Relativistic approach to nuclear spin-isospin excitations including quasiparticle-vibration coupling

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Western Michigan University, USA

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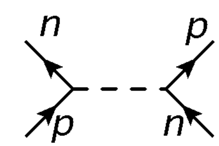
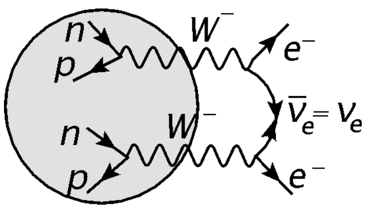
The study of nuclear isospin-transfer excitations has many applications in



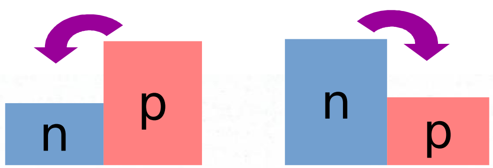
→ **Nuclear physics:** constraints on the (S,T) channels of the nuclear interaction...

→ **Particle physics:** nature of neutrinos ($0\nu\beta\beta$ decay), ...



→ **Astrophysics:**

Fermi and Gamow-Teller transitions determine the rates of many weak processes occurring in stellar environments...

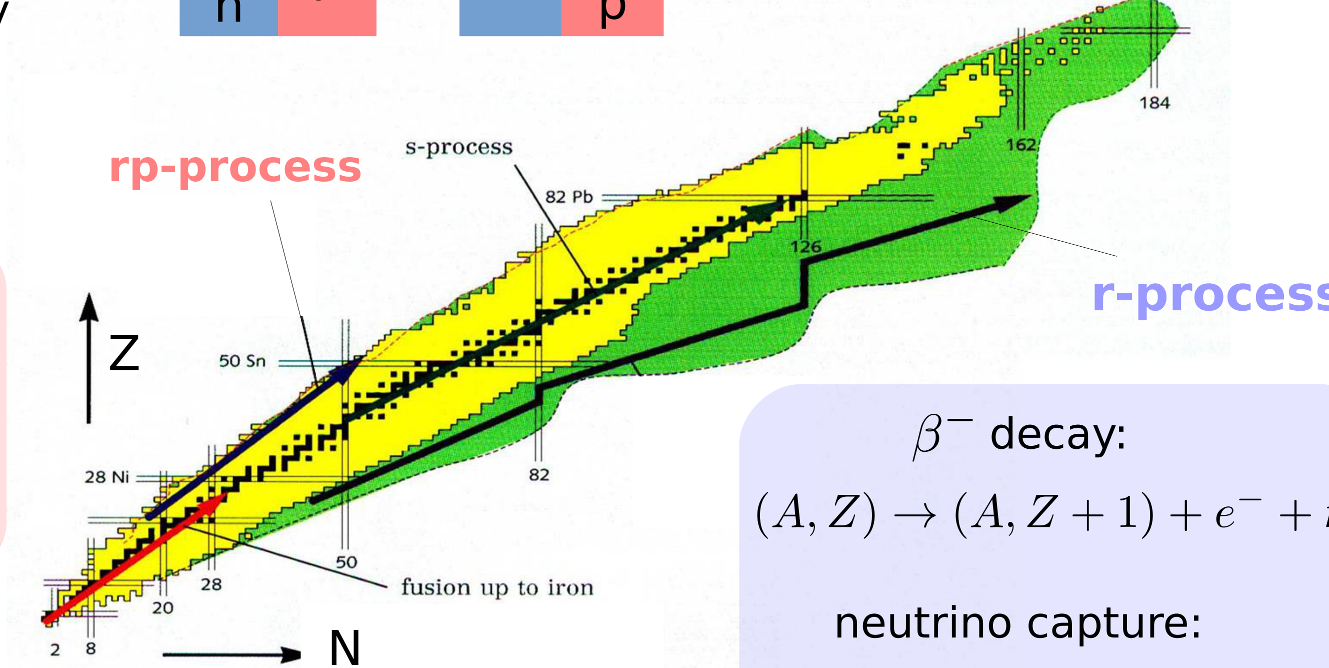


β^+ decay:

$$(A,Z) \rightarrow (A,Z-1) + e^+ + \nu_e$$

electron capture:

$$(A,Z) + e^- \rightarrow (A,Z-1) + \nu_e$$



β^- decay:

$$(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}_e$$

neutrino capture:

$$(A,Z) + \nu_e \rightarrow (A,Z+1) + e^-$$

Astrophysical modeling requires properties of nuclei far from stability not yet reached experimentally

→ need precise and consistent information from theory

Outline

- **Theoretical framework:** spin-isospin response of nuclei with relativistic quasiparticle-vibration coupling
- **Applications:** Gamow-Teller transitions in neutron-rich Nickel isotopes and β-decay half-lives
- **Conclusion**

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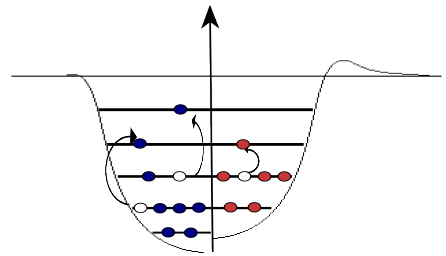
Response of nuclei to a weak external field – linear response theory

Weak external field F(t)



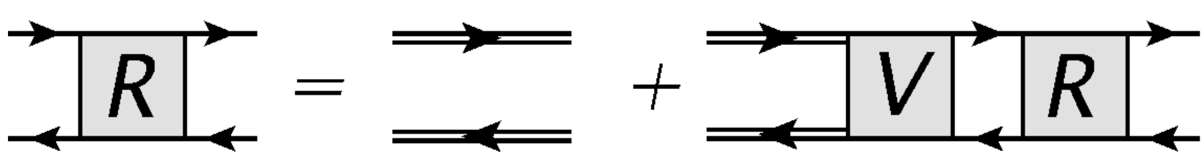
particle-hole excitations of nucleons

fluctuations of the nuclear density ρ

$$\delta\rho_{k_1,k_2}(\omega) = \sum_{k_1 k_2 k_3 k_4} R_{k_1 k_4, k_2 k_3}(\omega) F_{k_3 k_4}$$

Response function (particle-hole propagator)
solution of the **Bethe-Salpeter equation (BSE):**

$$R = GG - iGGVR$$



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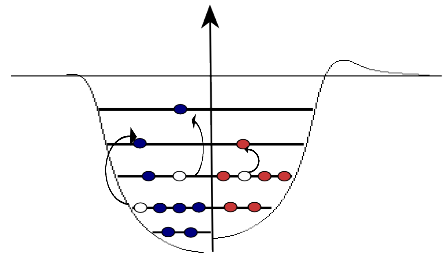

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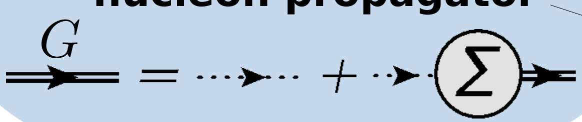
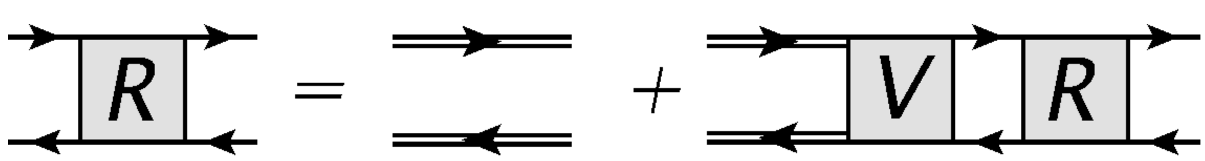


self-energy

$$R = GG - iGGVR$$



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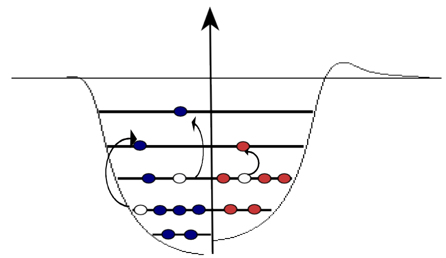

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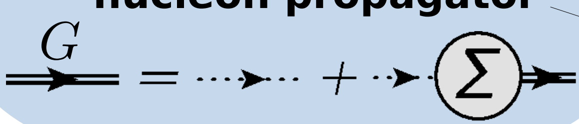
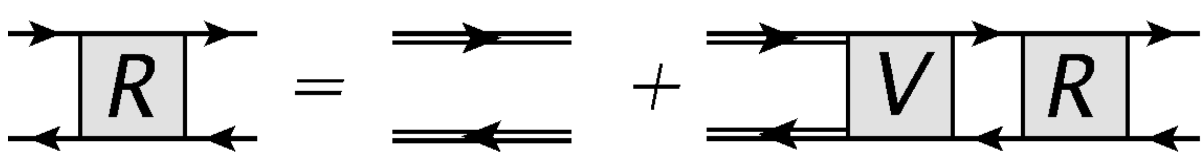


self-energy

$$R = GG - iGGVR$$

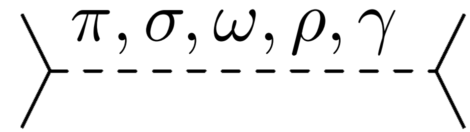
$$V = i\frac{\delta\Sigma}{\delta G}$$

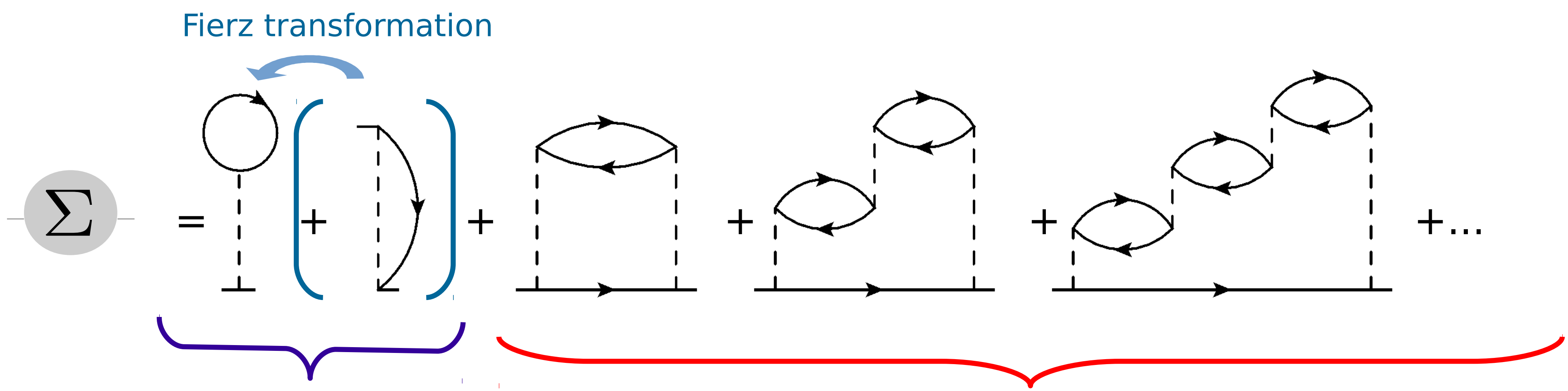
Effective in-medium interaction



Nucleonic self-energy

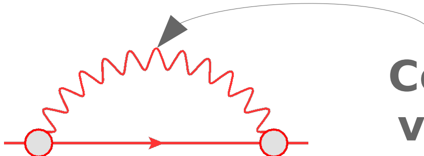
Expansion in term of the meson-exchange interaction:





static

Relativistic Hartree(-Fock)

∞ serie = 

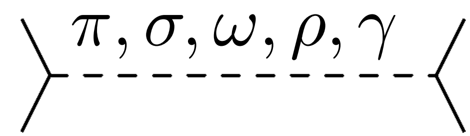
dynamic

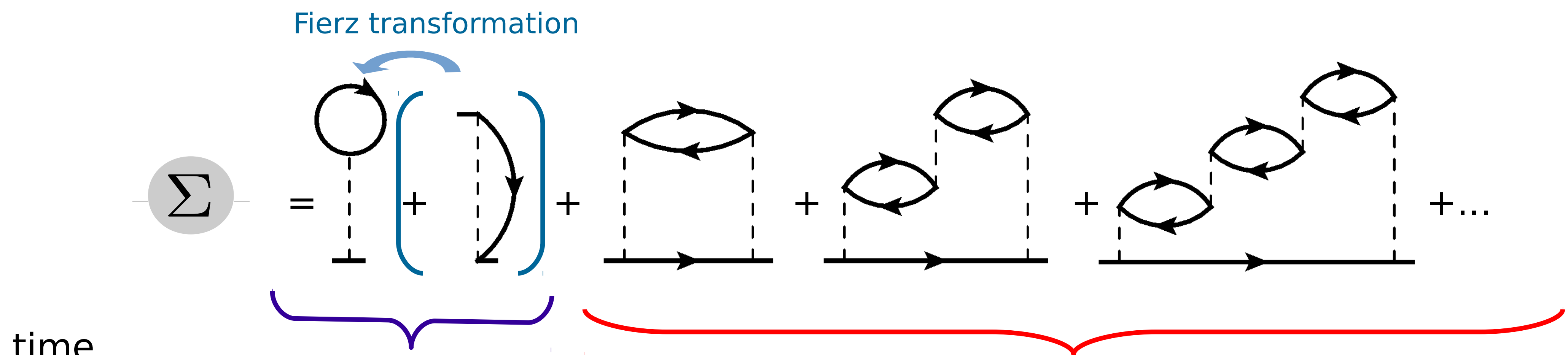
Particle-vibration coupling (PVC)

Collective vibration (phonon)

Nucleonic self-energy

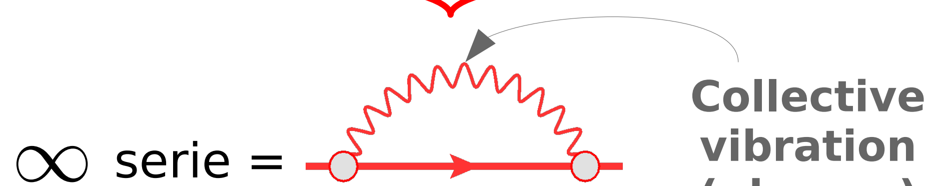
Expansion in term of the meson-exchange interaction:





static

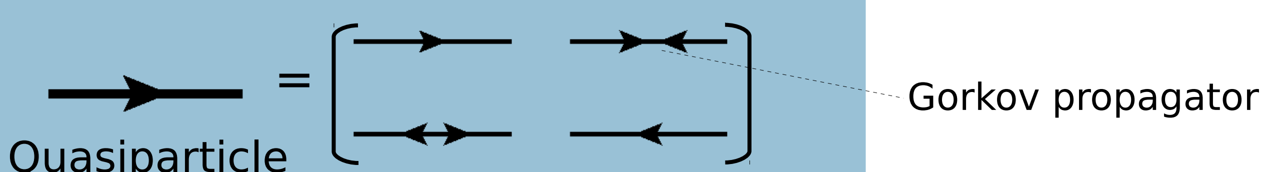
Relativistic Hartree(-Fock)
Bogoliubov



dynamic

Quasiparticle-vibration coupling (QPVC)

In open-shell nuclei:

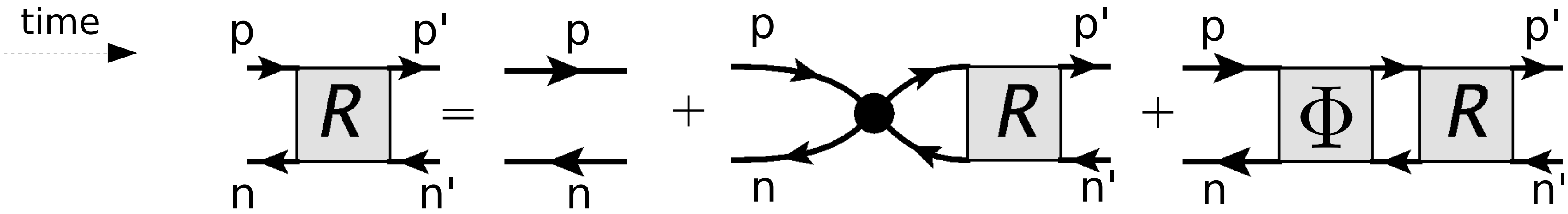


in single-particle space

Nuclear response with dynamic self-energy

[…] → Bethe-Salpeter equation in the proton-neutron channel:

$$R(\omega) = \widetilde{G}\widetilde{G} - i\widetilde{G}\widetilde{G}(\widetilde{V} + \Phi(\omega))R(\omega)$$



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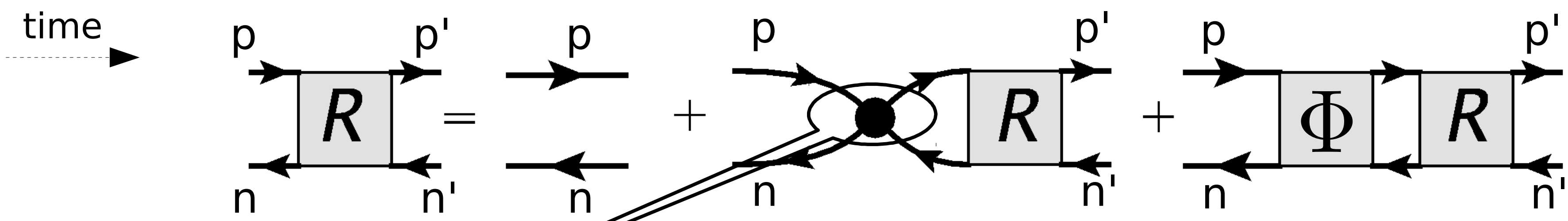
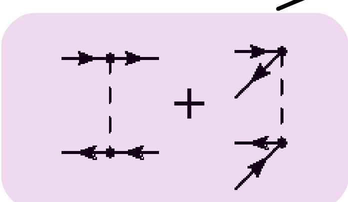
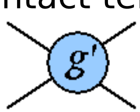




Isovector static meson exchange

$$\widetilde{V} = V_\pi + V_\rho + V_{\delta\pi}$$

Landau-Migdal contact term



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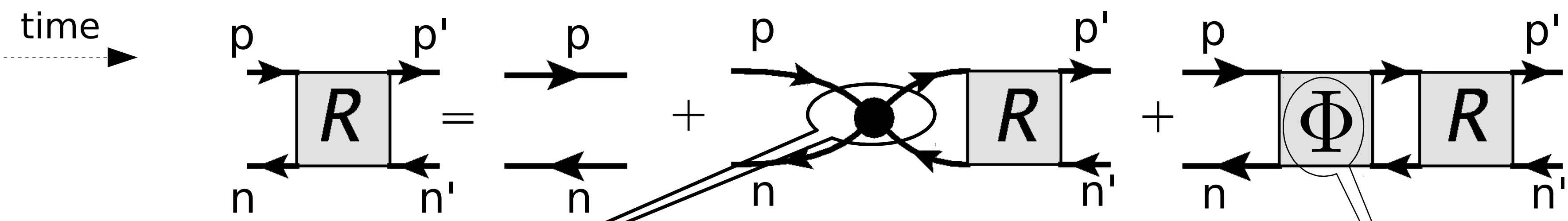

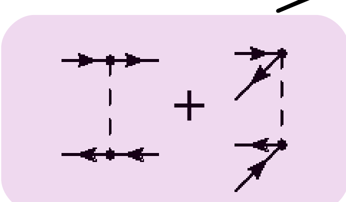

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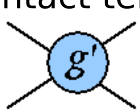
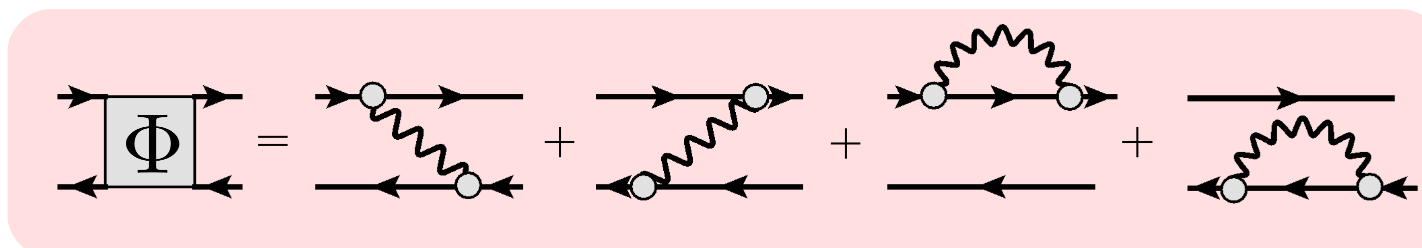


energy-dependent interaction:



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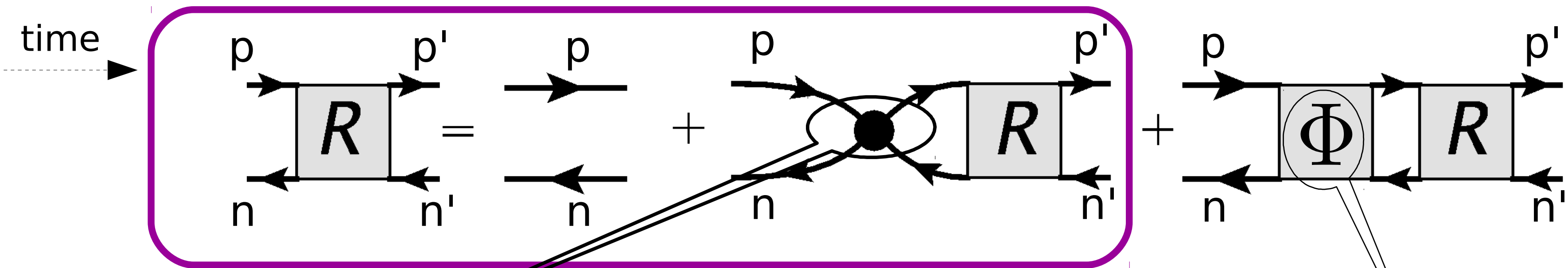
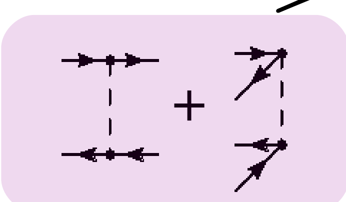
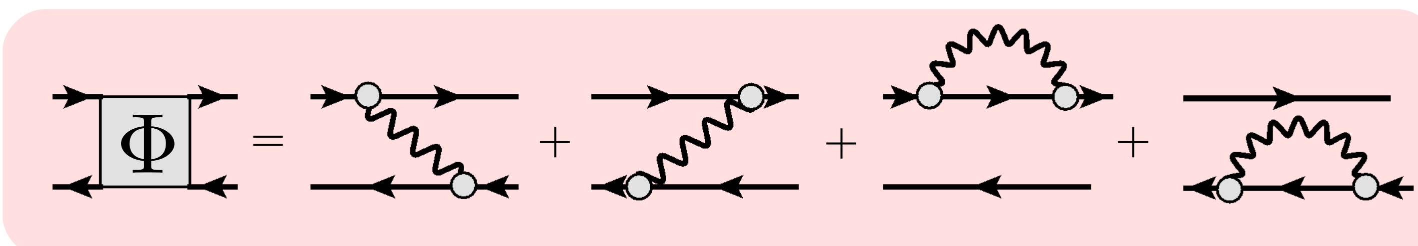


RQRPA

accounts for 2qp configurations (on correlated ground state)

energy-dependent interaction:





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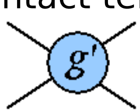

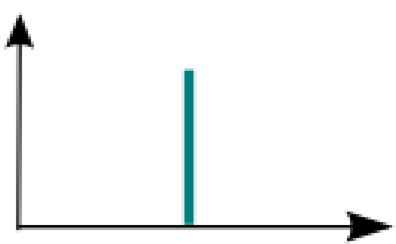

RQRPA state

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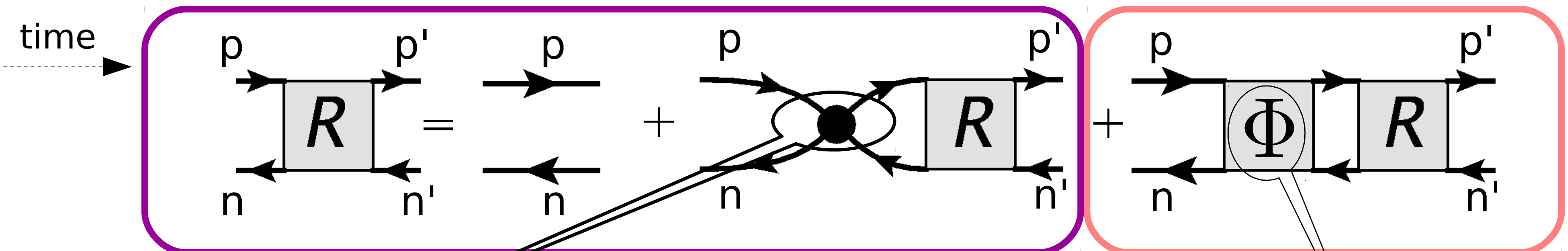

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+QPVC

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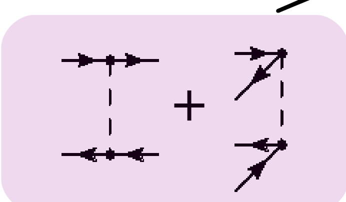

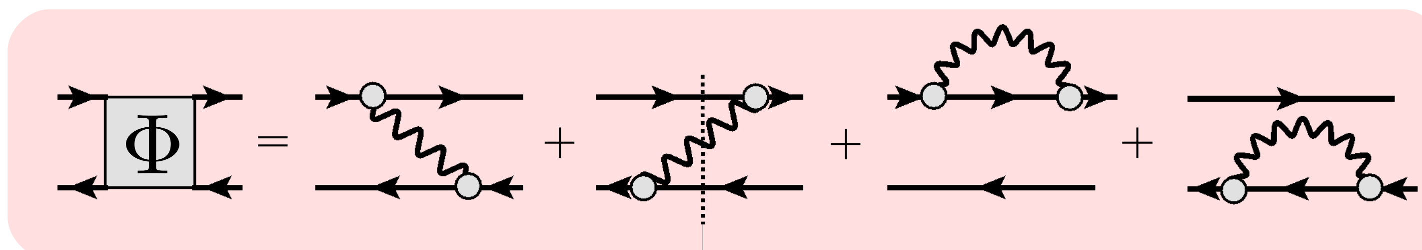

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accounts for 2qp ⊗ 1phonon = 4qp configurations

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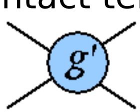
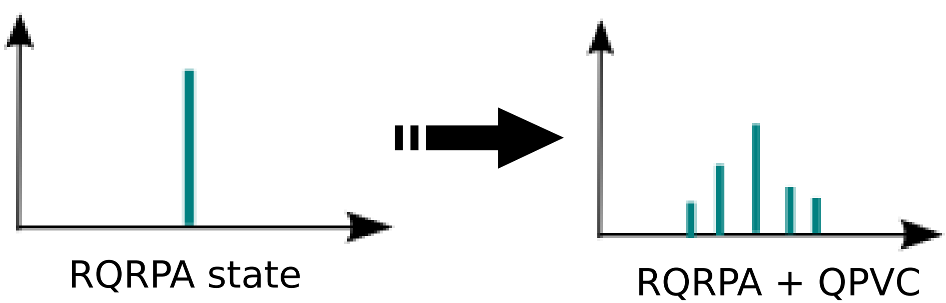




➩ fragmentation of many-body states

& possible shift

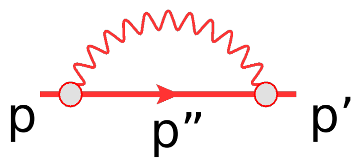
Outline

- **Theoretical framework:** **spin-isospin response of nuclei with relativistic quasiparticle-vibration coupling**
- **Applications:** **Gamow-Teller transitions in neutron-rich Nickel isotopes and β-decay half-lives**
- **Conclusion**

Gamow-Teller resonance in Nickel (Ni → Cu)

1st application:

coupling of quasiparticles to neutral (non isospin-flip) phonons
(2^+, 3^-, 4^+, 5^-, 6^+ up to 30 MeV)



Strength function:

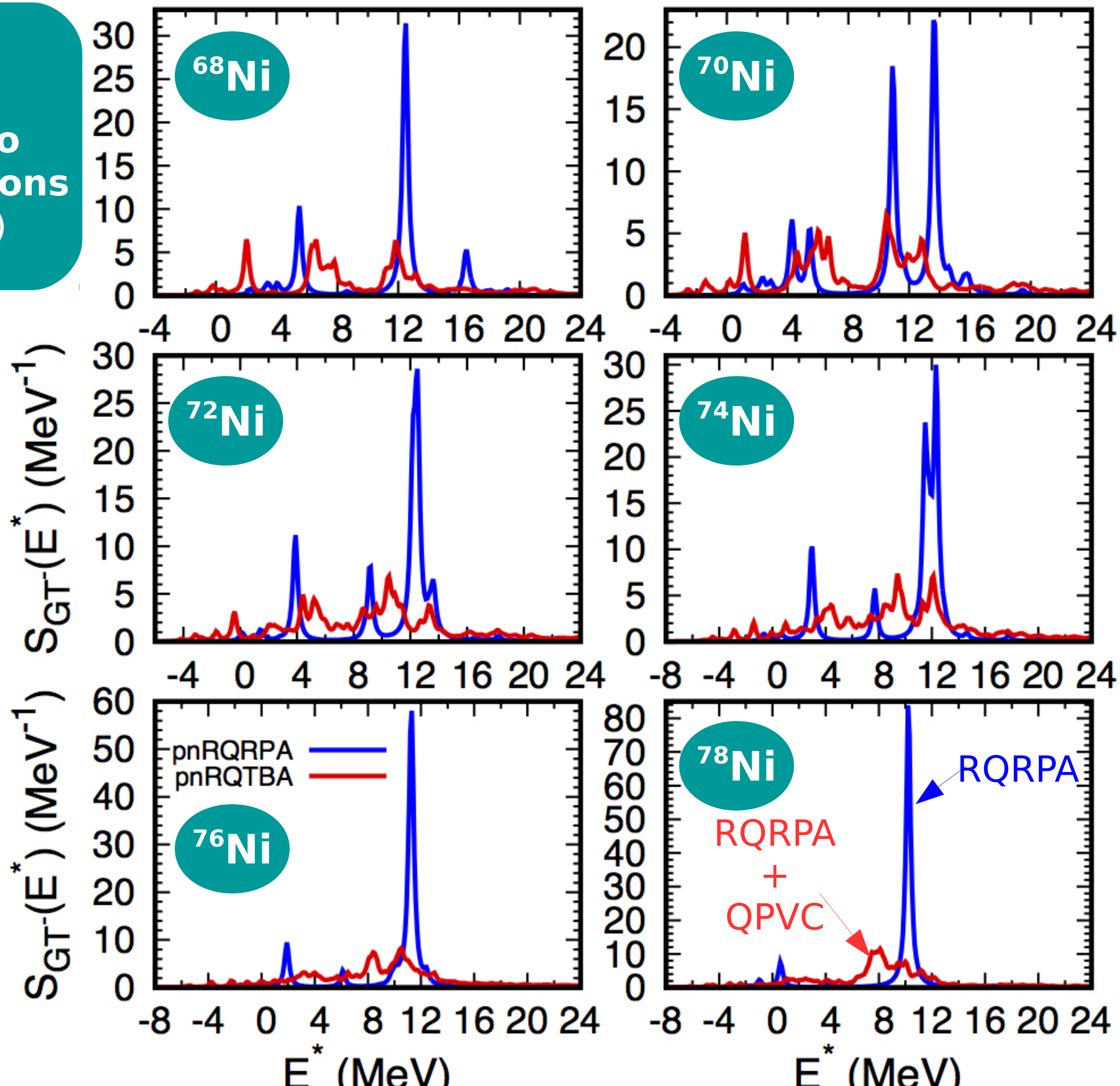
$$S(E) = -\frac{1}{\pi} \lim_{\Delta \to 0^+} \mathrm{Im}\, \Pi(E + i\Delta)$$

$$\Pi(\omega) = \langle F^\dagger R(\omega) F \rangle$$

external field

$$F_{GT^-} = \sum_i \sigma^{(i)} \tau_-^{(i)}$$

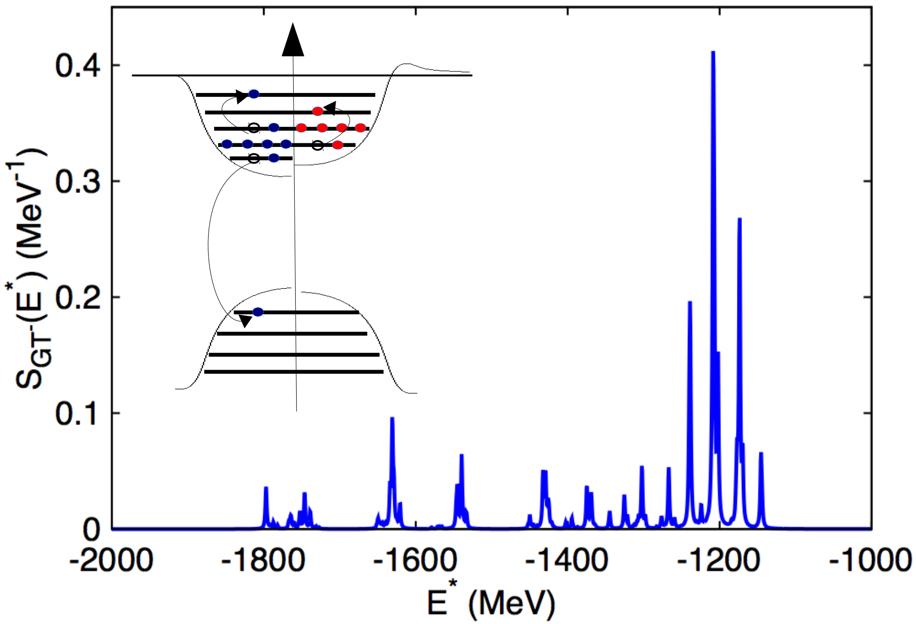
(Smearing Δ= 200 keV)

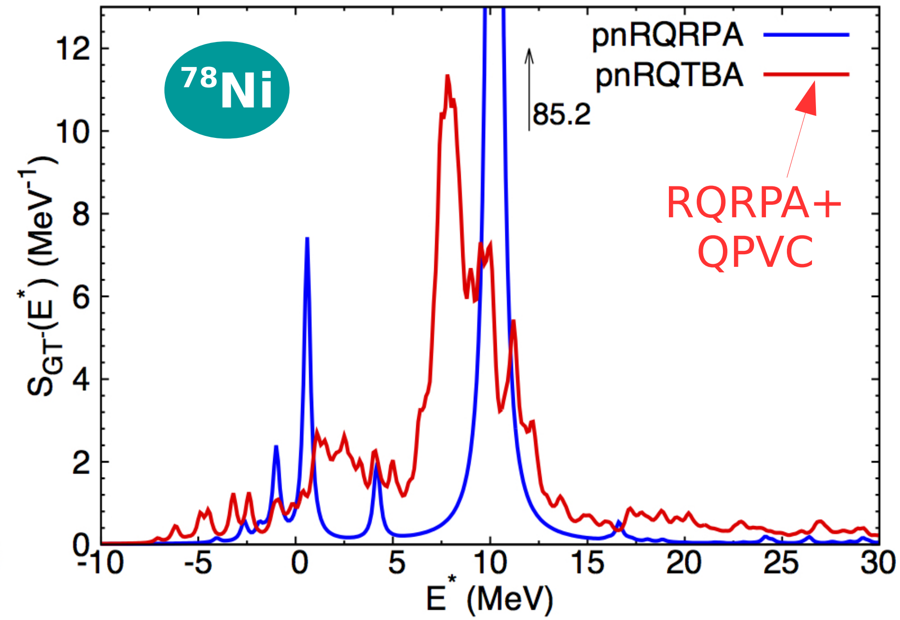


QPVC brings fragmentation of the strength and distribution over a larger energy range

C. R. and E. Litvinova EPJA 52, 205 (2016).

Gamow-Teller resonance in Nickel (Ni → Cu)

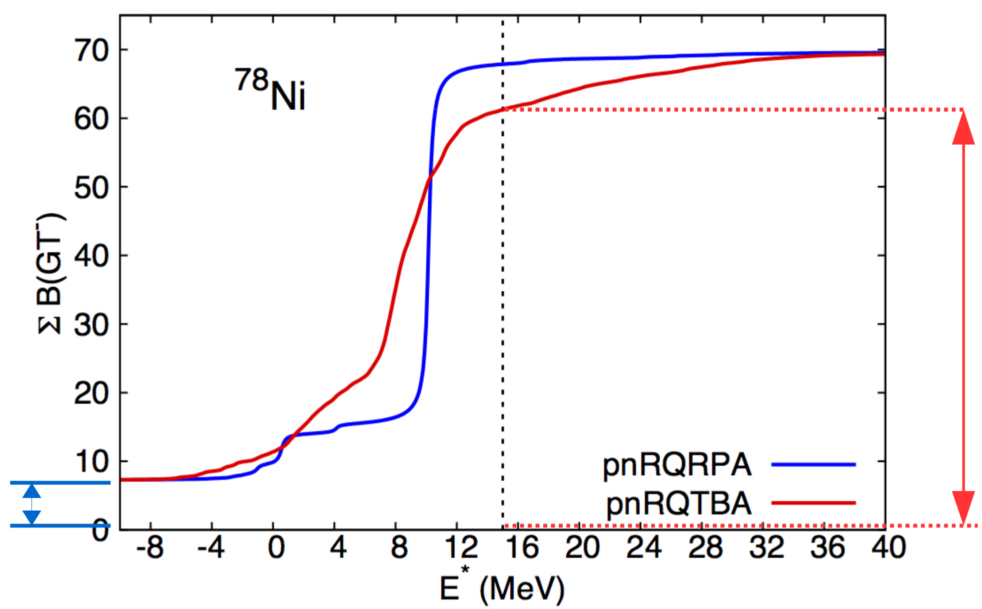




"Quenching problem":
The observed GT strength (~up to the GR region) in nuclei is ~40% less than the Ikeda sum rule

+ transitions from the Fermi sea to the Dirac sea (~10%)

[N. Paar et al., PRC 69, 054303]



Up to GR region ~86% of the total GT$^-$ strength

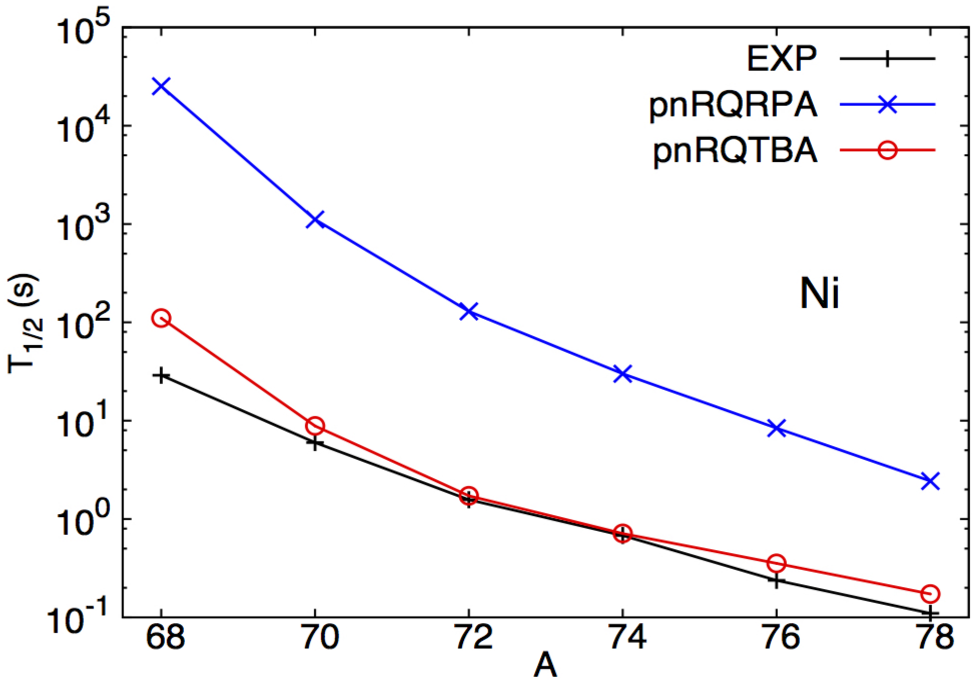
→ RQRPA strength naturally "quenched" due to complex configurations

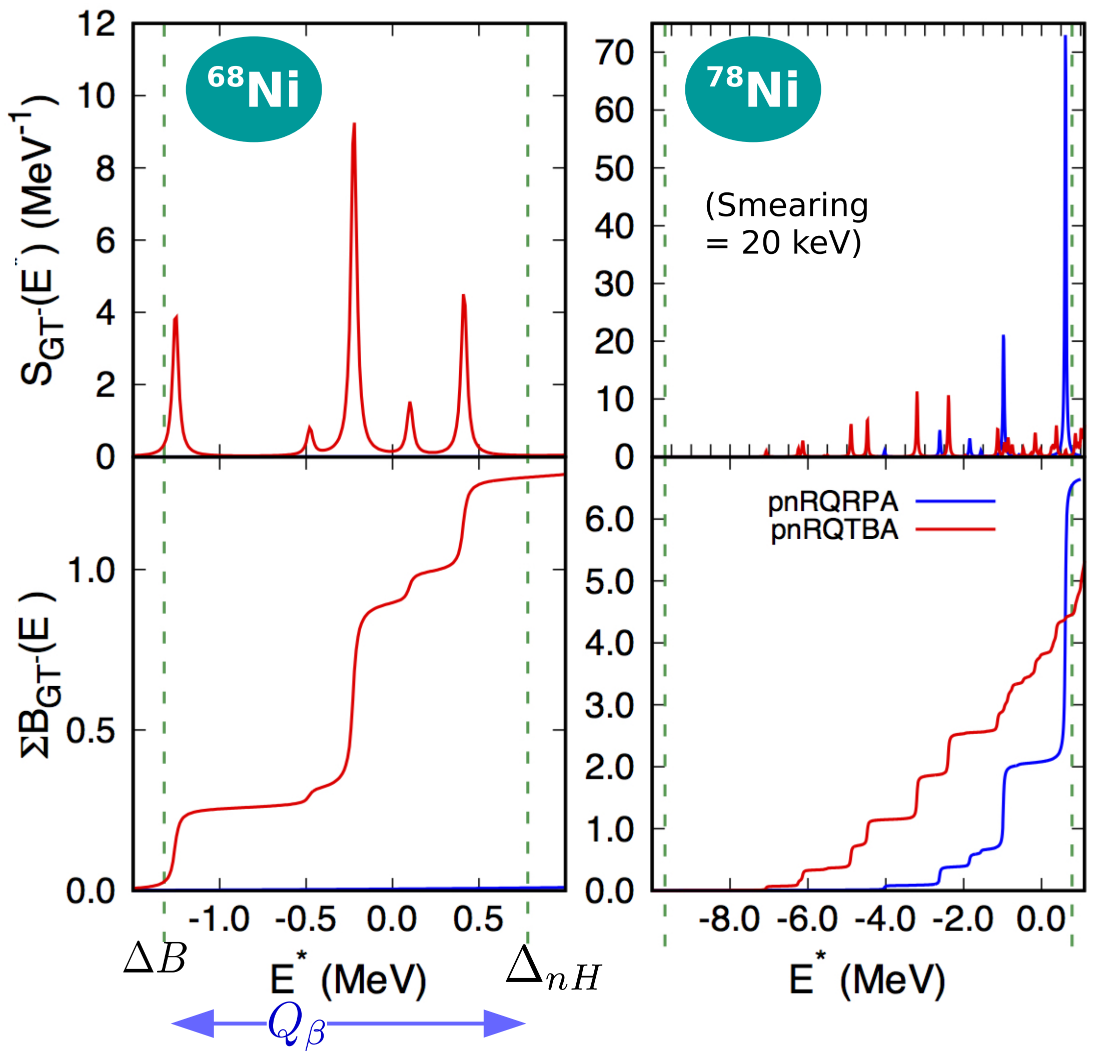
Beta-decay half-lives

E= Excitation energy with respect to the mother nucleus

$$\frac{1}{T_{1/2}} = \frac{g_a^2}{D}\int_{\Delta B}^{\Delta_{nH}} f(Z,\Delta_{np}-E)S(E)dE$$

$g_a = 1$ effective weak axial coupling constant





→ big improvement due to QuasiParticle Vibration Coupling!

^{68}Ni: appearance of strength in the Q_β window due to QPVC
→ finite lifetime

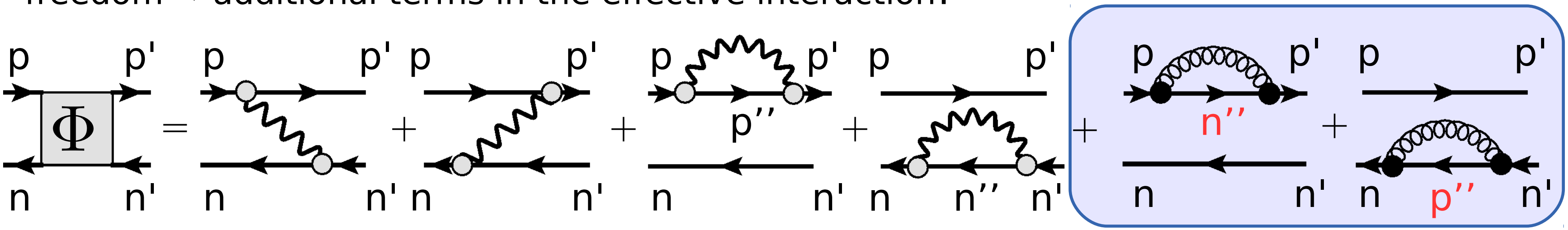
^{78}Ni: more strength with RQRPA but located at higher energies
→ smaller lifetime with QPVC due to phase space factor

exp data from nndc.bnl.gov

C.R. and E. Litvinova EPJA 52, 205 (2016).

New developments: coupling to charge-exchange phonons

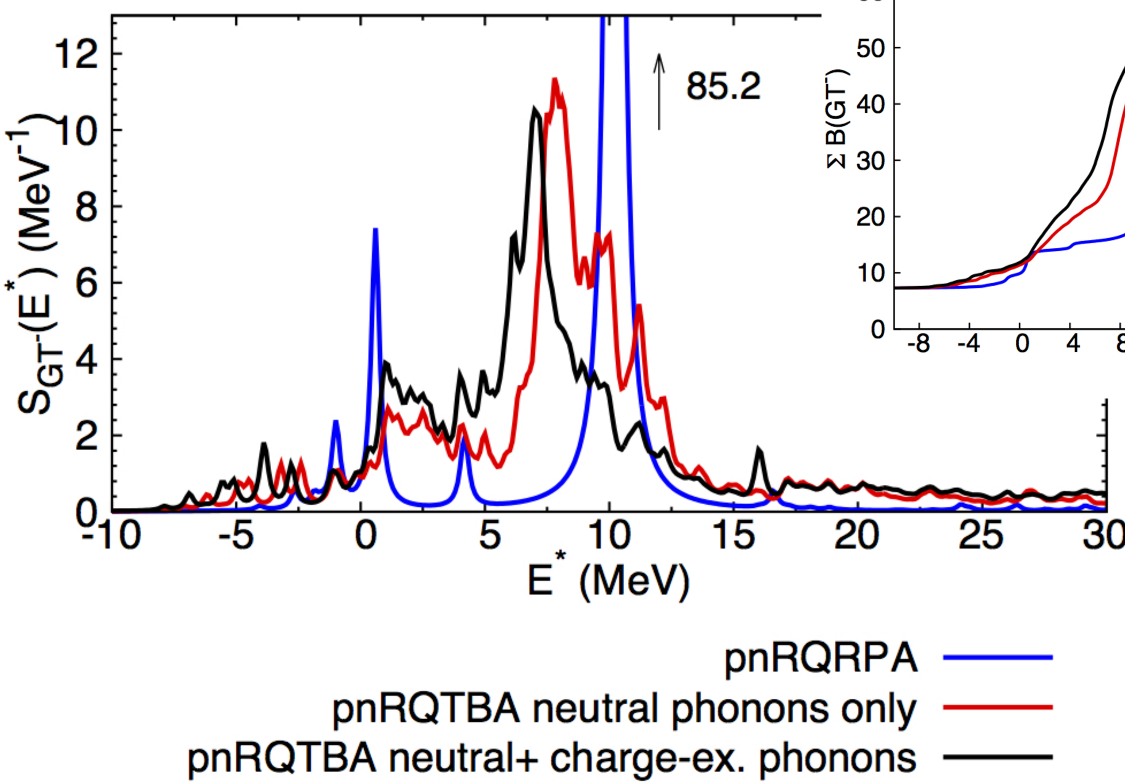
Existence of low-energy isospin-flip modes which can couple to single-nucleon degrees of freedom → additional terms in the effective interaction:

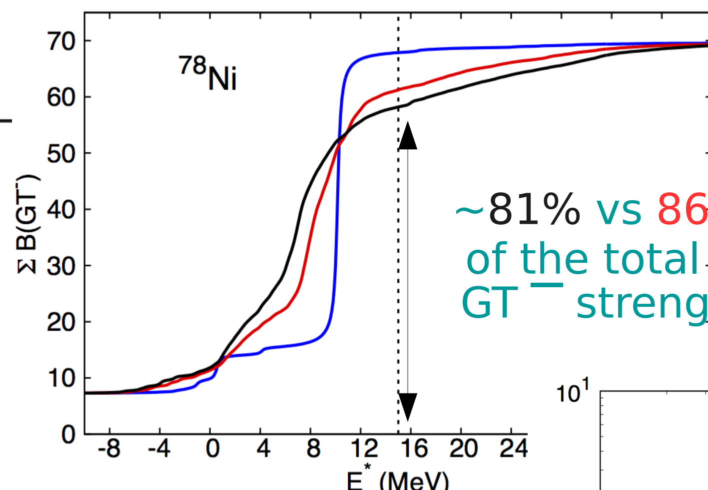


(No extra phonon-exchange term because of charge conservation)

Effect on the nuclear response:

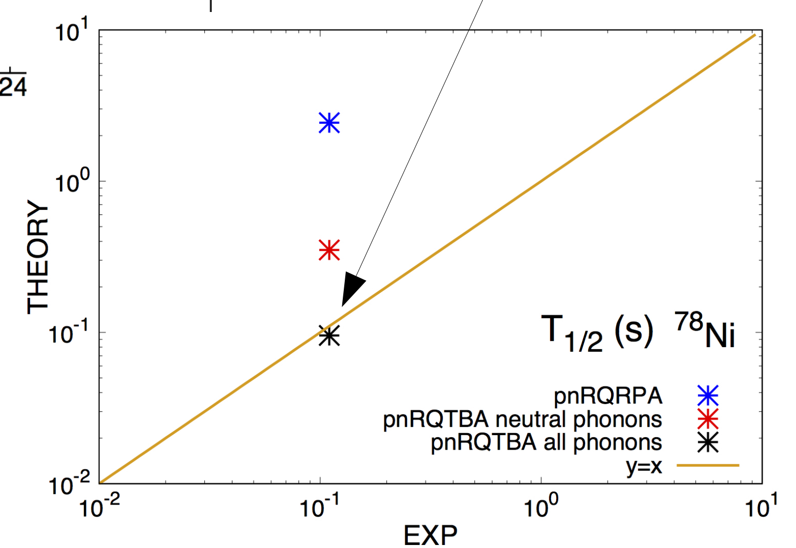
- Preliminary results for ^{78}Ni (coupling to $0^{\pm} \rightarrow 6^{\pm}$):





~81% vs 86% of the total GT$^-$ strength

Additional decrease of the half-life



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Conclusion - perspectives

→ Conclusions:

The pn-RQTBA (pn-RQRPA + QPVC) has potential to describe both

- the details of the low-lying transition strength → important for beta-decay half-lives and other rates of weak processes, which are very sensitive to the coupling between single-particle and collective degrees of freedom
- the overall strength distribution up to high excitation energy → important to reproduce (part of) the observed “quenching” of the GT strength without any artificial factor

→ Perspectives:

- Inclusion of the coupling to pn pairing phonons in doubly magic (N=Z) nuclei
- Inclusion of ground-state correlations (backward-going diagrams) beyond the RQRPA ones
- Application to double-beta decay
- Together with RQTBA in neutral channel, this framework provides a high-quality and consistent description of both phases of the r-process nucleosynthesis, (n,γ) and β-decay ⇒ implementation in astrophysical modeling

This work is supported by US-NSF Grants PHY-1404343 and PHY-1204486

Conclusion - perspectives

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- the ... important to re... without any a...

Thank you!

→ Persp...

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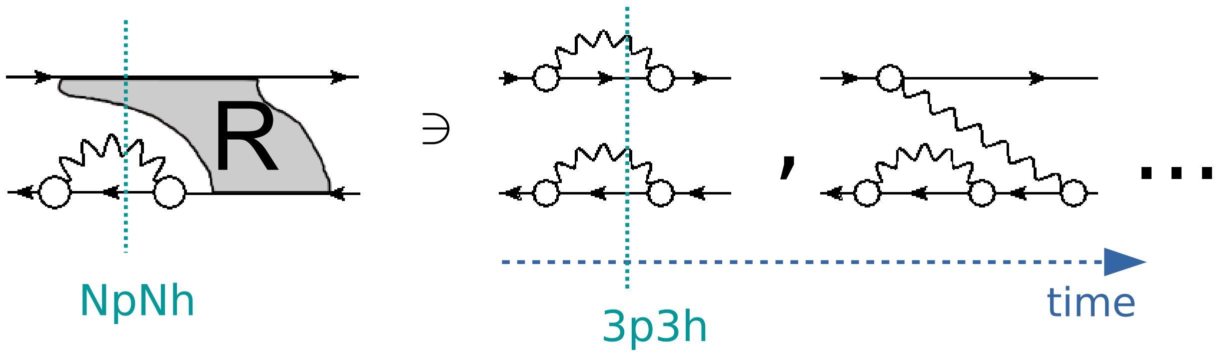
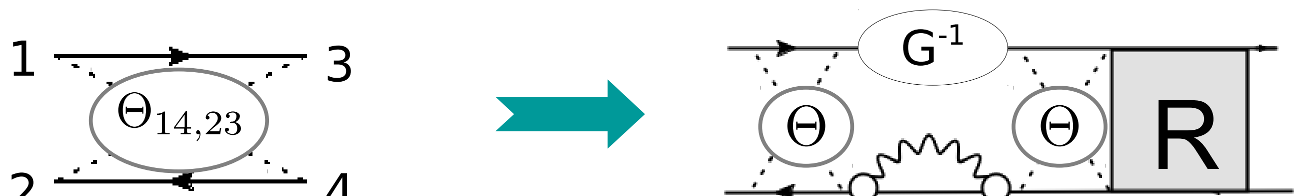
Backup

Time-Blocking Approximation

Problem: Integration over all intermediate times ⇒ complicated BSE (integrations do not separate), appearance of NpNh configurations:

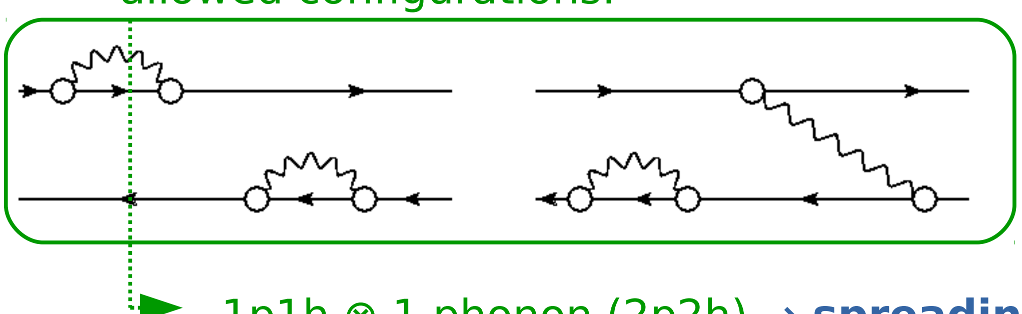


Solution: Time-Blocking Approximation [V.I. Tselyaev, Yad. Fiz. 50,1252 (1989)]



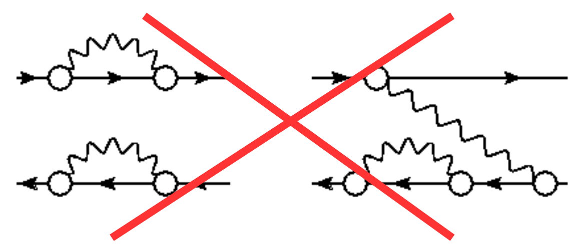
$\Theta_{14,23} = \theta(t_4 - t_1)\theta(t_3 - t_2)$

→ allowed configurations:



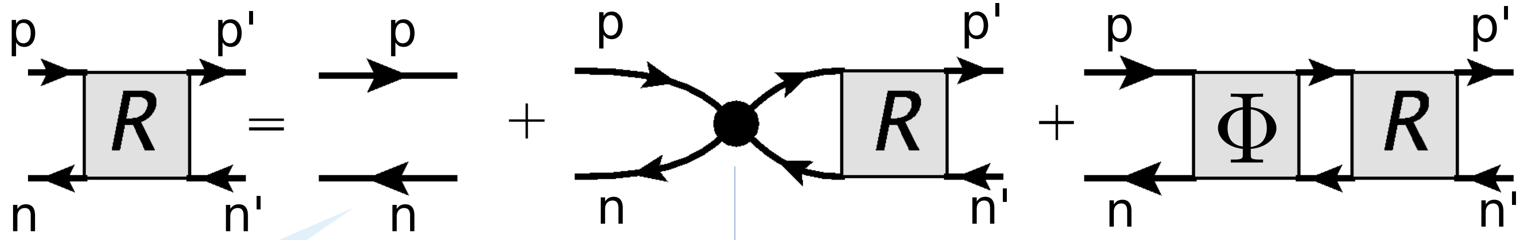
1p1h ⊗ 1 phonon (2p2h) → **spreading**

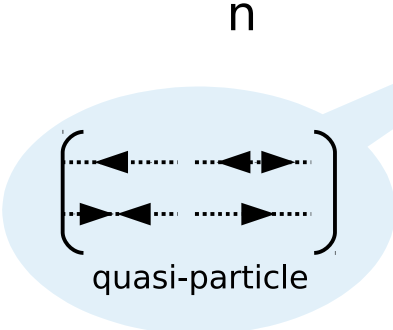
→ blocked configurations: 3p3h, 4p4h...



... but can be included in a next step
(under development)

Response function in the proton-neutron channel

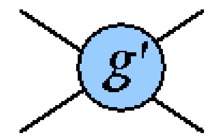




isovector interaction

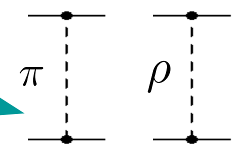
$$\widetilde{V} = V_\pi + V_\rho + V_{\delta\pi}$$

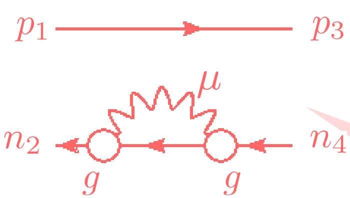
Landau-Migdal contact term

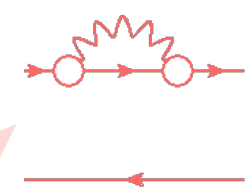


g' =0.6

free-space coupling constant



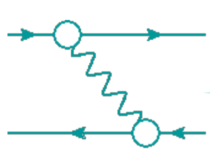


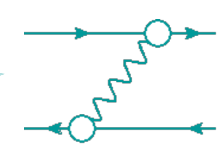


$$\Phi^{\eta}_{p_1 n_4, n_2 p_3}(\omega) =$$

$$\sum_{\mu\xi}\Bigg[\delta_{p_1p_3}\sum_{n_6}\frac{g^{\eta;-\xi}_{\mu;n_6n_2}g^{\eta;-\xi*}_{\mu;n_6n_4}}{\eta(\omega-\lambda_{pn})-E_{p_1}-E_{n_6}-\Omega_\mu}+\delta_{n_2n_4}\sum_{p_5}\frac{g^{\eta;\xi}_{\mu;p_1p_5}g^{\eta;\xi*}_{\mu;p_3p_5}}{\eta(\omega-\lambda_{pn})-E_{p_5}-E_{n_2}-\Omega_\mu}$$

$$-\frac{g^{\eta;\xi}_{\mu;p_1p_3}g^{\eta;-\xi*}_{\mu;n_2n_4}}{\eta(\omega-\lambda_{pn})-E_{p_3}-E_{n_2}-\Omega_\mu}-\frac{g^{\eta;\xi*}_{\mu;p_1p_3}g^{\eta;-\xi}_{\mu;n_4n_2}}{\eta(\omega-\lambda_{pn})-E_{p_1}-E_{n_4}-\Omega_\mu}\Bigg]$$





Note: simple-pole structure due to TBA → ensures locality and unitarity of the response
→ strength is positive-definite

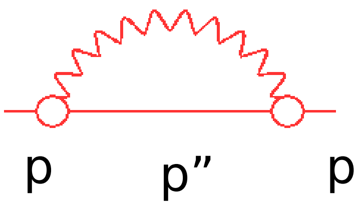
Numerical scheme

Relativistic mean-field with pairing

(RH+BCS, NL3, monopole pairing force)

Solve RQRPA

⇒ neutral (non-isospin flip) phonons with natural parities
2^+, 3^-, 4^+, 5^-, 6^+ up to 30 MeV and their coupling vertices



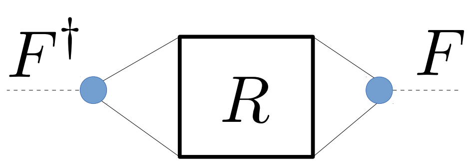
Solve BSE with RQTBA for the proton-neutron response function

(Gamow-Teller: $J^\pi = 1^+$)

Nuclear Polarizability:

$$\Pi(\omega) = F^\dagger R(\omega) F$$

external field



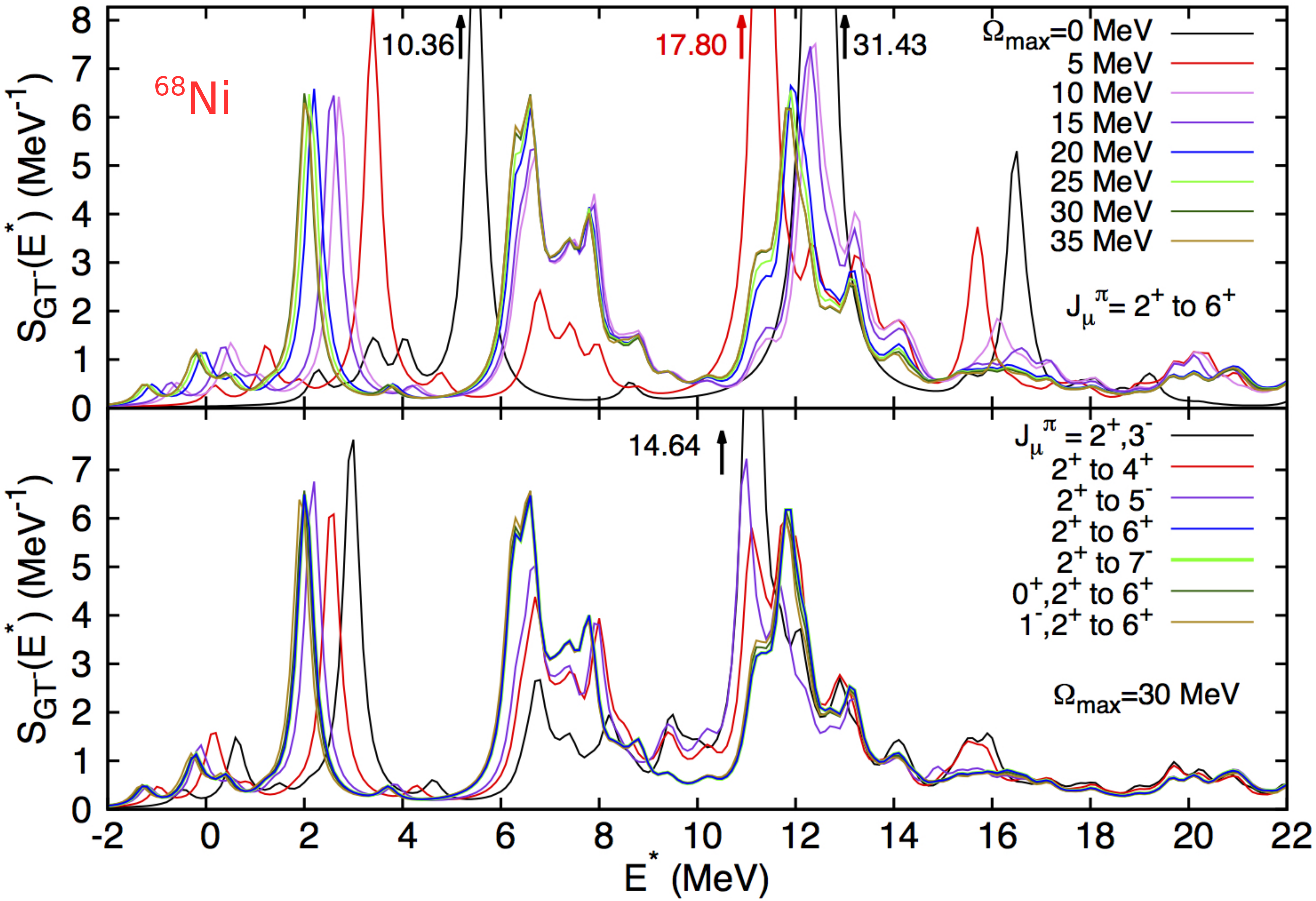
Strength function:

$$S(E) = -\frac{1}{\pi} \lim_{\Delta \to 0^+} \mathrm{Im}\, \Pi(E + i\Delta)$$

$$F_{GT^-} = \sum_i \sigma^{(i)} \tau_-^{(i)}$$

Gamow-Teller resonance in Nickel

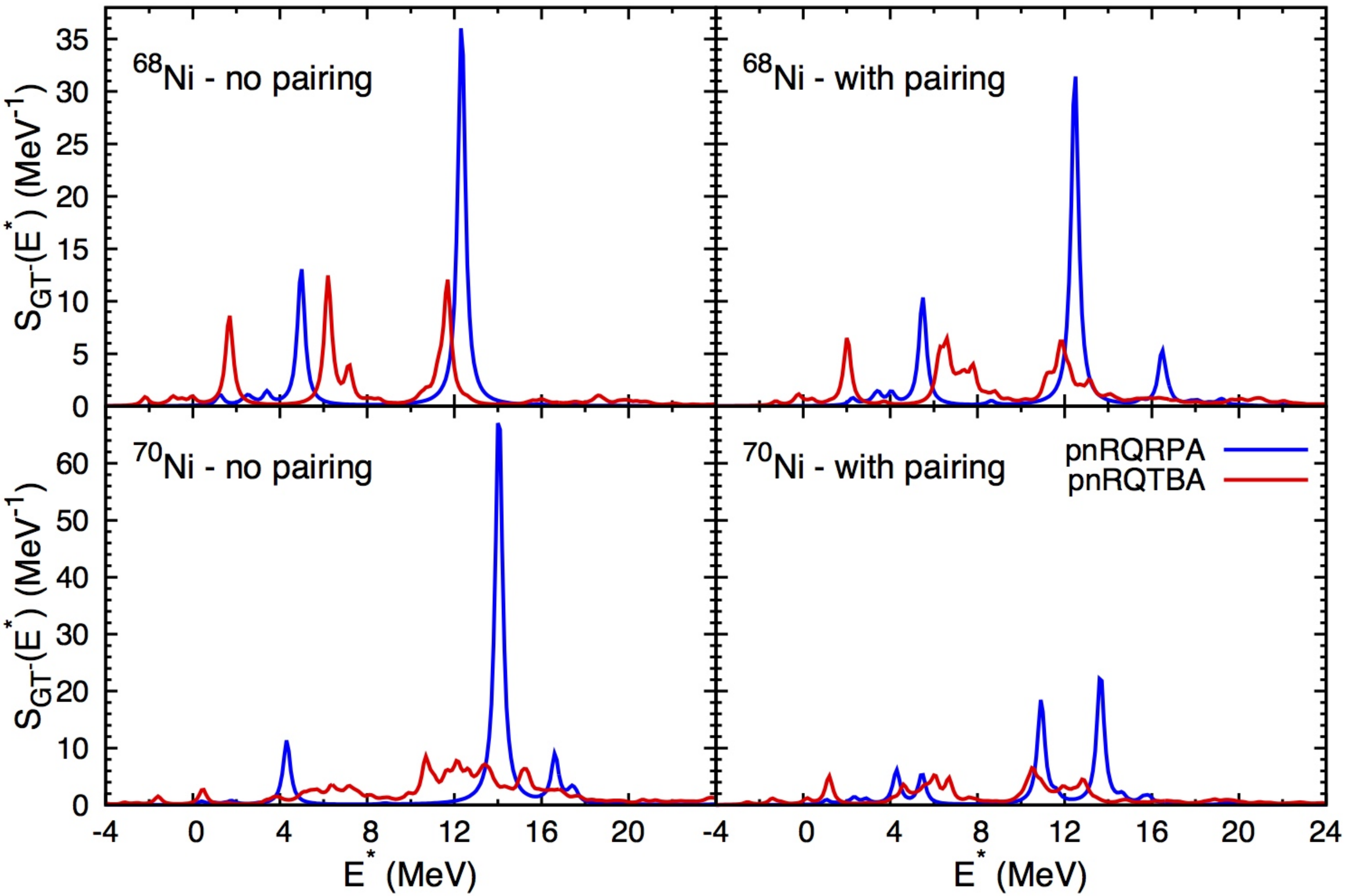
Convergence of the strength according to the phonon spectrum (neutral phonons):

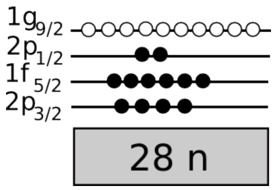


C. Robin and E. Litvinova EPJA 52, 205 (2016).

Gamow-Teller resonance in Nickel

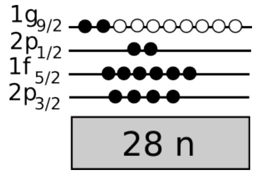
Effect of pairing correlations on the strength distribution:



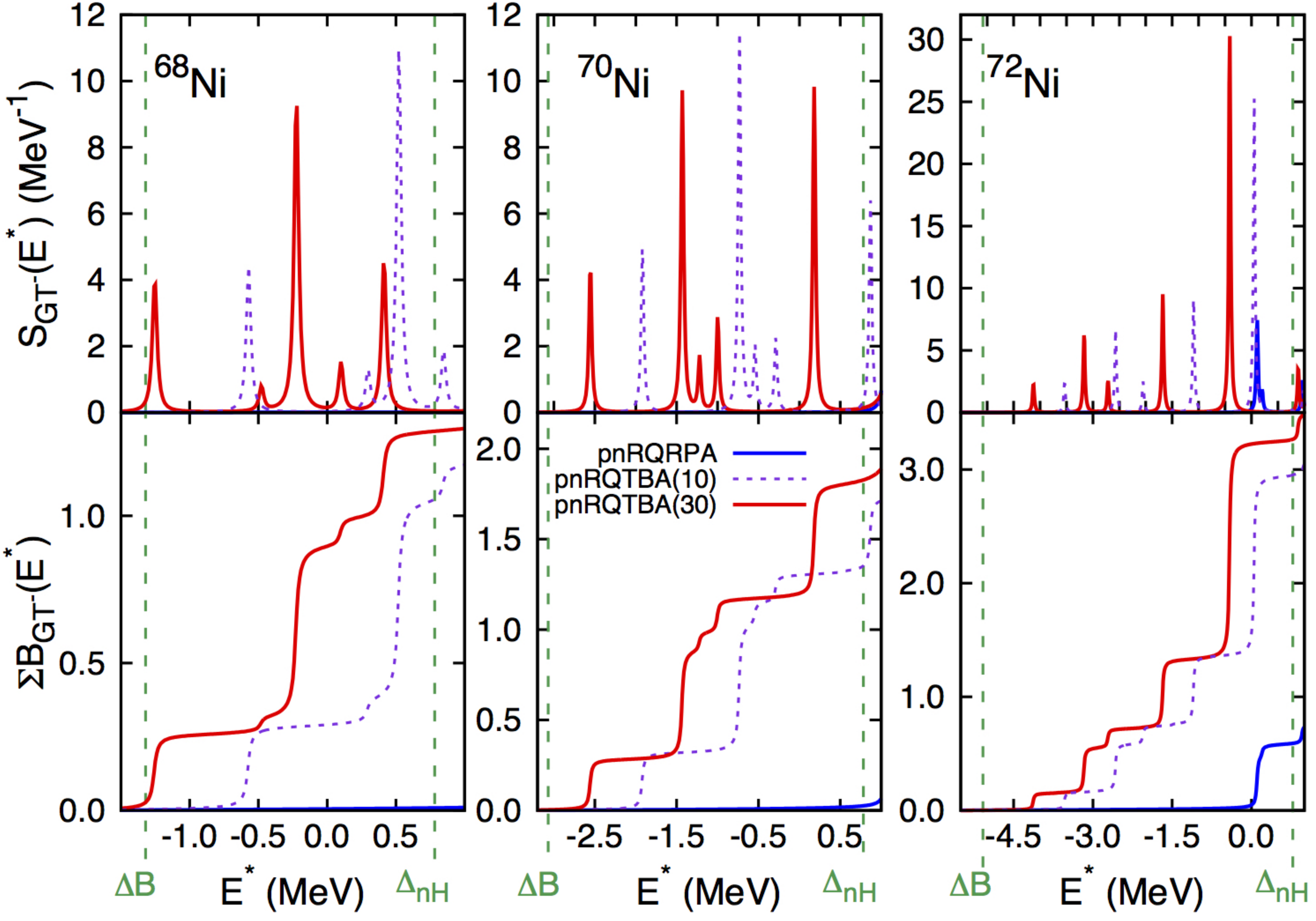


Pairing can bring fragmentation at the QRPA level (Landau damping)

QPVC brings spreading effects



Gamow-Teller resonance in Nickel



Gamow-Teller resonance in Nickel