Beyond RPA in the relativistic (quasi)particle-phonon coupling framework: applications to isospin-transfer modes in nuclei

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Workshop "Theory and applications of RPA-and-beyond methods in physics and chemistry"
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Outline

- **Introduction**
  Relativistic Nuclear Field Theory: connecting the scales of nuclear physics from Quantum Hadrodynamics to emergent collective phenomena

- **Response theory for isospin-transfer modes:**
  Gamow-Teller transitions, beta-decay half-lives, the "quenching" problem and the need for higher-order correlations

- **Ground-state correlations in the time-blocking approximation**

- **Conclusion & perspectives**

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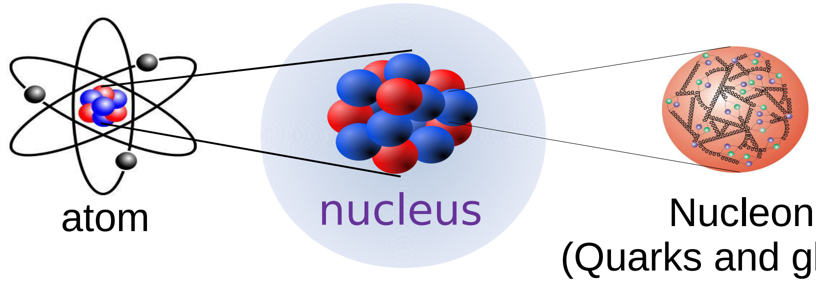
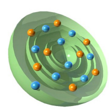
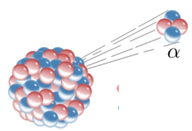


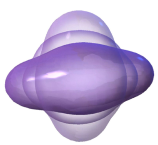
At the frontiers between microscopic & macroscopic worlds

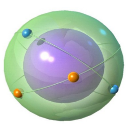
- Exhibits generic properties of many-body systems:

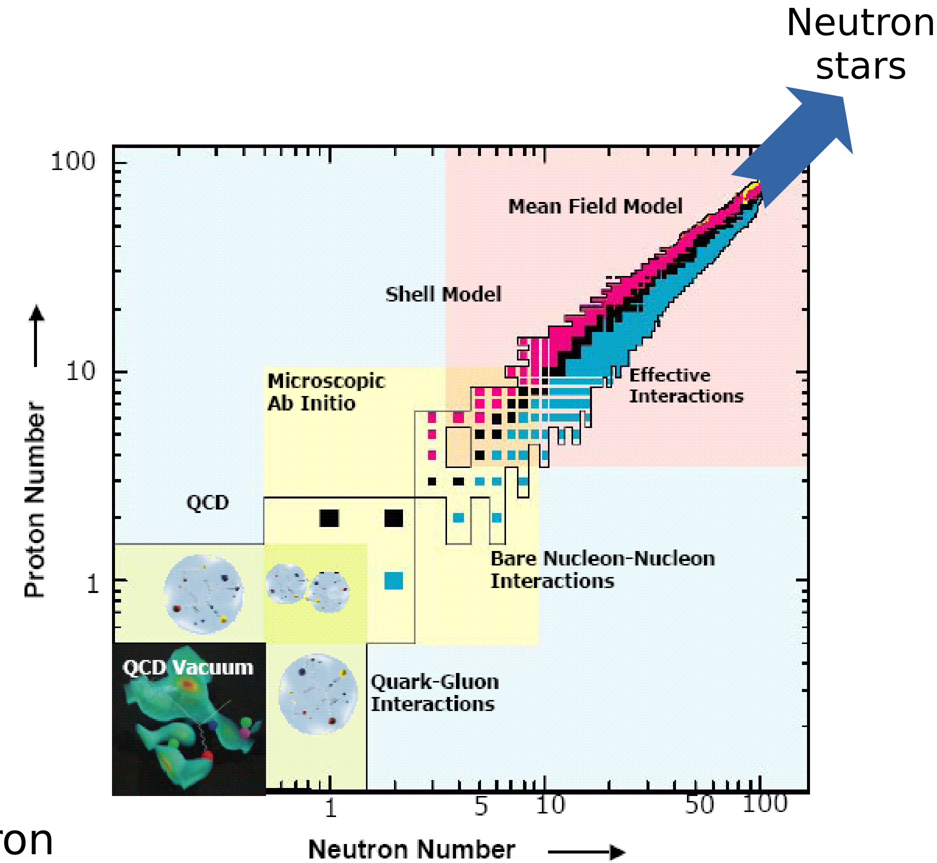




  - shell structure
  - particle-decay and radiation
  - emergent collective phenomena
  - superfluidity





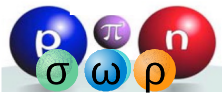


- Also has specific features:

  - Sensitive to 3 fundamental forces (strong, electromagnetic & weak)

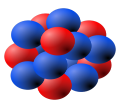
  - Two types of particles: neutrons & protons
    → new phenomena: neutron skin, proton-neutron pairing, isospin-transfer excitations...

Relativistic Nuclear Field Theory: foundations



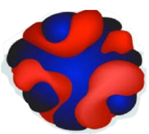
mesons

$m_{\pi,\sigma,\omega,\rho}$ ~140-800 MeV

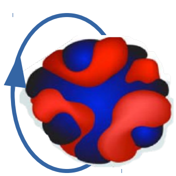


nucleons

S_n ~ 10 MeV

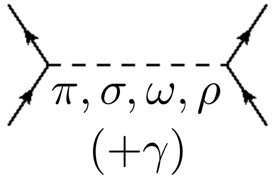


collective vibrations (phonons) ~ few MeV



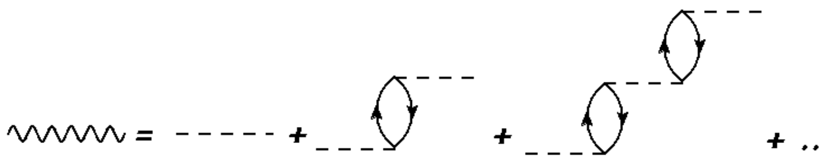
nucleons & phonons

... more correlations



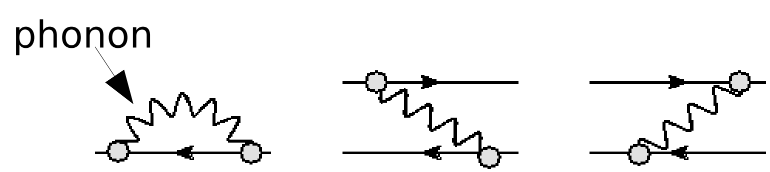
Quantum Hadrodynamics
- Relativistic nucleons

Relativistic mean-field
+ superfluidity



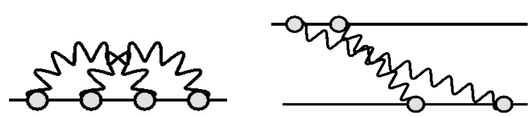
(1p-1h)

Relativistic Random Phase Approximation



(2p-2h)

Particle-Vibration coupling - Nuclear Field theory
– Time-Blocking



(3p-3h)

self-consistent extensions of the Relativistic Mean-Field via Green function techniques

successive corrections in the single-particle motion and effective interaction

... more correlations

Include complex configurations of nucleons step by step to:
- Keep the advantages of RPA methods applicability to many nuclei (up to heavy/superheavy)
- Ultimately achieve a highly-precise description of nuclear phenomena

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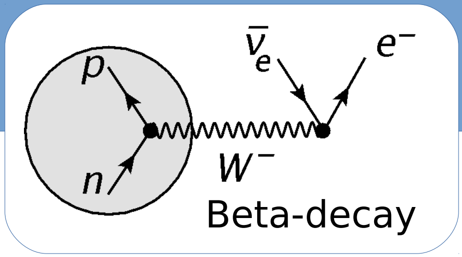
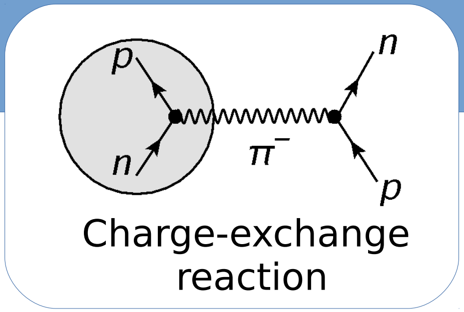
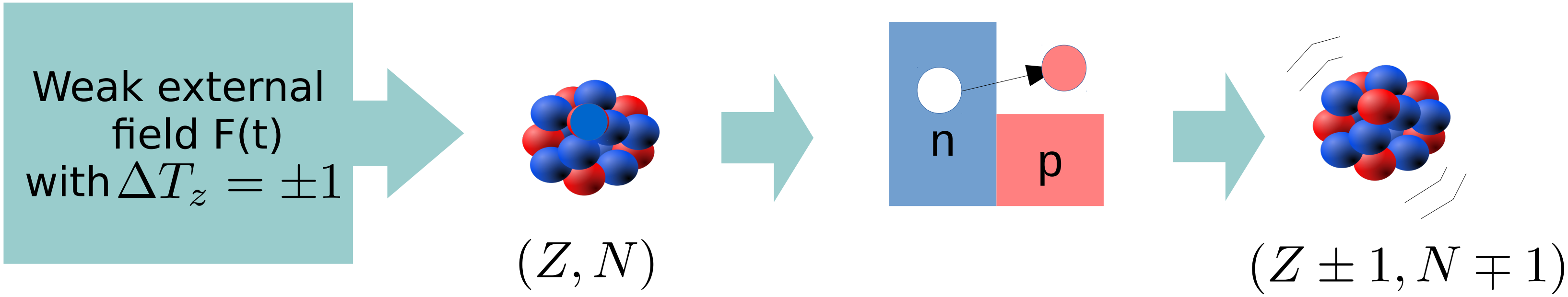
Isospin-transfer modes in nuclei

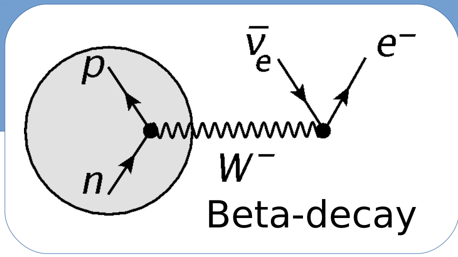


Response to an external field
involving a change of the isospin projection:





Isospin-transfer modes in nuclei



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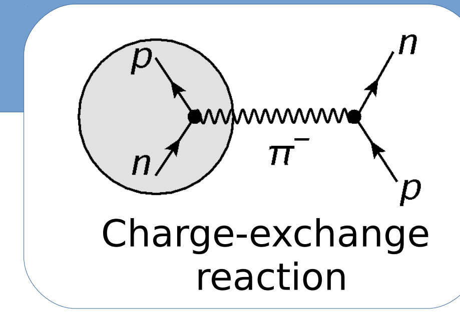
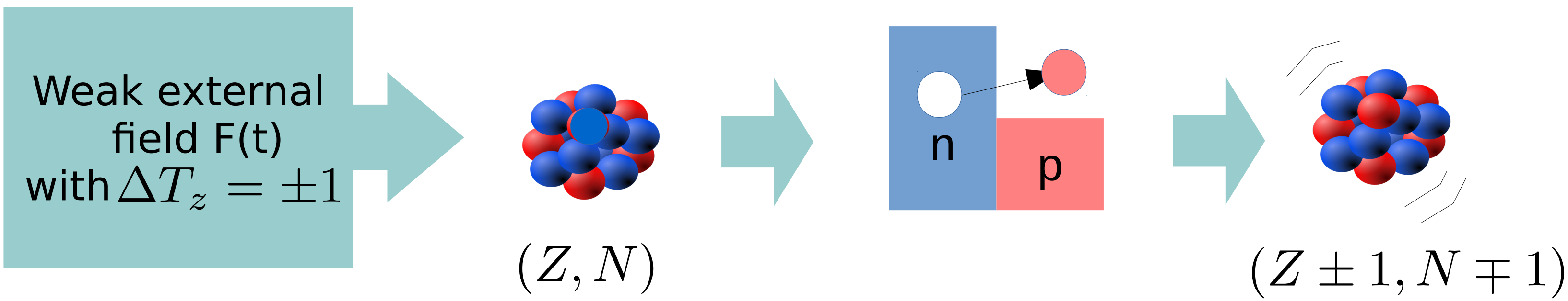
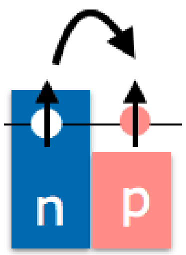
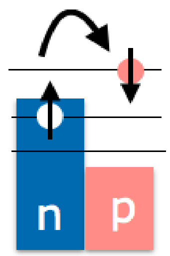






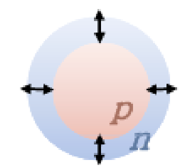
Fermi

$$F_F = \sum_n \tau_\pm^{(n)}$$



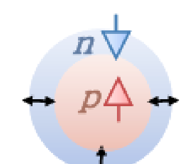
Gamow-Teller

$$F_{GT} = \sum_n \boldsymbol{\sigma}^i_{(n)} \tau_\pm^{(n)}$$



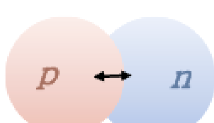
IVGMR

$$F_M = \sum_n r^2_{(n)} \tau_\pm^{(n)}$$



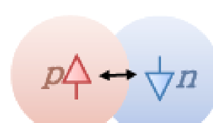
IVSMR

$$F_{SM} = \sum_n r^2_{(n)} \boldsymbol{\sigma}^i_{(n)} \tau_\pm^{(n)}$$



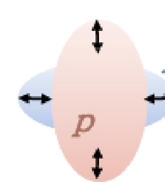
IVGDR

$$F_D = \sum_n r_{(n)} Y_1^{(n)} \tau_\pm^{(n)}$$

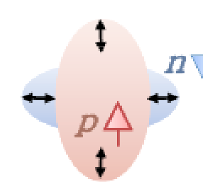


IVSDR

$$F_{SD}^\lambda = \sum_n r_{(n)} [\boldsymbol{\sigma}^i_{(n)} \otimes Y_1^{(n)}]_\lambda \tau_\pm^{(n)}$$



IVGQR

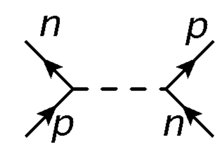


IVSQR

...

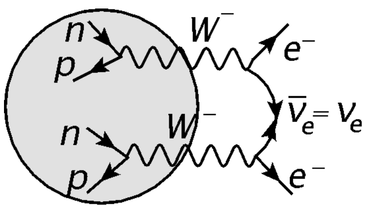
Isospin-transfer modes in nuclei

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



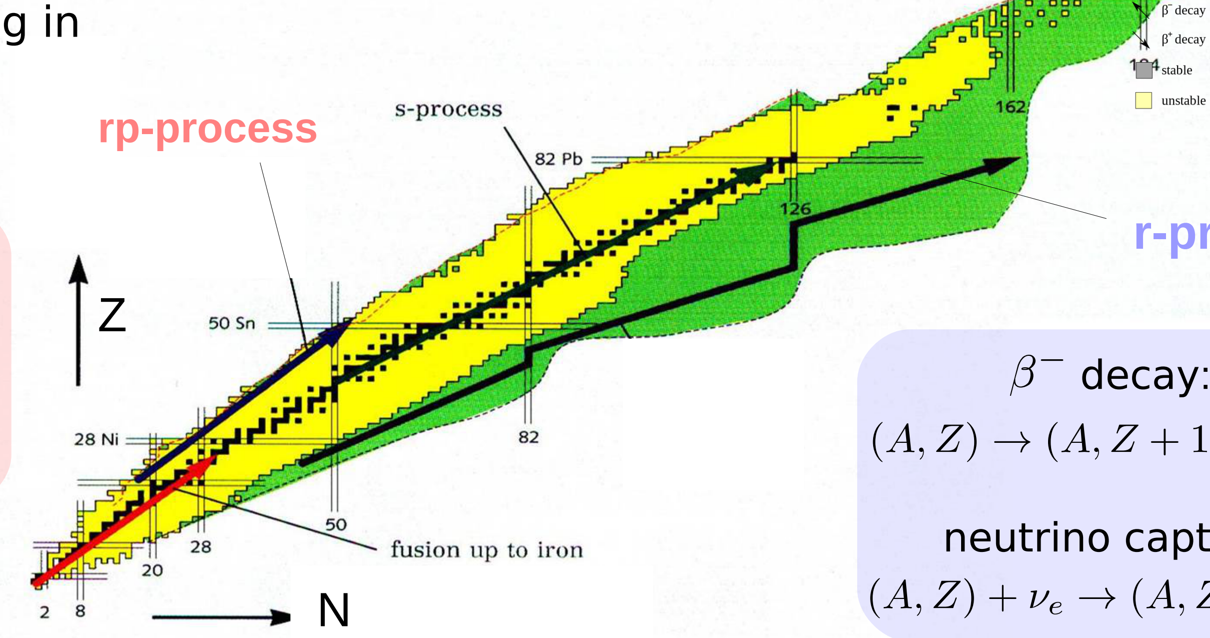
→ **Nuclear physics:** constraints on the (S,T) channels of the nuclear interaction...

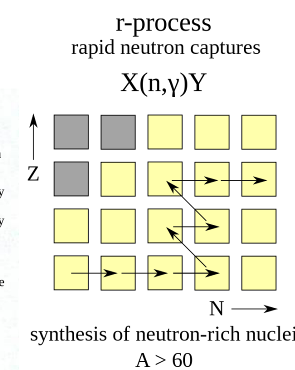
→ **Particle physics:** nature of neutrinos ($0\nu\beta\beta$ decay), ...



→ **Astrophysics:**

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





β^+ decay:

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

electron capture:

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

β^- decay:

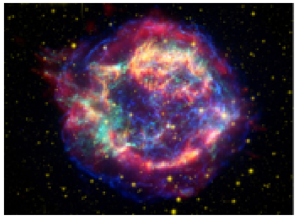
$$(A,Z) \to (A,Z+1) + e^- + \bar{\nu}_e$$

neutrino capture:

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

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

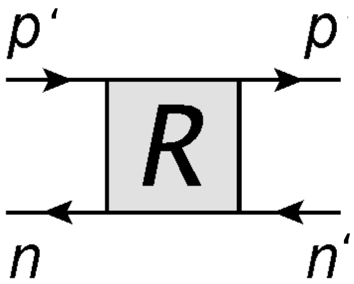
→ need precise, consistent and predictive information from theory for many nuclei



Response theory for isospin-transfer modes

Theoretically, all the information about the excited states is contained in the
proton-neutron response function
= propagator of 2 correlated proton and neutron (in the particle-hole channel)

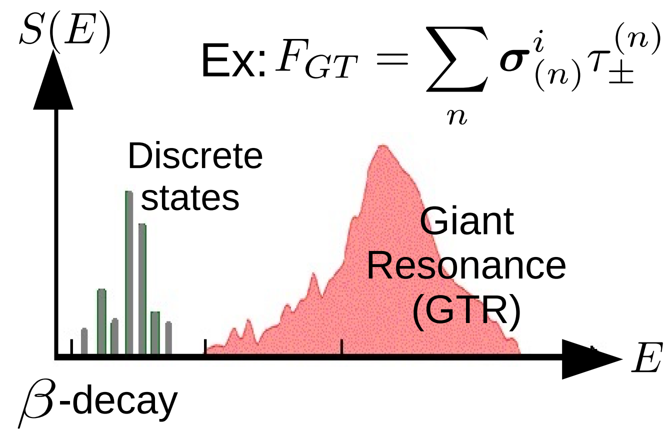
$$R^{ph}_{pn,n'p'}(t-t') = \langle 0|\mathcal{T}\left(\psi_p(t)\bar{\psi}_{n'}(t)\psi_n(t')\bar{\psi}_{p'}(t')\right)|0\rangle$$

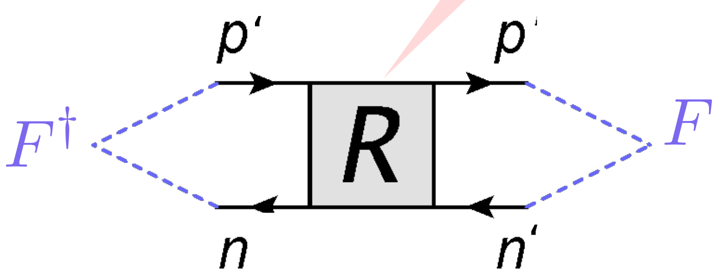


→ For instance, the strength distribution is:

$$S(E) = \sum_f |\langle \Psi_f|\hat{F}|\Psi_i\rangle|^2 \delta(E - E_f + E_i)$$

$$= -\frac{1}{\pi}\lim_{\Delta\to 0^+} \mathrm{Im}\,\langle \Psi_i|\hat{F}^\dagger R(E+i\Delta)\hat{F}|\Psi_i\rangle$$

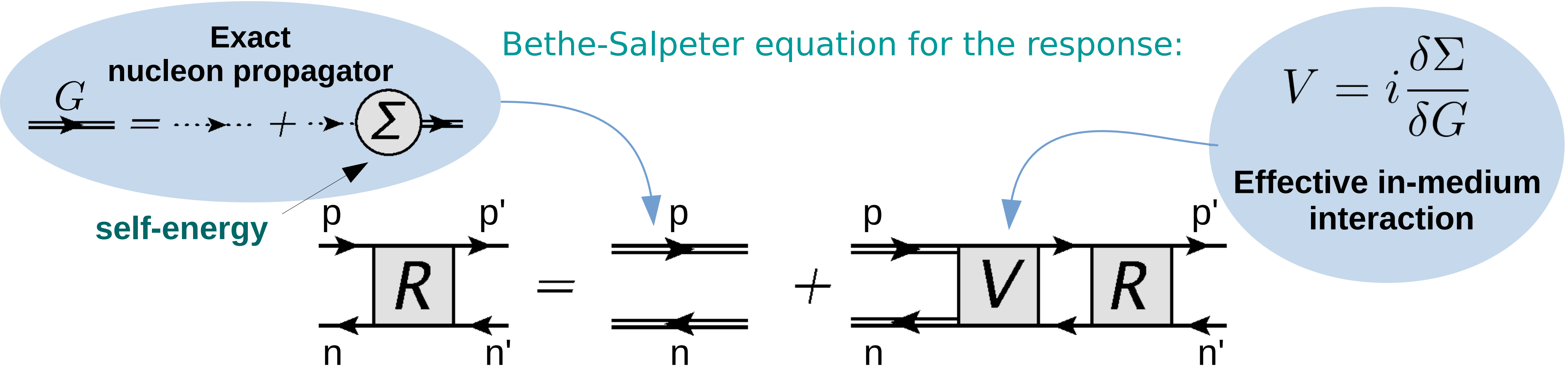




→ the response of the mother nucleus (N,Z) gives information
about the states of the daughter (N+1,Z-1) or (N-1,Z+1) nucleus

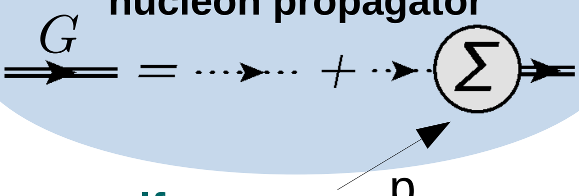
Response theory for isospin-transfer modes

Bethe-Salpeter equation for the response:



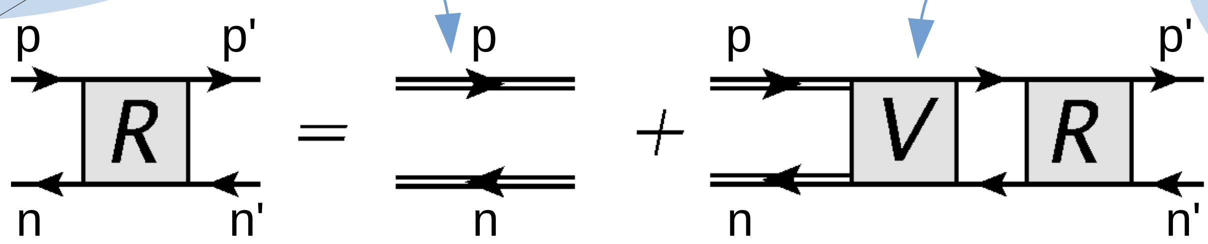
Response theory for isospin-transfer modes

Exact nucleon propagator



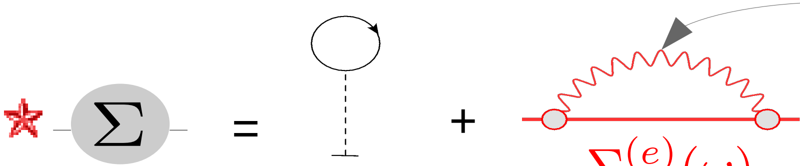
self-energy

Bethe-Salpeter equation for the response:



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

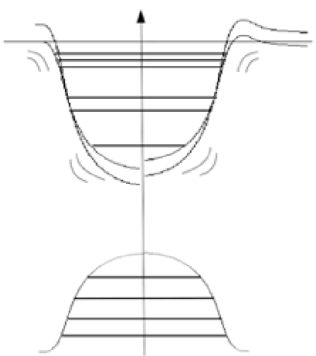
Effective in-medium interaction

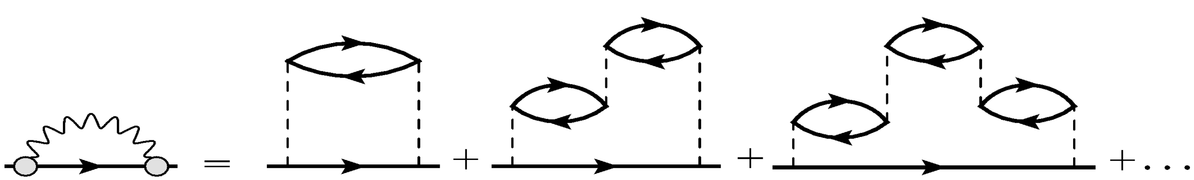


Static (Hartree)

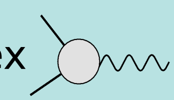
$\Sigma^{(e)}(\omega)$ dynamic

vibration (phonon)

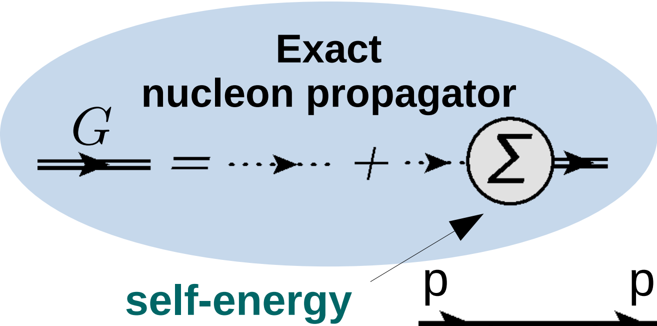




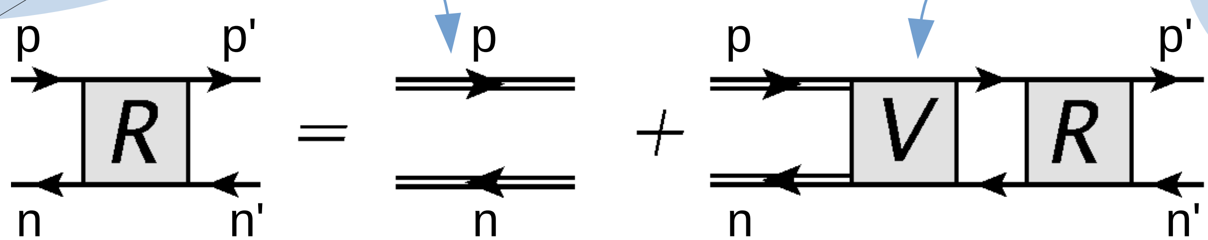
→ New-order parameter = PVC vertex



Response theory for isospin-transfer modes

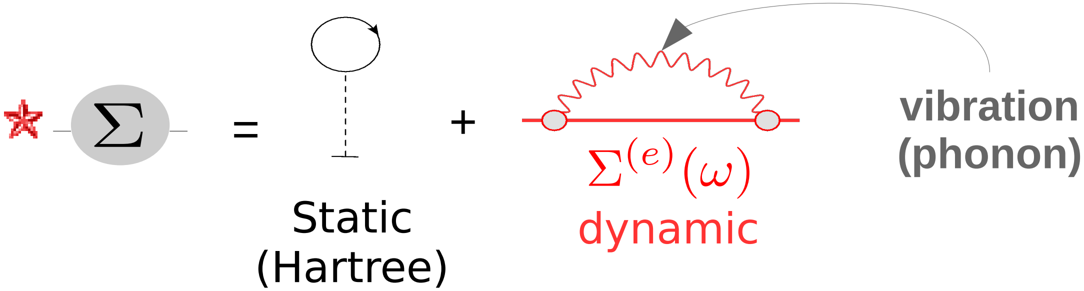


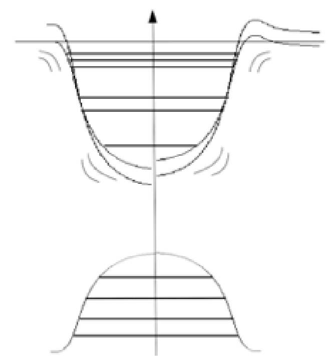
Bethe-Salpeter equation for the response:

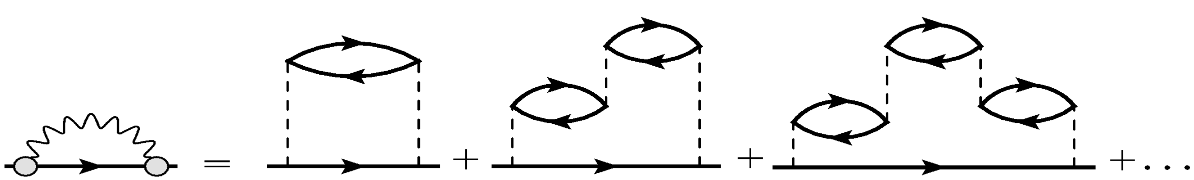


$$V = i\frac{\delta\Sigma}{\delta G}$$

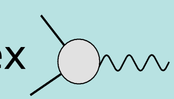
Effective in-medium interaction





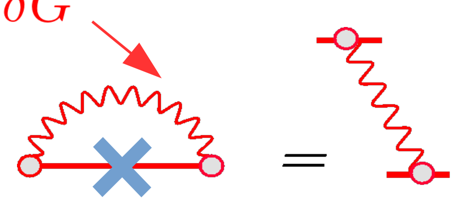


→ New-order parameter
= PVC vertex



$$V(\omega) = i\frac{\delta\widetilde{\Sigma}_{RHB}}{\delta G} + i\frac{\delta\Sigma^{e}(\omega)}{\delta G}$$

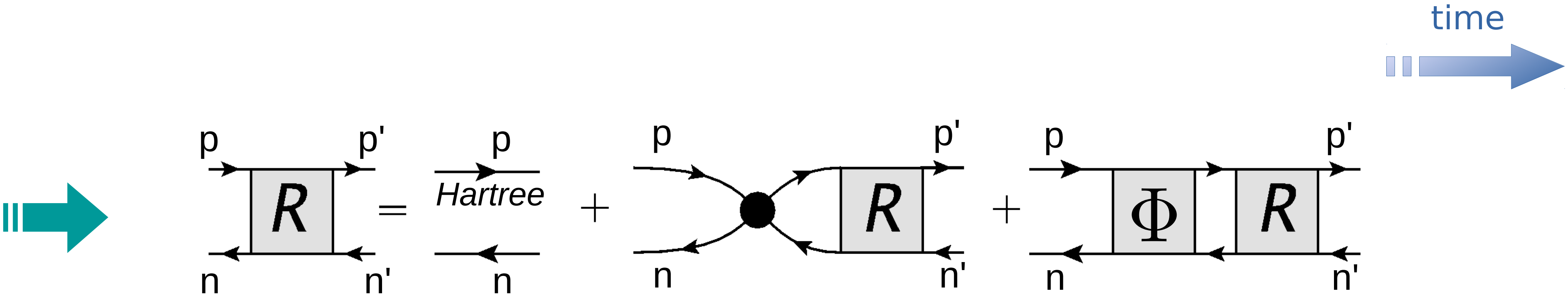
Static meson-exchange



Energy-dependent phonon exchange

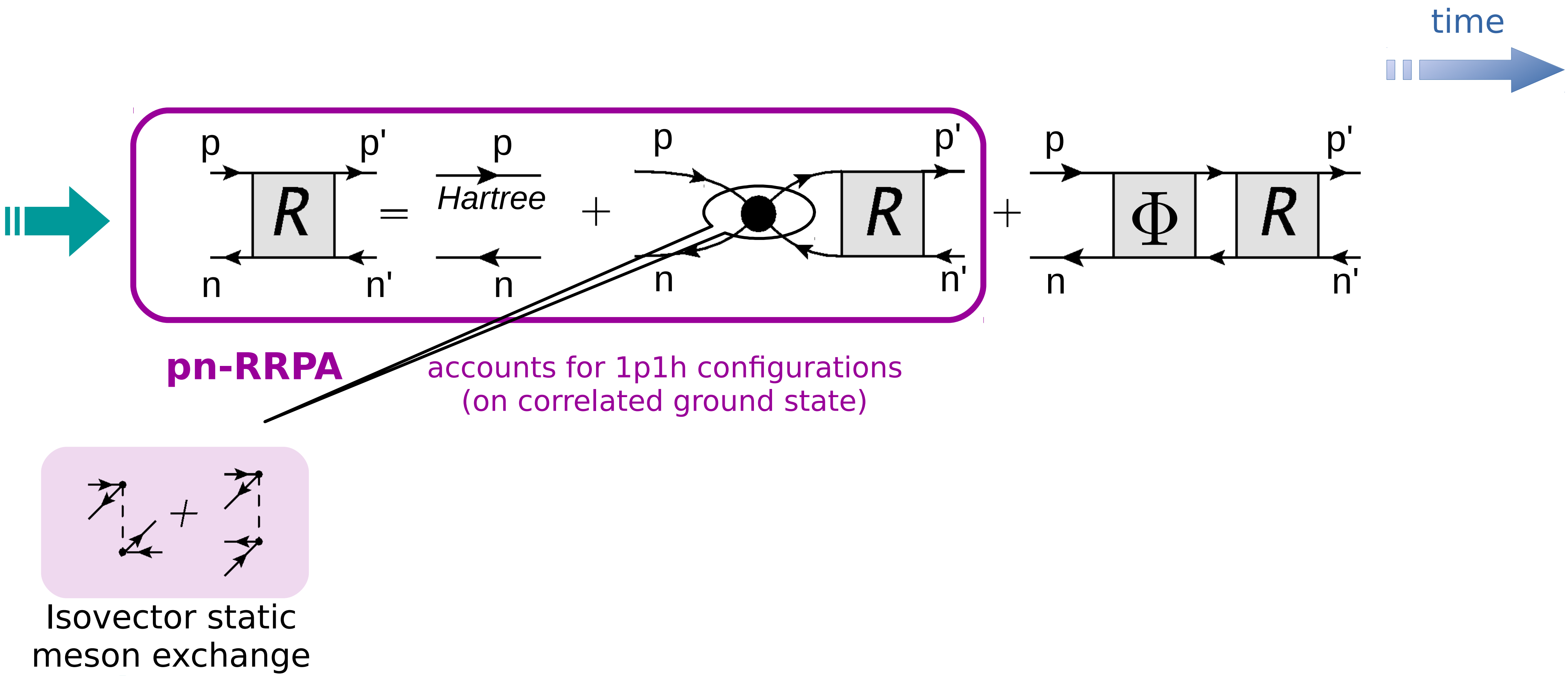
Response theory for isospin-transfer modes

In the Time-Blocking Approximation:



Response theory for isospin-transfer modes

In the Time-Blocking Approximation:

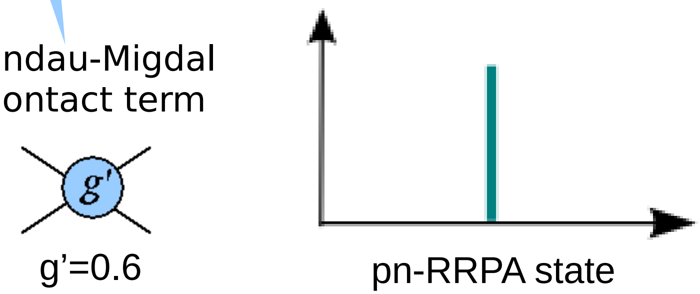


$$\widetilde{V} = V_\pi + V_\rho + V_{\delta\pi}$$

With free-space coupling constant

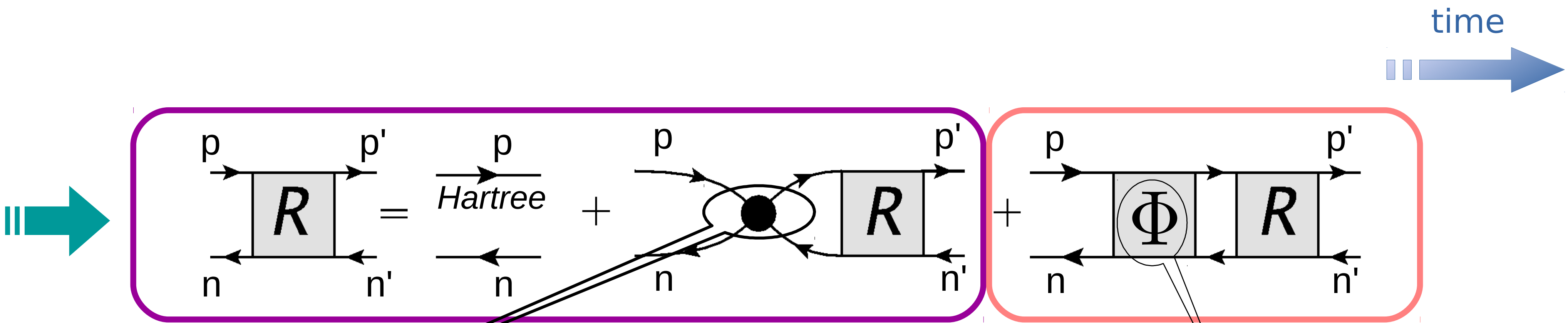
Landau-Migdal contact term

g'=0.6



Response theory for isospin-transfer modes

In the Time-Blocking Approximation:

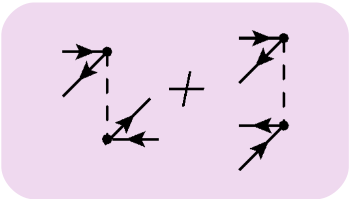


pn-RRPA

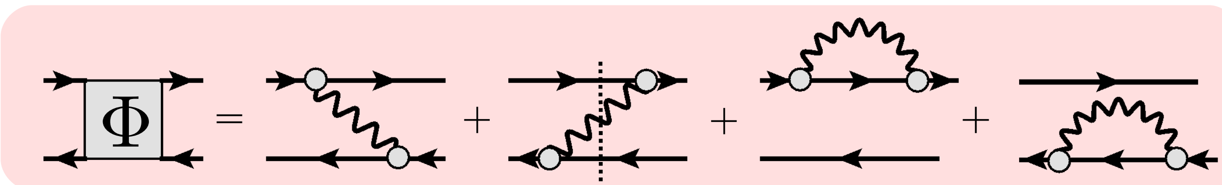
accounts for 1p1h configurations
(on correlated ground state)

+PVC

energy-dependent interaction:



Isovector static meson exchange



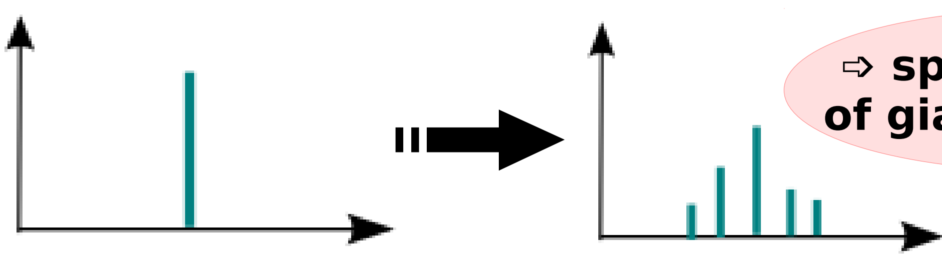
accounts for
1p1h ⊗ 1phonon = 2p2h
configurations

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

With free-space coupling constant

Landau-Migdal contact term

g'=0.6



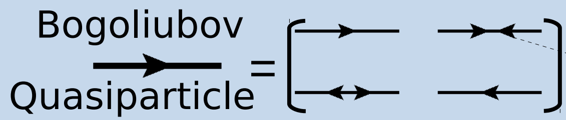
pn-RRPA state

pn-RRPA + PVC

⇨ spreading width of giant resonances

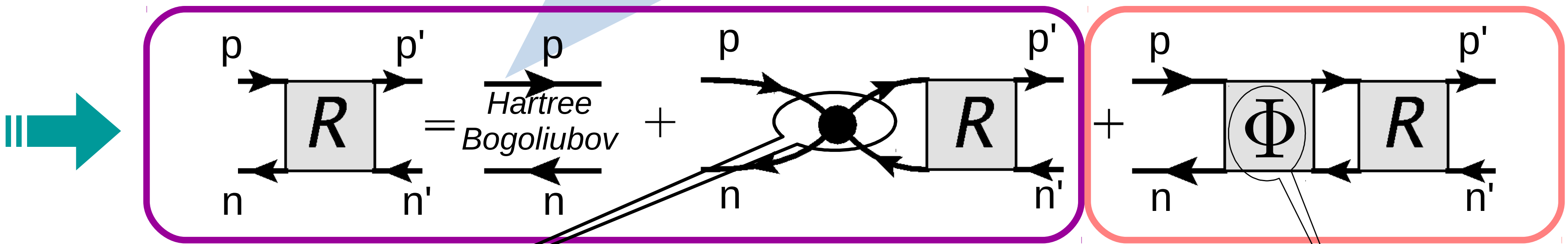
Response theory for isospin-transfer modes

In open-shell nuclei:



→ spinors of dimensions 16 (spin,isospin,relativity,pairing)

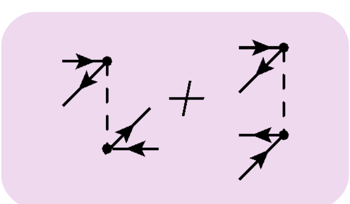
Gorkov propagator



pn-RQRPA accounts for 2qp configurations (on correlated ground state)

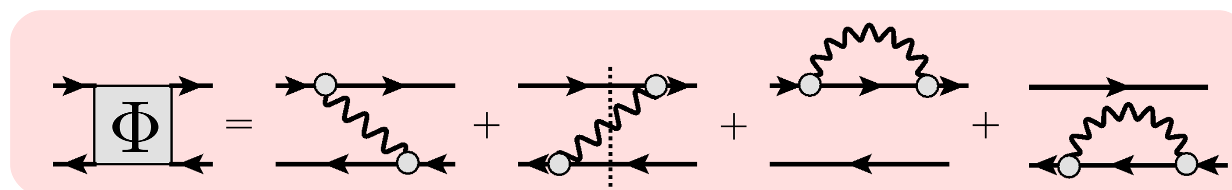
+QVC

energy-dependent interaction:



Isovector static meson exchange

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

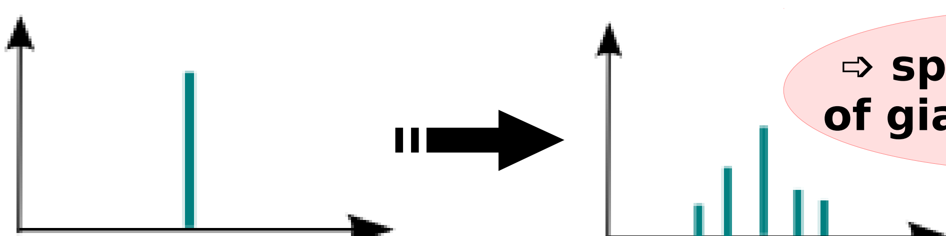


accounts for 2qp ⊗ 1phonon = 4qp configurations

With free-space coupling constant

Landau-Migdal contact term

g'=0.6

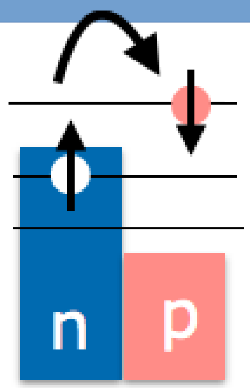


pn-RQRPA state

pn-RQRPA + QVC

⇨ spreading width of giant resonances

Gamow-Teller transitions in Nickel isotopes (Ni → Cu)



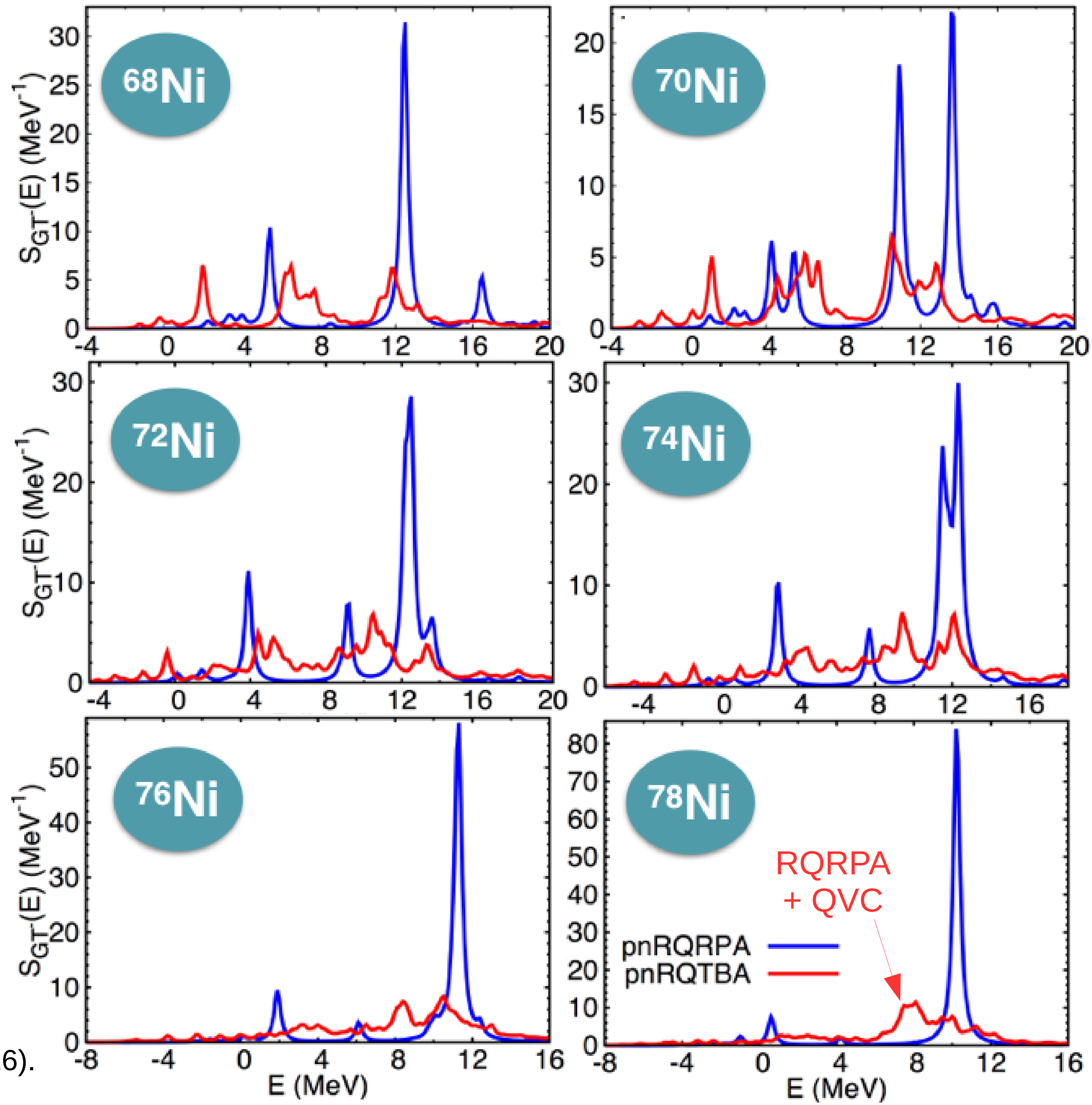
$$F_{GT^-} = \sum_n \begin{pmatrix} \sigma^i_{(n)} & 0 \\ 0 & \sigma^i_{(n)} \end{pmatrix} \tau_-^{(n)}$$

$$\Delta T_z = -1$$
$$\Delta S = 1$$
$$\Delta L = 0$$

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

(Smearing Δ= 200 keV)

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



Gamow-Teller transitions

Two major issues concerning the theoretical description of the GT strength:

- Details of the low-lying strength and prediction of beta-decay half-lives

- “Quenching problem” of the overall strength

Gamow-Teller transitions

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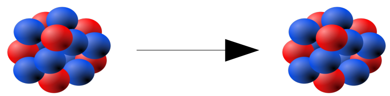
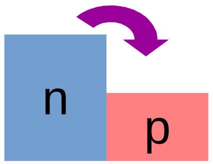
- “Quenching problem” of the overall strength

Low-energy GT strength and beta-decay half-lives

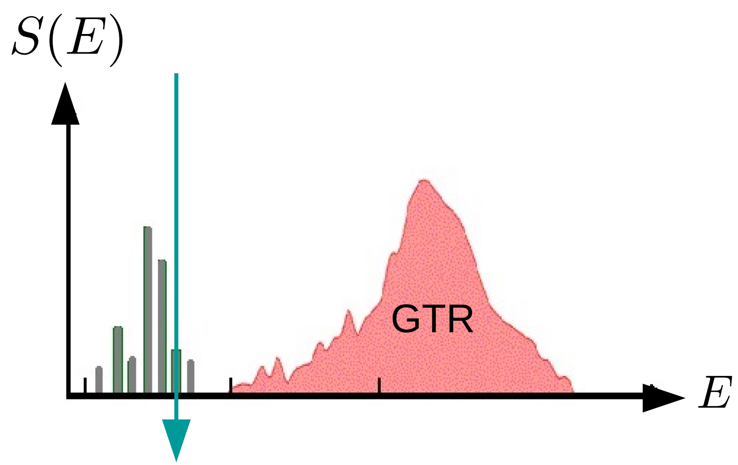
- ß⁻-decay:



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



It is mostly determined by the low-lying GT strength:



Maximal energy release = Q_β = M_{at}(Z,n) – M_{at}(Z+1,N-1)

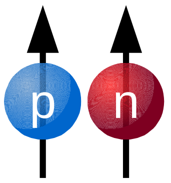
→ beta-decay half-lives: $$\frac{1}{T_{1/2}} = \frac{g_a^2}{D}\int^{Q_\beta} f(Z,Q_\beta - E)S(E)dE$$

Leptonic phase-space factor

Low-energy GT strength and beta-decay half-lives

Problem with QRPA description: the beta-decay half-lives are systematically overestimated.

→ issue overcome by considering T=0 pn-pairing



But this type of pairing is not well understood
(no deuteron condensate → T=0 pairing is dynamic (?)...)
And not well constrained ...

→ often treated phenomenologically with an additional static pn residual interaction in the particle-particle channel.

Low-energy GT strength and beta-decay half-lives

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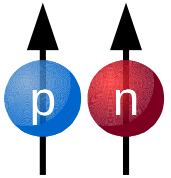


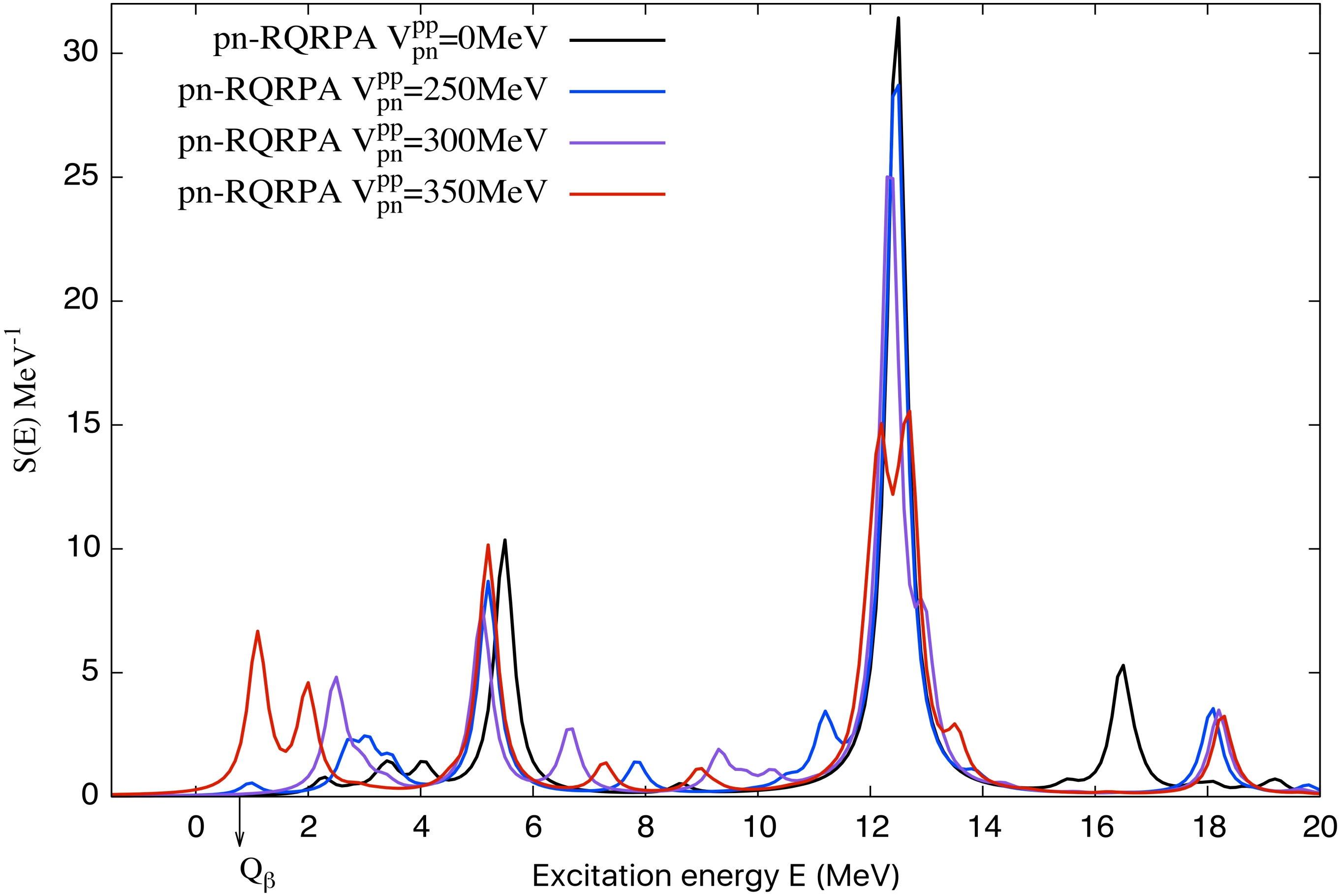
T=0, S=1

But this type of pairing is not well understood
(no deuteron condensate → T=0 pairing is dynamic (?)…)
And not well constrained …

→ often treated phenomenologically with an additional static pn residual interaction in the particle-particle channel.

→ Example in ^{68}Ni:

⇒ Lack of predictive power



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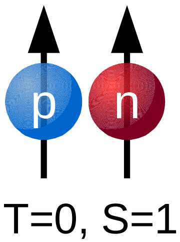
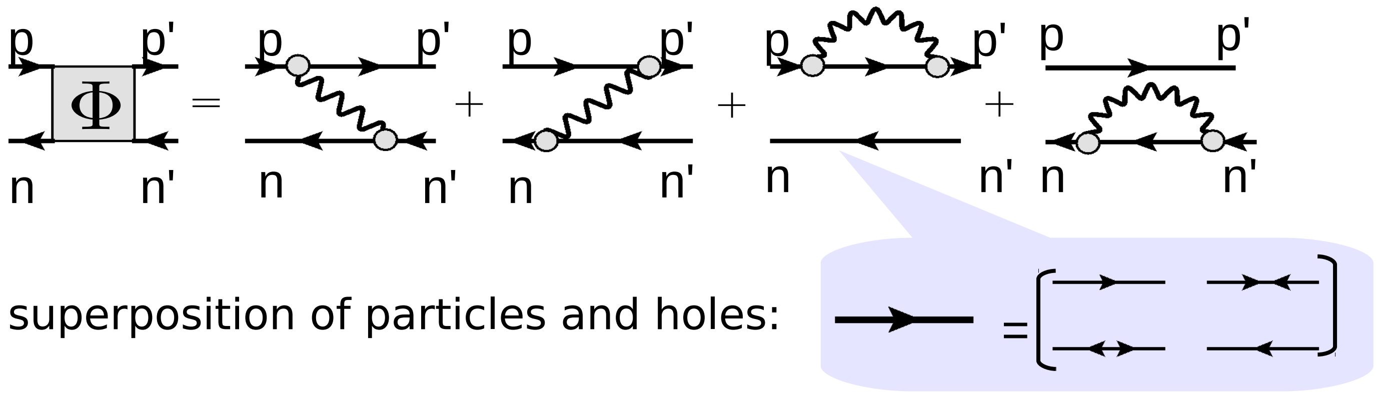


But this type of pairing is not well understood
(no deuteron condensate → T=0 pairing is dynamic (?)...)
And not well constrained ...

→ often treated phenomenologically with an additional static pn residual interaction in the particle-particle channel.

Goal: evaluate the effect of QVC on the half-lives and provide a possible microscopic mechanism for pn-pairing:



Quasiparticle = superposition of particles and holes:

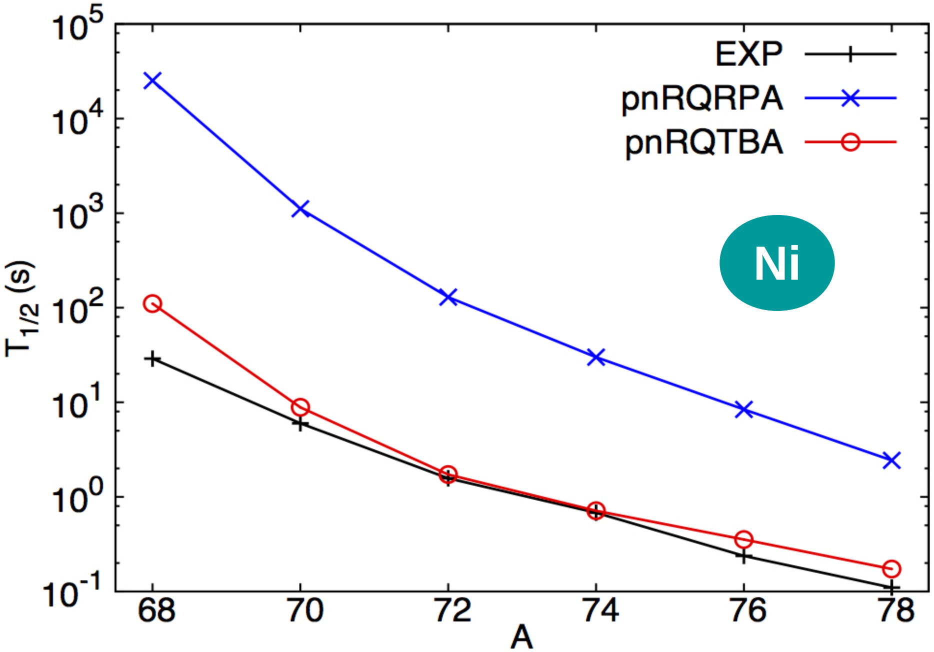
→ QVC generates a pn effective interaction in the particle-hole and particle-particle channels.

→ QVC can provide an underlying mechanism for dynamical proton-neutron pairing

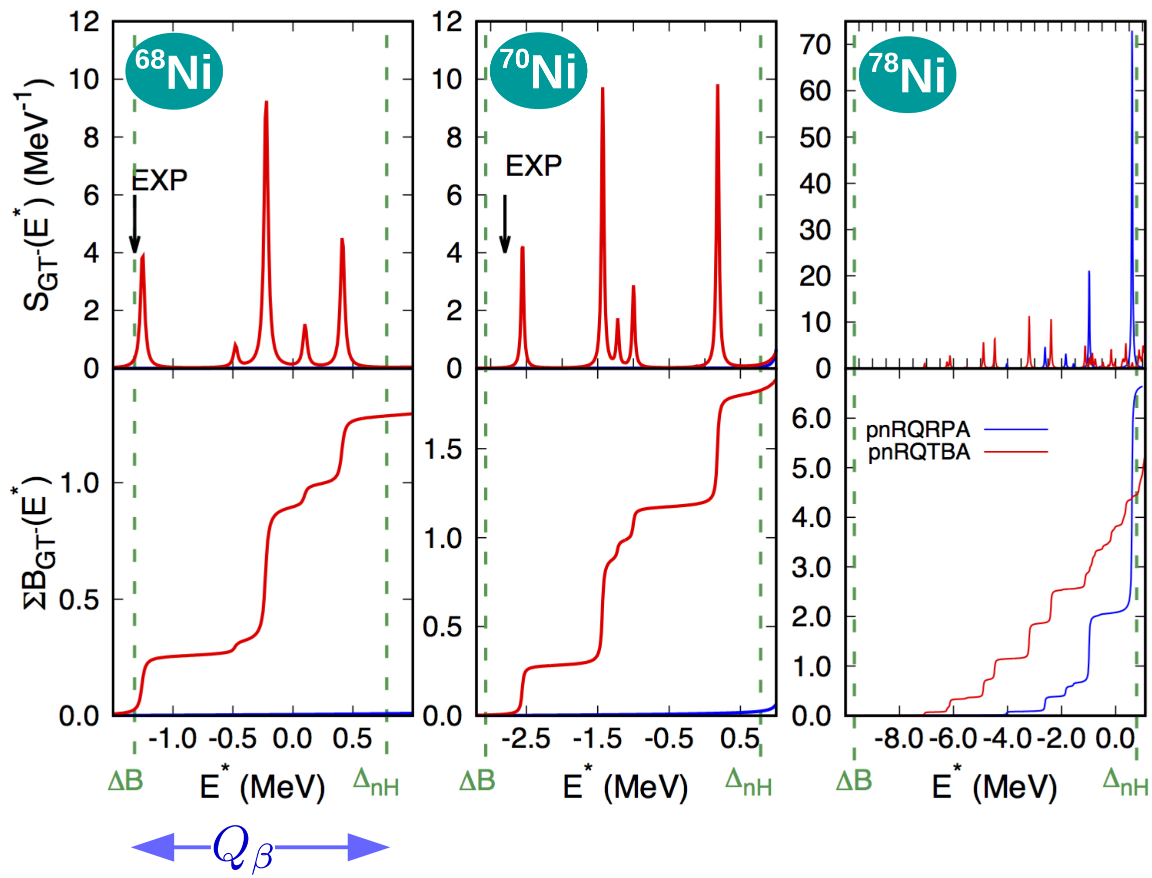
Low-energy GT strength and beta-decay half-lives

- Half-lives and low-energy strength:

With g_a=1



→ big improvement due to QVC!



- ^{68}Ni and ^{70}Ni : appearance of strength in the Q_β window due to QVC → finite lifetime
- ^{78}Ni: more strength with RQRPA but located at higher energies → smaller lifetime with QVC due to phase space factor

exp data from nndc.bnl.gov

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

Gamow-Teller transitions

Two major issues concerning the theoretical description of the GT strength:

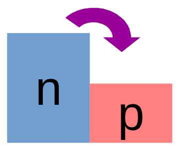
- Details of the low-lying strength and prediction of beta-decay half-lives

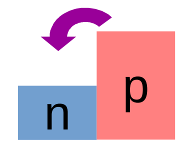
- "Quenching problem" of the overall strength

Gamow-Teller transitions and the "quenching" problem

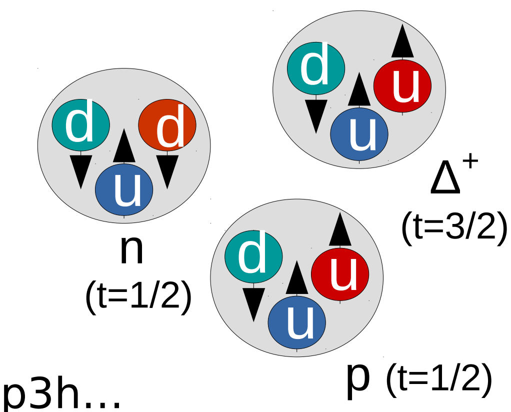
- "Quenching problem":

The observed GT strength (~up to the GR region) in nuclei is ~30-40% less than the model independent Ikeda sum rule: $S_- - S_+ = 3(N-Z)$

$S_- = \sum B(GT^-)$ 

$S_+ = \sum B(GT^+)$ 

$\Rightarrow$ some strength is pushed at high energies → possible mechanisms?



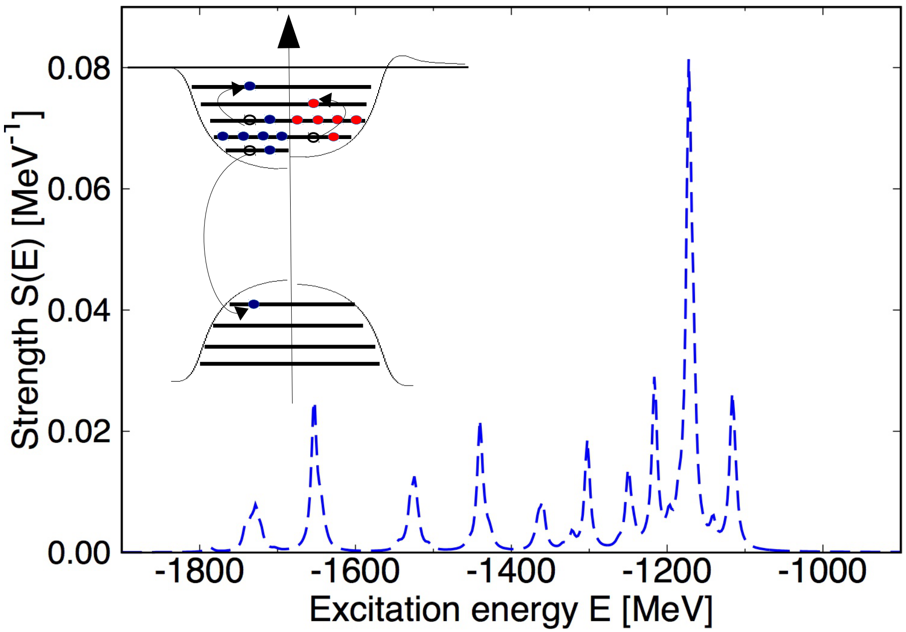
- Coupling of 1p1h to Δ baryon (believed to be small)
- Coupling of 1p1h to higher-order configurations such as 2p2h, 3p3h... (Believed to be the most important)

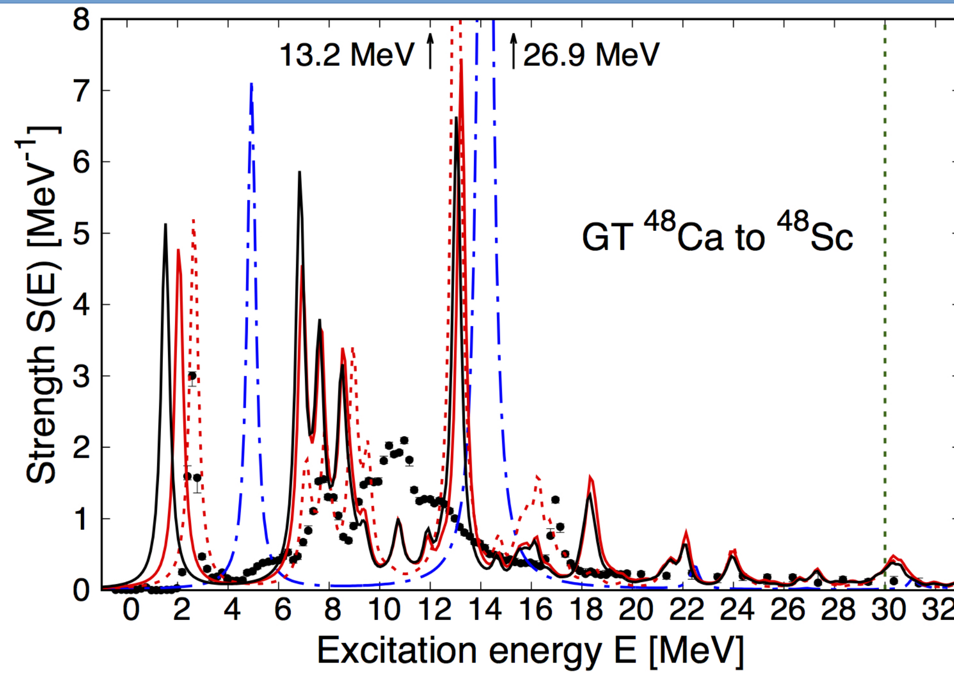
$\Rightarrow$ important to introduce complex configurations in large model spaces

At present with RNFT+TBA:

- 2(q)p-2(q)h configurations
- in an energy window from 30 MeV up to ~100 MeV in light or doubly magic nuclei

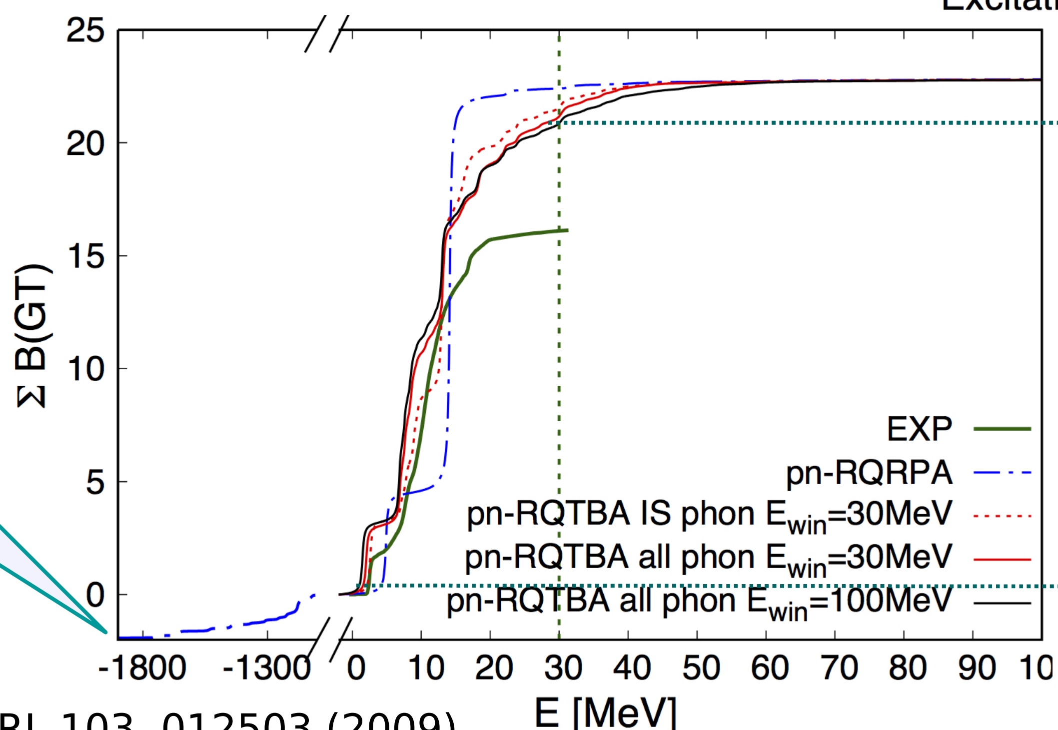
Gamow-Teller transitions and the “quenching” problem





+ transitions from the Fermi sea to the Dirac sea (~8%)

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



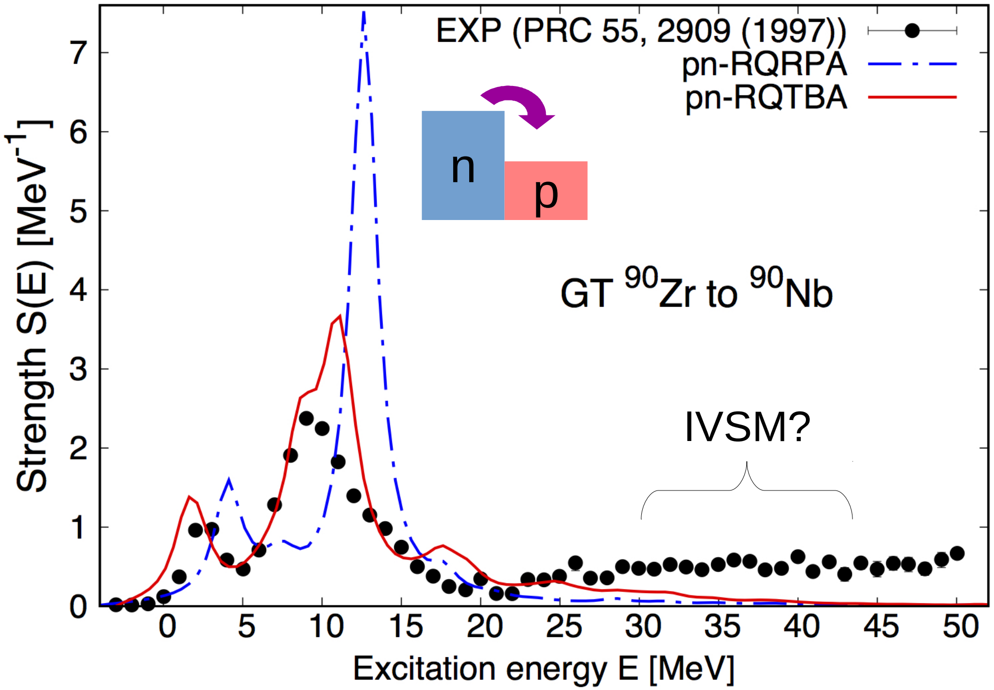
Up to 30 MeV: **~91%** (vs 98% in RQRPA) of the total GT_ strength

→ RQRPA strength naturally “quenched” due to complex configurations

But not enough... (exp: 71%)

EXP: K. Yako et al., PRL 103, 012503 (2009)

Gamow-Teller transitions and the “quenching” problem



GT strength only:

0-50 MeV:

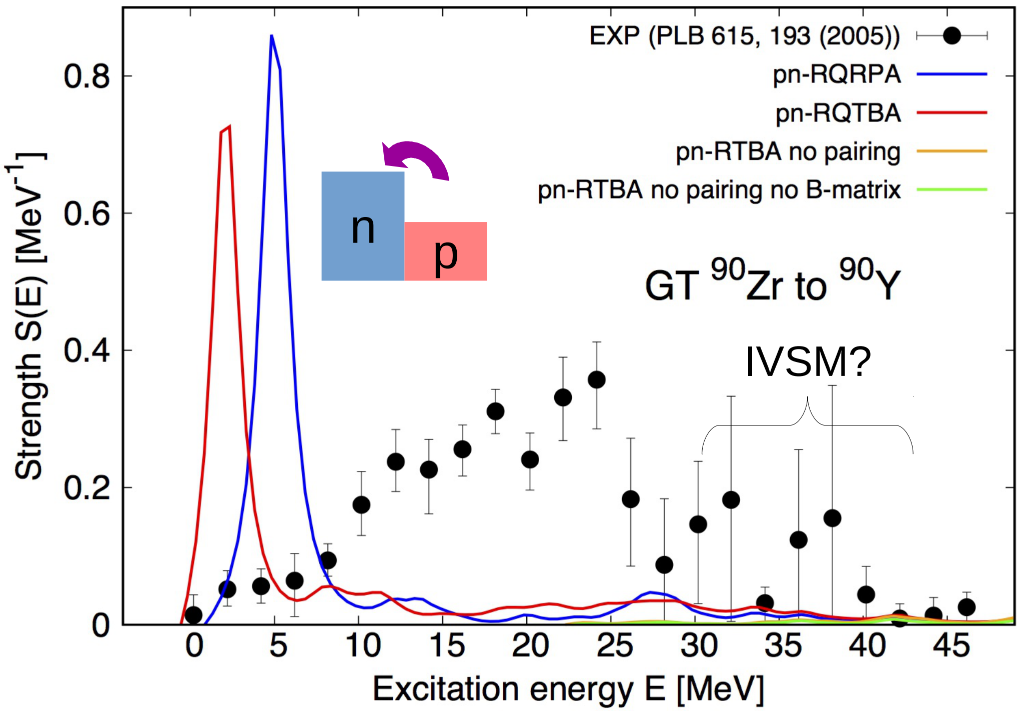
$S_-^{EXP} \sim 29.3$

$S_-^{RQTBA} \sim 30.35$

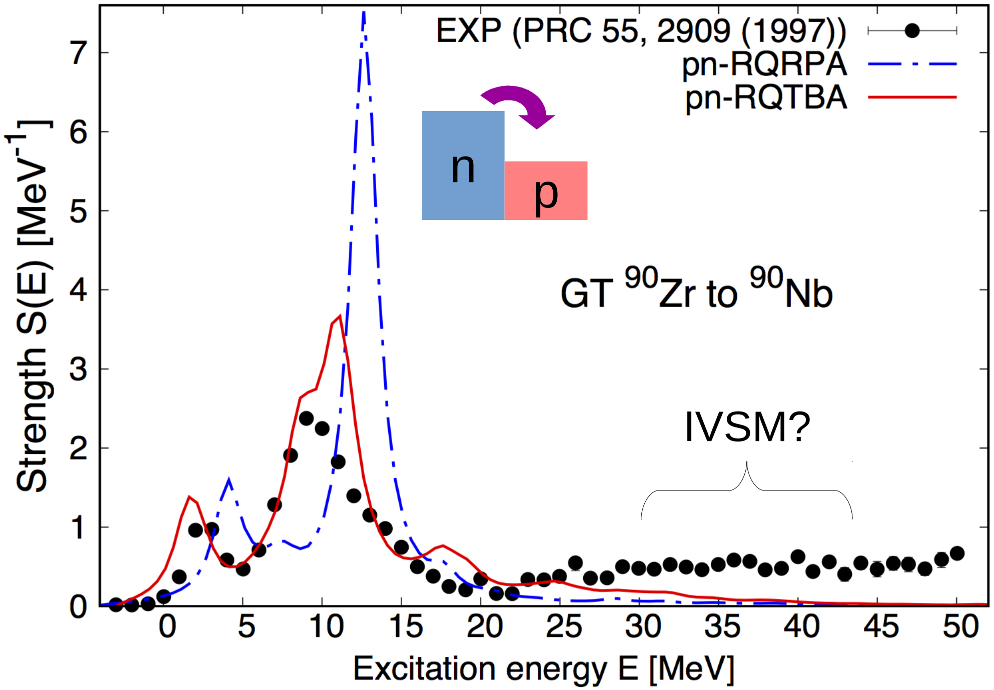
0-32 MeV:

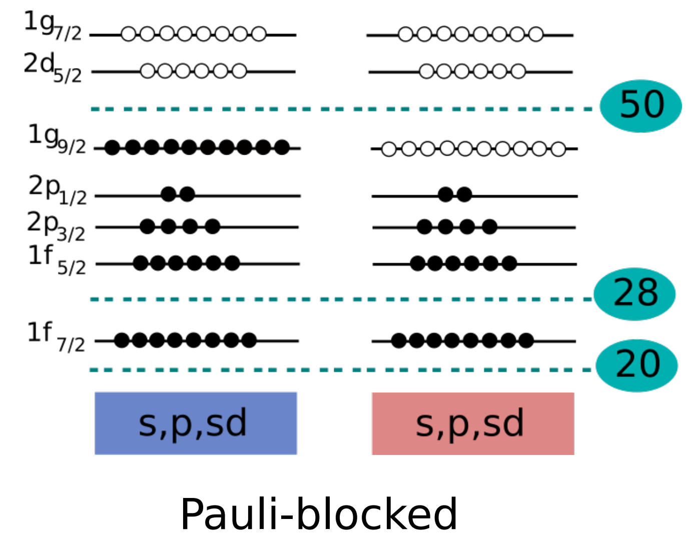
$S_+^{EXP} \sim 2.9$

$S_+^{RQTBA} \sim 2.54$



Gamow-Teller transitions and the "quenching" problem





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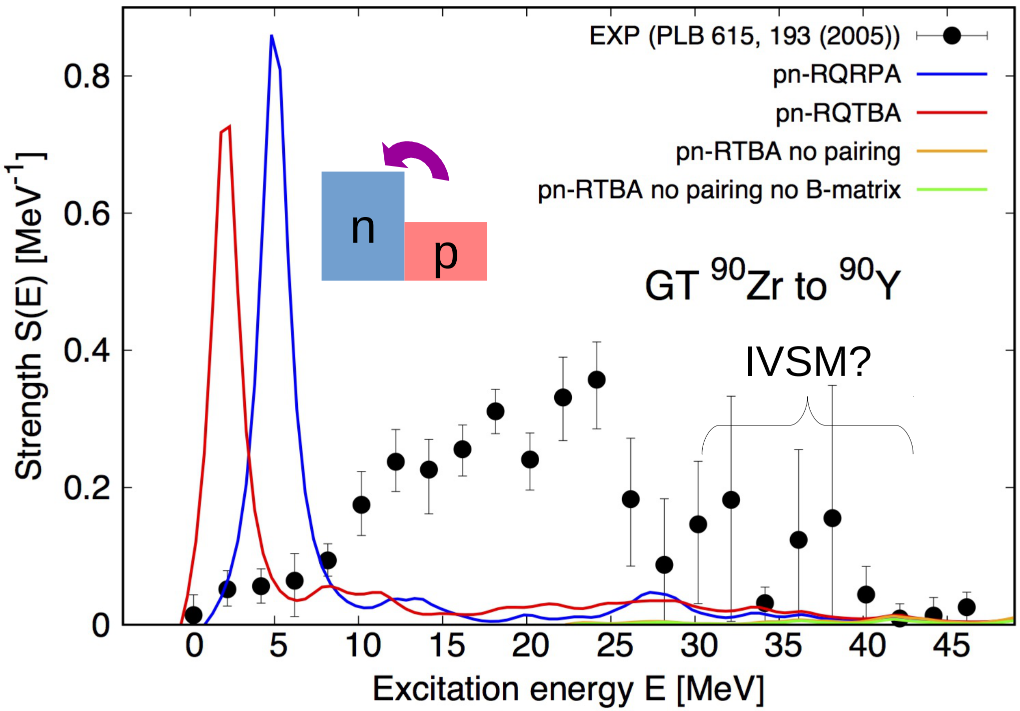
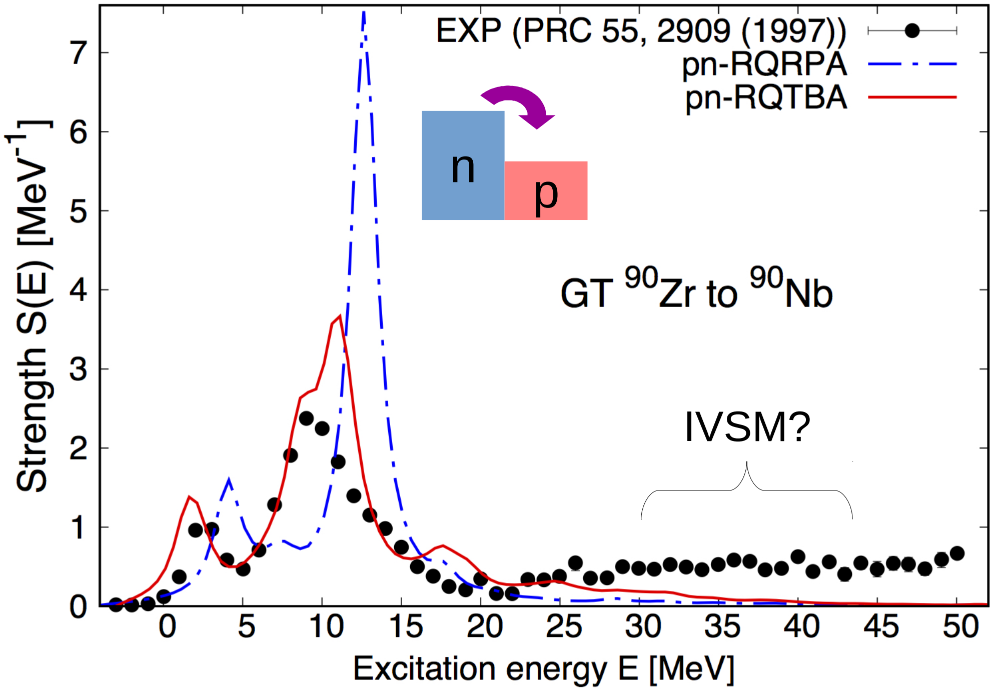
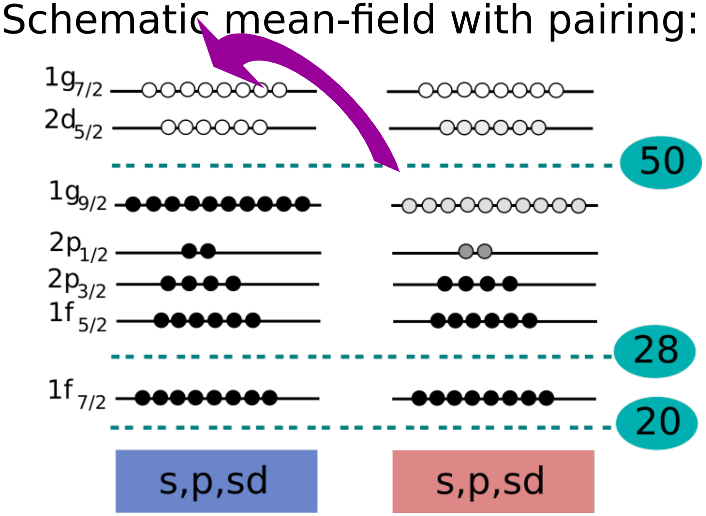


Gamow-Teller transitions and the “quenching” problem



Schematic mean-field with pairing:



GT strength in β$^+$ channel caused by ground-state correlations (pairing here). But need further fragmentation → GSC induced by QVC ?

GT strength only:

0-50 MeV:

$$S_{-}^{EXP} \sim 29.3$$

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0-32 MeV:

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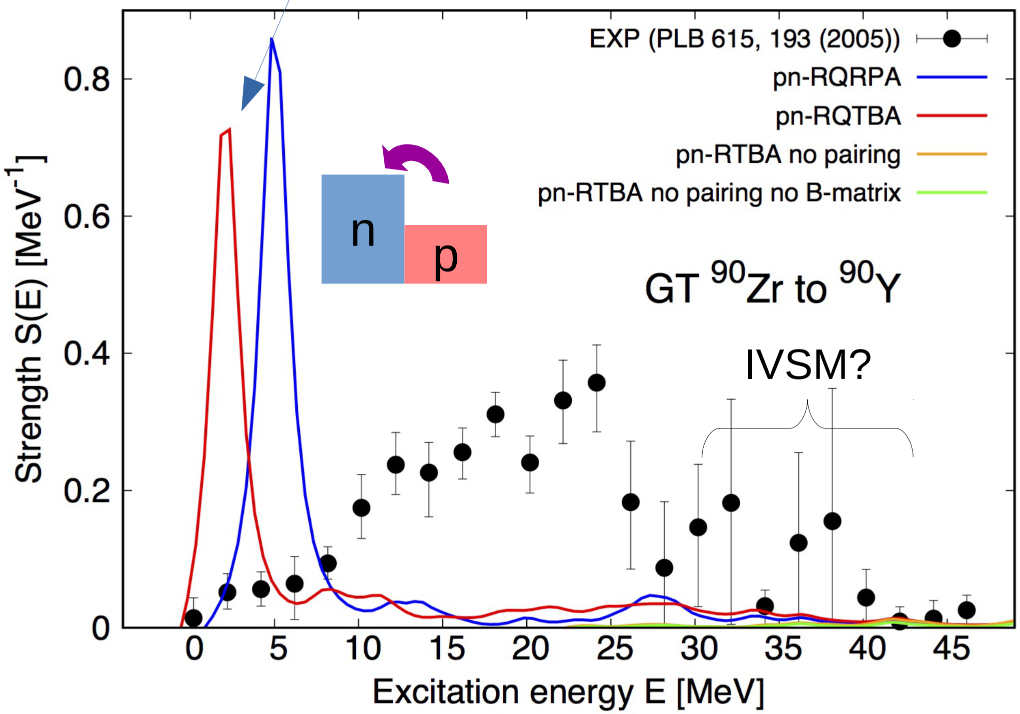

Outline

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  Relativistic Nuclear Field Theory: connecting the scales of nuclear physics from Quantum Hadrodynamics to emergent collective phenomena

- **Response theory for isospin-transfer modes:**
  Gamow-Teller transitions, beta-decay half-lives, the "quenching" problem and the need for higher-order correlations

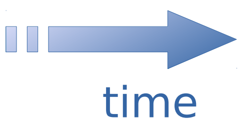
- **Ground-state correlations in the time-blocking approximation**

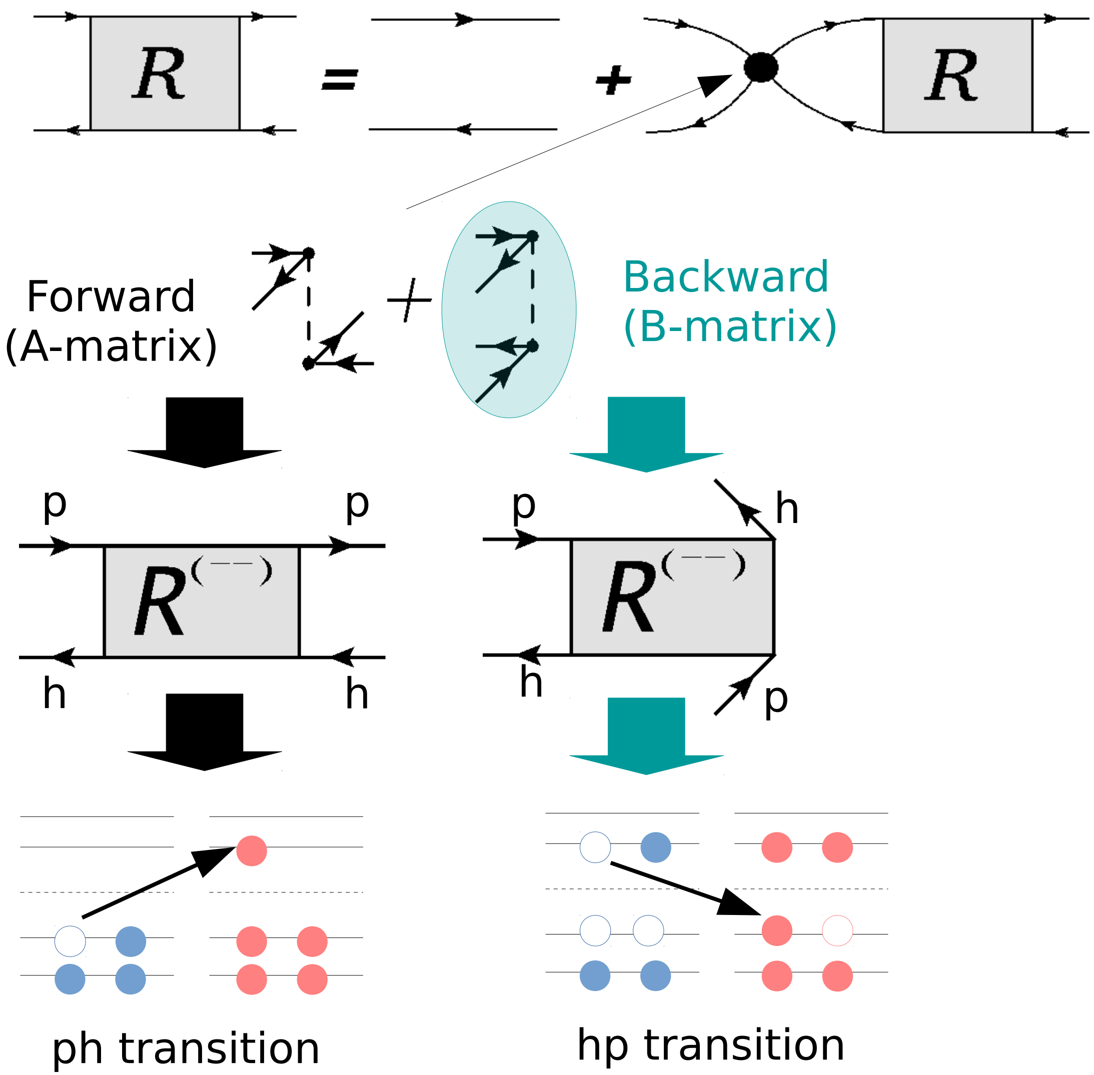
- **Conclusion & perspectives**

Ground-state correlations in RNFT

Ground-state correlations (GSC) in the Green’s functions formalism are generated by the so-called “backward-going diagrams”:

In R(Q)RPA:





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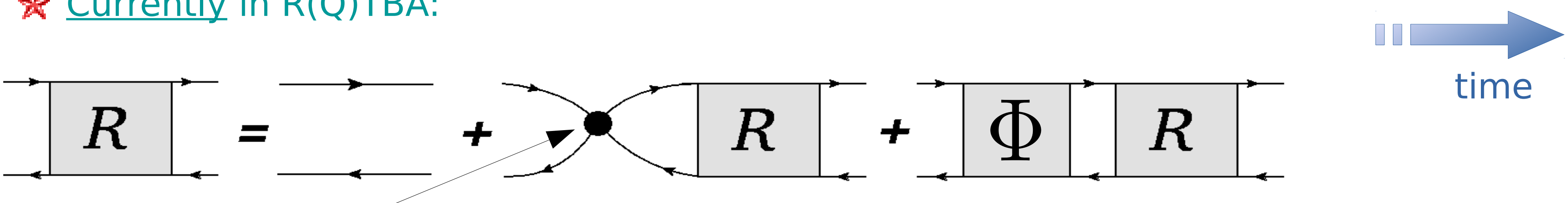
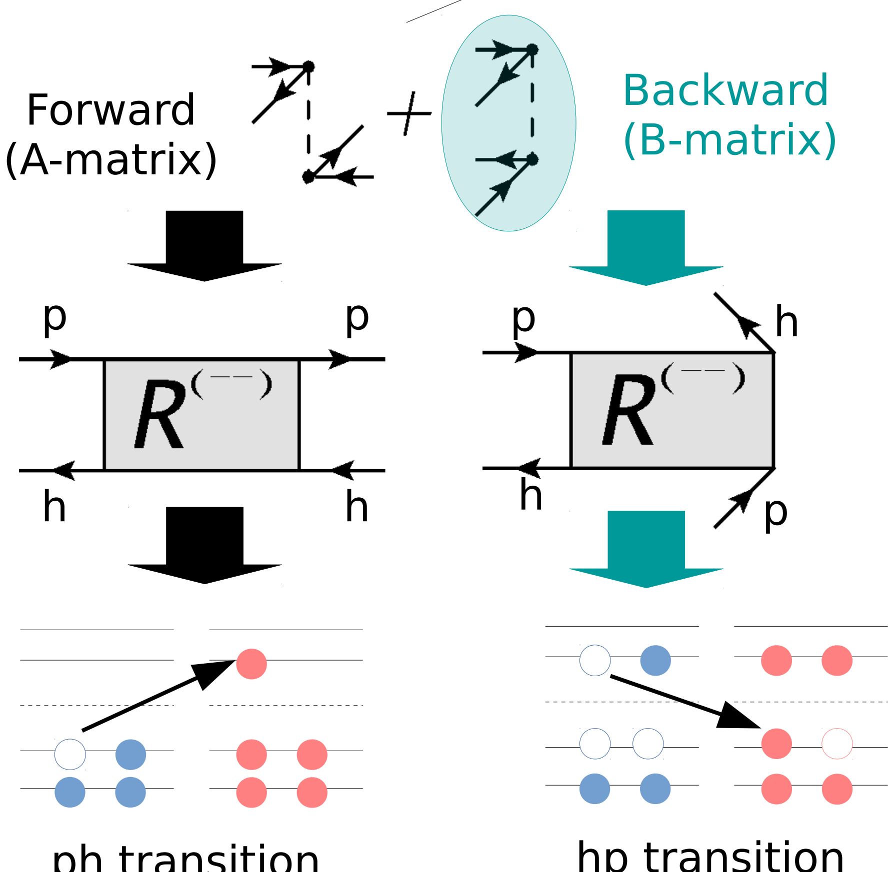
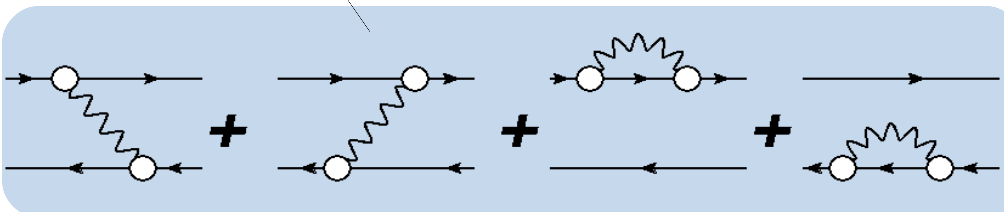
☆ Currently in R(Q)TBA:





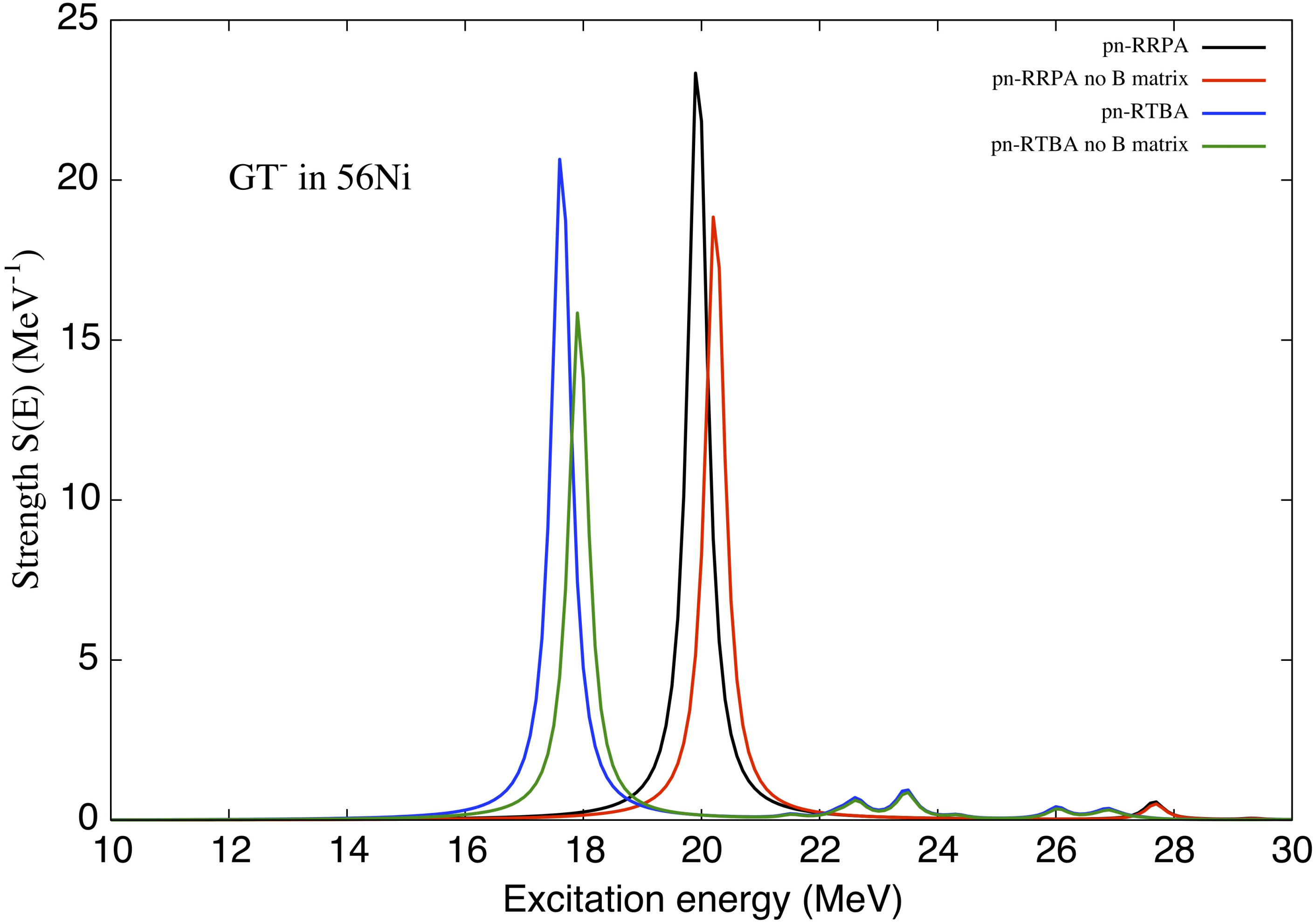


Only forward-going diagrams

⇉ no GSC induced by (quasi)vibration coupling

Ground-state correlations in RNFT

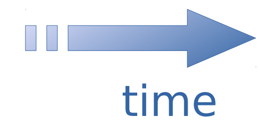
- The B-matrix usually has a minor effect on isospin-transfer modes.
  Example: Role of the B-matrix on the Gamow-Teller strength in ^{56}Ni:

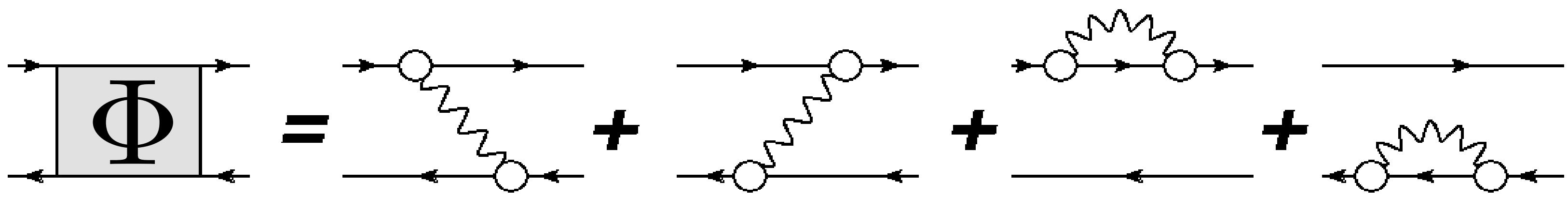


→ small effect although it is known from Shell-Model calculations that the ground-state wave function of ^{56}Ni is importantly fragmented (~65% of 0p-0h configuration).

Ground-state correlations in RNFT

- When GSC induced by QVC are included in the TBA, the component $R^{(--)}$ of the response are modified by the following diagrams:





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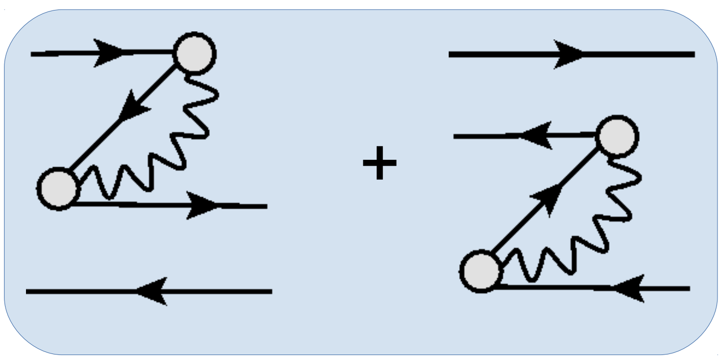
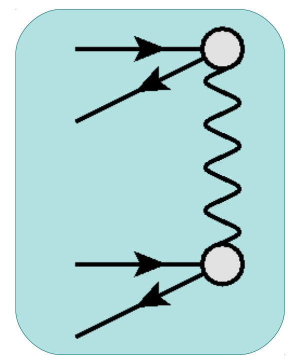


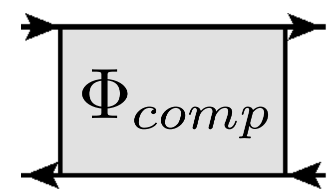
Add to the A-matrix
-
Dynamic but do not introduce new poles

+



Adds to the B-matrix
-
Static

+



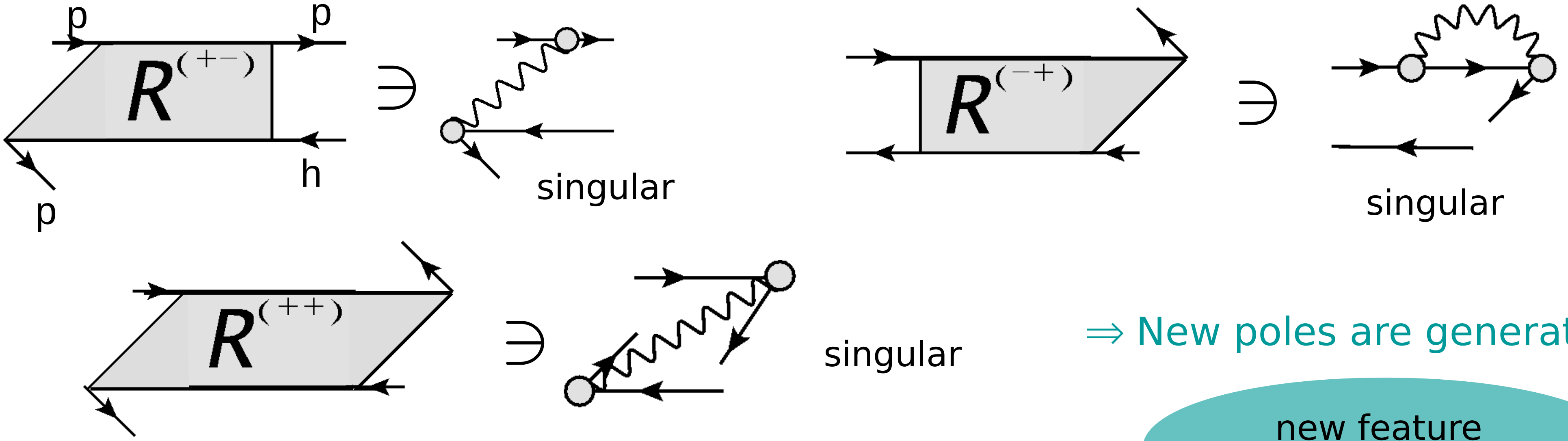
To compensate for double-counting of double self-energy insertions

No new states → these diagrams only shift the previous R(Q)TBA poles

S.P. Kamerdzhiev, G.Ya. Tertychny, V.I. Tselyaev, Fiz. Elem. Chastits At. Yadra 28, 333–390 (1997)

Ground-state correlations in RNFT

Additionally, new components of the response appear:



⇒ New poles are generated

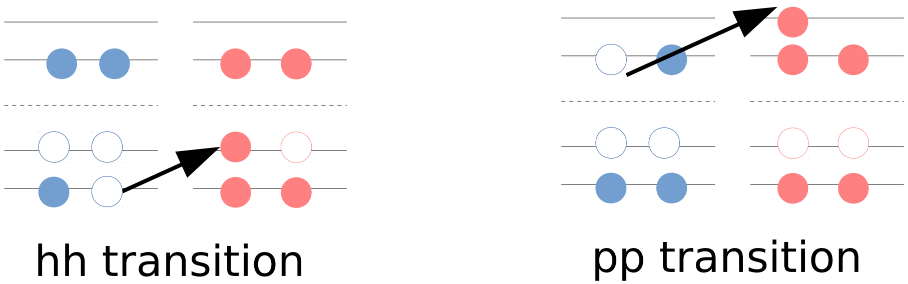
new feature compared to (Q)RPA

These components are related to $R^{(--)}$ through:

$$R(\omega) = \left(1 + Q^{(+-)}(\omega)\right) R^{(--)}(\omega) \left(1 + Q^{(-+)}(\omega)\right) + P^{(++)}(\omega)$$

→ the dimensions of the problem remain the same!

They induce new types of transitions:



→ These effects should be very important for (p,n) strength in n-rich nuclei & (n,p) strength in p-rich nuclei

S.P. Kamerdzhiev, G.Ya. Tertychny, V.I. Tselyaev, Fiz. Elem. Chastits At. Yadra 28, 333–390 (1997)

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Conclusion, perspectives

→ Conclusions:

- The RNFT is a powerful framework for the microscopic description of mid-mass to heavy nuclei, which allows the account for complex configurations of nucleons in a large model space.
- It has been quite successful in the description of neutral excitations (E. Litvinova's talk).
- It appears promising in the spin-isospin channel (description of both the low-energy strength and overall distribution to higher excitation energy).
- However, in its present formulation (time-blocking approximation) it is often not sufficient.

→ Perspectives:

- Inclusion of higher-order configurations (E. Litvinova's talk) and ground-state correlations (ongoing)
- Application to double-charge exchange and double-beta decay ($2\nu\beta\beta$ and $0\nu\beta\beta$)
- Together with RNFT in the 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
- Long-term goals: inclusion of the Fock term, inclusion of two-body currents and Delta resonance, start from bare interaction.

Thank you!

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