INT-05-3

Dynamical pairing effects on soft quadrupole vibrations in deformed unstable nuclei close to the neutron drip line

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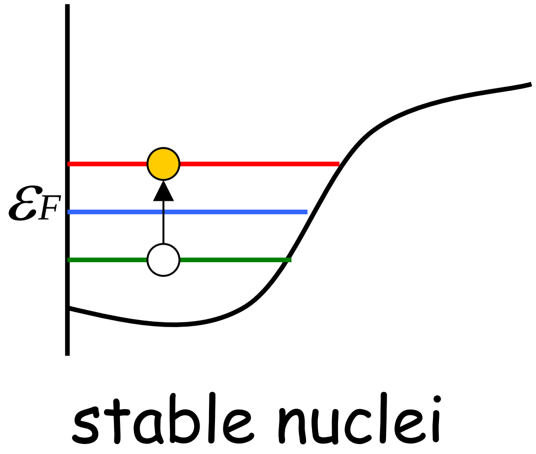
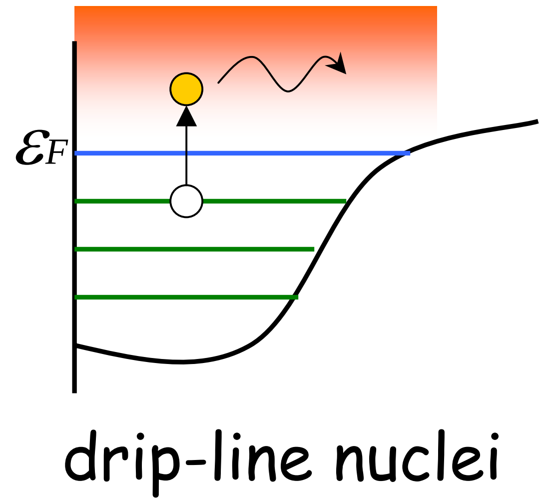
10/11/05

Collective vibrations ~superposition of particle-hole excitations





coupling to continuum states

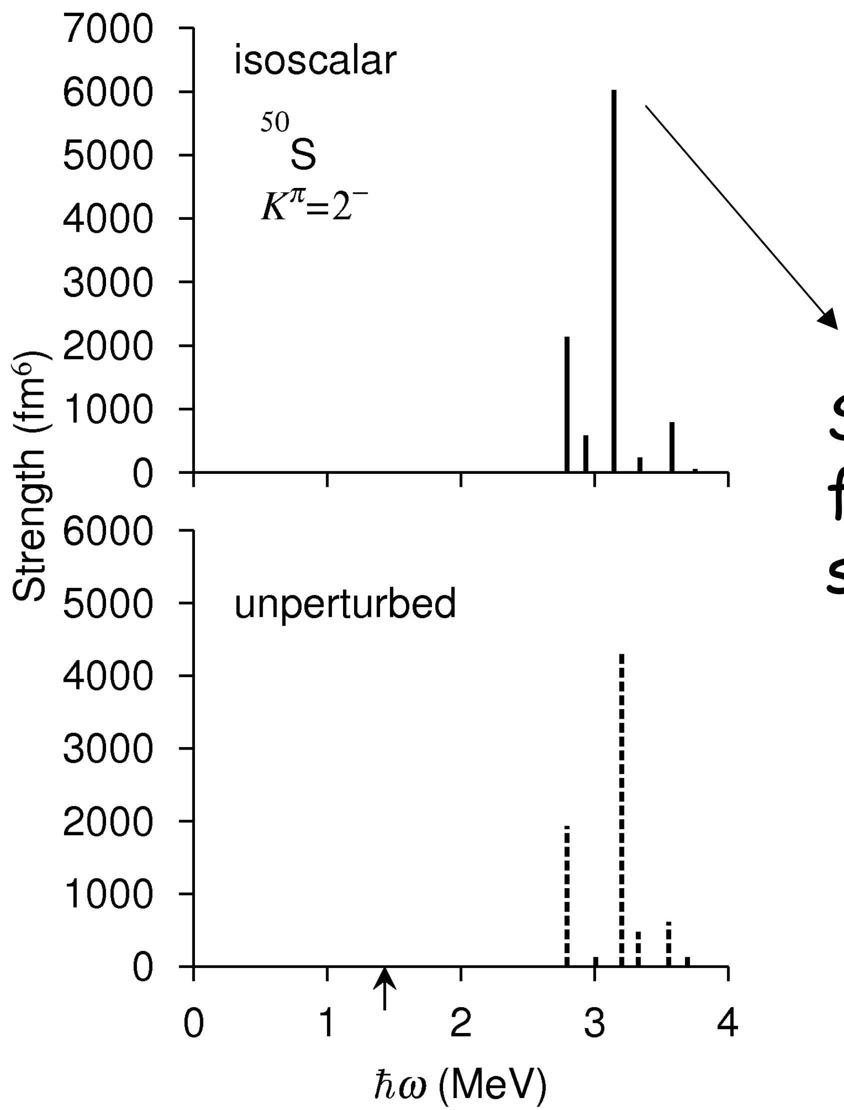
- Excitations into the continuum
- Pair correlations in the continuum

↓

Mechanism for generation of collective modes in the new situation ?

Dominance of single-particle excitation

Octupole excitations on SD state in ^{50}S



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

Deformed RPA
without pairing

Single-particle excitation from weakly bound to resonant state is dominant.

$$X_{ph} \simeq 0.97$$

Collective modes disappear ??

Effect of pairing

QRPA calculations for investigation properties of excitation modes in neutron-rich nuclei

Spherical nuclei e.g. Matsuo et al., PRC71 (2005), 064326

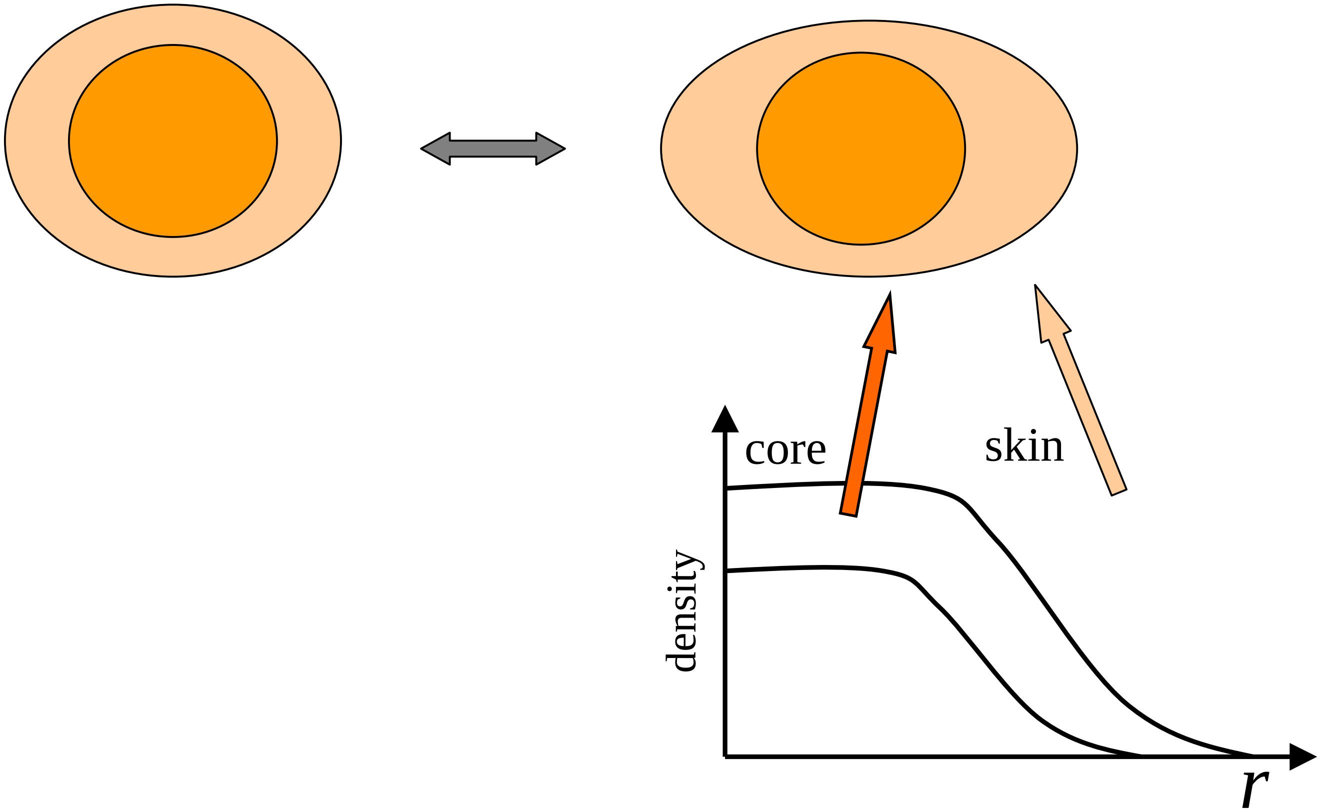
pairing	Hartree-Fock-Bogoliubov method
continuum	Out-going boundary condition

Deformed nuclei Hagino et al., NPA731 (2004), 264c

pairing	BCS approximation, neglect dynamical pairing
continuum	Box boundary condition
deformation	Expansion in spherical basis

Low-lying modes unique to neutron-rich nuclei

Quadrupole vibration of neutron skin



Effect of Deformation ?   Pairing ?   Continuum ?

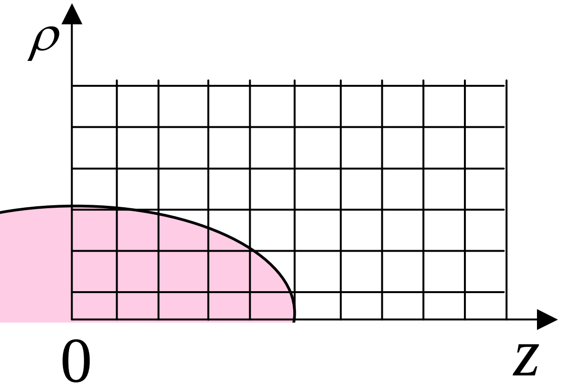
In deformed superfluid system close to the drip line → Soft K=0^+ mode ?

QRPA calculation simultaneously taking into account

Deformation → Deformed HFB

Pairing

Continuum → Box discretization



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

H.O. basis ✗→ Spatially extended structure

→ First results of such a calculation

Investigation of deformed neutron-rich nuclei

Ground state

Coordinate-space HFB equation

$$\begin{pmatrix} h(\mathbf{r})-\lambda & \tilde{h}(\mathbf{r}) \\ \tilde{h}(\mathbf{r}) & -h(\mathbf{r})+\lambda \end{pmatrix}\begin{pmatrix} \varphi_1(E,\mathbf{r}) \\ \varphi_2(E,\mathbf{r}) \end{pmatrix} = E\begin{pmatrix} \varphi_1(E,\mathbf{r}) \\ \varphi_2(E,\mathbf{r}) \end{pmatrix}$$

$$E_{\mathrm{cutoff}} = 50\mathrm{MeV}$$

Mean-field　Deformed Woods-Saxon potential

$$h = -\frac{\hbar^2}{2m}\nabla^2 + V_{\mathrm{WS}} f + V_{\mathrm{SO}} \nabla f \bullet (\sigma \times \mathbf{p})$$

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

Pair-field　Density-dependent delta interaction

$$\tilde{h} = \frac{V_0}{2}\left(1-\frac{\rho(\mathbf{r})}{\rho_0}\right)$$

$$V_0 = -450 \text{ MeV fm}^3, \ \rho_0 = 0.16 \text{ fm}^{-3}$$

Excited state

QRPA equation in the AB matrix formulation

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

Residual interaction

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

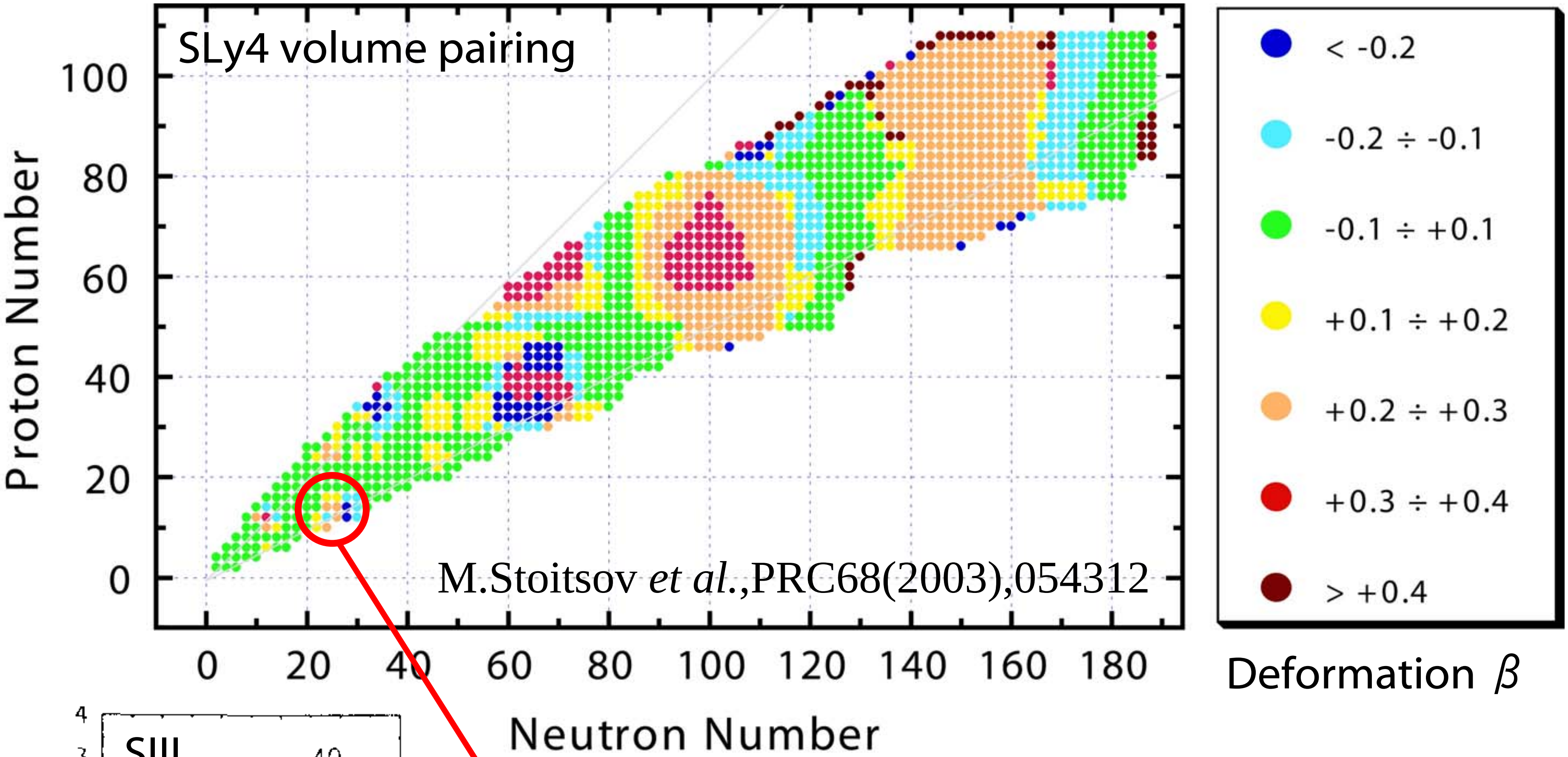
p-p channel $v_{\mathrm{pp}}(\mathbf{r},\mathbf{r}') = V_0\left(1-\frac{\rho(\mathbf{r})}{\rho_0}\right)\delta(\mathbf{r}-\mathbf{r}')$

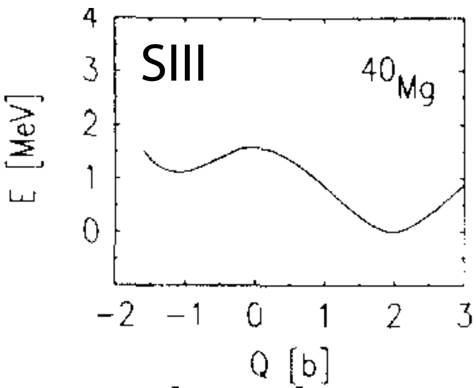
Spurious modes should be zero excitation energy.

$$v \rightarrow f \cdot v$$

Normalize the interaction strength

Deformed unstable nuclei





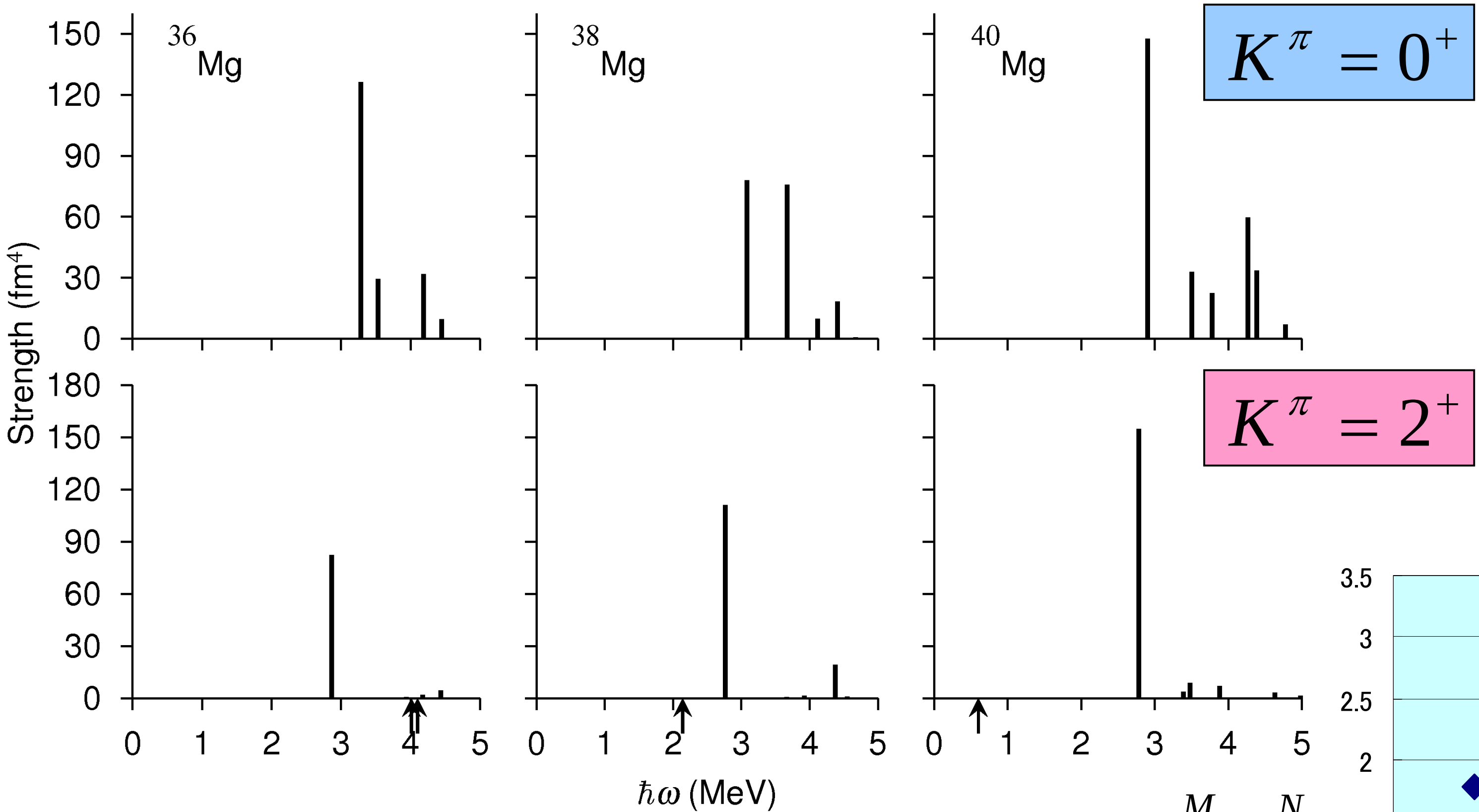
J.Terasaki *et al.*,NPA621(1997)706

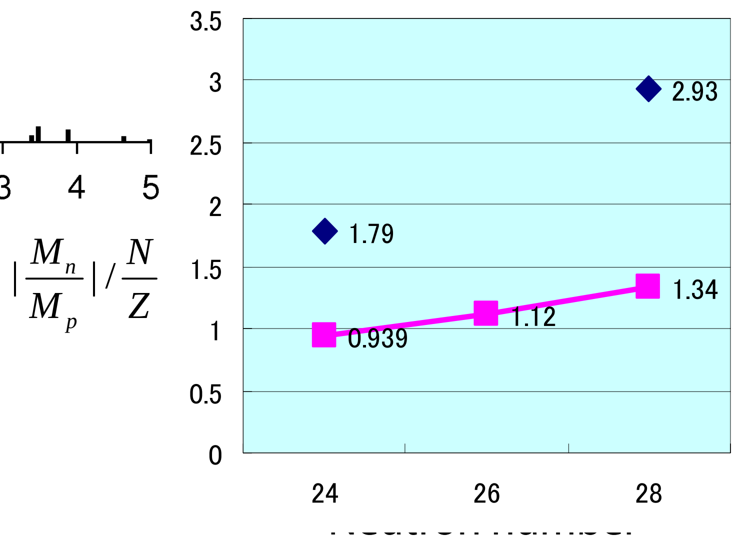
Mg region

As an example of deformed neutron drip-line nuclei

Low-frequency quadrupole vibrations in deformed Mg isotopes close to the drip line

Isoscalar quadrupole transition strengths (intrinsic)



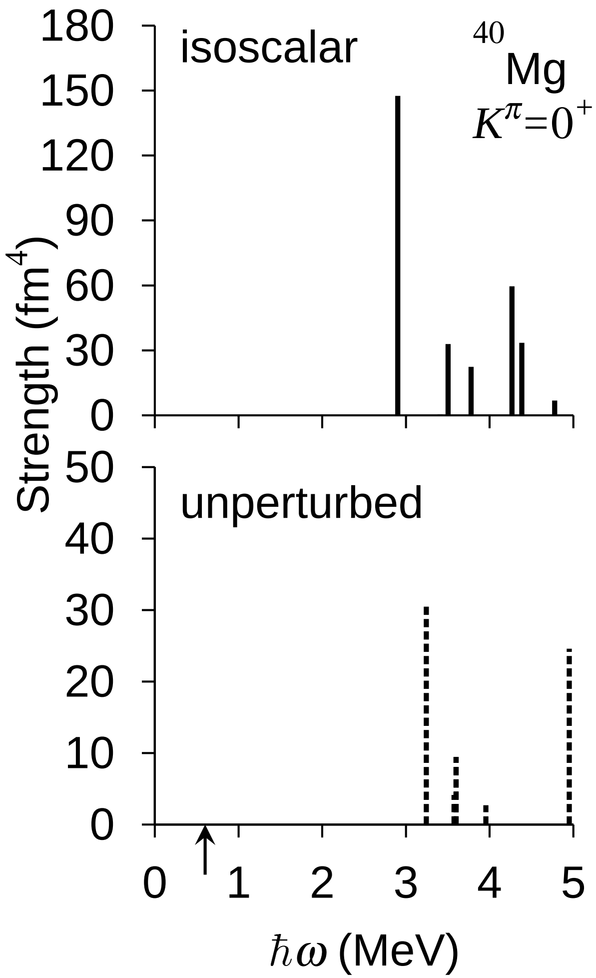


Neutron number increasing

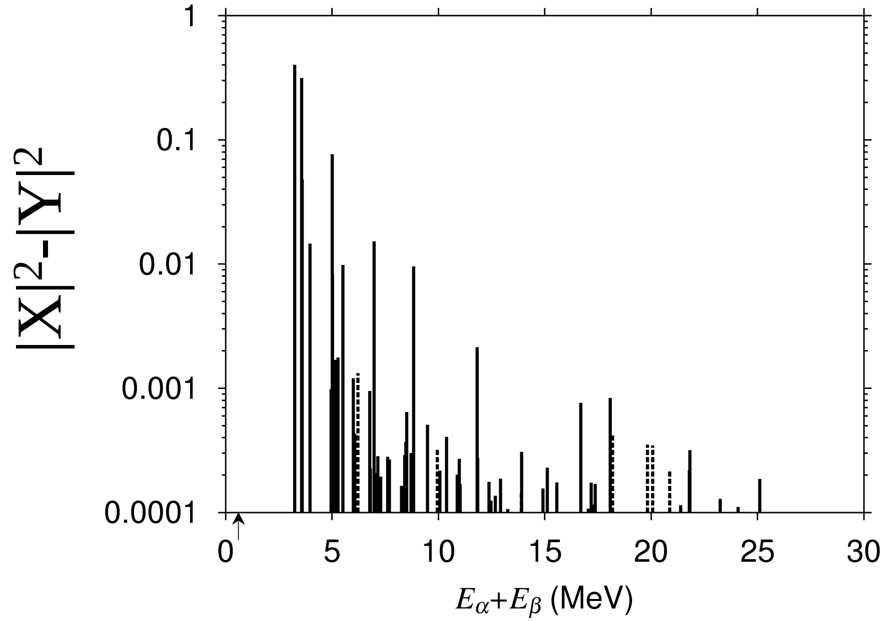
Enhancement of neutron excitation

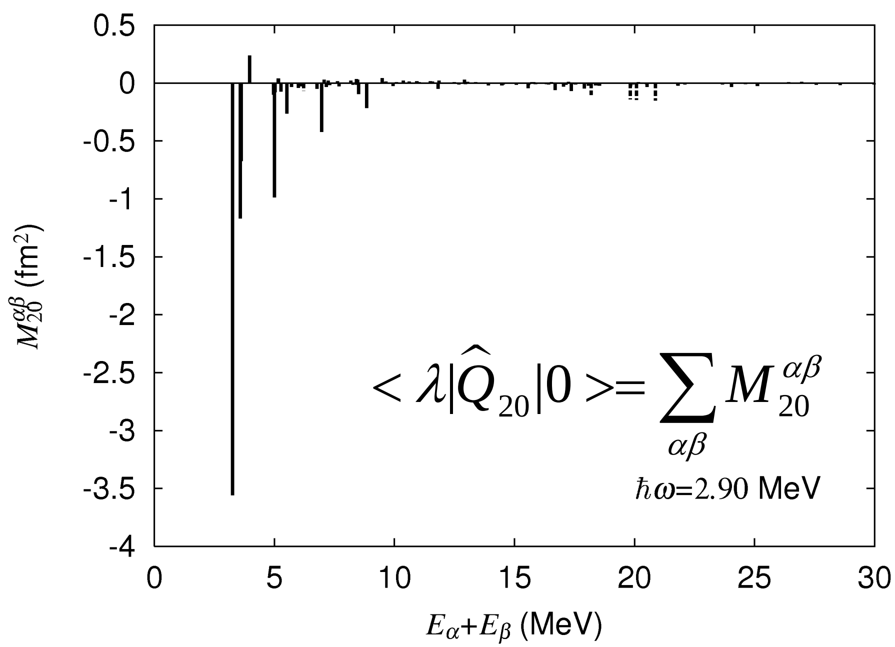
Soft K=0⁺ mode in deformed ^{40}Mg

$$\left|\frac{M_n}{M_p}\right| \Big/ \frac{N}{Z} = \frac{6.78}{2.33} = 2.9$$

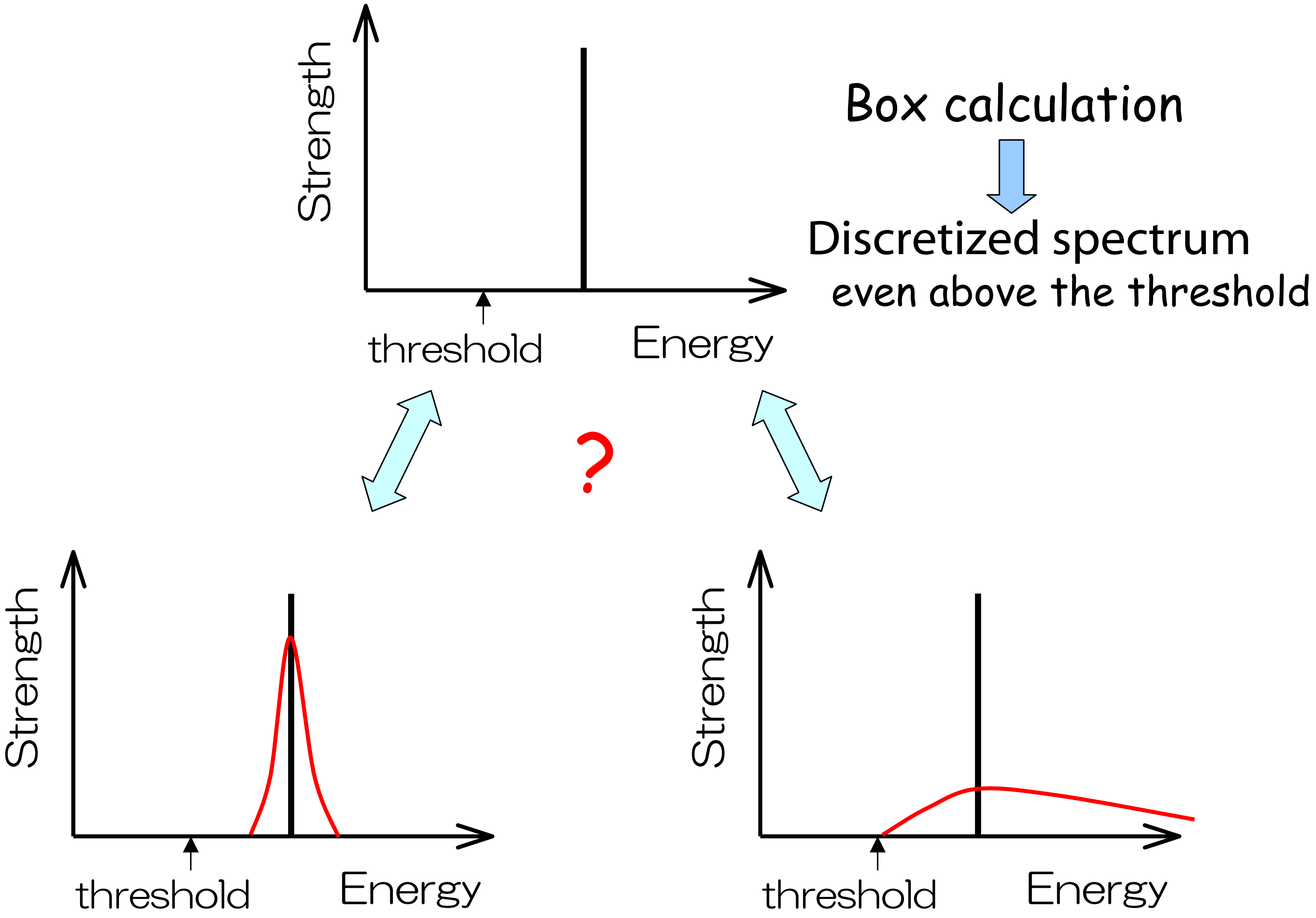


1 W.u.=8.13 fm^4

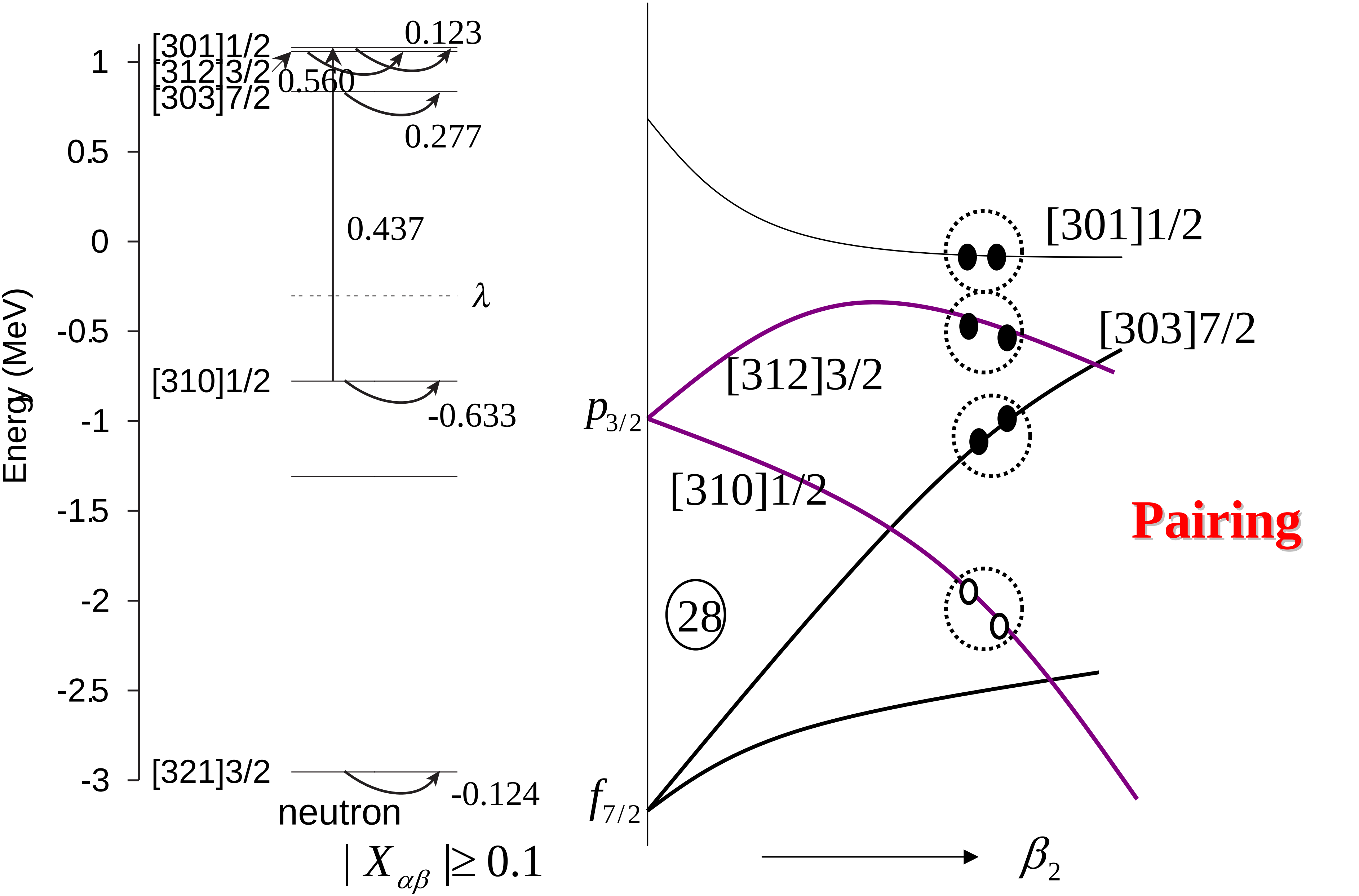




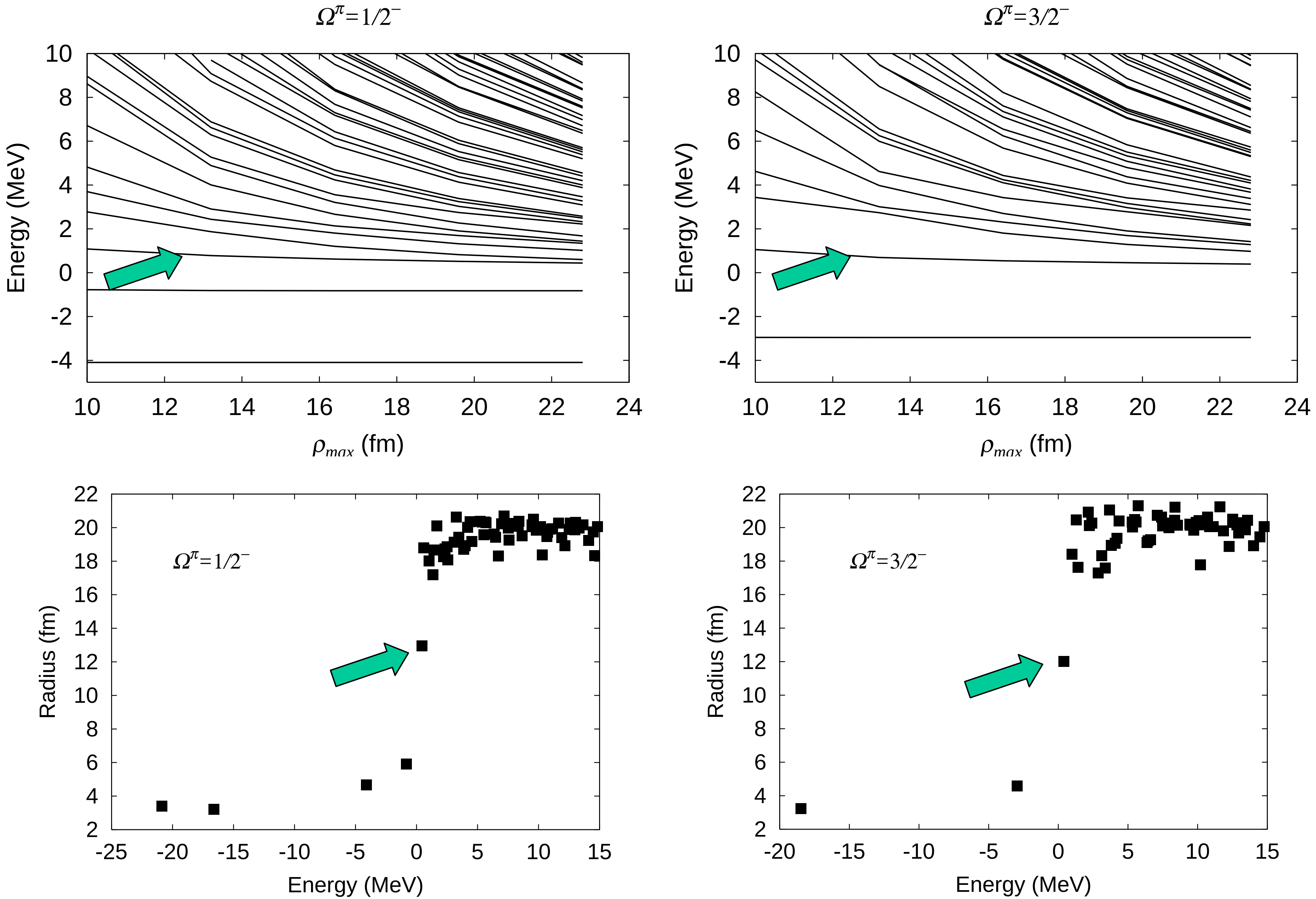
Physically meaningful or box artificial?



Structure of soft K=0$^+$ mode in ^{40}Mg

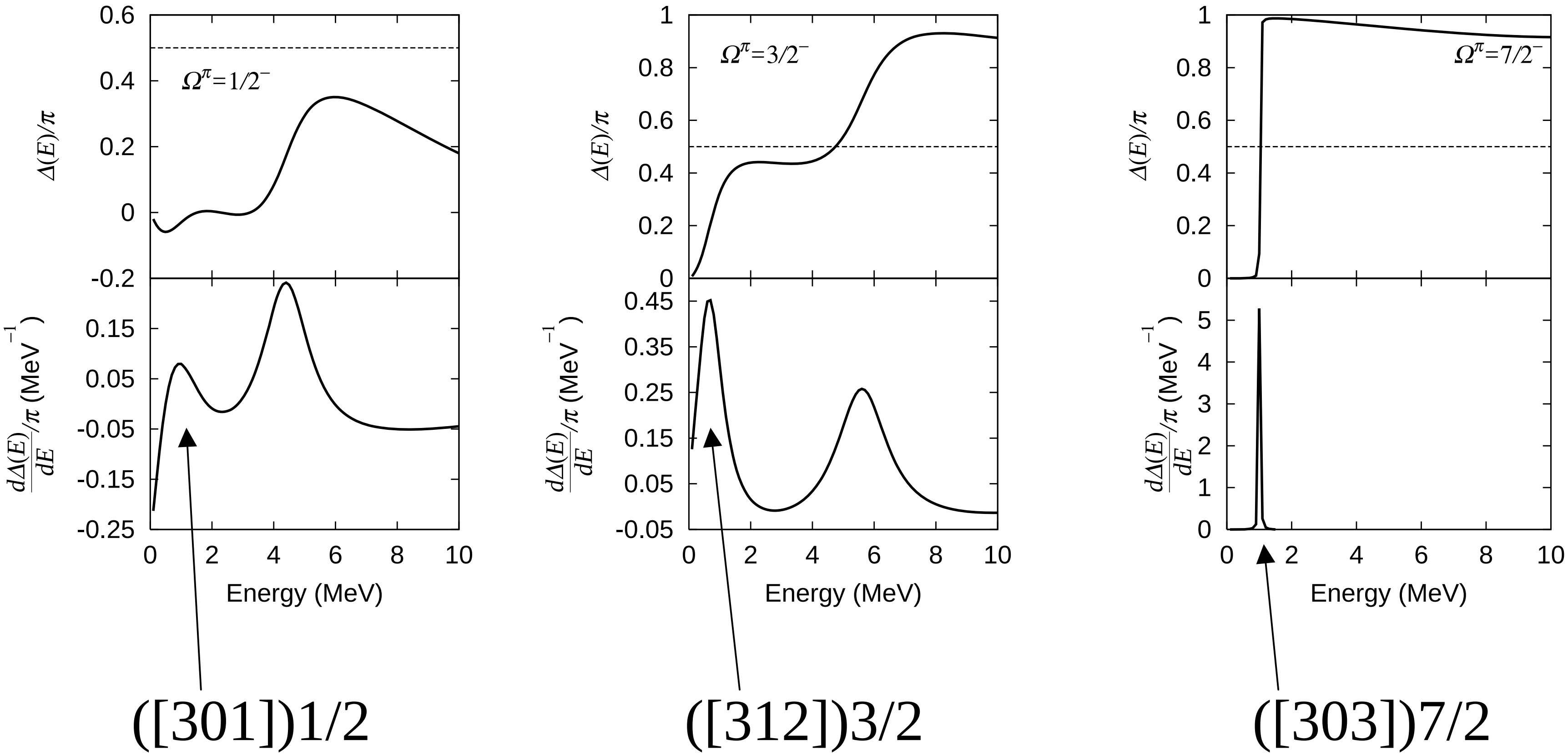


Properties of positive energy states



Eigenphase sum $\Delta(E) = \sum_a \delta_a(E),\ (U^{\dagger}SU)_{aa'} = e^{2i\delta_a(E)}\delta_{a,a'}$

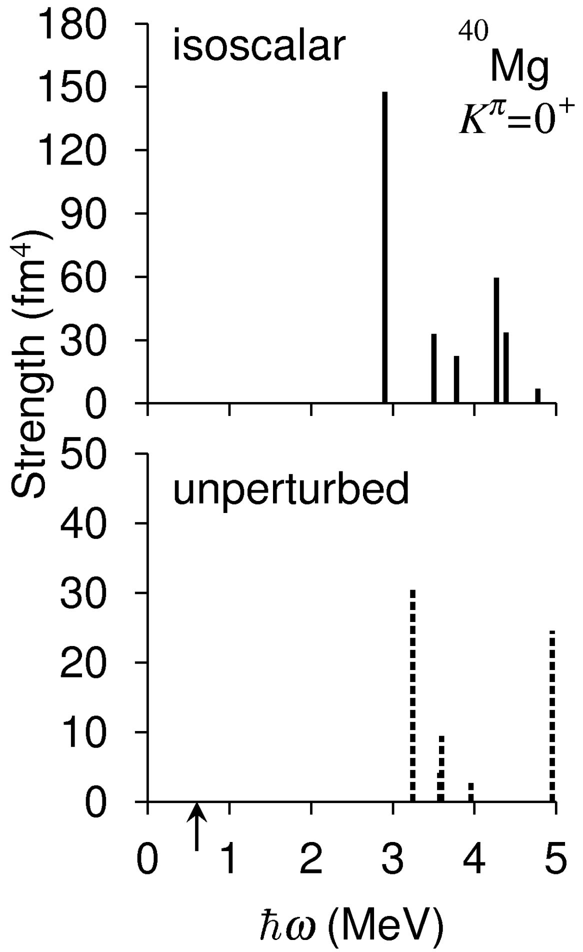
Hagino *et al.*, NPA735(2004)55

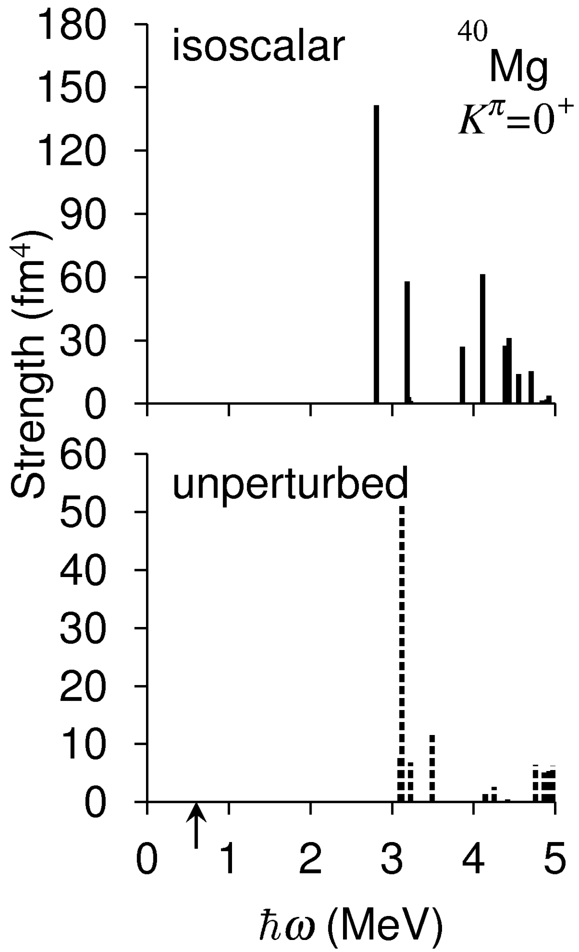


Main 2qp excitations generating the K=0⁺ state are associated with one-particle resonant or bound states.

⇨ This K=0⁺ mode can be considered as a resonance.

Box size dependence





$\rho_{\max} \times z_{\max} = 10.0 \text{ fm} \times 12.8 \text{ fm}$

$\rho_{\max} \times z_{\max} = 13.2 \text{ fm} \times 16.0 \text{ fm}$

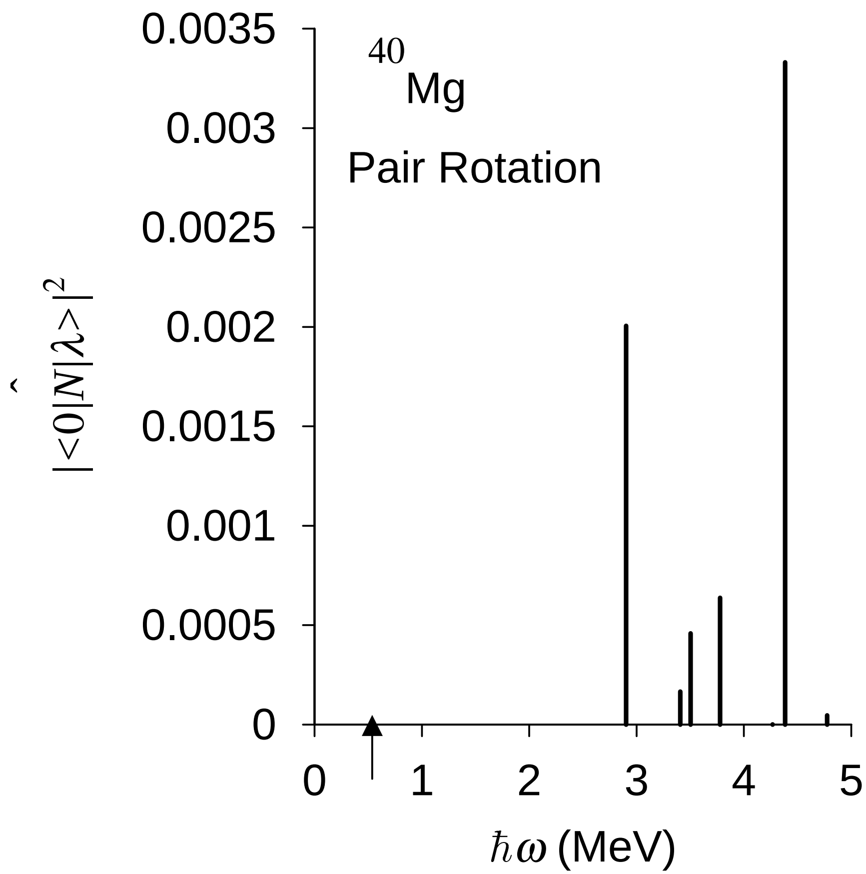
Coupling with spurious mode

Trial wave functions

HFB approximation ← Particle number violation

Restoration of broken symmetry

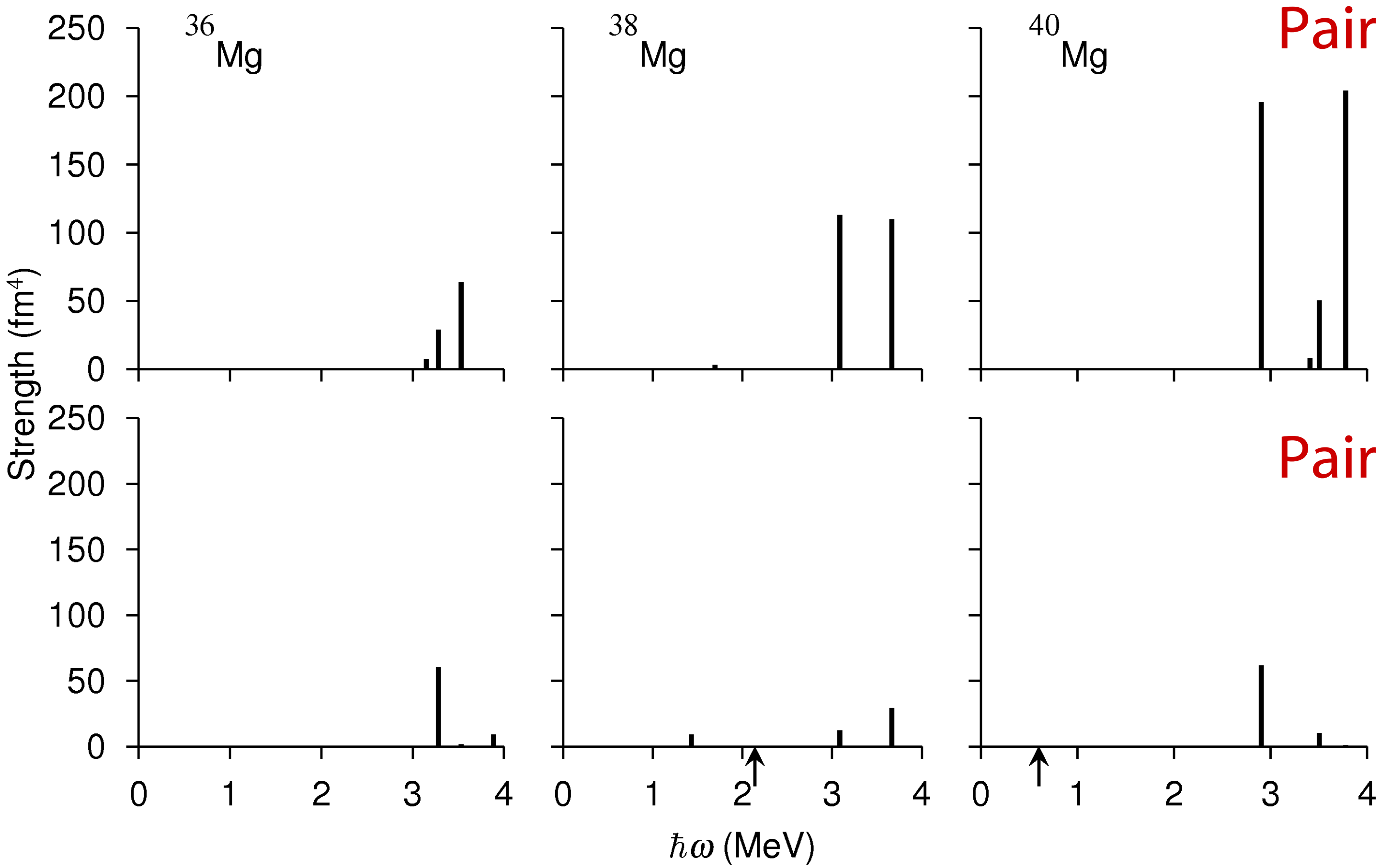
$$K^{\pi} = 0^{+}$$ Pair rotation



Two-neutron pair transition strengths

$$\hat{T}_{add} = \int d\mathbf{r} r^2 Y_{20} \psi^+(\mathbf{r},\uparrow)\psi^+(\mathbf{r},\downarrow) \;, \quad \hat{T}_{rem} = \int d\mathbf{r} r^2 Y_{20} \psi(\mathbf{r},\downarrow)\psi(\mathbf{r},\uparrow)$$

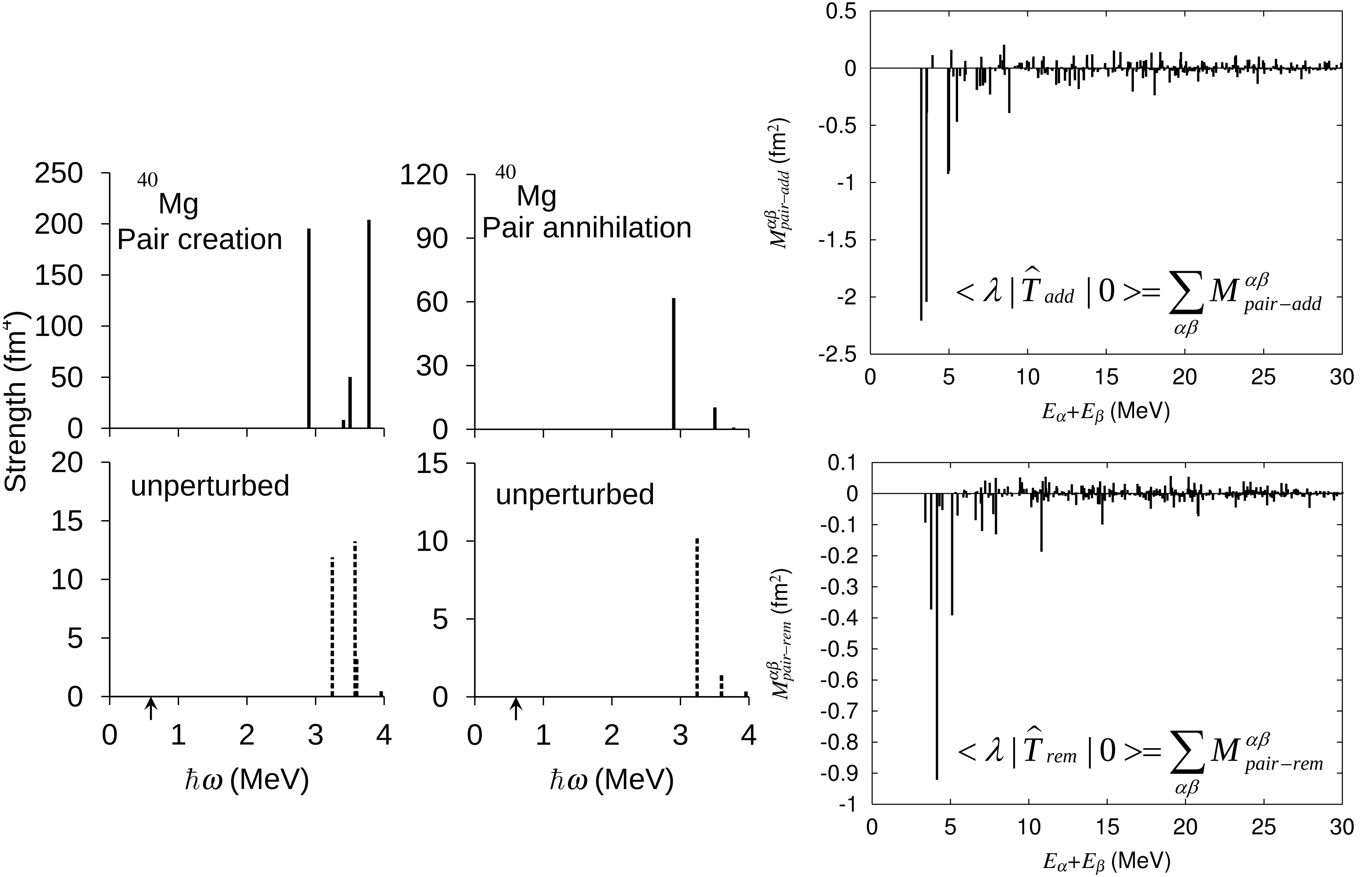
$$|<\lambda|\hat{T}|0>|^2$$



Pair creation

Pair annihilation

Neutron-pair creation/annihilation



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 correlation

Effect of dynamical pairing

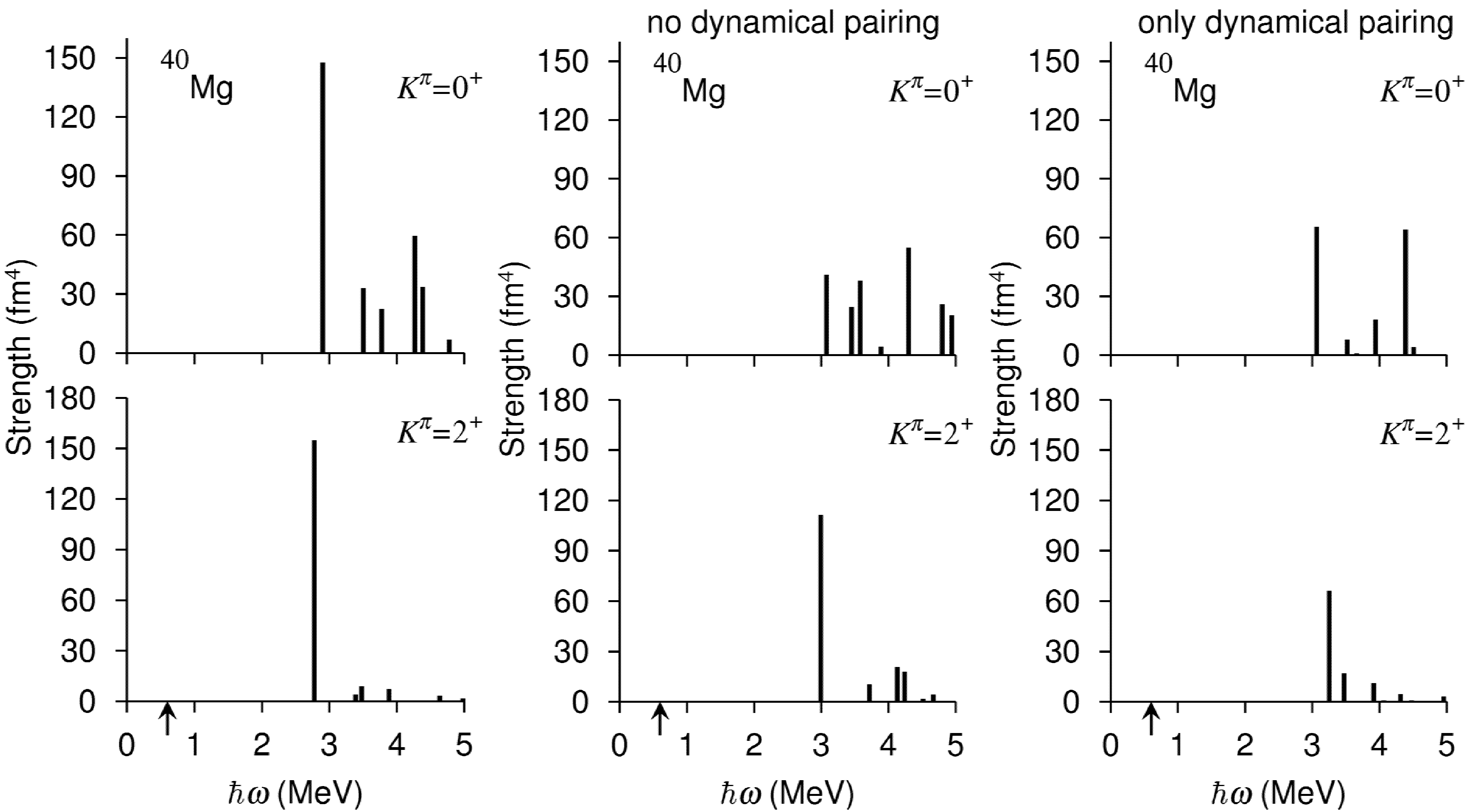
Weakly bound system

Spatial structure of quasiparticle wave functions

Dynamical pairing

Superposition of p-h, p-p and h-h vibrations

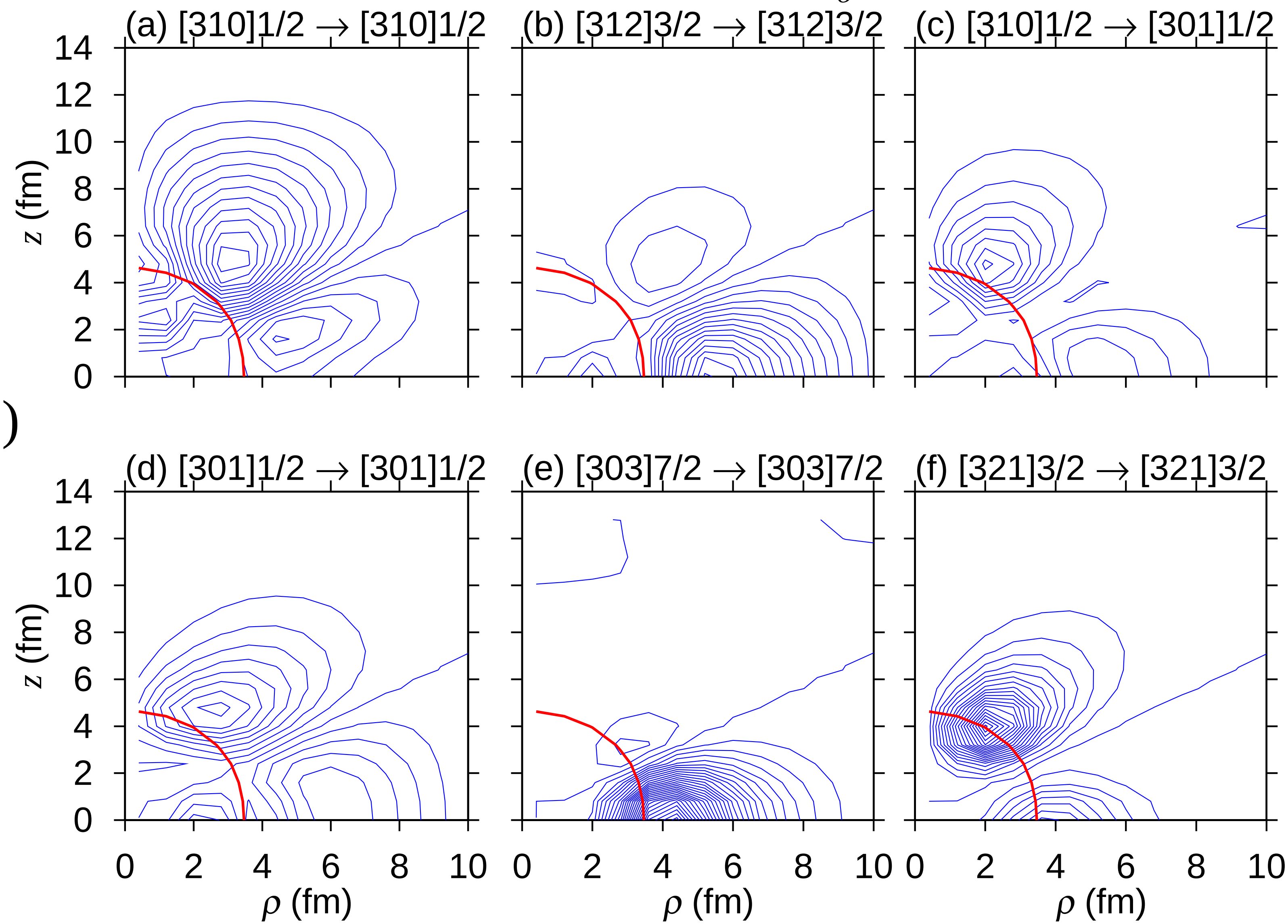
→ **Generation of the coherence**



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

$$< \alpha\beta | \hat{Q}_{20} | 0 > \equiv \int d\rho dz Q_{20}^{\alpha\beta}(\rho, z) \qquad \hat{Q}_{20} = \sum_{\sigma} \int d\mathbf{r} r^2 Y_{20} \psi^{+}(\mathbf{r},\sigma)\psi(\mathbf{r},\sigma)$$

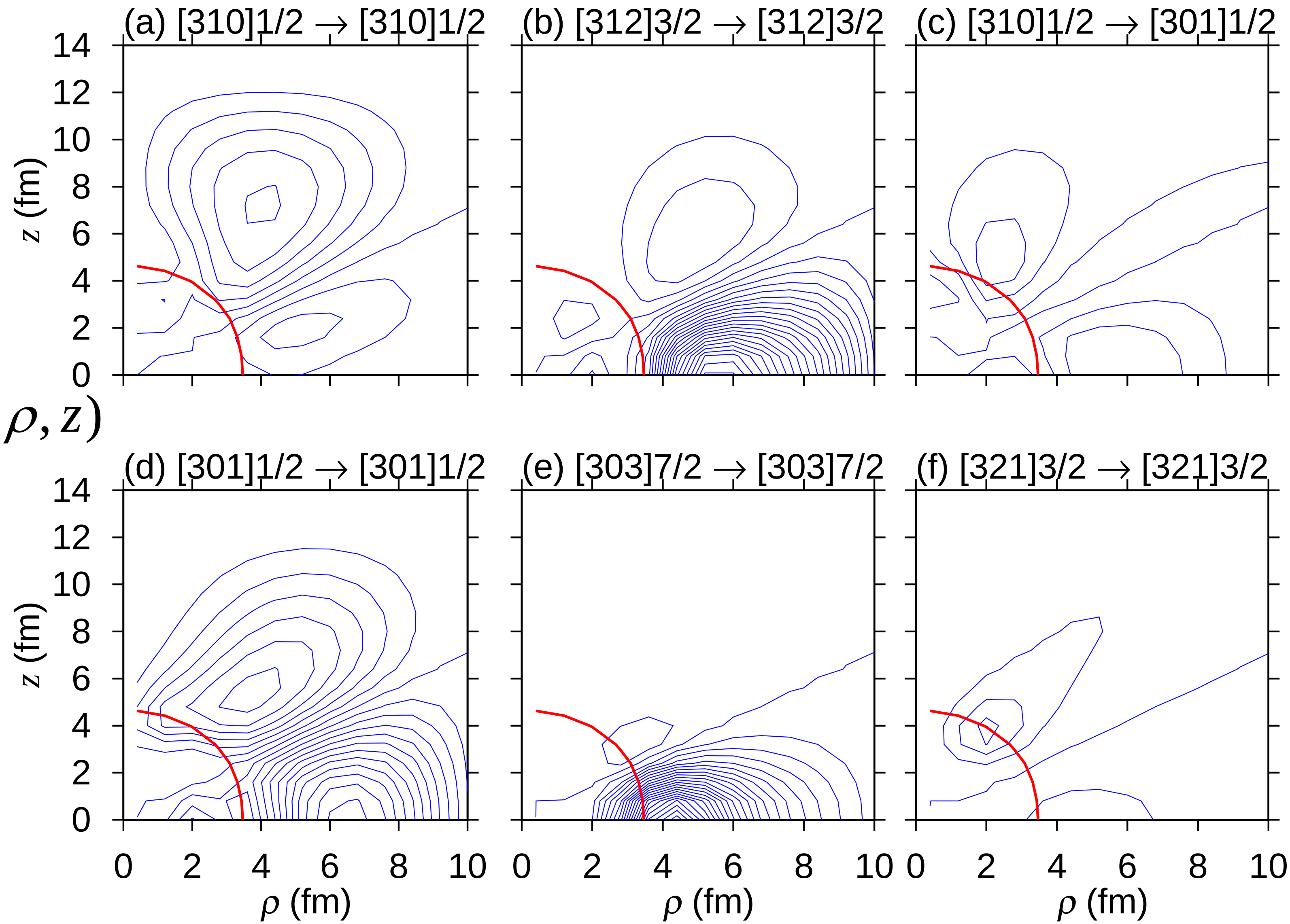
$Q_{20}^{\alpha\beta}(\rho, z)$



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

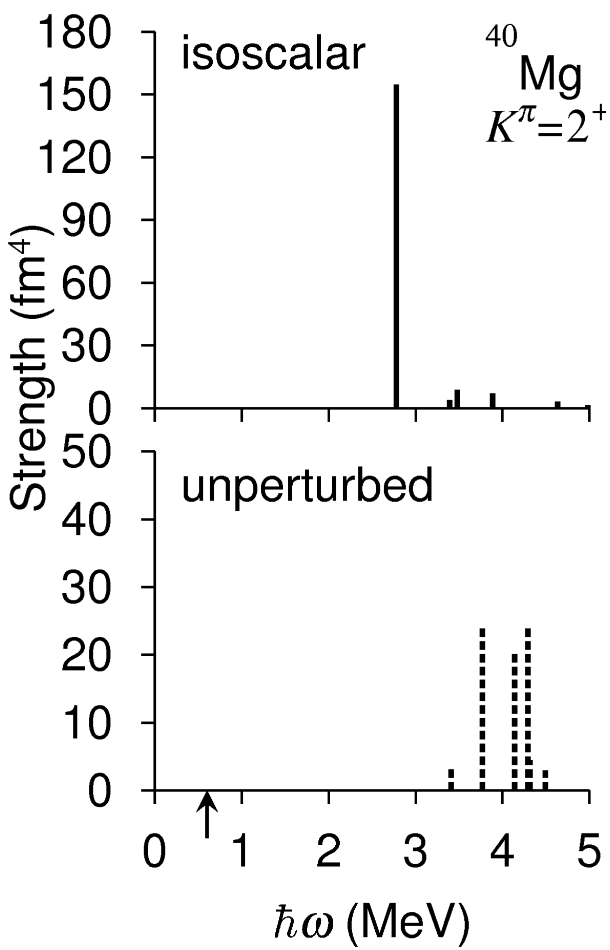
$$<\alpha\beta|\hat{T}|0> \equiv \int d\rho dz Q^{\alpha\beta}_{pair-add}(\rho,z) \qquad \hat{T} = \int d\mathbf{r} r^2 Y_{20} \psi^+(\mathbf{r},\uparrow)\psi^+(\mathbf{r},\downarrow)$$

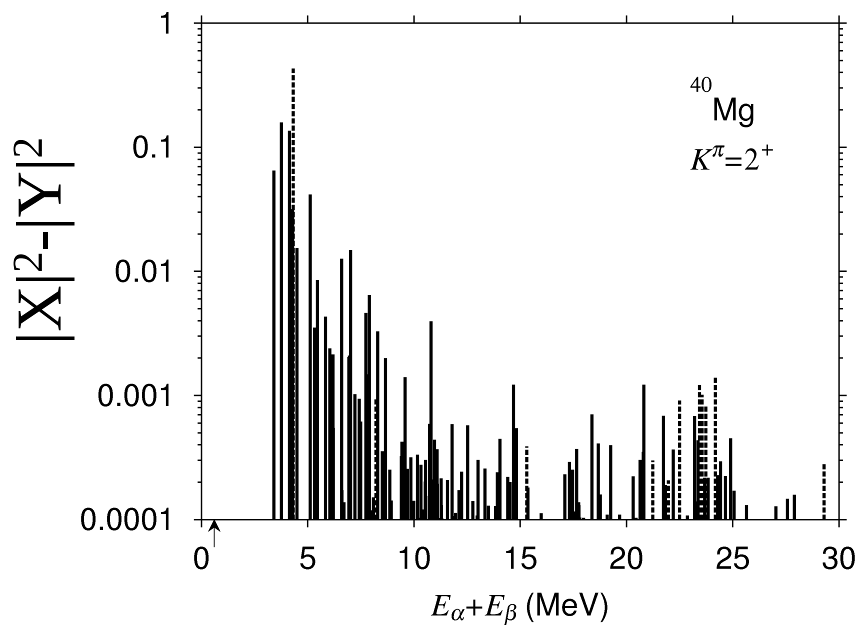
$$Q^{\alpha\beta}_{pair-add}(\rho,z)$$

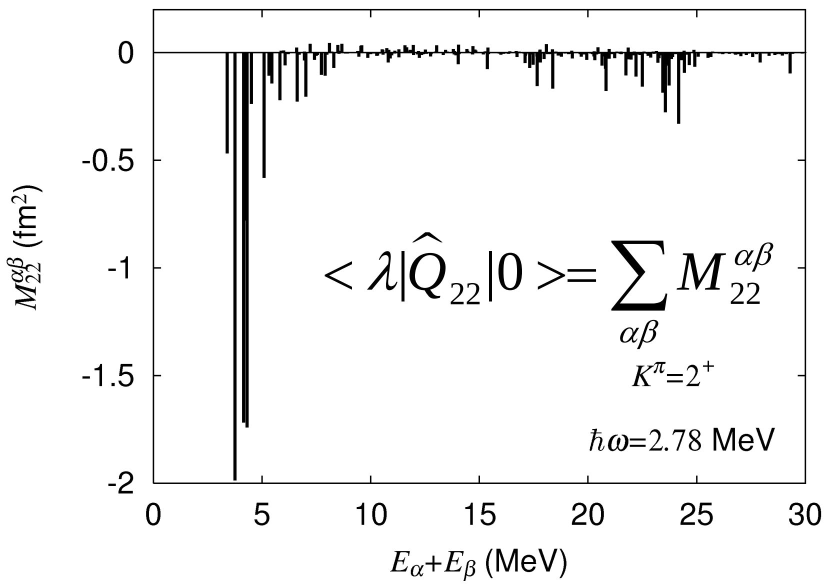


Soft K=2$^+$ mode in deformed ^{40}Mg

$$\left|\frac{M_n}{M_p}\right| \Big/ \frac{N}{Z} = \frac{9.43}{3.02} = 3.13$$







1 W.u.=8.13 fm^4

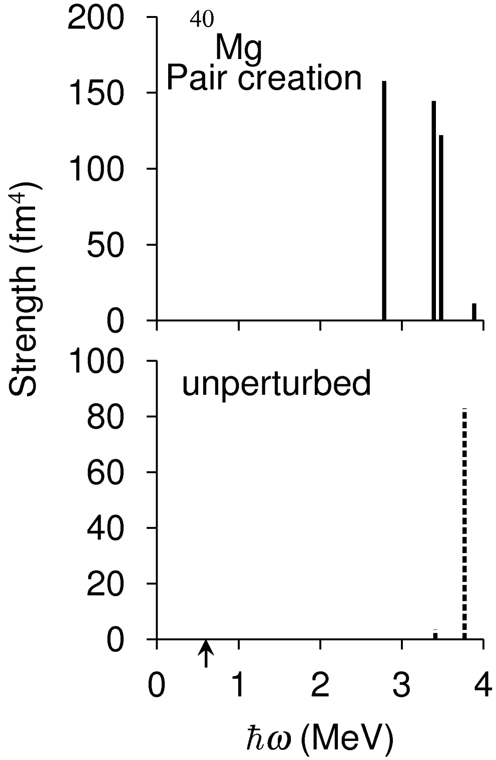
Neutron-pair creation/annihilation

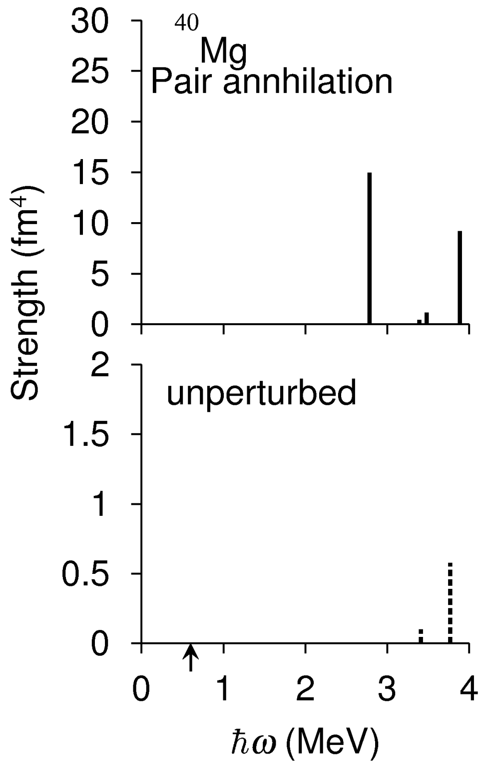
Quadrupole pairing

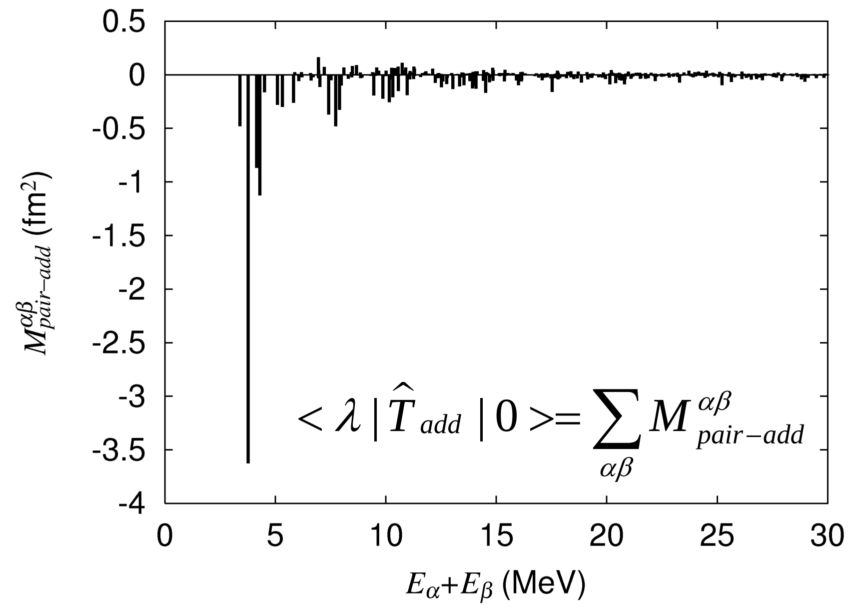
$$\hat{T}_{add} = \int d\mathbf{r}\, r^2 Y_{22}\psi^+(\mathbf{r},\uparrow)\psi^+(\mathbf{r},\downarrow)$$

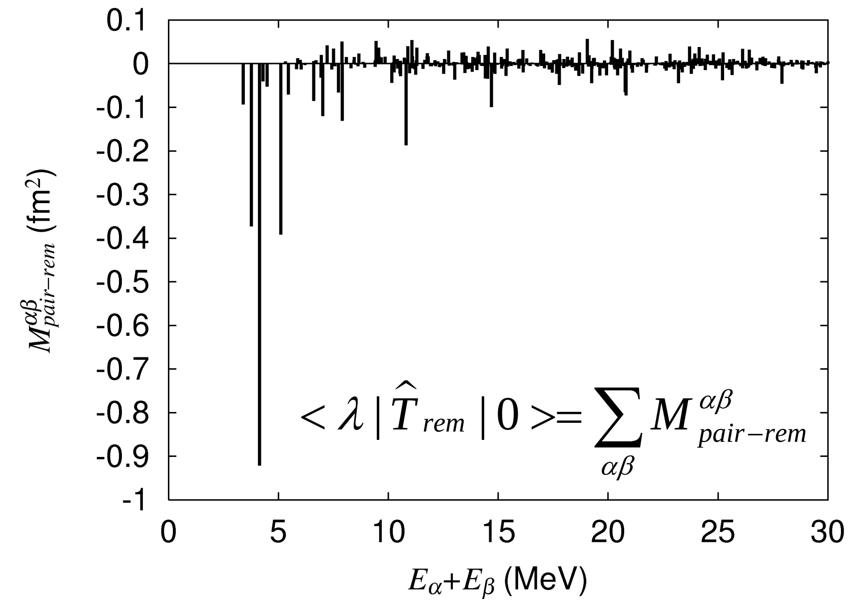
$$\hat{T}_{rem} = \int d\mathbf{r}\, r^2 Y_{22}\psi(\mathbf{r},\downarrow)\psi(\mathbf{r},\uparrow)$$

$$|<\lambda|\hat{T}|0>|^2$$









Summary

We have investigated properties of excitation modes in deformed Mg isotopes close to the neutron drip line.

Deformed QRPA calculation based on coordinate-space HFB including the continuum

We have obtained soft $K=0^+$ and 2^+ modes in $^{36\text{-}40}$Mg.

Spatial extension of two-quasiparticle wave functions

⇨ Large transition strengths

Coupling between quadrupole vib. and pairing vib.

Similar spatial structure of quasiparticle w.f. near the Fermi level

⇨ Generating coherent mode

$K=0^+$ mode is particularly sensitive to the dynamical pairing.

⇨ Good indicator of pair correlation in deformed drip-line nuclei