Pairing in spin-isospin responses

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Contents / Key words

Self-consistent deformed pnQRPA for spin-isospin responses

Self-consistency:

- ✓ T=1 pairing and IAS
- ✓ Collectivity of GT giant resonance

Possible new type of collective mode:

- ✓ T=0 proton-neutron pairing vibrations

Self-consistent pnQRPA for spin-isospin responses

starting point: Skyrme EDF $\mathcal{E}[\rho(\boldsymbol{r}), \tilde{\rho}(\boldsymbol{r})]$

variation w.r.t densities

The coordinate-space Hartree-Fock-Bogoliubov eq. for ground states

J. Dobaczewski et al., NPA422(1984)103

$$\begin{pmatrix} h^q(\boldsymbol{r},\sigma) - \lambda^q & \tilde{h}^q(\boldsymbol{r},\sigma) \\ \tilde{h}^q(\boldsymbol{r},\sigma) & -(h^q(\boldsymbol{r},\sigma) - \lambda^q) \end{pmatrix} \begin{pmatrix} \varphi^q_{1,\alpha}(\boldsymbol{r},\sigma) \\ \varphi^q_{2,\alpha}(\boldsymbol{r},\sigma) \end{pmatrix} = E_\alpha \begin{pmatrix} \varphi^q_{1,\alpha}(\boldsymbol{r},\sigma) \\ \varphi^q_{2,\alpha}(\boldsymbol{r},\sigma) \end{pmatrix}$$

$q = \nu,\ \pi$

"s.p." hamiltonian and pair potential: $h^q = \dfrac{\delta \mathcal{E}}{\delta \rho^q}, \qquad \tilde{h}^q = \dfrac{\delta \mathcal{E}}{\delta \tilde{\rho}^q}$

quasiparticle basis $\alpha, \beta \cdots$

The proton-neutron quasiparticle RPA eq. for excited states $[\hat{H}, \hat{O}^\dagger_\lambda]|\Psi_\lambda\rangle = \omega_\lambda \hat{O}^\dagger_\lambda |\Psi_\lambda\rangle$

Collective excitation = coherent superposition of 2qp excitations:

$$\hat{O}^\dagger_\lambda = \sum_{\alpha\beta} X^\lambda_{\alpha\beta} \hat{a}^\dagger_{\alpha,\nu} \hat{a}^\dagger_{\beta,\pi} - Y^\lambda_{\alpha\beta} \hat{a}_{\bar{\beta},\pi} \hat{a}_{\bar{\alpha},\nu}$$

residual interactions derived self-consistently :

$$v_{\text{res}}(\boldsymbol{r}_1, \boldsymbol{r}_2) = \frac{\delta^2 \mathcal{E}}{\delta \rho_{1t_3}(\boldsymbol{r}_1) \delta \rho_{1t_3}(\boldsymbol{r}_2)} \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 + \frac{\delta^2 \mathcal{E}}{\delta \boldsymbol{s}_{1t_3}(\boldsymbol{r}_1) \delta \boldsymbol{s}_{1t_3}(\boldsymbol{r}_2)} \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2$$

Recent progress

EDF-based self-consistent pnQRPA for axially-deformed nuclei

w/o any free parameters (almost all the) arbitrary nuclei

PTEP
Prog. Theor. Exp. Phys. **2013**, 113D02 (17 pages)
DOI: 10.1093/ptep/ptt091

Spin–isospin response of deformed neutron-rich nuclei in a self-consistent Skyrme energy-density-functional approach

Kenichi Yoshida*

Matrix QRPA

Skyrme

PHYSICAL REVIEW C **87**, 064302 (2013)

Large-scale calculations of the double-β decay of ^{76}Ge, ^{130}Te, ^{136}Xe, and ^{150}Nd in the deformed self-consistent Skyrme quasiparticle random-phase approximation

M. T. Mustonen[1,2,*] and J. Engel[1,†]

Matrix QRPA

PHYSICAL REVIEW C **90**, 024308 (2014)

Finite-amplitude method for charge-changing transitions in axially deformed nuclei

M. T. Mustonen,[1,*] T. Shafer,[1,†] Z. Zenginerler,[2,‡] and J. Engel[1,§]

FAM-QRPA

PHYSICAL REVIEW C **89**, 044306 (2014)

Gamow-Teller strength in deformed nuclei within the self-consistent charge-exchange quasiparticle random-phase approximation with the Gogny force

M. Martini,[1,2,3] S. Péru,[3] and S. Goriely[1]

Matrix QRPA

Gogny

Restoration of the isospin symmetry breaking (ISB)

Even w/o the Coulomb int., the ISB occurs in N>Z nuclei in a MFA

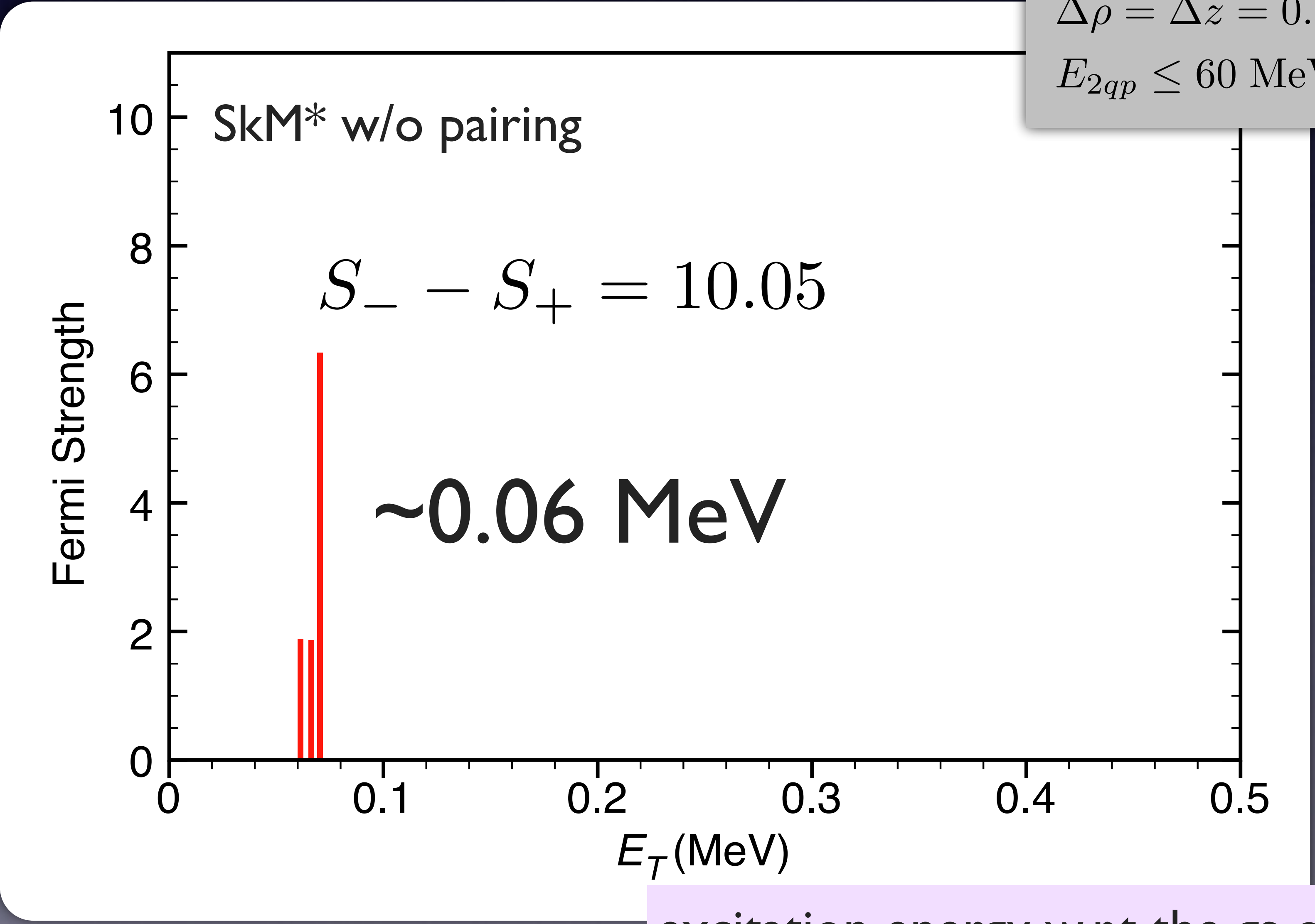
$$[H_{\mathrm{MF}}, T_-] \neq 0$$

C. A. Engelbrecht and R. H. Lemmer, PRL24(1970)607

→ IAS appears as a NG mode in the pnRPA

Ex. ^{90}Zr (N-Z=10) w/o Coulomb

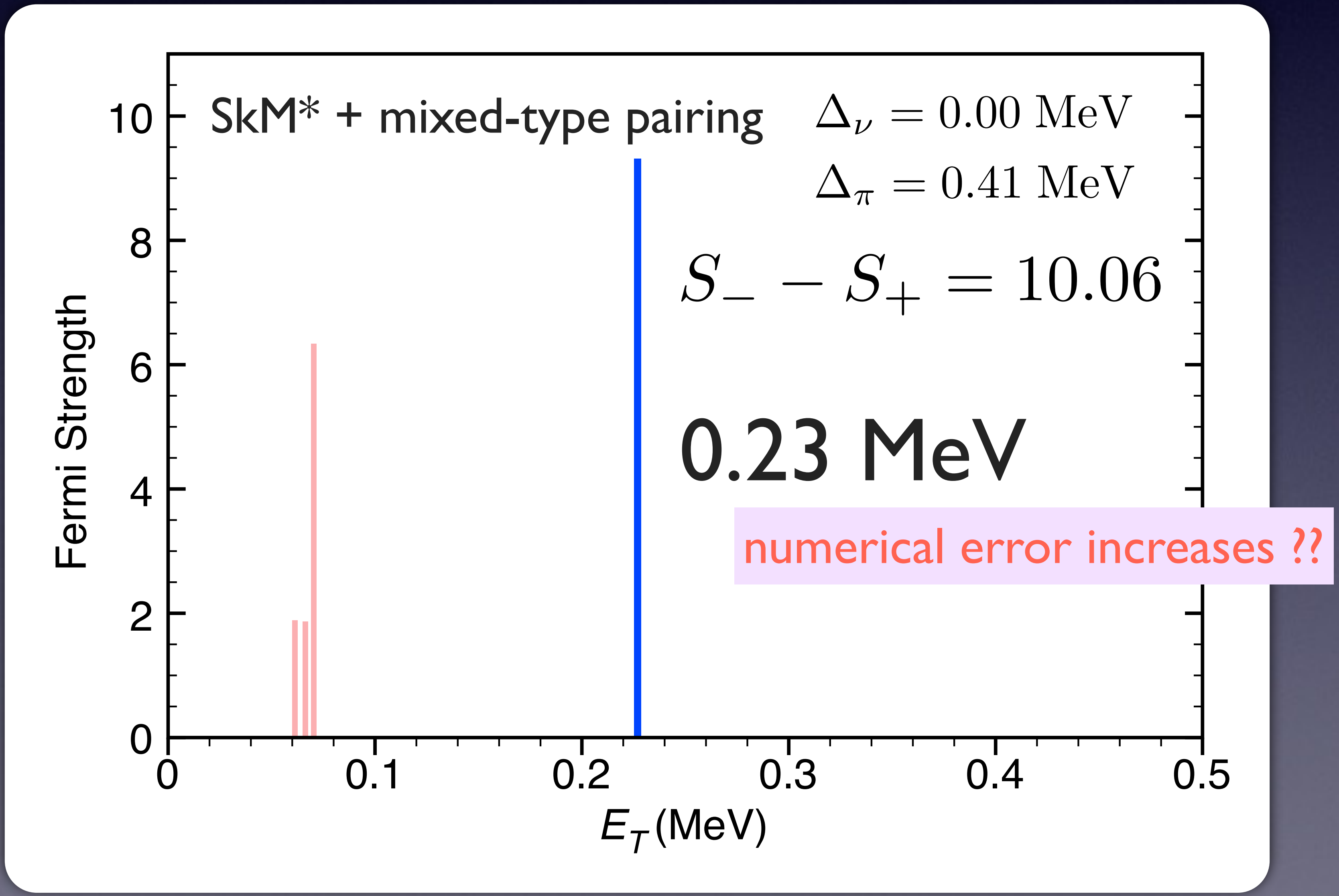
$\rho_{\max} \times z_{\max} = 14.7\ \mathrm{fm} \times 14.4\ \mathrm{fm}$
$\Delta\rho = \Delta z = 0.6\ \mathrm{fm}$
$E_{2qp} \leq 60\ \mathrm{MeV}$



excitation energy w.r.t the gs of ^{90}Zr

Restoration of the isospin symmetry breaking (ISB)

Ex. ^{90}Zr (N-Z=10) w/o Coulomb, w/ pairing

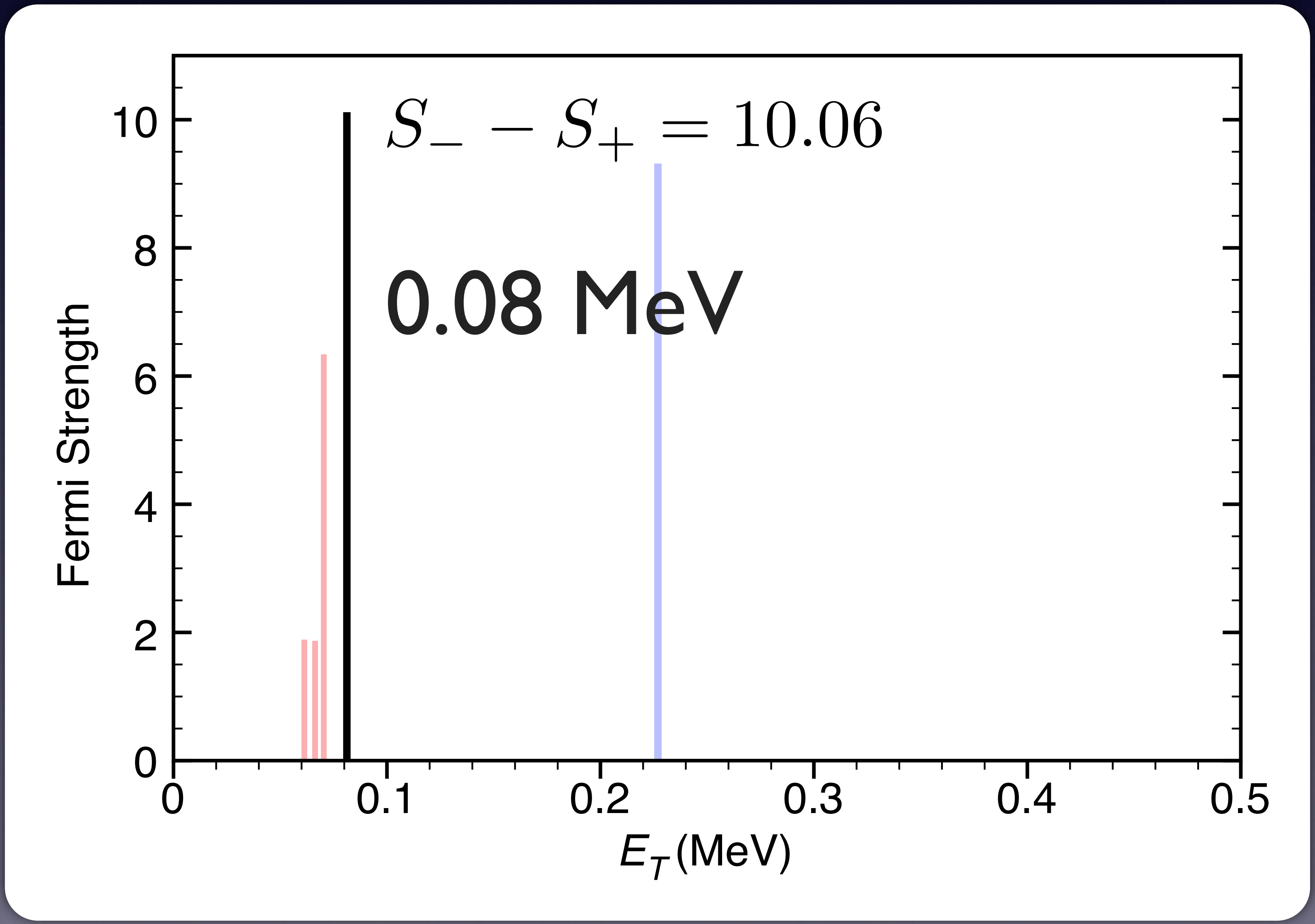


Restoration of the isospin symmetry breaking (ISB)

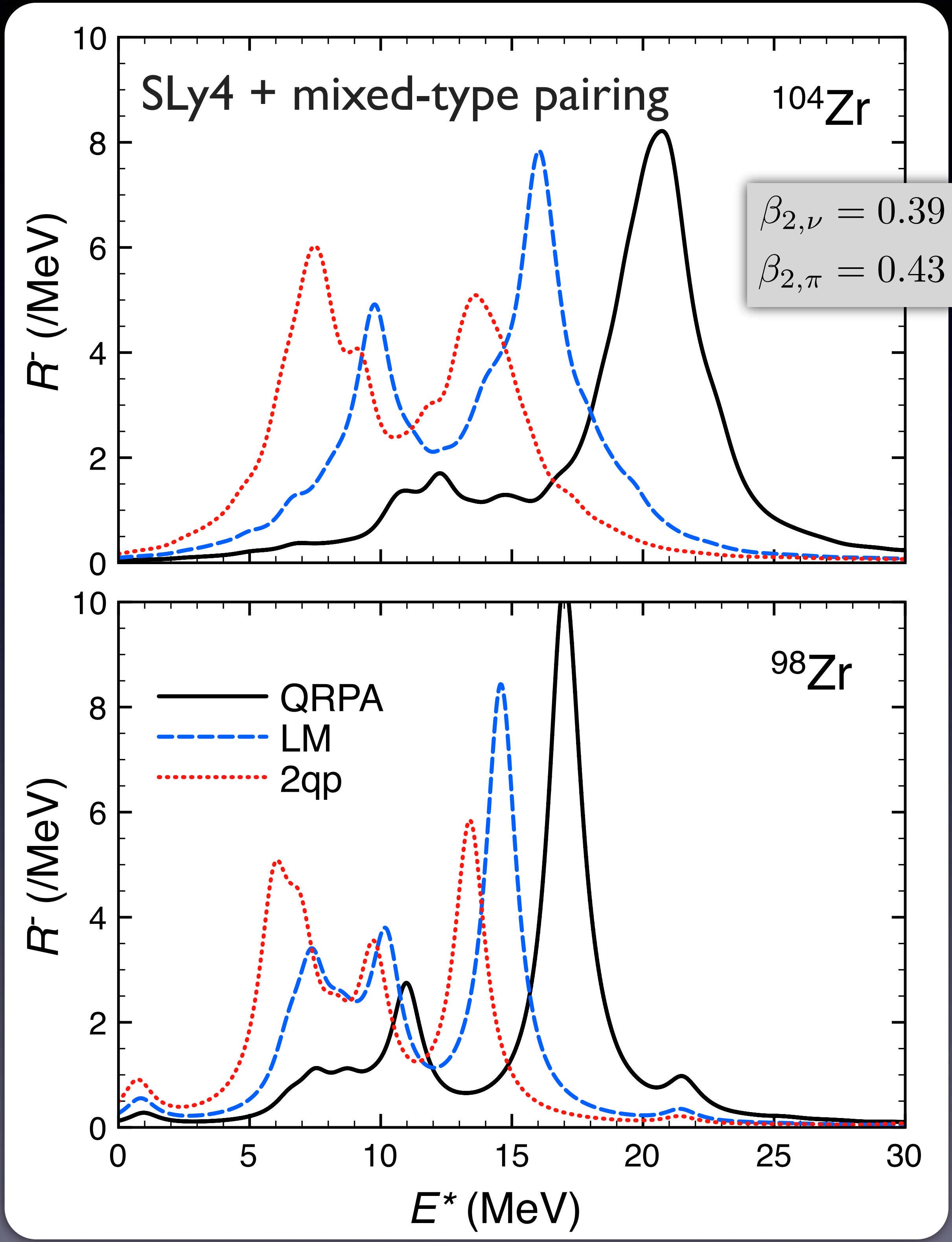
Ex. ^{90}Zr (N-Z=10) w/o Coulomb

inclusion of the S=0 pairing interaction in the pnQRPA

$$v_{\rm pp}(\boldsymbol{r},\boldsymbol{r}') = V_0\left[1-\frac{1}{2}\frac{\rho(\boldsymbol{r})}{\rho_0}\right]\delta(\boldsymbol{r}-\boldsymbol{r}')$$



GTGR: the need of self-consistency



$\beta_{2,\nu} = 0.39$
$\beta_{2,\pi} = 0.43$

✓the collectivity generated by the Landau-Migdal approximation is weak

$$v_{\rm ph}(\boldsymbol{r}_1\boldsymbol{r}_2) = N_0^{-1}\left[f_0'\tau_1\cdot\tau_2 + g_0'\sigma_1\cdot\sigma_2\tau_1\cdot\tau_2\right]\delta(\boldsymbol{r}_1-\boldsymbol{r}_2)$$

LM parameter:
M. Bender et al., PRC65(2002)054322

the self-consistent treatment of the static and dynamic calculations is needed for a quantitative description of the GTGR proton-neutron pairing vibrations

✓ collectivity of T=0 and T=1 types

Ref: PRC90(2014)031303R

Pairing vibration and condensation (of neutrons)

cf. Bès and Broglia

neutron-pair operator; a probe to see the collectivity

$$\hat{P}_{T=1,T_z=1,S=0} \equiv \frac{1}{2}\sum_{\sigma,\sigma'}\sum_{\tau,\tau'}\int d\boldsymbol{r}\hat{\psi}(\boldsymbol{r}\sigma\tau)\delta_{\sigma,\sigma'}\langle\tau|\tau_+|\tau'\rangle\hat{\psi}(\boldsymbol{r}\bar{\sigma}'\bar{\tau}') = \sqrt{2}\int d\boldsymbol{r}\hat{\psi}_\nu(\boldsymbol{r}\downarrow)\hat{\psi}_\nu(\boldsymbol{r}\uparrow)$$

$$\hat{\psi}(\boldsymbol{r}\bar{\sigma}\bar{\tau}) = (-2\sigma)(-2\tau)\hat{\psi}(\boldsymbol{r}-\sigma-\tau)$$

pairing condensation: order parameter

$$q \equiv \langle\hat{P}_{T=1,T_z=1,S=0}\rangle = \sqrt{2}\int d\boldsymbol{r}\,\tilde{\rho}_\nu(\boldsymbol{r})$$

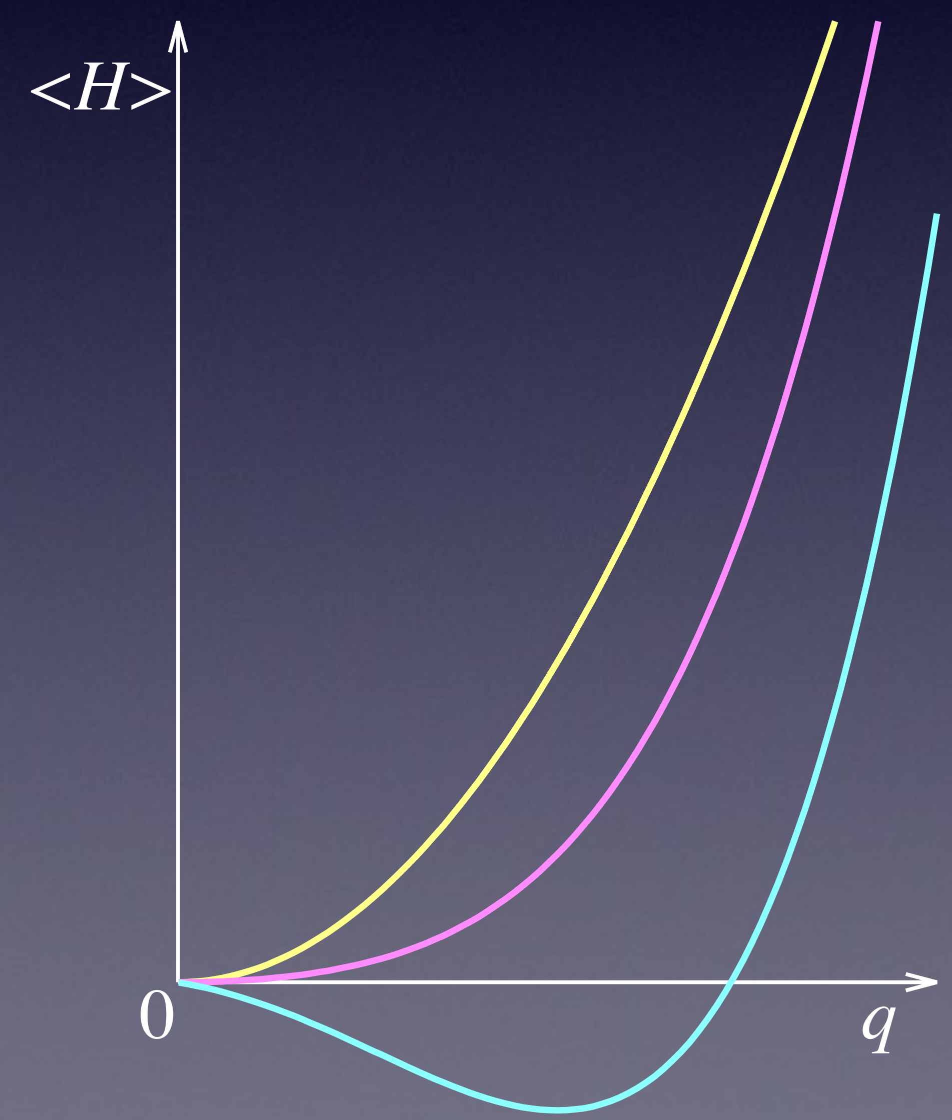
pairing gap: $\Delta \sim \int d\boldsymbol{r}\tilde{h}(\boldsymbol{r})\tilde{\rho}(\boldsymbol{r})$

pairing vibration;
precursory soft mode: $|\lambda\rangle$

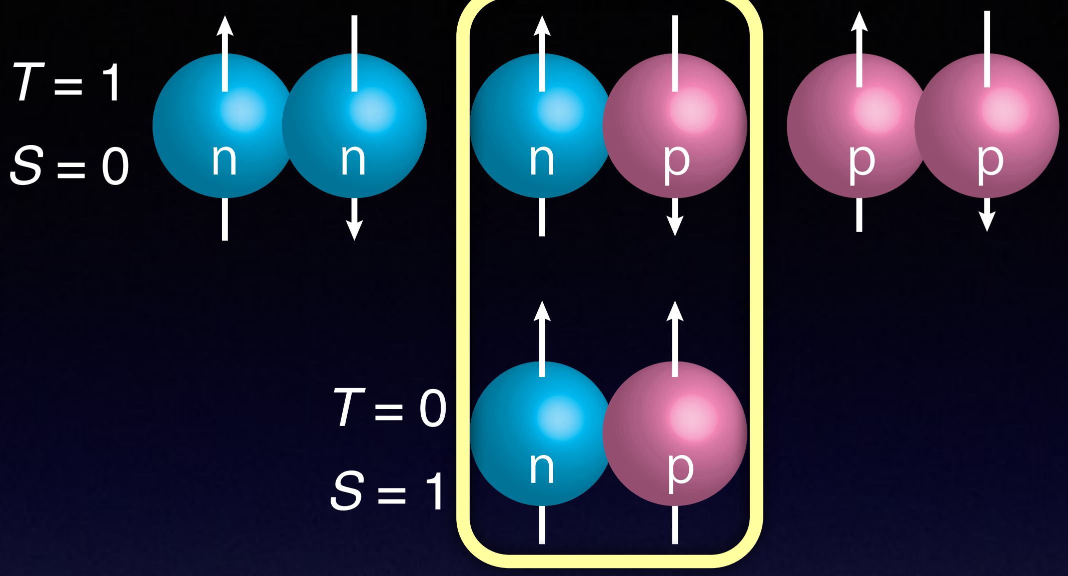
w/ an enhanced transition strength

$$|\langle\lambda|\hat{P}_{T=1,T_z=1,S=0}|\rangle|^2$$

is seen in normal nuclei (q=0)



Proton-neutron pairing collectivity



T=1 (T_z=0), S=0 pair

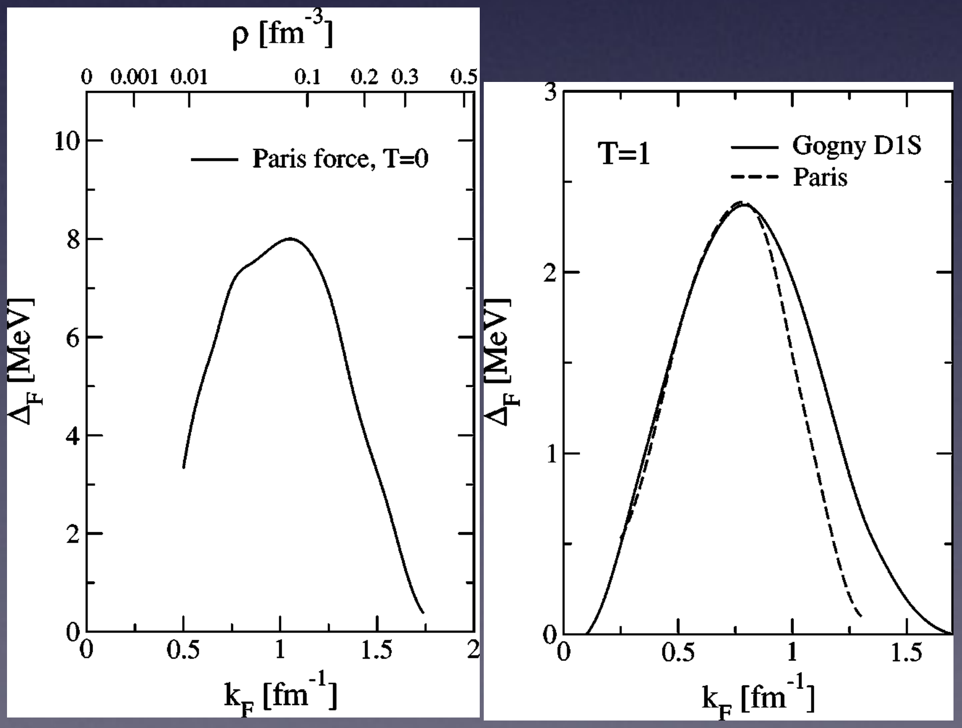
$$\hat{P}_{T=1,T_z=0,S=0} \equiv \frac{1}{2}\sum_{\sigma,\sigma'}\sum_{\tau,\tau'}\int d\boldsymbol{r}\hat{\psi}(\boldsymbol{r}\sigma\tau)\delta_{\sigma,\sigma'}\langle\tau|\tau_0|\tau'\rangle\hat{\psi}(\boldsymbol{r}\bar{\sigma}'\bar{\tau}')$$

strong collectivity is expected as in nn and pp pairings

T=0, S=1 (S_z=0,±1) pair

$$\hat{P}_{T=0,S=1} \equiv \frac{1}{2}\sum_{\sigma,\sigma'}\sum_{\tau,\tau'}\int d\boldsymbol{r}\hat{\psi}(\boldsymbol{r}\sigma\tau)\delta_{\tau,\tau'}\langle\sigma|\boldsymbol{\sigma}|\sigma'\rangle\hat{\psi}(\boldsymbol{r}\bar{\sigma}'\bar{\tau}')$$

$$\Delta_{01} > \Delta_{10}$$



E. Garrido et al., PRC63(2001)037304

many works on the possible occurrence of the condensation, but largely unknown

"no experimental evidence so far"

S. Frauendorf and A. O. Macchiavelli, Prog. Part. Nucl. Phys. 78 (2014) 24

Pairing phase diagram: Pairing vibration and rotation

G.G.Dussel et al., NPA450(1986)164

two-level solvable model: $H = 2N_2 - X_{10} \sum_{\substack{ll'=l_1 l_2 \\ \mu}} D^+_{\mu l} D_{\mu l'} - X_{01} \sum_{\substack{l,l'=l_1 l_2 \\ \mu}} P^+_{\mu l} P_{\mu l'}$

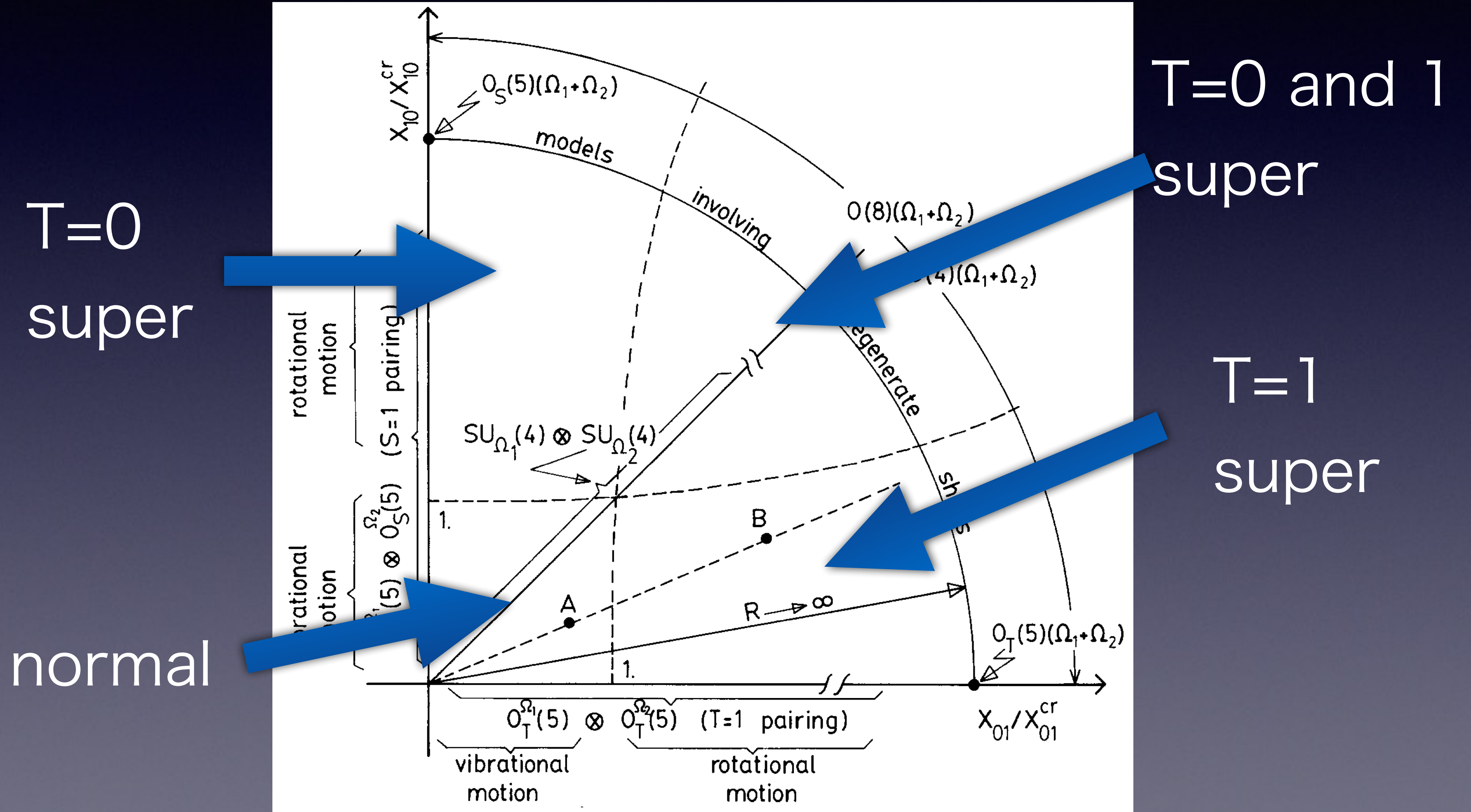


Fig. 1. The two-dimensional space of phases of the model. Various limiting schemes are indicated.

Interactions employed for pn-pairing vibrations in fp-shell nuclei

KSB(HFB) eq:

SGII + surface pairing

V_0 = -520 MeV fm^3

^{44}Ti

Δn = 1.82 MeV

Δp = 1.87 MeV

pnQRPA eq:

p-h channel: SGII

p-p channel:

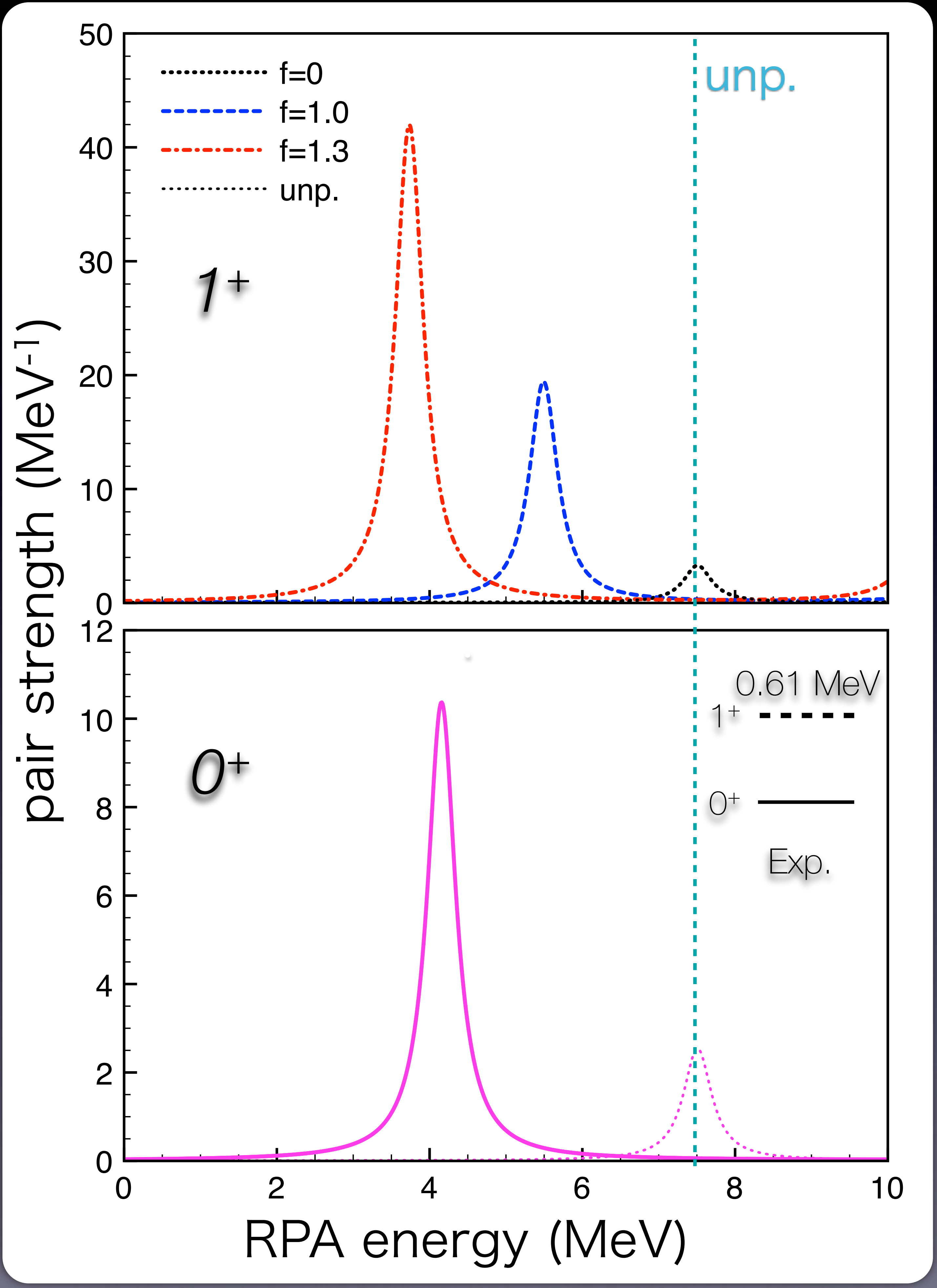
S=0: $$v_{\rm pp}(\boldsymbol{r},\boldsymbol{r}') = V_0\left[1-\frac{\rho(\boldsymbol{r})}{\rho_0}\right]\delta(\boldsymbol{r}-\boldsymbol{r}')$$ self-consistent

S=1: $$v_{\rm pp}(\boldsymbol{r},\boldsymbol{r}') = fV_0\left[1-\frac{\rho(\boldsymbol{r})}{\rho_0}\right]\delta(\boldsymbol{r}-\boldsymbol{r}')$$ "arbitrary"

changing "f" to see an effect of the residual interaction

cf. C. Bai et al., PLB719(2013)116

^{40}Ca → ^{42}Sc



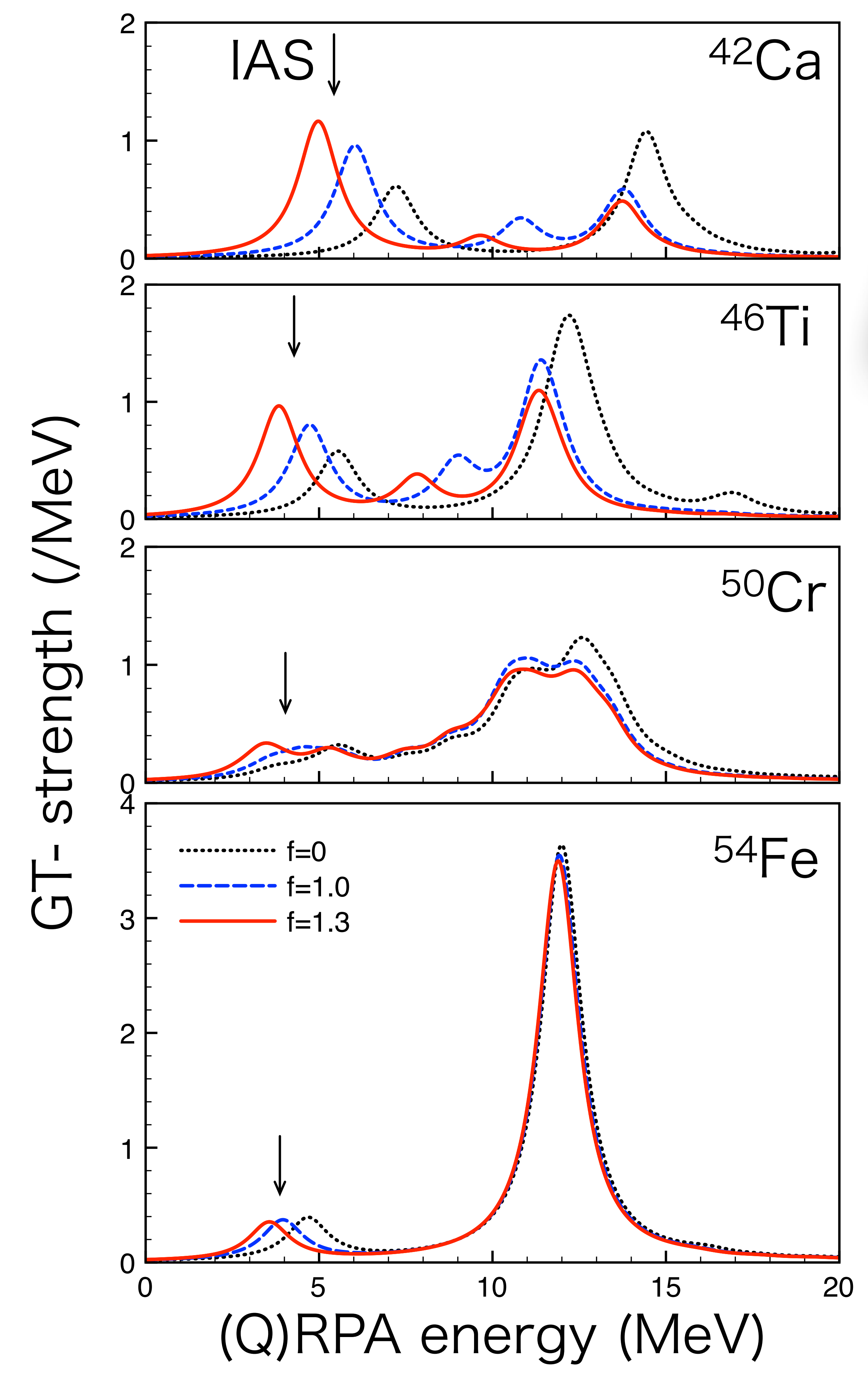
f=1.3

^{42}Sc		$J^\pi = 1^+$	$J^\pi = 0^+$
configuration	$E_\alpha + E_\beta$	$M^{S=1,S_z=0}_{\alpha\beta}$	$M^{S=0}_{\alpha\beta}$
$\pi 1f_{7/2} \otimes \nu 1f_{7/2}$	7.5	1.70	2.85
$\pi 1f_{7/2} \otimes \nu 1f_{5/2}$	15.2	0.62	
$\pi 1f_{5/2} \otimes \nu 1f_{7/2}$	14.7	0.51	
$\pi 2p_{3/2} \otimes \nu 2p_{3/2}$	16.1	0.17	0.22
$\pi 1d_{3/2} \otimes \nu 1d_{3/2}$	4.2	0.25	0.48
$\pi 2s_{1/2} \otimes \nu 2s_{1/2}$	6.6	0.25	
$\pi 1d_{3/2} \otimes \nu 1d_{5/2}$	10.1	0.32	
$\pi 1d_{5/2} \otimes \nu 1d_{3/2}$	10.2	0.32	
$\pi 1d_{5/2} \otimes \nu 1d_{5/2}$	16.1	0.16	0.31

Transition matrix element

$$\langle \lambda | \hat{P}^\dagger_{T,S} | 0 \rangle = \sum_{\alpha\beta} M^{T,S}_{\alpha\beta}$$

- ✓ coherent superposition of (f)^2 excitation
- ✓ sizable hole-hole excitations

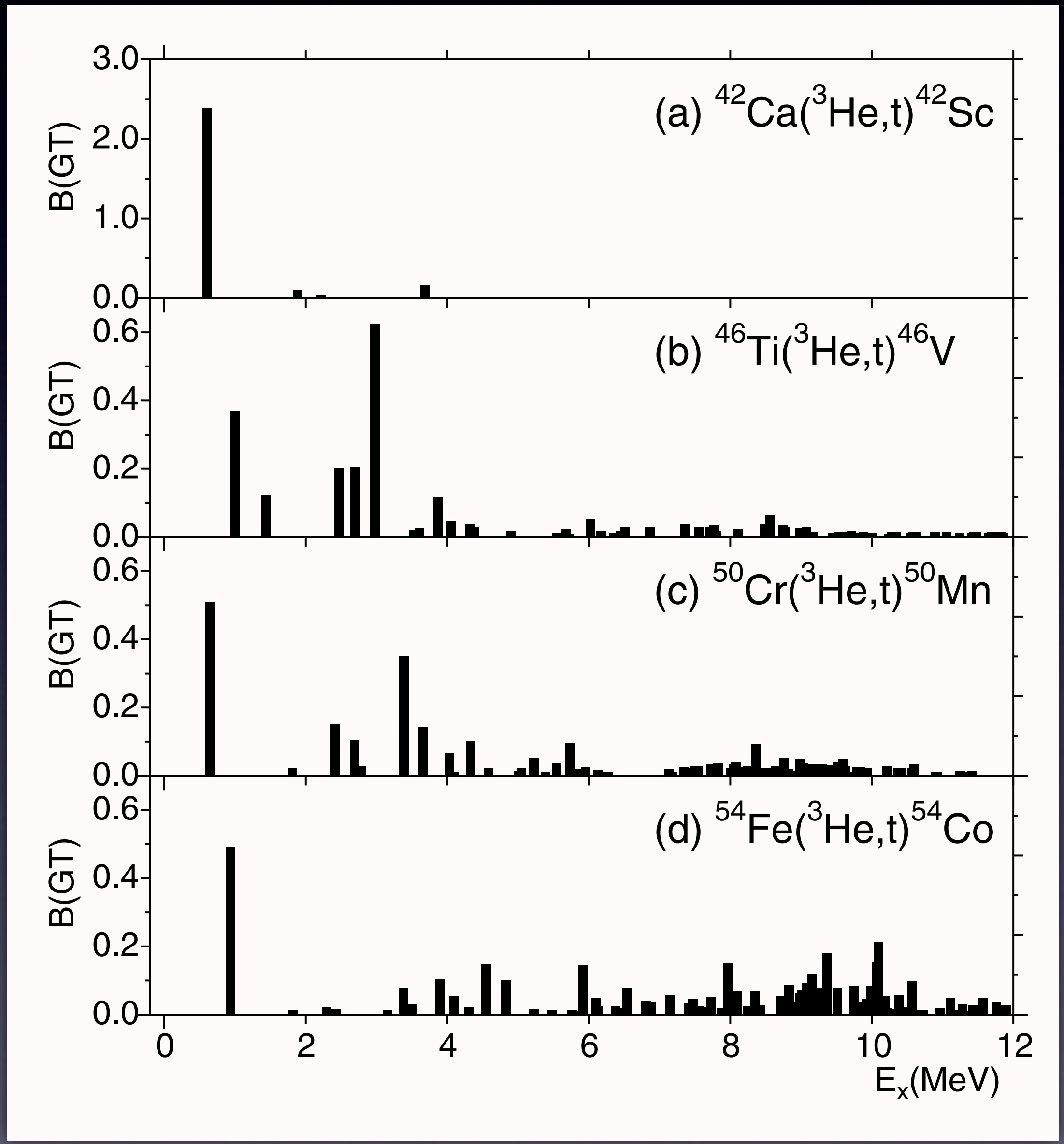


pn-pairing more effective

Y. Fujita et al, PRL112(2014)112502

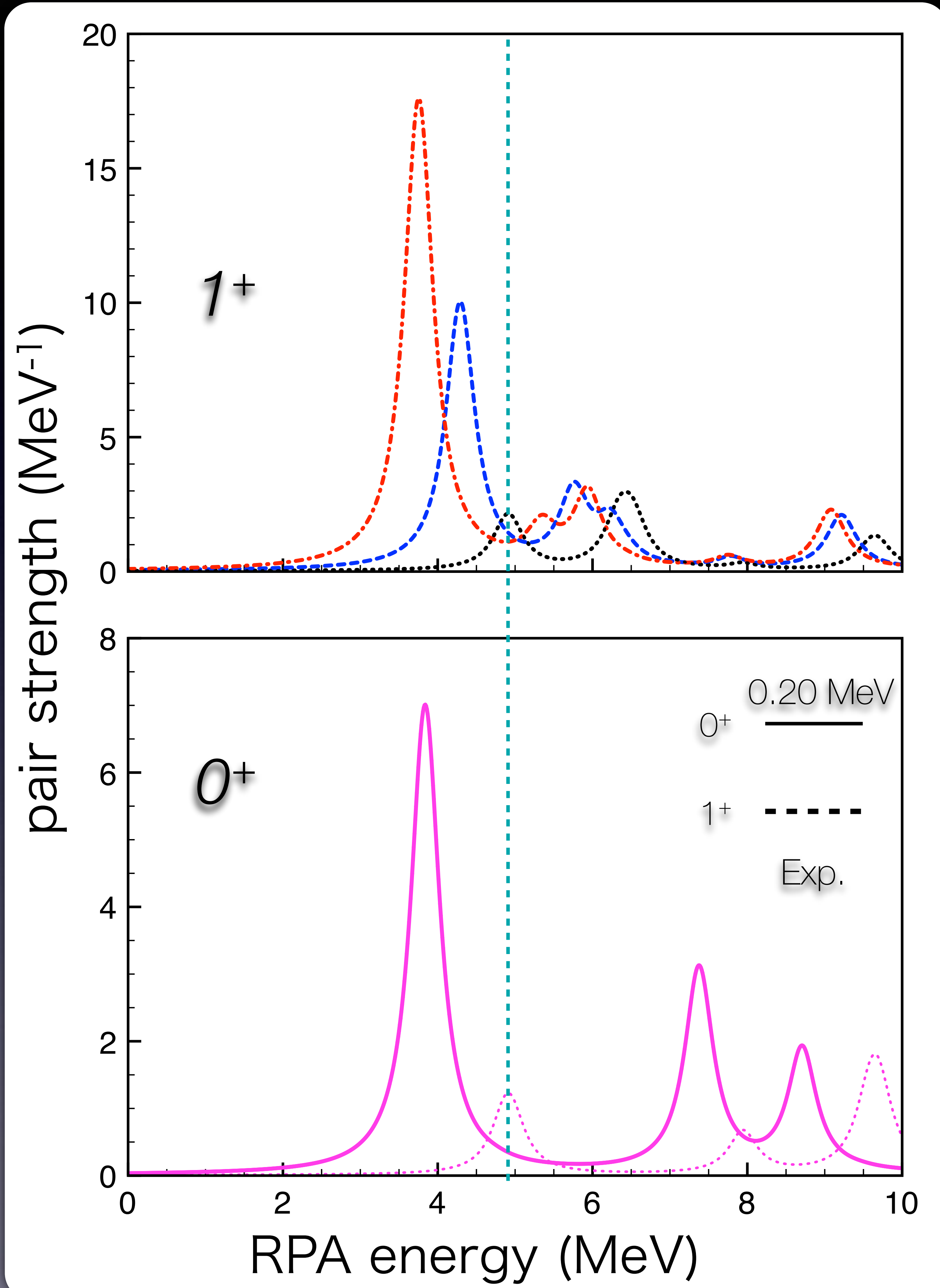
C. L. Bai et al, PRC90(2014)054335

"Low-energy super GT state" in ^{42}Sc



T. Adachi, Y. Fujita et al., NPA788 (2007) 70c

^{56}Ni → ^{58}Cu



f=1.3

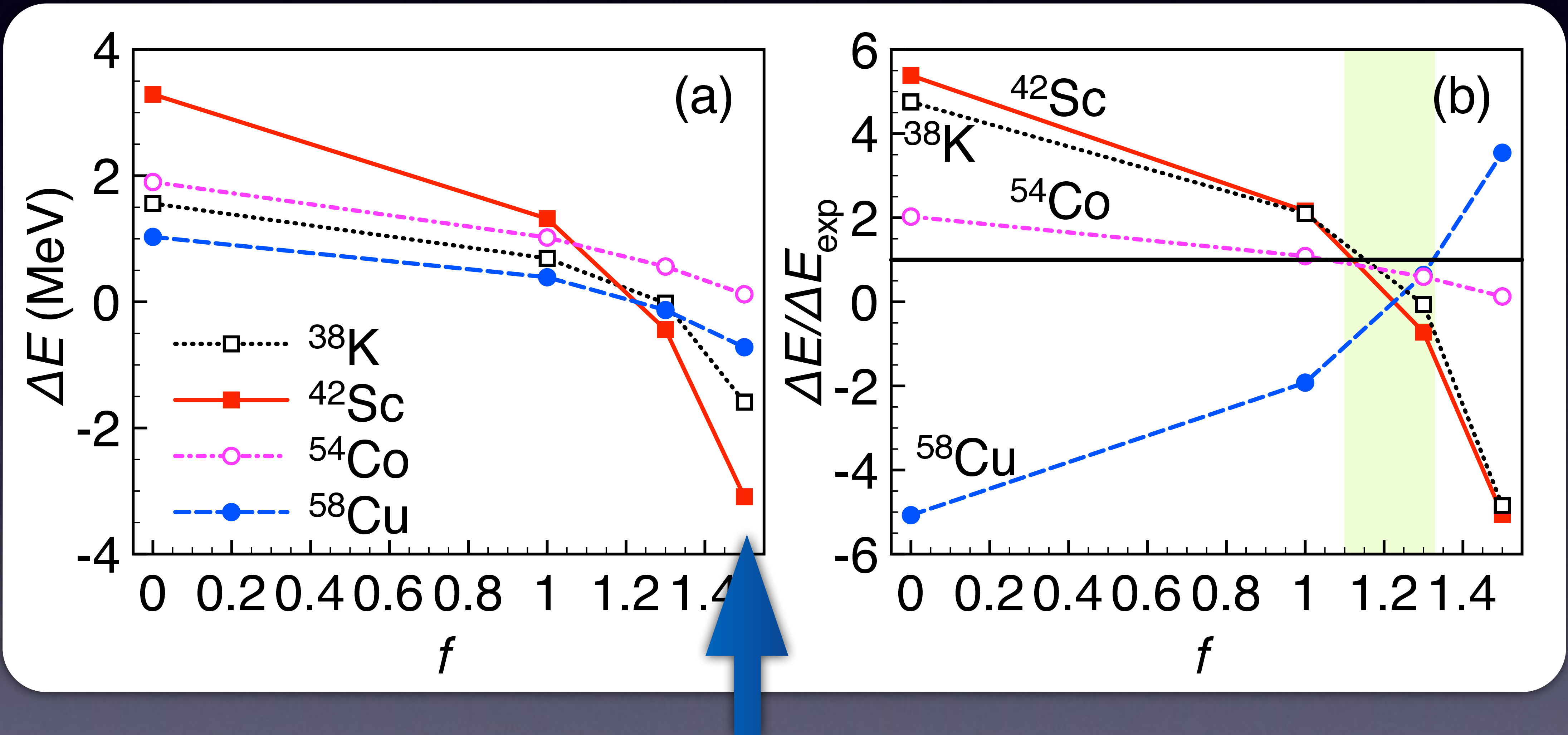
^{58}Cu		$J^\pi = 1^+$	$J^\pi = 0^+$
configuration	$E_\alpha + E_\beta$	$M_{\alpha\beta}^{S=1,S_z=0}$	$M_{\alpha\beta}^{S=0}$
$\pi 2p_{3/2} \otimes \nu 2p_{3/2}$	4.5	1.28	1.90
$\pi 2p_{1/2} \otimes \nu 2p_{3/2}$	6.4	0.39	
$\pi 2p_{3/2} \otimes \nu 2p_{1/2}$	6.5	0.37	
$\pi 2p_{1/2} \otimes \nu 2p_{1/2}$	7.9		0.26
$\pi 1f_{5/2} \otimes \nu 1f_{5/2}$	9.7	0.15	0.55
$\pi 1f_{7/2} \otimes \nu 1f_{7/2}$	5.1	0.17	0.50

- ✓ coherent superposition of (p)^2 and $(f_{5/2})^2$ excitations
- ✓ $(f_{7/2})^2$ excitation as a ground-state correlation

weaker collectivity than in ^{40}Ca

Collective pn-pairing vibration mode precursory to the T=0 pairing condensation

$\Delta E = \omega_{1+} - \omega_{0+}$

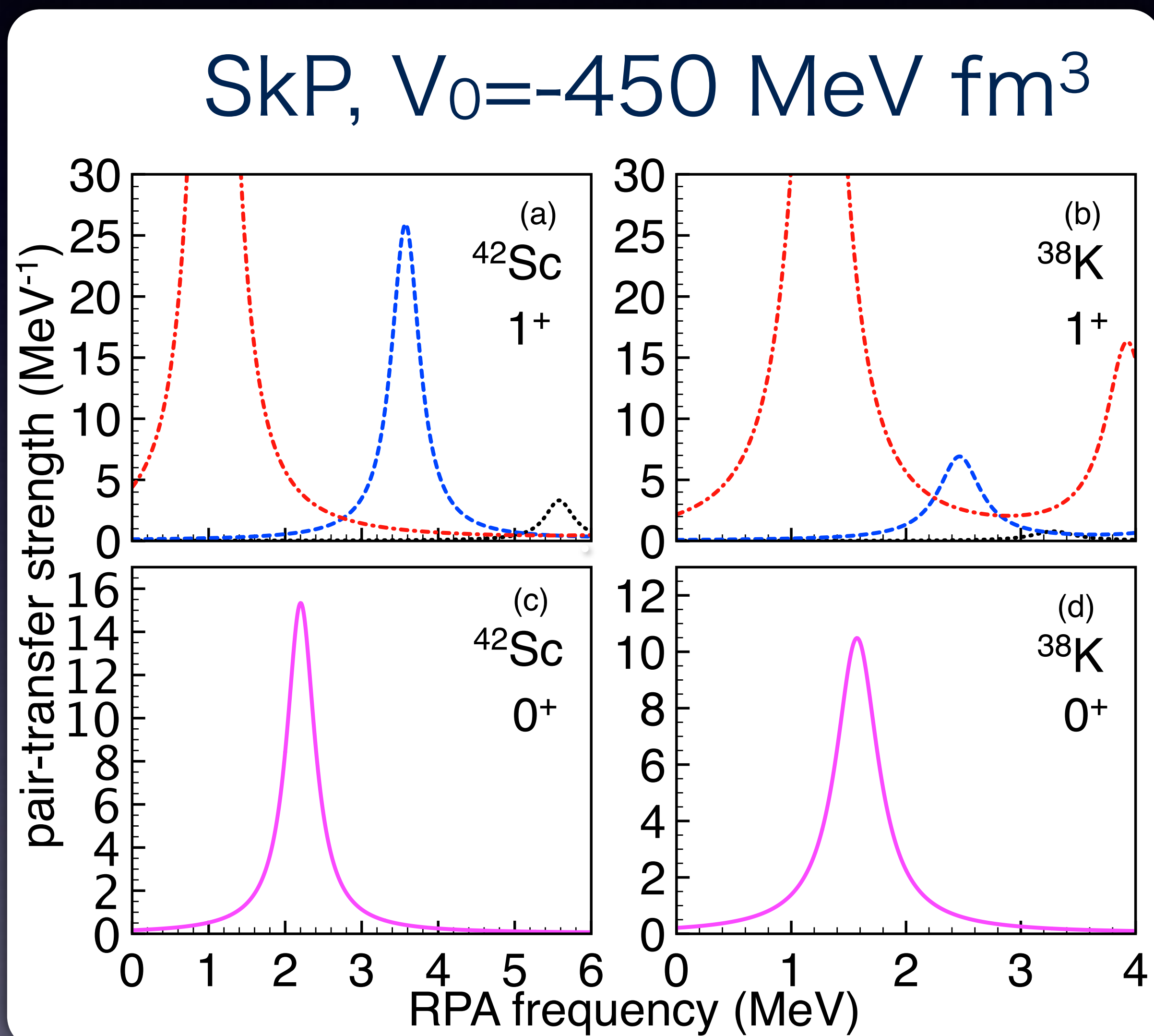


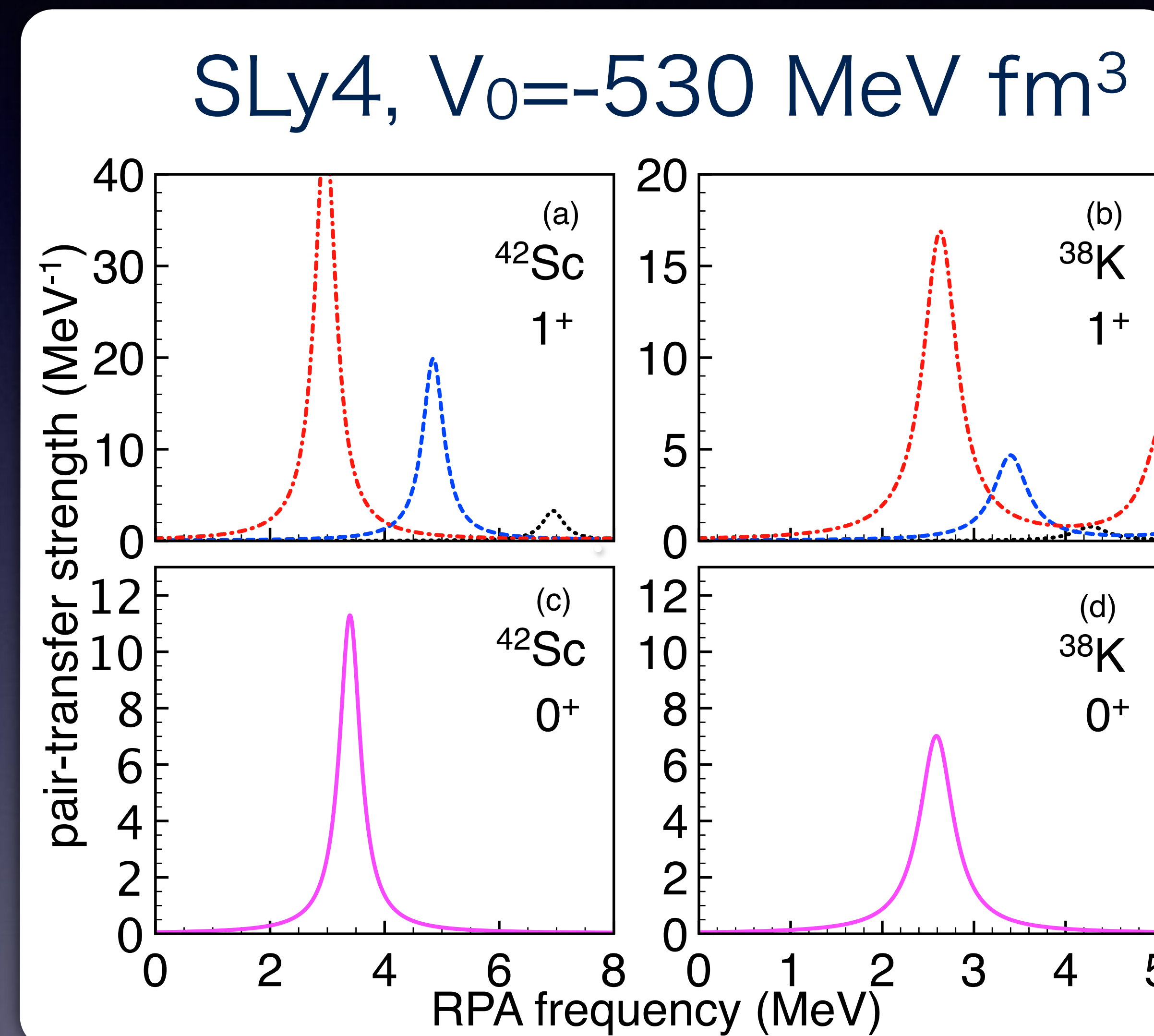
approaching the critical point to the T=0 pairing condensation

f_c=1.53 (^{40}Ca)

Interaction dependence:

no qualitative difference





SkP: lower energy due to high effective mass

^{42}Sc

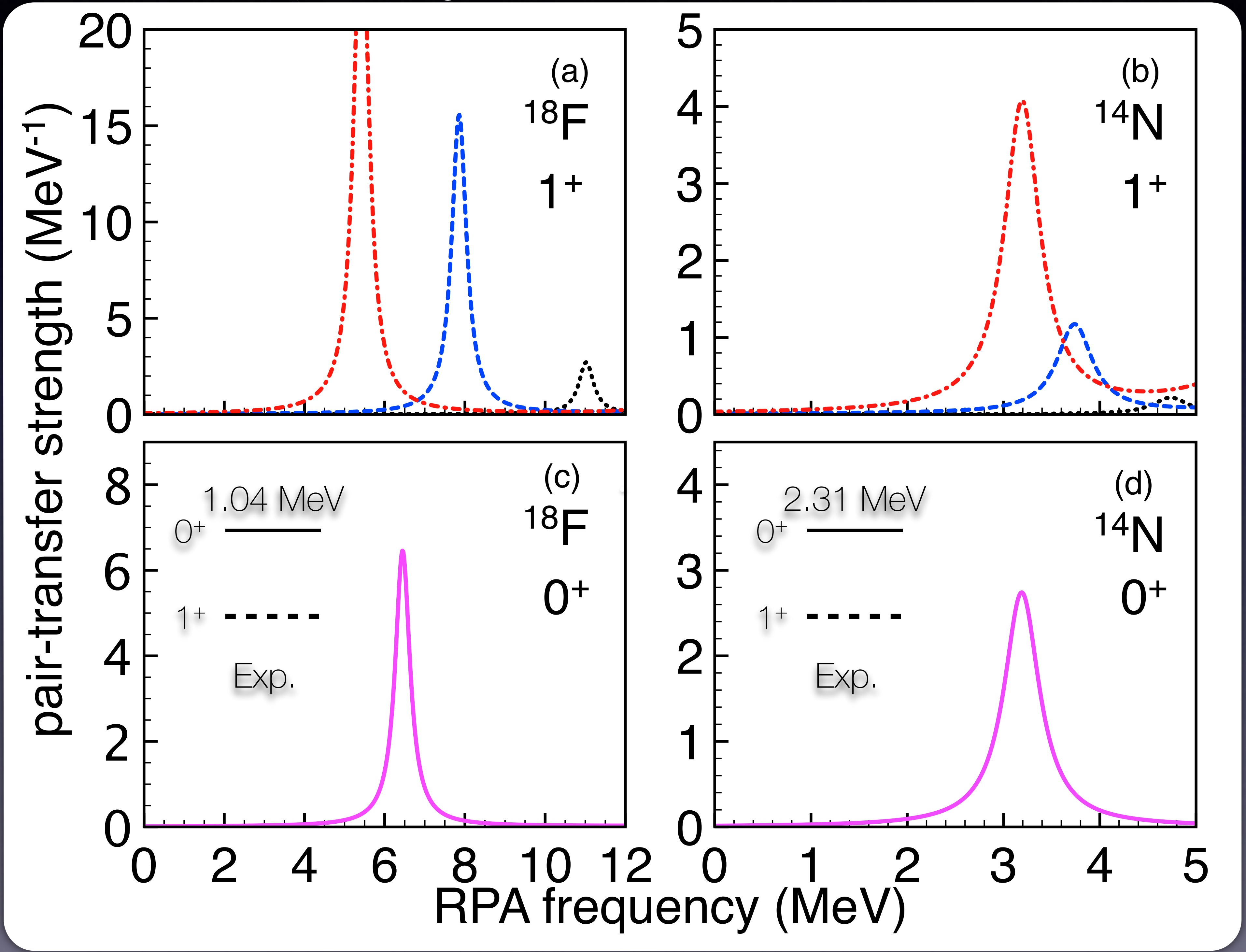
B(M1)$_{exp}$=6.3±0.3 μ_N^2 : PRC75(2007)064321

	core+2N in single-j(*)	3-body model (pnTDA)(**)	pnRPA (f=1.3)	pnRPA (f=1.0)
$\sum_i g_l(i)\vec{l}(i)$	3.40	2.91	2.54	2.71
$g_s^{\mathrm{IV}} \sum_i \tau_z(i)\vec{s}(i)$	5.34	6.34	6.77	6.35
$g_s^{\mathrm{IS}} \sum_i \vec{s}(i)$	0	2×10^{-3}	-4×10^{-2}	-2×10^{-2}
$B(M1\downarrow)(\mu_N^2)$	6.08	6.81	6.90	6.53

(*)Lisetskiy et al.,PRC60(1999)064310
(**)Tanimura et al., PTEP(2014)053D02

pn-pairing vibrations in ^{16}O: another example of LS-closed system

SGII + surface pairing: V_0=-490 MeV fm^3

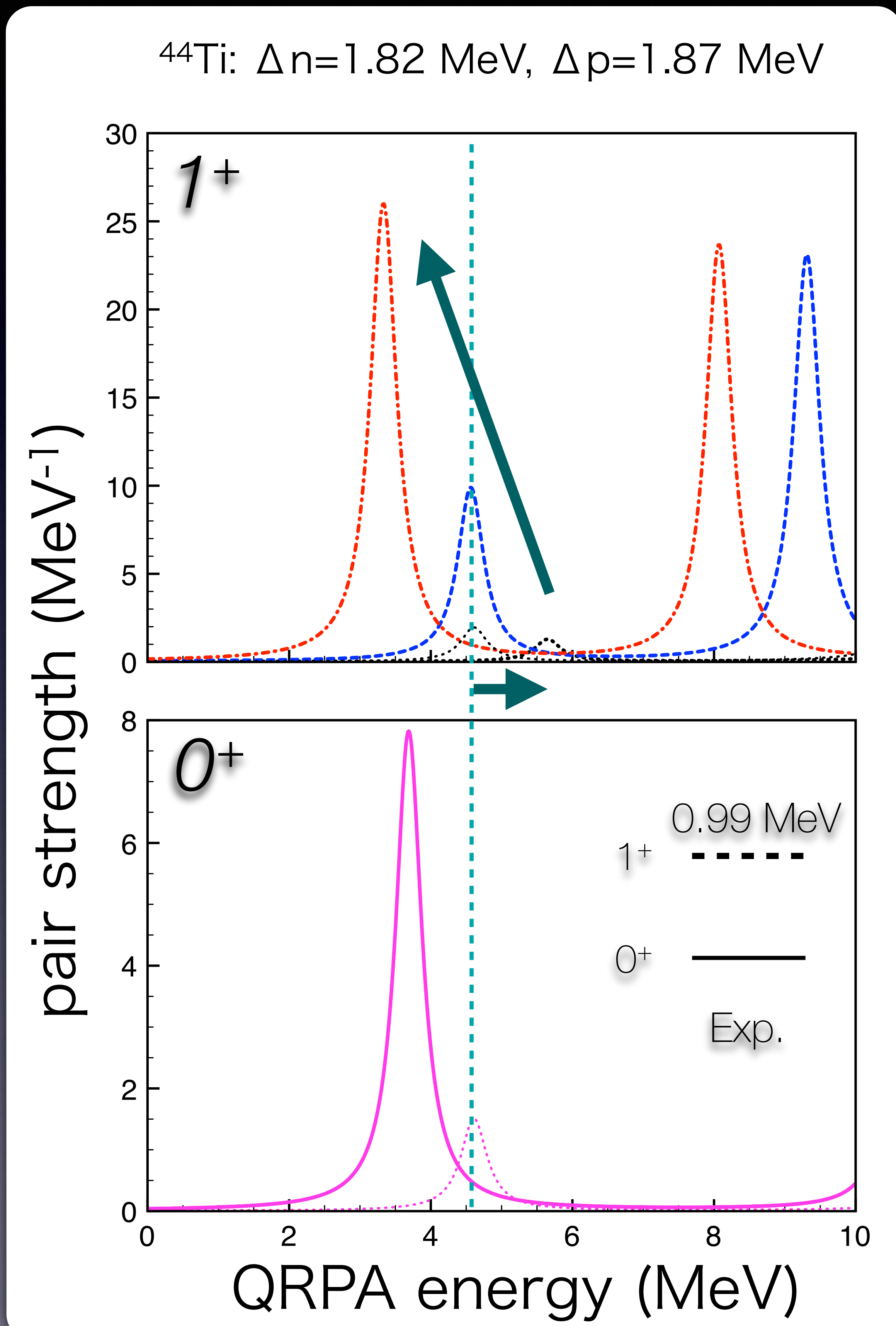


pn-pairing vibrations in the open-shell nuclei

w/ T=1 pairing condensation

^{44}Ti

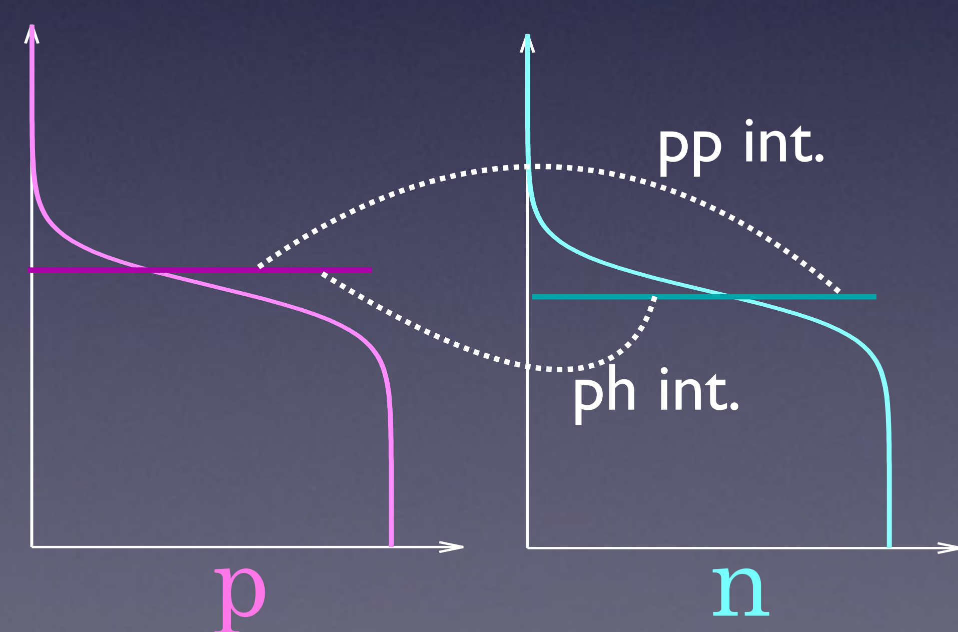
^{46}V



repulsive ph interaction

(GT-type)

attractive pp interaction



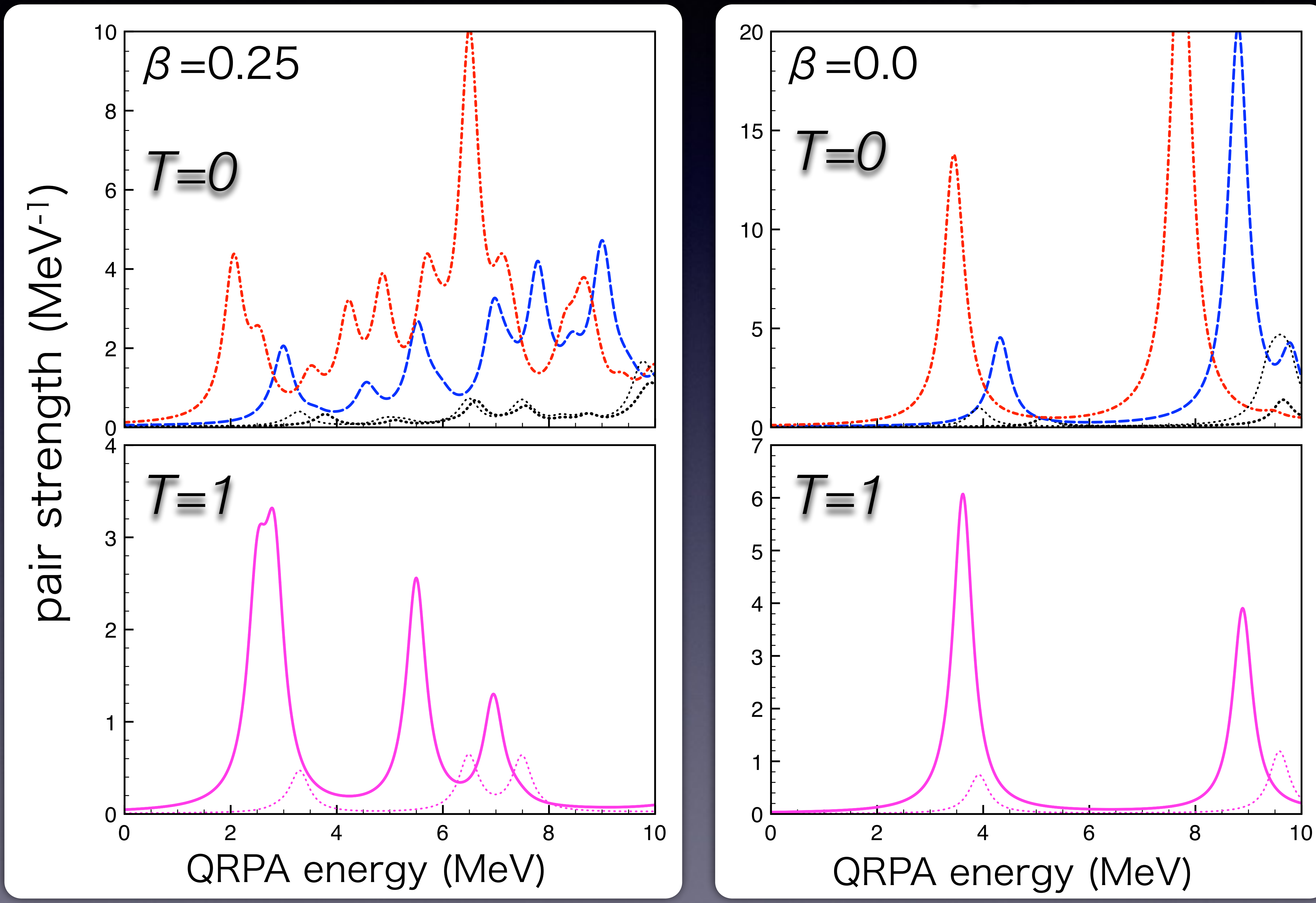
“^{44}Ti + 2qp excitation”

pn-pairing vibrations in the mid-shell nuclei

w/ T=1 pairing condensation and quadrupole def.

^{48}Cr → ^{50}Mn

constrained HFB+pnQRPA



Summary

✓ self-consistent deformed pnQRPA

- investigation of a rich variety of excitation modes
- quest for new types of collective mode

Possible occurrence of a new kind of collective mode associated with the spin-triplet pairing condensation

In LS-closed nuclei, the spin-orbit partners have a coherent contribution to the collective mode.

We can study the nature of T=0 pairing in nuclei even if they are in the "normal" phase.

We don't need to stick about an emergence of the spin-triplet pairing condensation.