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Spin-isospin responses in low energy:
roles of many-body correlations

Kyoto Univ.
Kenichi Yoshida

GRADUATE SCHOOL OF FACULTY OF SCIENCE
KYOTO UNIVERSITY

Unique features of atomic nucleus

Spin-isospin d.o.f: made of "four" types of fermions

Strongly-correlated nucleons: superfluidity/superconductivity, spin-singlet/triplet

Surface and shape: deformation

Distribution of densities in space

for the ground-state (static) w/ time-reversal inv.

particle (normal) density

$$\rho_\nu(\boldsymbol{r}) = \sum_\sigma \langle \psi_\nu^\dagger(\boldsymbol{r}\sigma)\psi_\nu(\boldsymbol{r}\sigma)\rangle$$

$$\rho_\pi(\boldsymbol{r}) = \sum_\sigma \langle \psi_\pi^\dagger(\boldsymbol{r}\sigma)\psi_\pi(\boldsymbol{r}\sigma)\rangle$$

onset of multipole deformation:

$$Q_\lambda = \int d\boldsymbol{r} r^\lambda Y_\lambda(\hat{r})\psi^\dagger(\boldsymbol{r})\psi(\boldsymbol{r}), \qquad \langle Q_\lambda\rangle \neq 0$$

pair (abnormal) density

$$\tilde{\rho}_\nu(\boldsymbol{r}) = \langle \psi_\nu(\boldsymbol{r}\downarrow)\psi_\nu(\boldsymbol{r}\uparrow)\rangle$$

$$\tilde{\rho}_\pi(\boldsymbol{r}) = \langle \psi_\pi(\boldsymbol{r}\downarrow)\psi_\pi(\boldsymbol{r}\uparrow)\rangle$$

assuming no S=1 superfluidity

Unique features of atomic nucleus

- Spin-isospin d.o.f: “four” types of fermion
- Strongly-correlated nucleons: superfluidity/superconductivity, spin-singlet/triplet
- Surface and shape: deformation

Distribution of densities in space/time for dynamics

particle (normal) density

$$\rho_0(\boldsymbol{r}t) = \sum_{\sigma}\sum_{\tau}\langle\psi^\dagger(\boldsymbol{r}\sigma\tau t)\psi(\boldsymbol{r}\sigma\tau t)\rangle$$

$$\rho_{1,\mu_\tau}(\boldsymbol{r}t) = \sum_{\sigma}\sum_{\tau,\tau'}\langle\psi^\dagger(\boldsymbol{r}\sigma\tau t)\psi(\boldsymbol{r}\sigma\tau' t)\rangle\langle\tau|\boldsymbol{\tau}_{\mu_\tau}|\tau'\rangle$$

$$s_{0,\mu_\sigma}(\boldsymbol{r}t) = \sum_{\sigma,\sigma'}\sum_{\tau}\langle\psi^\dagger(\boldsymbol{r}\sigma\tau t)\psi(\boldsymbol{r}\sigma'\tau t)\rangle\langle\sigma|\boldsymbol{\sigma}_{\mu_\sigma}|\sigma'\rangle$$

$$s_{1,\mu_\sigma,\mu_\tau}(\boldsymbol{r}t) = \sum_{\sigma,\sigma'}\sum_{\tau,\tau'}\langle\psi^\dagger(\boldsymbol{r}\sigma\tau t)\psi(\boldsymbol{r}\sigma'\tau' t)\rangle\langle\sigma|\boldsymbol{\sigma}_{\mu_\sigma}|\sigma'\rangle\langle\tau|\boldsymbol{\tau}_{\mu_\tau}|\tau'\rangle$$

pair (abnormal) density

$$\tilde{\rho}_{0,\mu_\sigma}(\boldsymbol{r}t) = \frac{1}{2}\sum_{\sigma,\sigma'}\sum_{\tau}\langle\psi(\boldsymbol{r}\sigma\tau t)\psi(\boldsymbol{r}\bar{\sigma}'\bar{\tau}t)\rangle\langle\sigma|\boldsymbol{\sigma}_{\mu_\sigma}|\sigma'\rangle$$

$$\tilde{\rho}_{1,\mu_\tau}(\boldsymbol{r}t) = \frac{1}{2}\sum_{\sigma}\sum_{\tau,\tau'}\langle\psi(\boldsymbol{r}\sigma\tau t)\psi(\boldsymbol{r}\bar{\sigma}\bar{\tau}' t)\rangle\langle\tau|\boldsymbol{\tau}_{\mu_\tau}|\tau'\rangle$$

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

Spin-isospin response

present only in nuclear system

$$s_{1,\mu_\sigma,\mu_\tau}(\boldsymbol{r}t) = \sum_{\sigma,\sigma'}\sum_{\tau,\tau'}\langle\psi^\dagger(\boldsymbol{r}\sigma\tau t)\psi(\boldsymbol{r}\sigma'\tau' t)\rangle\langle\sigma|\boldsymbol{\sigma}_{\mu_\sigma}|\sigma'\rangle\langle\tau|\boldsymbol{\tau}_{\mu_\tau}|\tau'\rangle$$

$$\rho(\boldsymbol{r}) + [\delta s^{\lambda}_{1,\mu_\sigma,\mu_\tau}(\boldsymbol{r})e^{-i\omega_\lambda t} + \mathrm{c.c}]$$ in linear-response of TDDFT

physical observables in spin-isospin response

$$\left|\int d\boldsymbol{r} f(\boldsymbol{r})\delta s^{\lambda}_{1,\mu_\sigma,\mu_\tau}(\boldsymbol{r})\right|^2$$

Gamow-Teller strength distribution: w/ isospin-change $\mu_\tau = \pm 1$

$$S^{\mu_\tau}_{\mu_\sigma}(\omega) = \sum_{\lambda}\left|\int d\boldsymbol{r}\delta s^{\lambda}_{1,\mu_\sigma,\mu_\tau}(\boldsymbol{r})\right|^2 \delta(\omega-\omega_\lambda)$$

GT matrix element to low-frequency states:
key quantity to beta-decay rate

Skyrme energy-density functional approach

Energy functional: $\mathcal{E} = \int d\boldsymbol{r}\mathcal{H}(\boldsymbol{r})$

Energy density: $\mathcal{H} = \mathcal{H}_{\rm kin} + \mathcal{H}_{\rm Skyrme} + \mathcal{H}_{\rm em}$

Skyrme energy density: $\mathcal{H}_{\rm Skyrme} = \sum_{t=0,1} \sum_{t_3=-t}^{t} \left(\mathcal{H}_{tt_3}^{\rm even} + \mathcal{H}_{tt_3}^{\rm odd} \right)$

$$\mathcal{H}_{tt_3}^{\rm even} = C_t^{\rho} \rho_{tt_3}^2 + C_t^{\Delta\rho} \rho_{tt_3} \Delta\rho_{tt_3} + C_t^{\tau} \rho_{tt_3}\tau_{tt_3} + C_t^{\nabla J} \rho_{tt_3} \nabla \cdot \mathbf{J}_{tt_3} + C_t^{J} \overleftrightarrow{J}^{2}_{tt_3}$$

$$\mathcal{H}_{tt_3}^{\rm odd} = C_t^{s} \mathbf{s}_{tt_3}^2 + C_t^{\Delta s} \mathbf{s}_{tt_3} \cdot \Delta \mathbf{s}_{tt_3} + C_t^{T} \mathbf{s}_{tt_3} \cdot \mathbf{T}_{tt_3} + C_t^{\nabla s} (\nabla \cdot \mathbf{s}_{tt_3})^2 + C_t^{j} \mathbf{j}_{tt_3}^2 + C_t^{\nabla j} \mathbf{s}_{tt_3} \cdot \nabla \times \mathbf{j}_{tt_3}$$

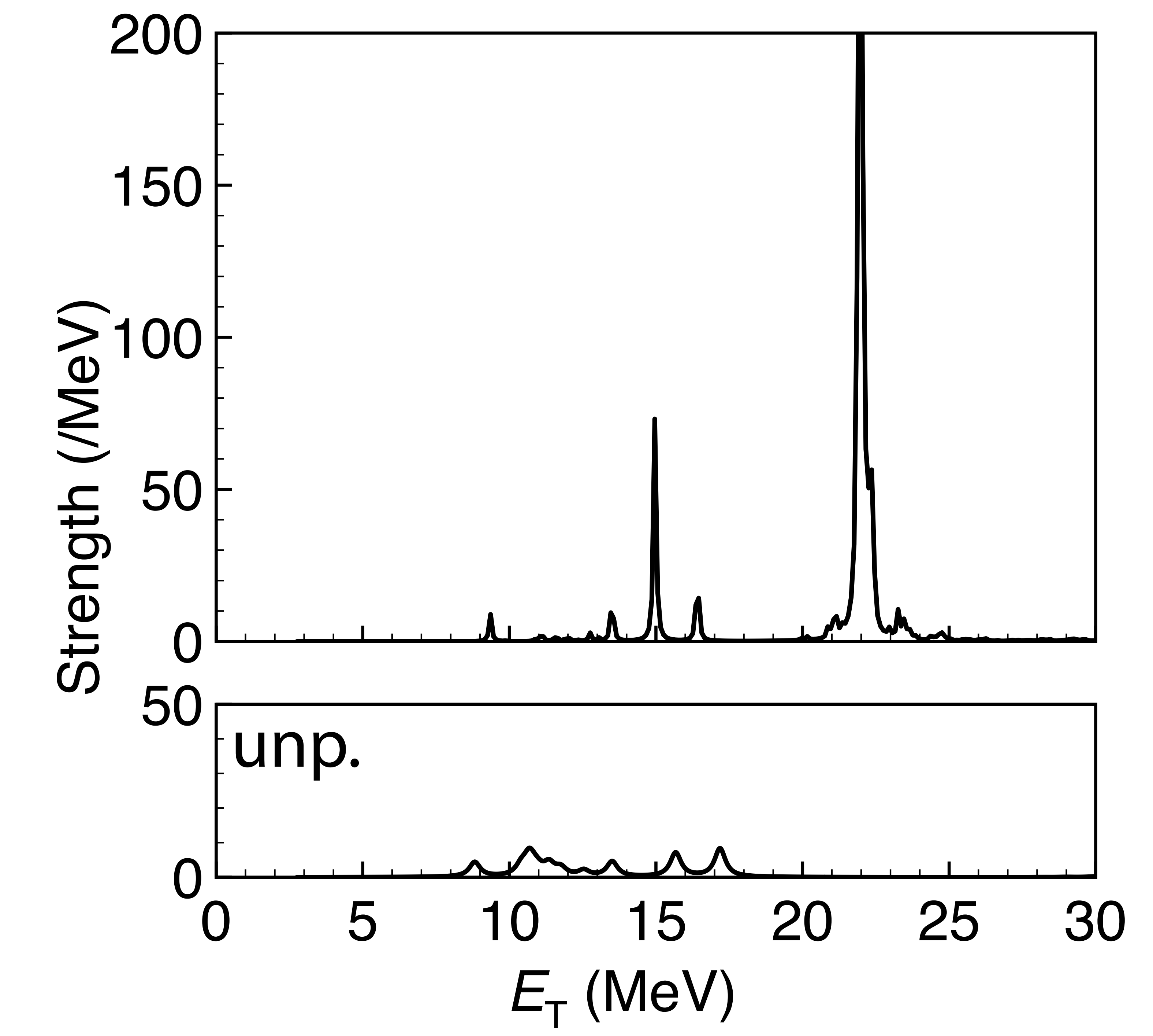
Poorly known (poorly constrained):

- T-odd Skyrme energy density
  - vanishes for ground-state of even-even nuclei
- Isovector (t=1) coupling constants
  - less information on nuclei with neutron (proton) excess

vector-isovector density ↕ Gamow-Teller

Many-body correlations essential in low energy

^{208}Pb, SGII

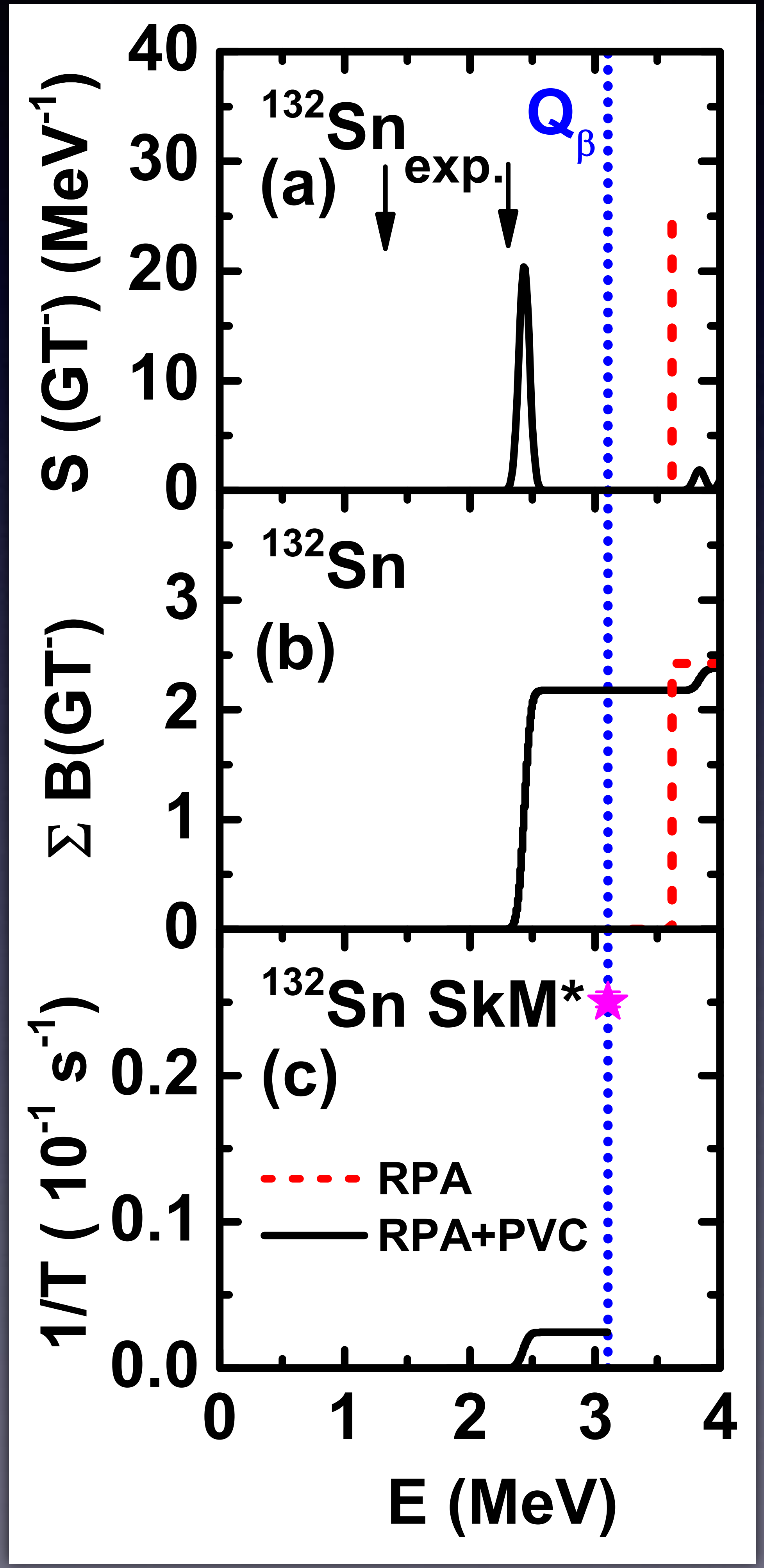


Most of the strengths are gathered in the high-energy giant resonance

Tiny low-lying strengths

^{132}Sn

spherical and normal-fluid nucleus



Y. F. Niu et al., PRL114(2015)142501

RPA(LR-TDDFT)

single peak

Phonon coupling

spreading

lowering

$T_{1/2}$: ∞ →finite

Many-body correlations essential in low energy

Kohn-Sham + RPA (LR-TDDFT)

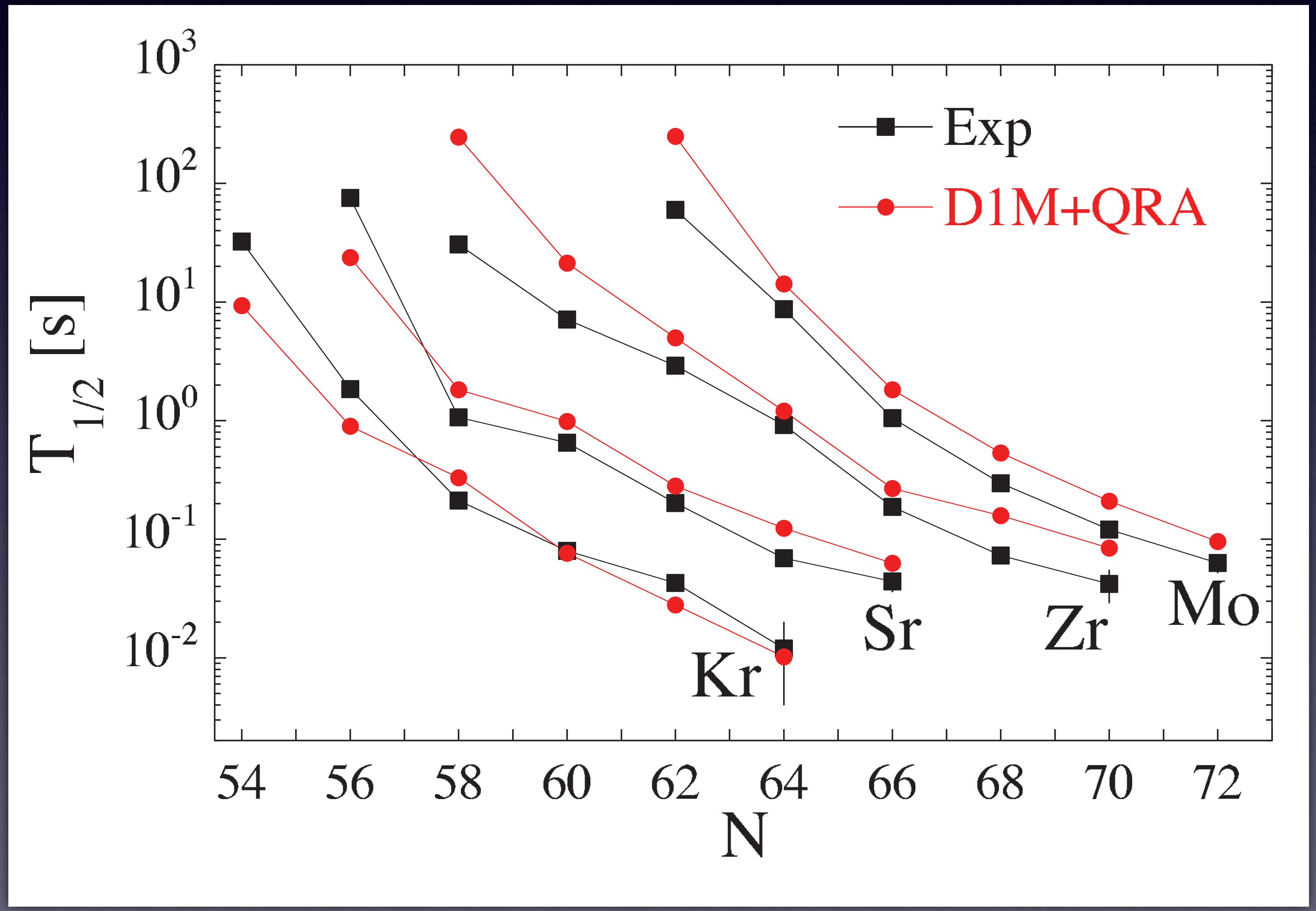
deformation
superfluidity

MB correlations showing up in open-shell nuclei

Deformed Kohn-Sham-Bogoliubov
+ Quasiparticle RPA (LR-TDDFT)

M. T. Mustonen and J. Engel, PRC87(2013)064302
KY, PTEP2013(2013)113D02
M. Martini et al., PRC89(2014)044306

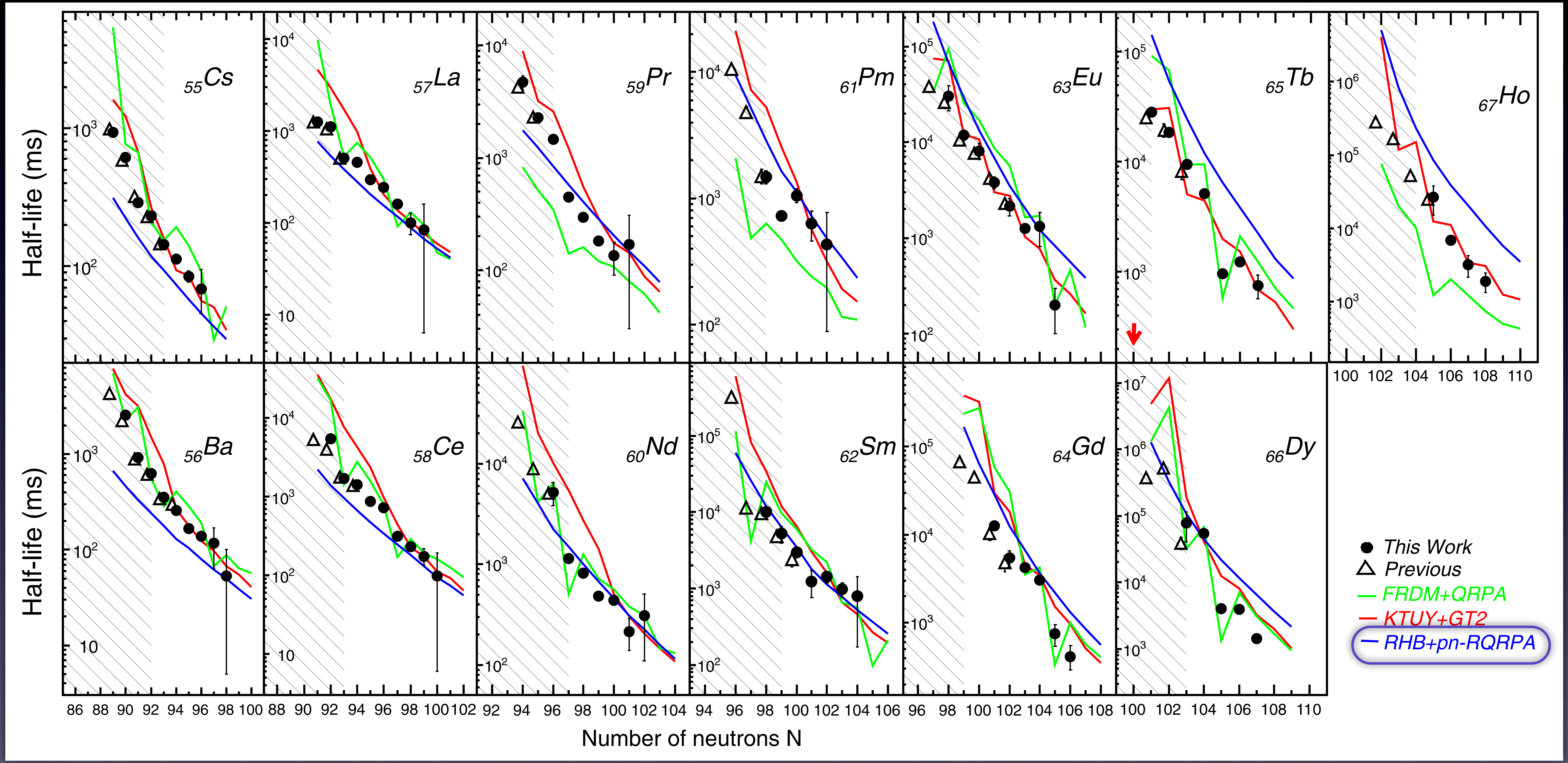
β-decay half-lives of deformed nuclei



M. Martini et al., PRC89(2014)044306

β-decay study at RIBF for the rare-earth elements production of the r-process

J. Wu, S. Nishimura et al., PRL118(2017)072701



Rare-earth nuclei

far from the magic numbers

strongly deformed in space/ gauge space

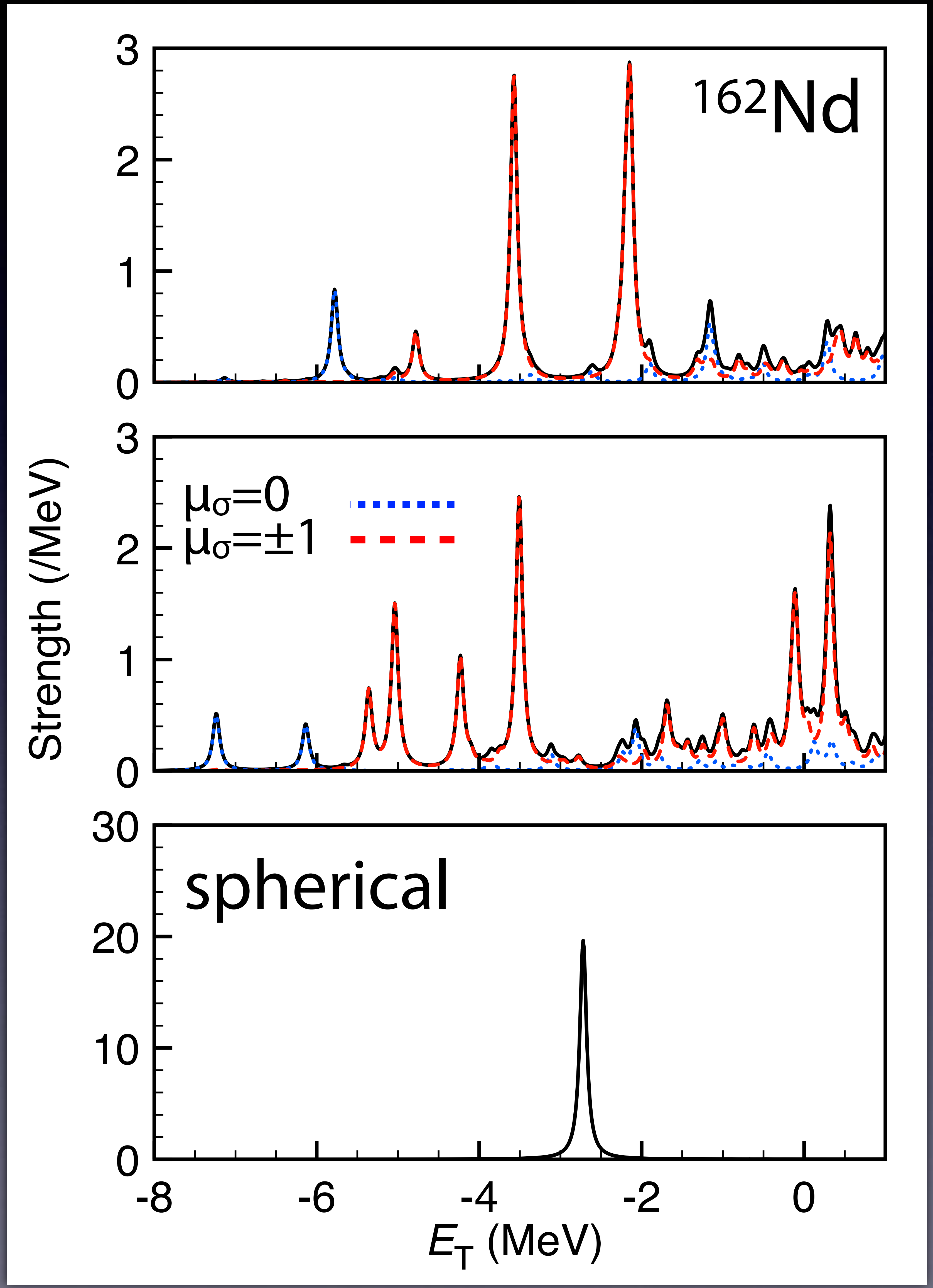
role of MB correlations?

Nuclear DFT cal.

assuming the spherical shape

reasonably produces the obs.

Pairing and deformation for low-lying GT states



Exp.

$T_{1/2} = 0.31(20)$ s

$T_{1/2} = 0.27$ s

superfluidity

Energies are shifted higher

pairing gaps

Low-lying strengths are reduced

distortion of Fermi surfaces

$T_{1/2} = 0.14$ s

deformation

Quadrupole deformation ≃2^+ phonon condensation

non-perturbed phonon coupling

fragmentation and appearance of low-lying states

$T_{1/2} = 0.53$ s

Strengths are concentrated on a single state w/ high energy

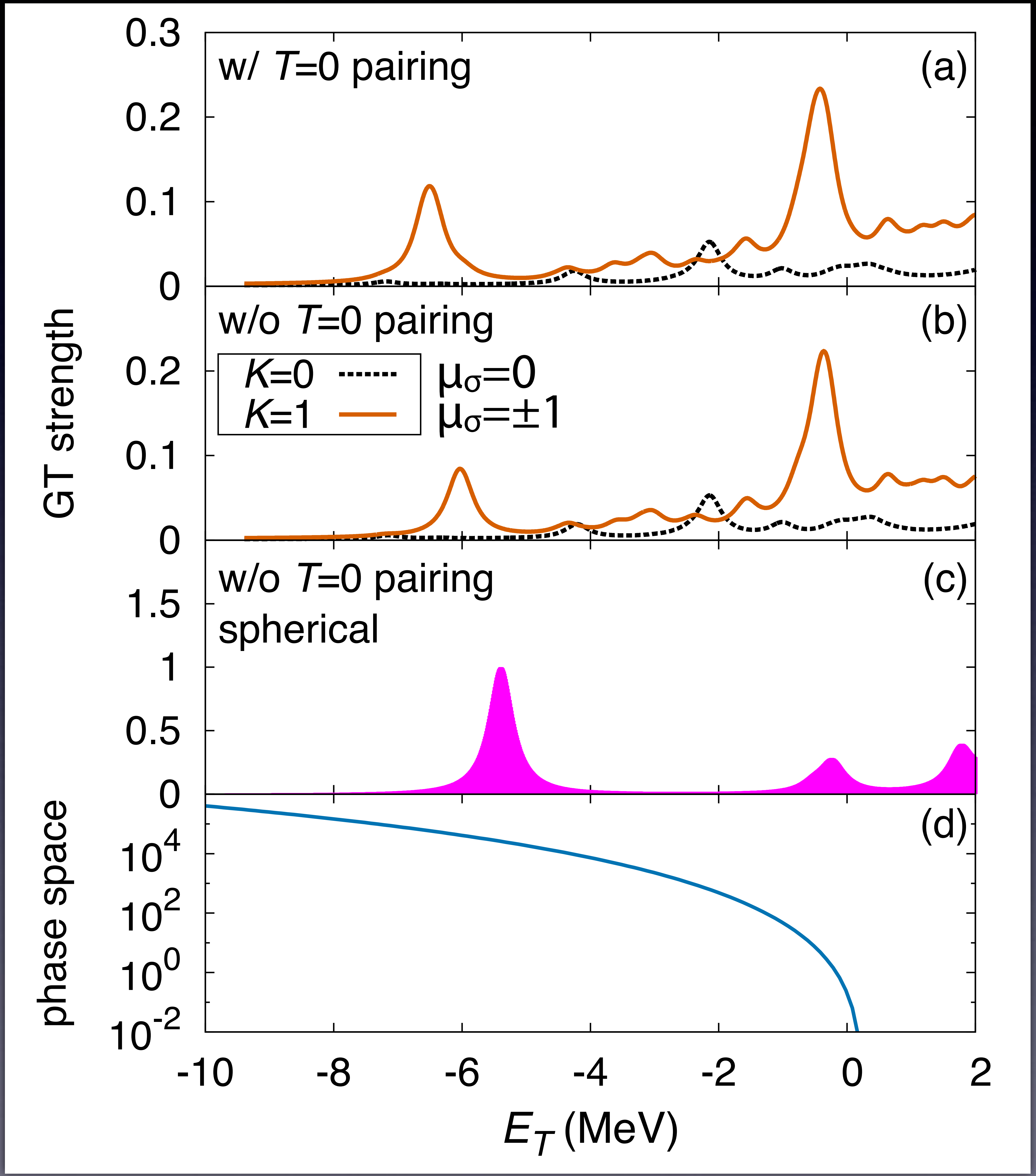
$\nu 1h_{9/2} \rightarrow \pi 1h_{11/2}$

SLy4 + pairing functional of M. Yamagami et al., PRC80(2009)064301

Pairing and deformation for low-lying GT states

S. Nishimura et al., PRL106(2011)052502

^{106}Zr



KY, JPS Conf. Proc. 6(2015)020017

SLy4

$T_{1/2} = 0.21$ s

$T_{1/2} = 0.41$ s

deformation
superfluidity

$T_{1/2} = 0.07$ s

Exp.
$T_{1/2} = 0.186(11)$ s

Effect of MB correlations on β-decay rate depends very much on the nuclide (shell structure)

Summary

TDDFT gives an intuitive picture of nuclear dynamics
by looking at the density distributions

Linear response is a powerful method to investigate vibration of densities

allowing the breaking of symmetries: rotational symmetry in space/gauge space, we can include the many-body correlations in a simple way

(Q)RPA on top of the ordered (deformed) state takes the non-perturbed phonon coupling effect into account