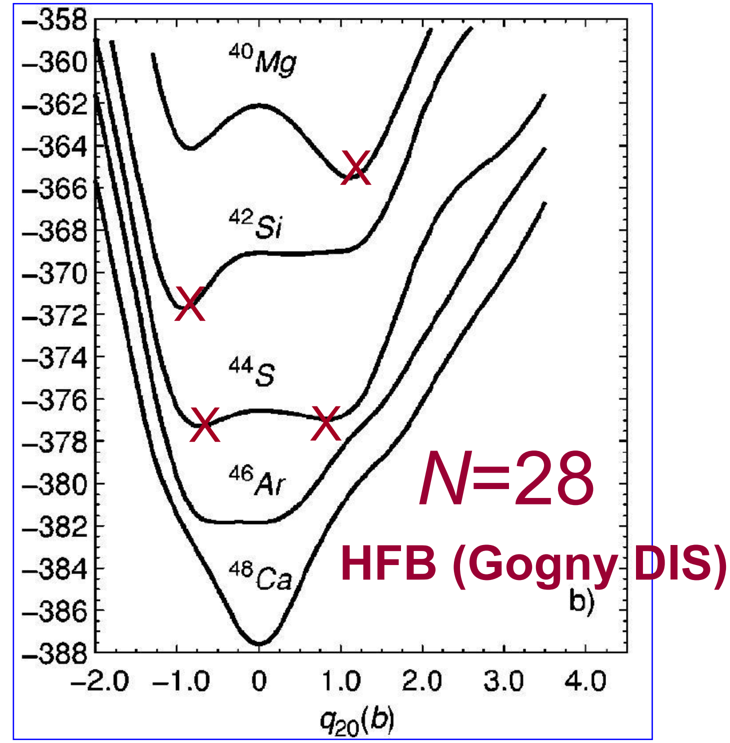
In neutron drip-line nuclei

Collective modes disappear ??

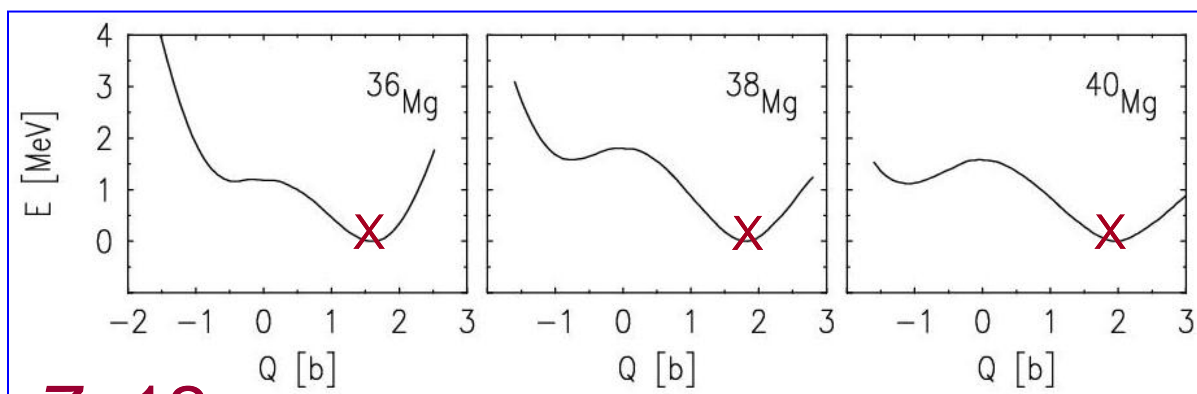
We have to investigate the effect of pairing

Deformed weakly bound systems





R.Rodriguez-Guzman, J.L.Egido, L.M.Robledo
Phys. Rev. C65, 024304 (2002)

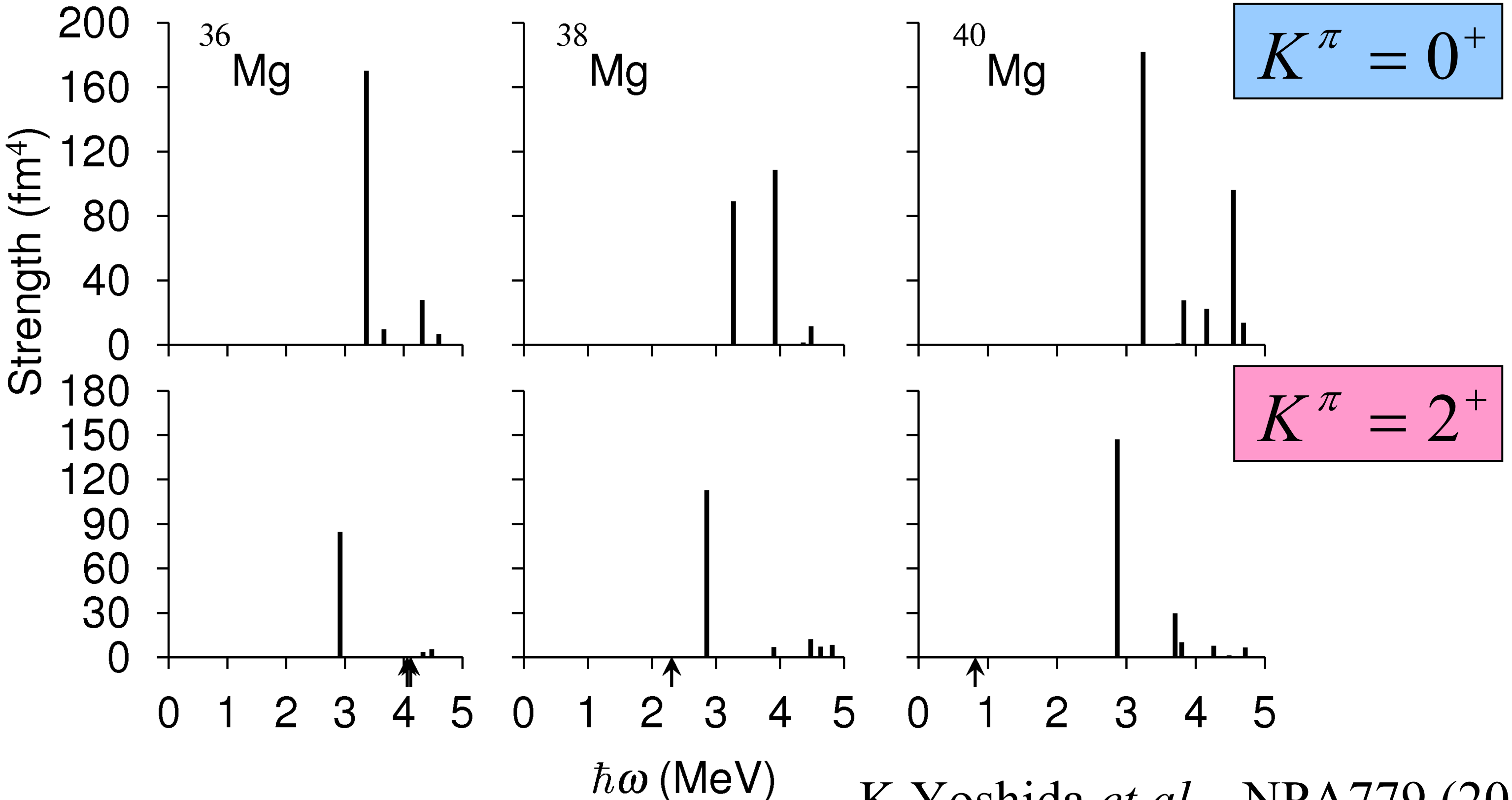


Z=12
HFB (Skyrme SIII)

J.Terasaki, H.Flocard, P.-H.Heenen, P.Bonche
Nucl.Phys. A621, 706 (1997)

Quadrupole vibrations in magnesium isotopes close to the neutron drip line

Isoscalar quadrupole transition strengths (intrinsic)

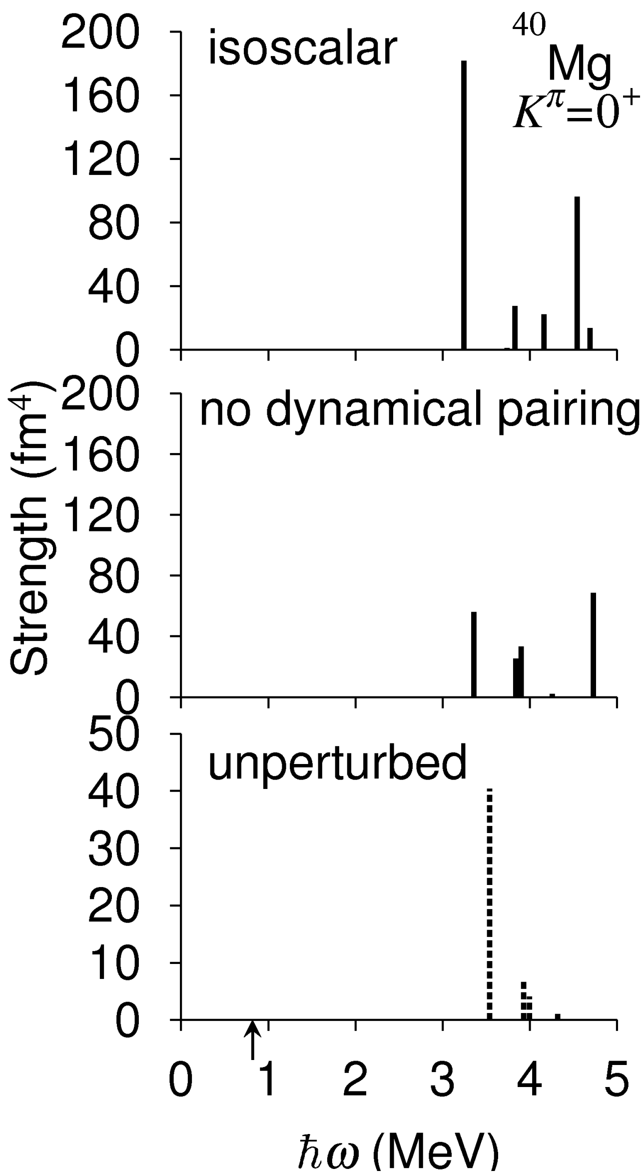


K.Yoshida *et al.*, NPA779 (2006) 99

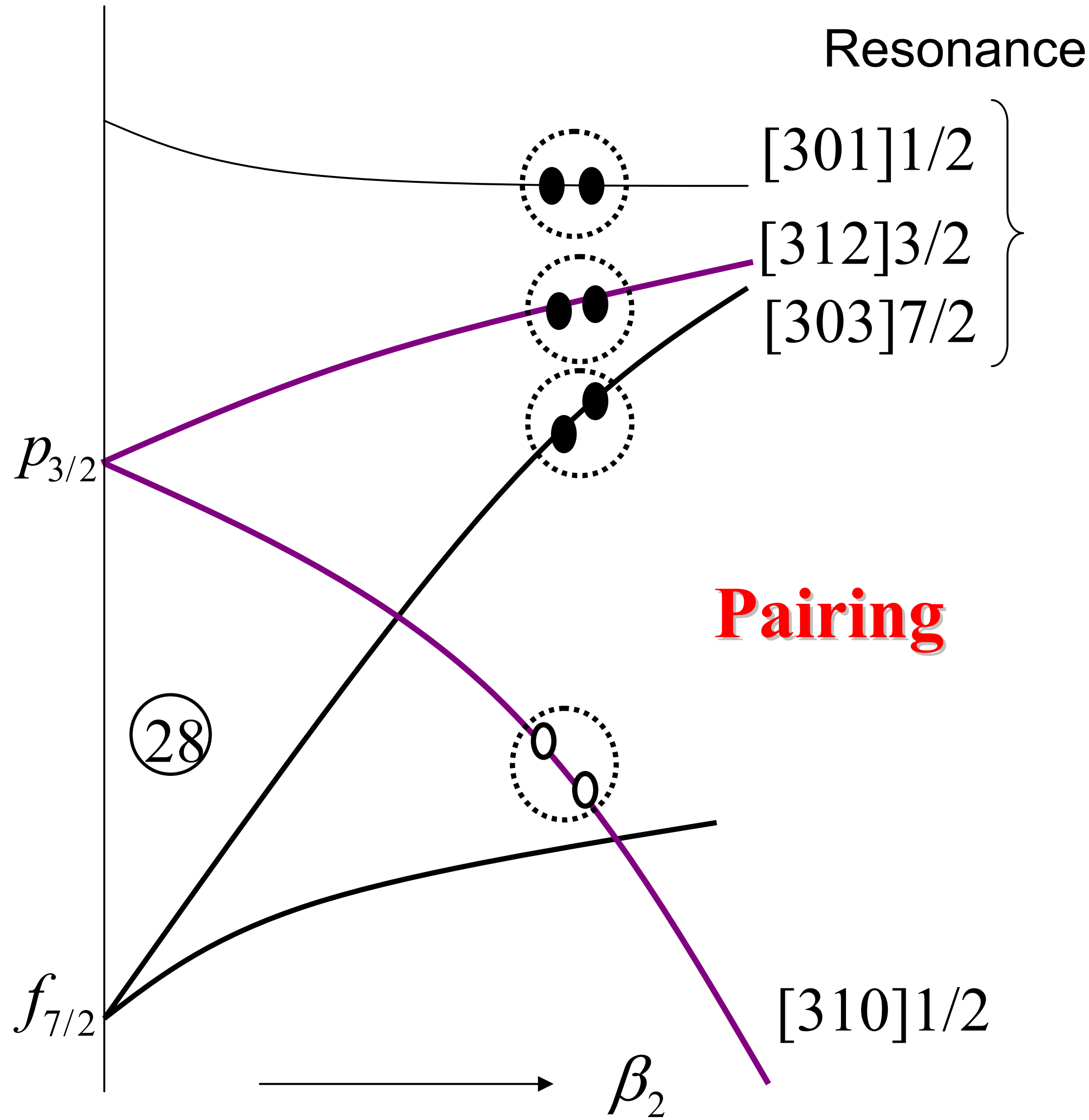
Neutron number increasing

Enhancement of neutron excitation

Microscopic Structure of the $K=0^+$ modes in ^{40}Mg

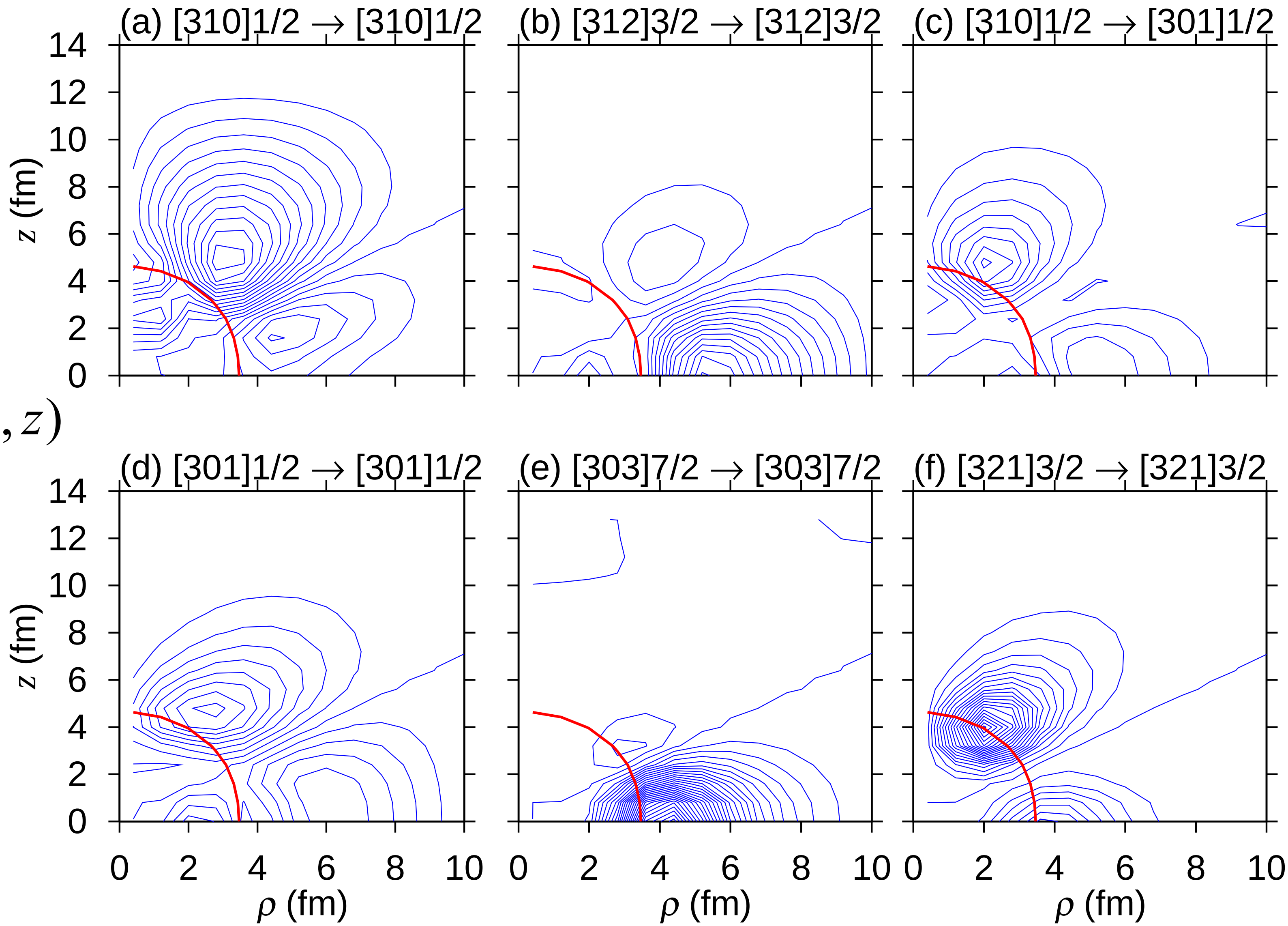


1 W.u.=8.1 fm^4



Spatial structure of 2qp excitations (p-h channel)

$$\langle \alpha\beta | \hat{Q}_{20} | \mathrm{HFB} \rangle \equiv \int d\rho dz Q^{(\mathrm{uv})}_{20,\alpha\beta}(\rho, z) \qquad \hat{Q}_{20} = \sum_{\sigma} \int d\mathbf{r} r^2 Y_{20} \psi^{+}(\mathbf{r},\sigma)\psi(\mathbf{r},\sigma)$$



$$Q^{(\mathrm{uv})}_{20,\alpha\beta}(\rho, z)$$

Mechanism for generation of soft $K=0^+$ mode

Collective both in p-h and in p-p channel

How to generate the coherent mode?

Why are the transition strengths large ?   ~ 10-20 W.u. (intrinsic)

Two key points

Pair correlations

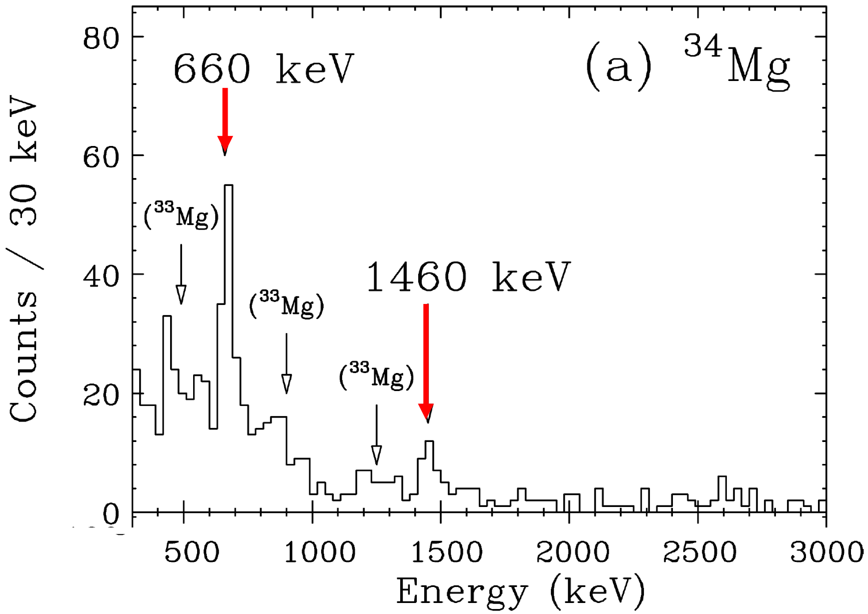
Effect of dynamical pairing

Weakly bound system

Spatially extended structure of quasiparticle wave functions

Deformations of neutron-rich Mg isotopes

K.Yoneda *et al.*, PLB499(2001)233

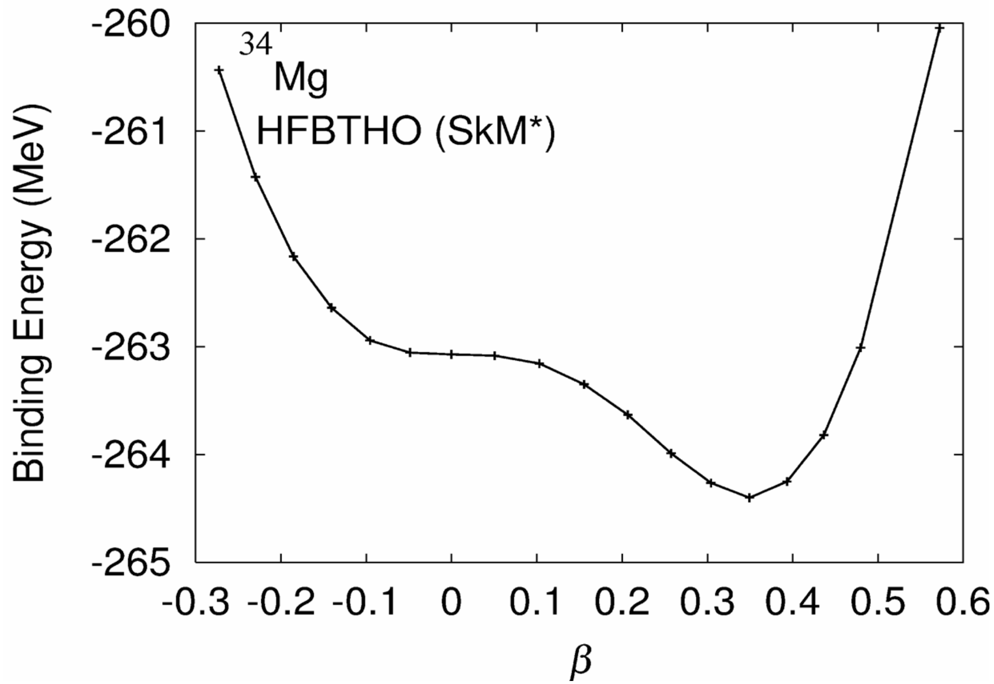


$$\frac{E(4_1^+)}{E(2_1^+)} = \frac{2120(\text{keV})}{660(\text{keV})} = 3.2$$

^{34}Mg is well deformed.

"Skyrme-HFB deformed nuclear mass table"

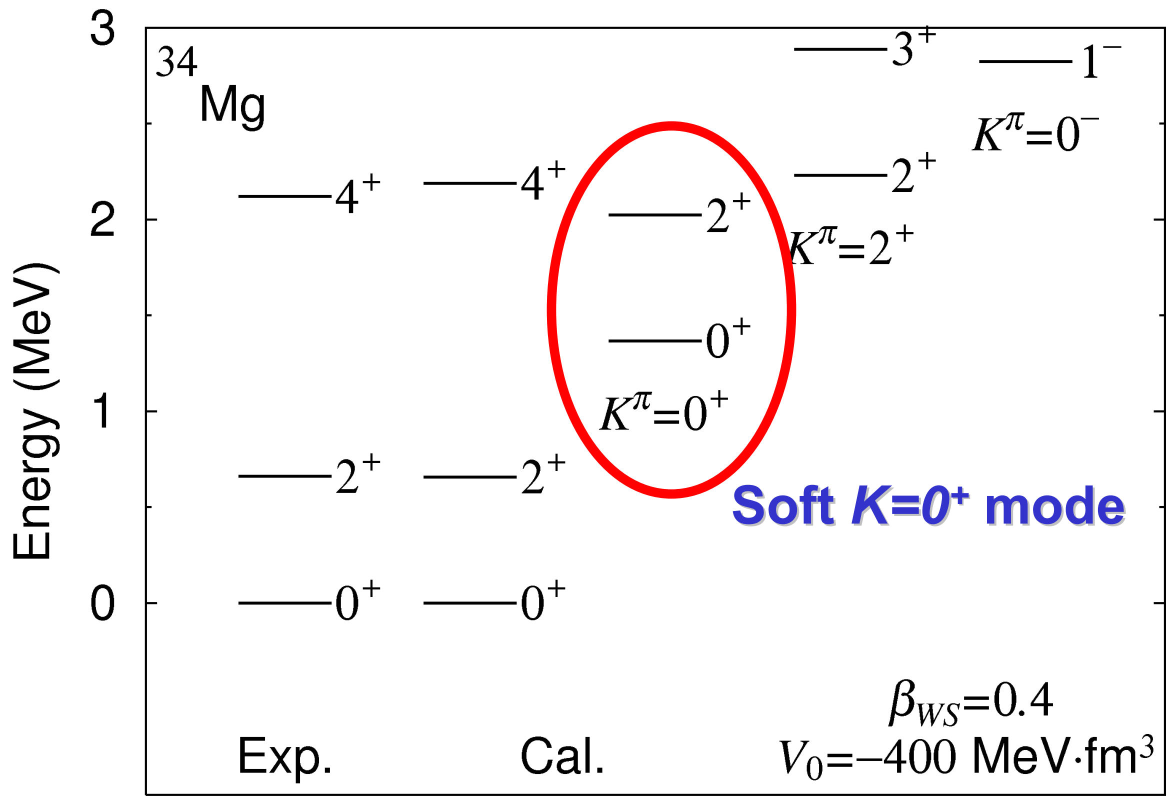
M.Stoitsov *et al.*,PRC68(2003)054312



The program "HFBTHO" (v1.66p)

M.Stoitsov *et al.*, Comp.Phys.Comm.167(2005)43

Low-lying levels in ^{34}Mg



$$E(I,K) = \hbar\omega_{\mathrm{RPA}} + \frac{\hbar^2}{2J_{\mathrm{TV}}}\left(I(I+1) - K^2\right)$$

Microscopically calculated

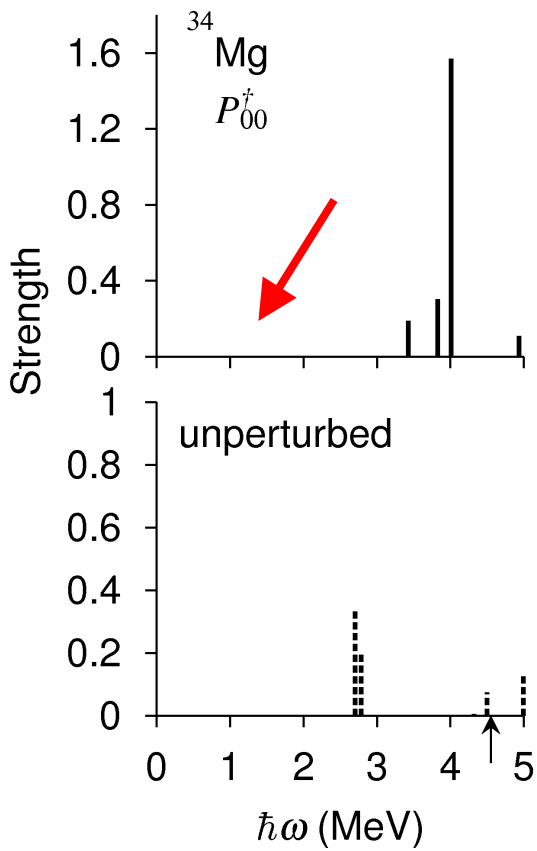
Two neutron pair transition strengths

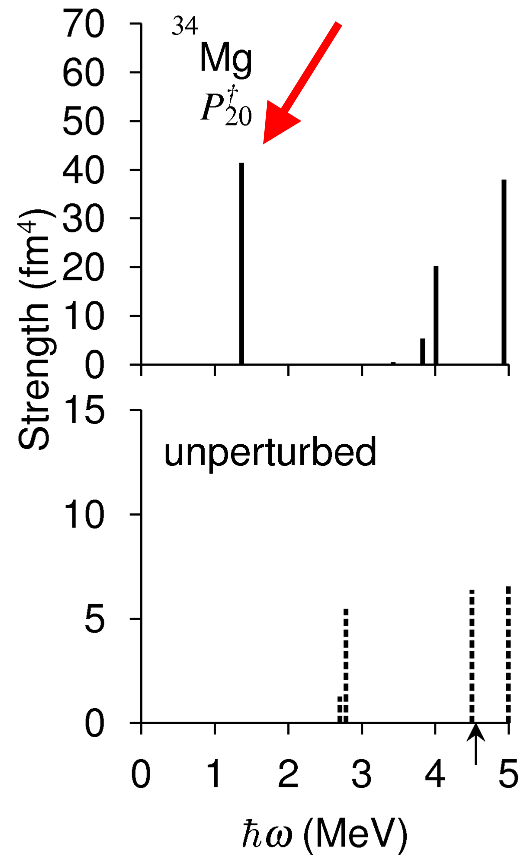
Monopole pairing

$$P_{00}^{+} = \int d\mathbf{r}\,\psi^{+}(\mathbf{r},\uparrow)\psi^{+}(\mathbf{r},\downarrow)$$

Quadrupole pairing

$$P_{20}^{+} = \int d\mathbf{r}\,r^{2}Y_{20}(\hat{\mathbf{r}})\psi^{+}(\mathbf{r},\uparrow)\psi^{+}(\mathbf{r},\downarrow)$$



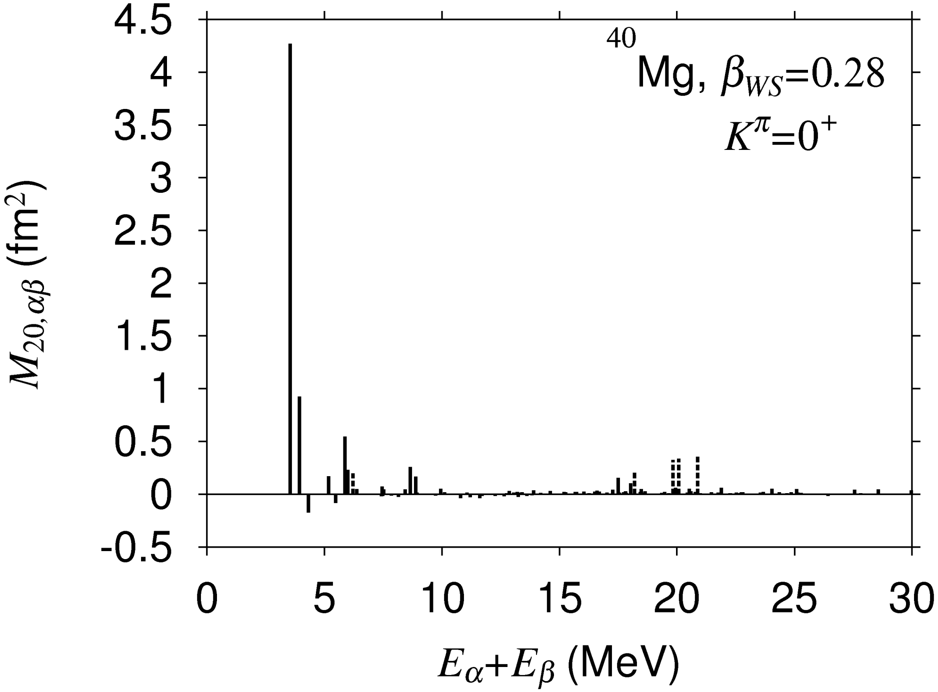


Comparison of the $K=0^+$ modes in ^{40}Mg and ^{34}Mg

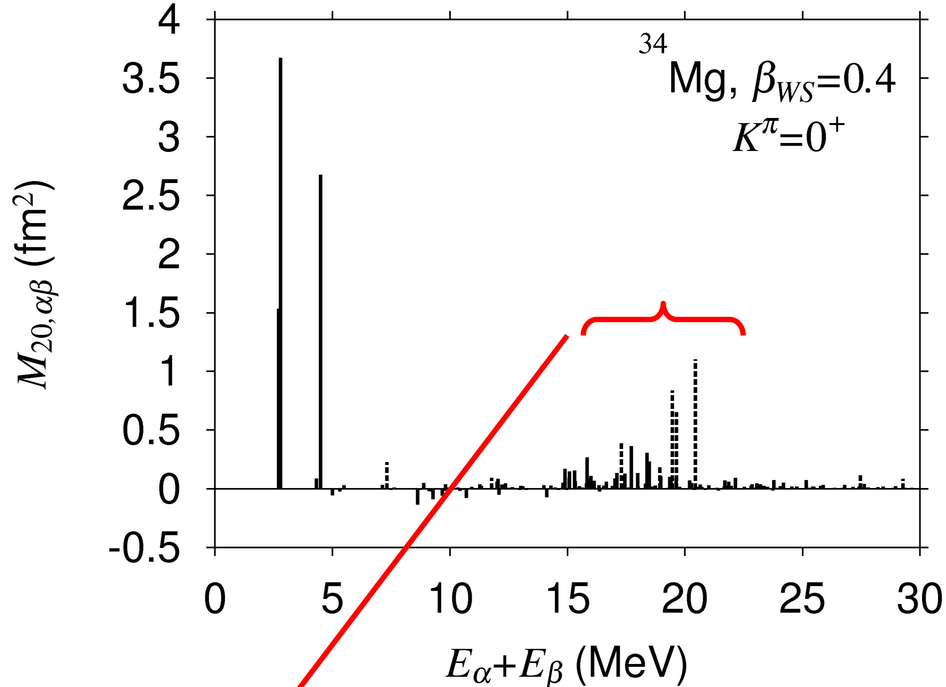
Matrix elements of 2qp excitations generating the *K=0*⁺ mode

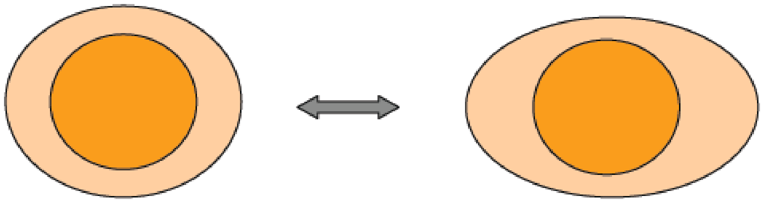
$$\left\langle \Psi_\lambda^{\mathrm{RPA}} \left| \hat{Q}_{20} \right| \Psi_0^{\mathrm{RPA}} \right\rangle = \sum_{\alpha\beta} M_{20,\alpha\beta}^{(\mathrm{uv})}$$

$B(E2) = 3.4\, e^2 \mathrm{fm}^4$



$B(E2) = 15.9\, e^2 \mathrm{fm}^4$





$2\hbar\omega$ excitations of proton

$\pi[211]3/2 \rightarrow \pi[431]3/2$ (19.5 MeV)

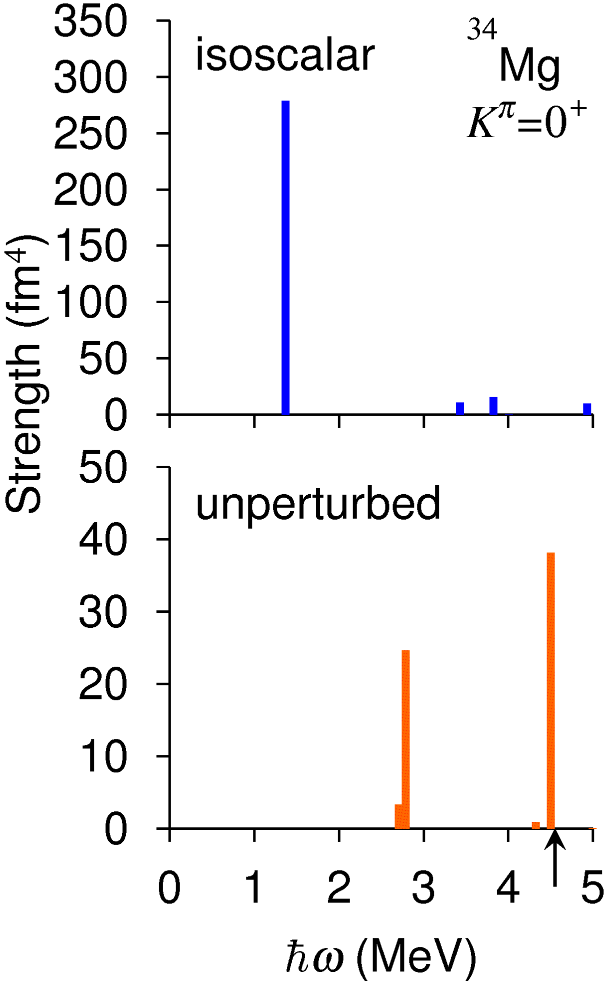
$\pi[101]3/2 \rightarrow \pi[321]3/2$ (17.3 MeV)

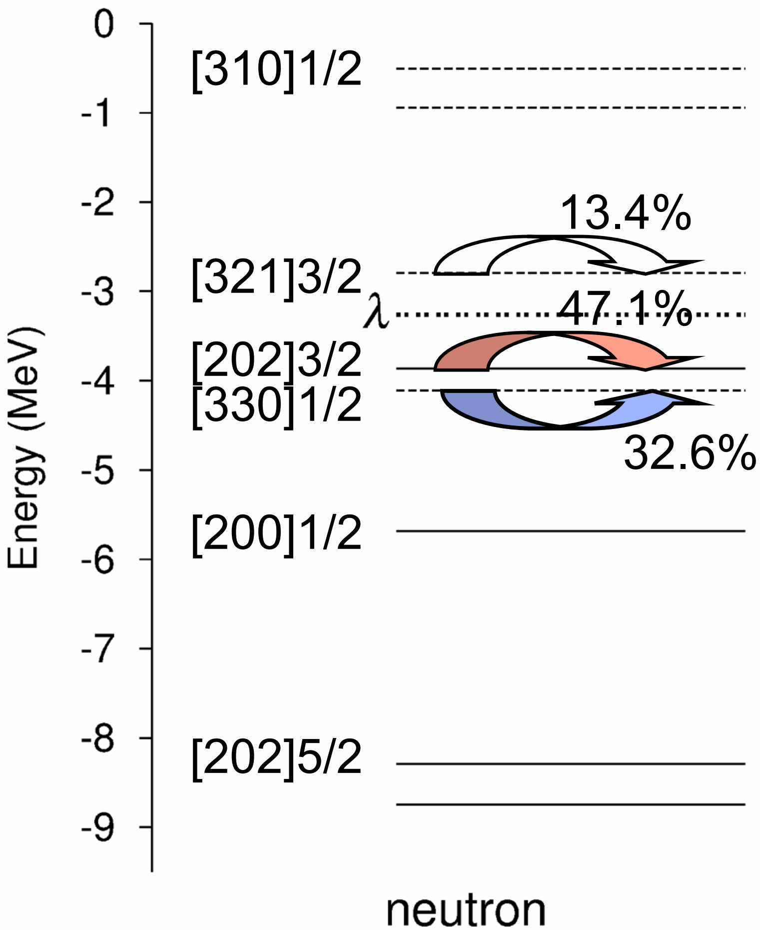
$\pi[110]1/2 \rightarrow \pi[330]1/2$ (19.6 MeV)

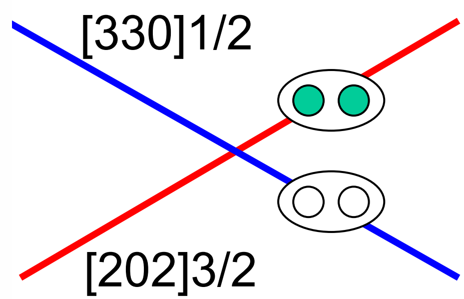
$\pi[220]1/2 \rightarrow \pi[440]1/2$ (20.1 MeV)

Soft K=0^+ mode in ^{34}Mg

$\beta_2 = 0.4$

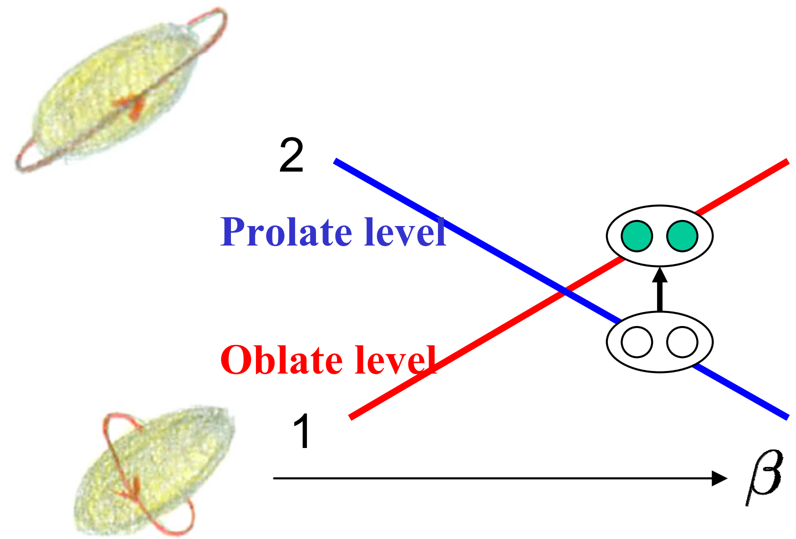






1 W.u.=6.5 fm^4

Quadrupole fluctuation of the neutron pair density



Ground state

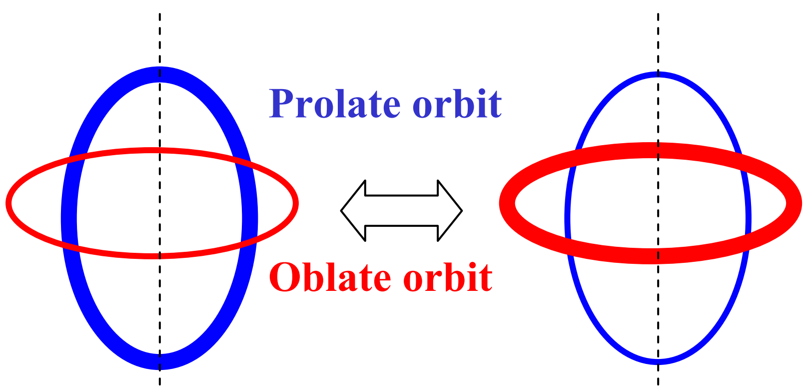
$$|0> = \frac{1}{\sqrt{a^2+b^2}}(a|\nu_1\overline{\nu_1}> + b|\nu_2\overline{\nu_2}>)$$

Excited state

$$|0'> = \frac{1}{\sqrt{a^2+b^2}}(-b|\nu_1\overline{\nu_1}> + a|\nu_2\overline{\nu_2}>)$$

Transition matrix element

$$\Rightarrow \quad <0'|r^2Y_{20}|0> = \frac{2ab}{a^2+b^2}\{<\nu_2|r^2Y_{20}|\nu_2> - <\nu_1|r^2Y_{20}|\nu_1>\}$$

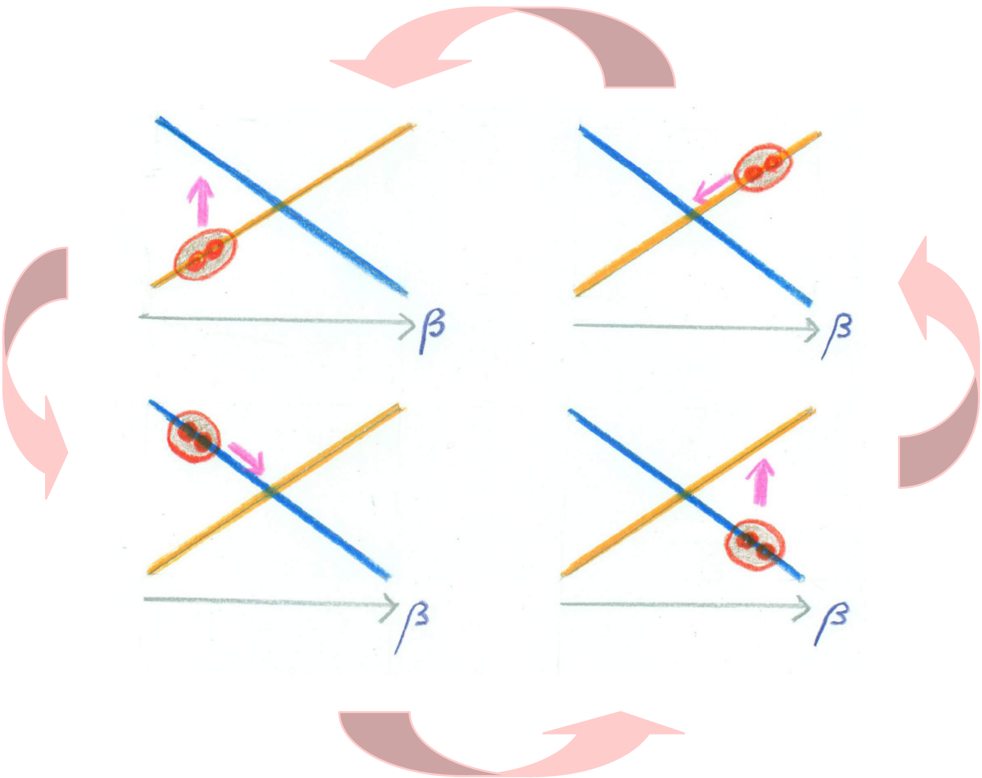


Coherent for opposite sign

(Bohr-Mottelson)

Quadrupole oscillation of pair density

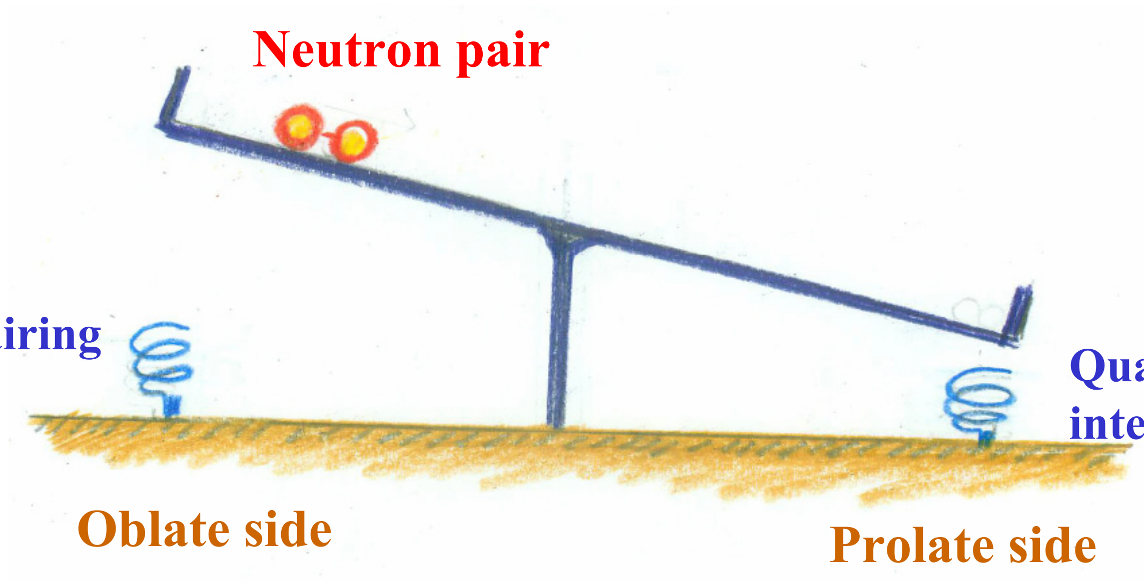
Mechanism of coupling between the pair-density fluctuation and the quadrupole shape vibration



BCS picture

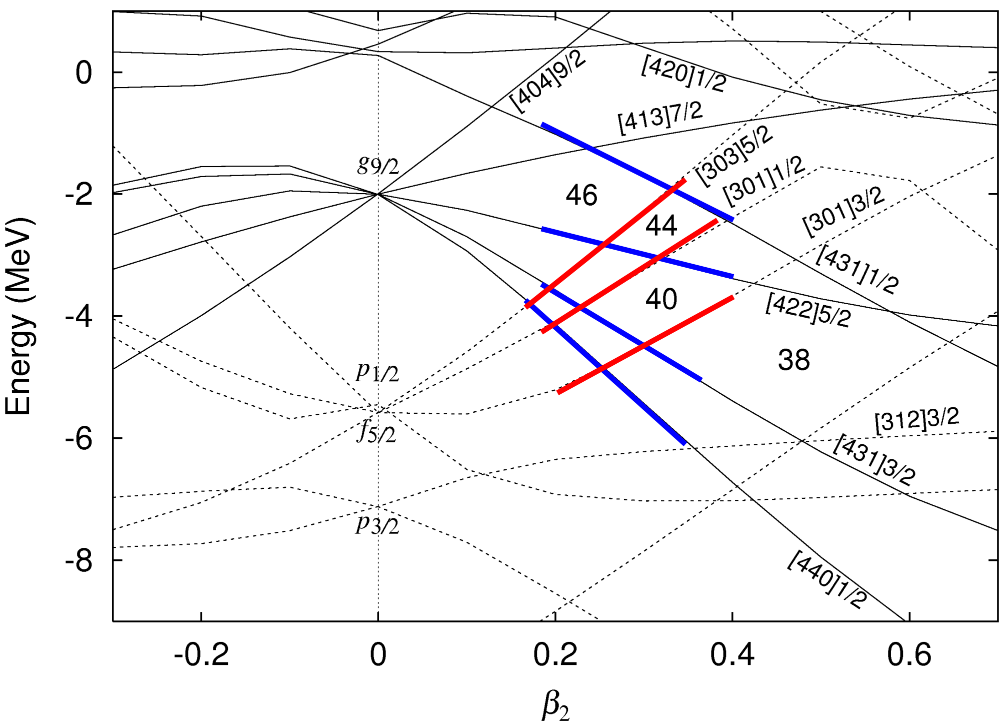
Di-neutron picture

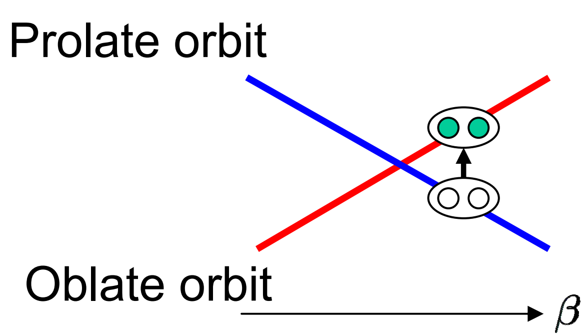
See-saw Mechanism



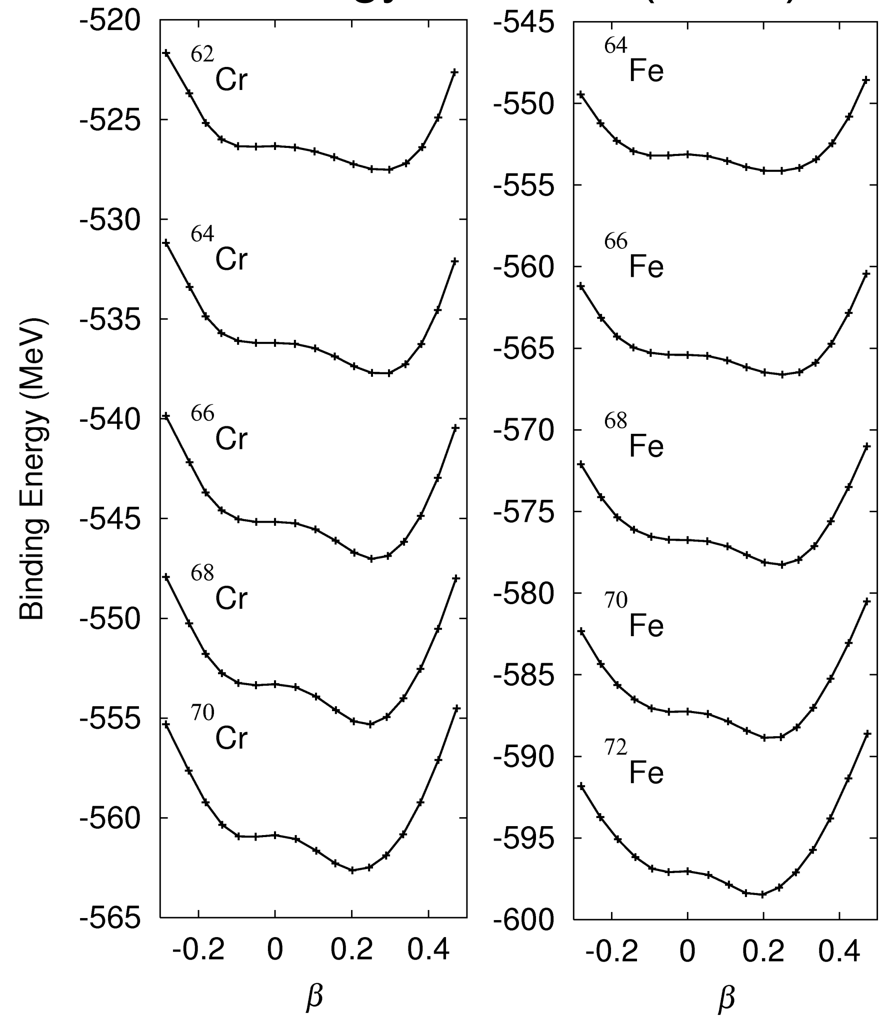
Neutron-rich Cr and Fe isotopes

Neutron single-particle energies of ^{64}Cr





Potential energy surfaces (SkM*)

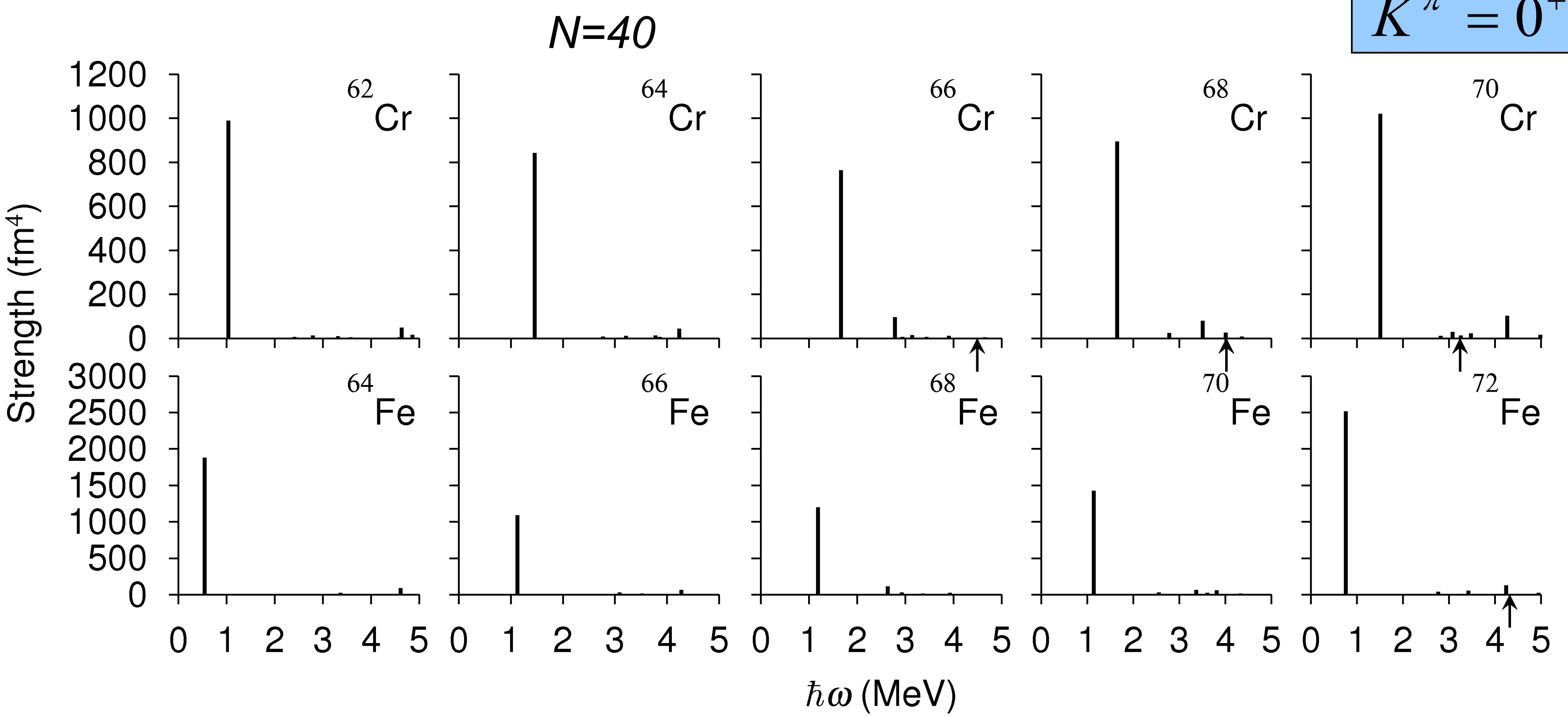


The program “HFBTHO” (v1.66p)

M.Stoitsov *et al.*, Comp.Phys.Comm.167(2005)43

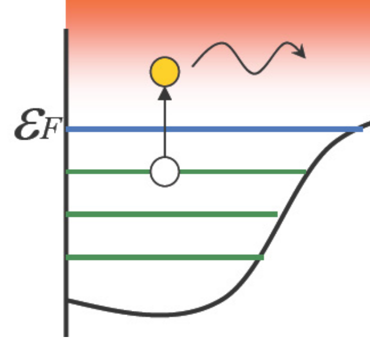
Soft $K=0^+$ modes in deformed neutron-rich nuclei

$\beta_2 = 0.3$



1 W.u.=15~18 fm^4

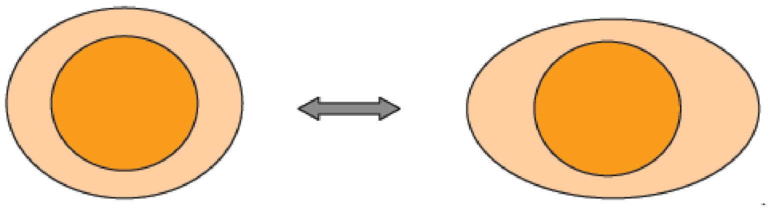
Conclusion



On the basis of the deformed QRPA calculation, we have suggested that

Soft $K^{\pi} = 0^{+}$ modes in deformed neutron-rich nuclei indicate

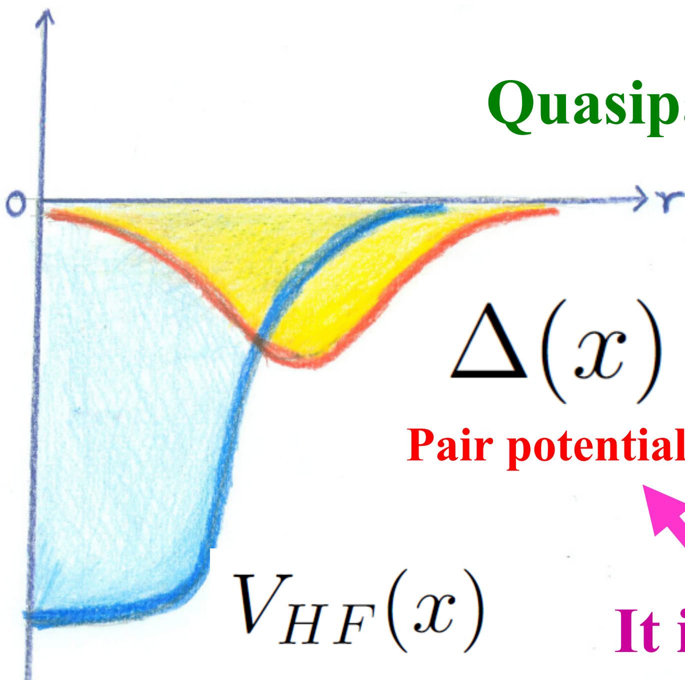
- **Importance of anisotropic spacial structure of pairing correlations (quadrupole pairing) in generating their collectivities**
- **Striking enhancement of transition strengths associated with very extended wave functions (loosely bound and resonance states)**



New quasipartcle picture different from the BCS quasiparticle

Hartree-Fock-Bogoluibov mean field

$$\begin{pmatrix} t + V_{HF}(x) - \lambda & \Delta(x) \\ -\Delta^*(x) & -t - V_{HF}(x) + \lambda \end{pmatrix} \begin{pmatrix} u(x) \\ v(x) \end{pmatrix} = E \begin{pmatrix} u(x) \\ v(x) \end{pmatrix}$$



$\Delta(x)$

Pair potential

$V_{HF}(x)$

HF potential

Quasiparticle wave function for $E > |\lambda|$

upper component	$u(x)$	**non-localized**
lower component	$v(x)$	**localized**

It is extended outside of the surface of the HF density distribution !!