Finite-temperature nuclear response in the relativistic framework

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Introduction

- *Motivation: to build a consistent and predictive approach to describe the entire nuclear chart (ideally, an arbitrary strongly-correlated many-body system), numerically executable and useful for applications.*

- *Challenges: the nuclear hierarchy problem, complexity of NN-interaction.*

- *Accurate non-perturbative solutions: Relativistic Nuclear Field Theory (RNFT). Emerged as a synthesis of Landau-Migdal Fermi-liquid theory, Copenhagen-Milano NFT and Quantum Hadrodynamics (QHD); now put in the context of a systematic equation of motion (EOM) formalism and linked to ab-initio interactions.*

- ***n-body correlation functions:** complete characteristics of strongly-coupled many-body systems. Define all dynamical and geometrical properties of nuclear and condensed matter systems, quantum chemistry, **various QFT's**.*

- *Nuclear 2-body correlation functions = observable nuclear response to major neutral and charge-exchange probes: giant EM resonances, Gamow-Teller, spin dipole etc. (neutron capture, gamma and beta decays, pair transfer, …). New: 3p3h correlated configurations have been included up to high excitation energies in medium-mass nuclei.*

- *Nuclear response at finite temperature: (correlated 2p2h) thermal RNFT for transitions between nuclear excited states.*

- *Conclusions and perspectives.*

Equation of motion (EOM) for particle-hole response

Many-body Hamiltonian: $$H = \sum_{12} t_{12}\psi^\dagger{}_1\psi_2 + \frac{1}{4}\sum_{1234}\bar{v}_{1234}\psi^\dagger{}_1\psi^\dagger{}_2\psi_4\psi_3$$ *(or relativistic)*

Particle-hole response (correlation function):

$$R^{(ph)}_{12,1'2'}(t-t') = -i\langle T(\psi_1^\dagger\psi_2)(t)(\psi_{2'}^\dagger\psi_{1'})(t')\rangle$$

spectra of excitations, masses, decays, …

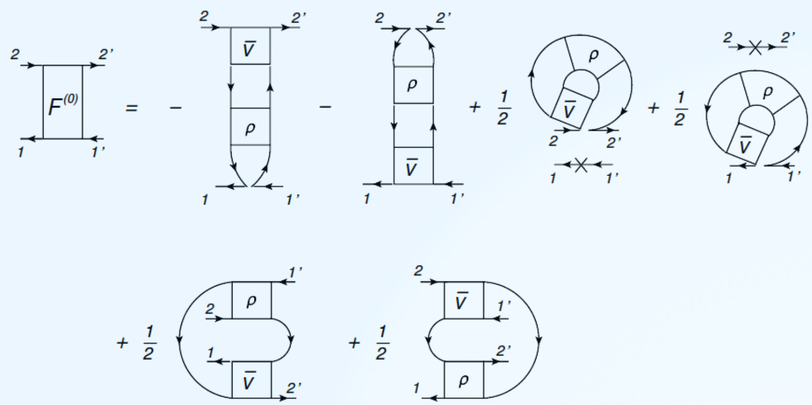
EOM:

$$R(\omega) = R^{(0)}(\omega) + R^{(0)}(\omega)F(\omega)R(\omega) \qquad (*) \qquad F(t-t') = F^{(0)}\delta(t-t') + F^{(r)}(t-t')$$

Free propagator — $R^{(0)}(\omega)$

Irreducible kernel: — $F(\omega)$

instantaneous term ("bosonic" mean field):



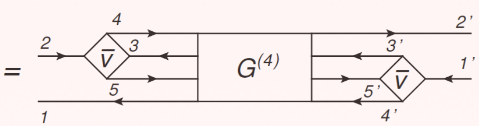
Mean field $F^{(0)}$, where $$\rho_{12,1'2'} = \lim_{t\to t'-0} R(12,1'2')$$

*contains the full solution of (*) **including the dynamical term!***

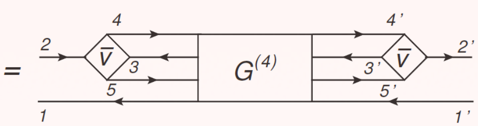
t-dependent (dynamical) term:

$$F^{(r)}_{12,1'2'}(t-t') = F^{(r;11)}_{12,1'2'}(t-t') + F^{(r;12)}_{12,1'2'}(t-t') + F^{(r;21)}_{12,1'2'}(t-t') + F^{(r;22)}_{12,1'2'}(t-t')$$

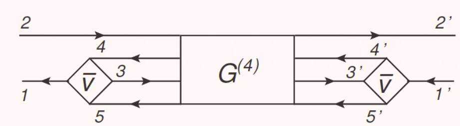
$F^{(r;11)}_{121'2'} =$



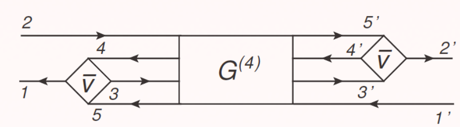
$F^{(r;12)}_{121'2'} =$



$F^{(r;21)}_{121'2'} =$



$F^{(r;22)}_{121'2'} =$



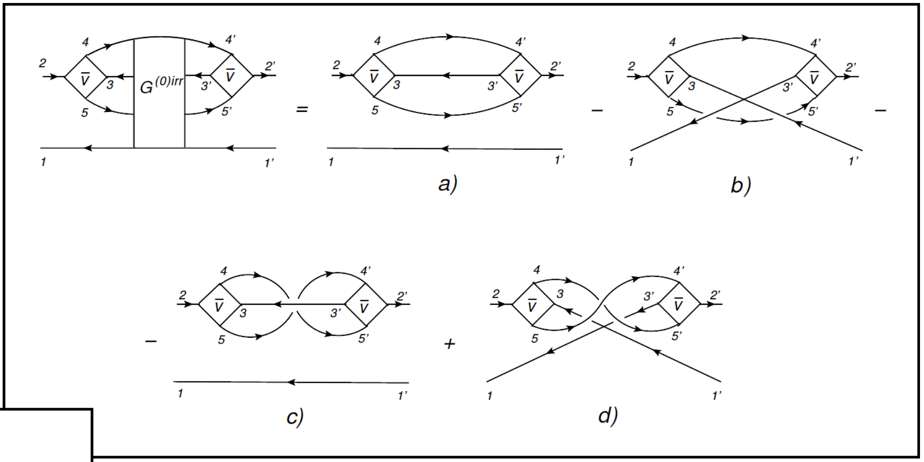
EOM: S. Adachi and P. Schuck, NPA496, 485 (1989).
J. Dukelsky, G. Roepke, and P. Schuck, NPA 625, 14 (1995).
P. Schuck and M. Tohyama, PRB 93, 165117 (2016). Etc.

Expansion of the dynamics kernel $F^{(r;12)irr}$: truncation on the 2-body level

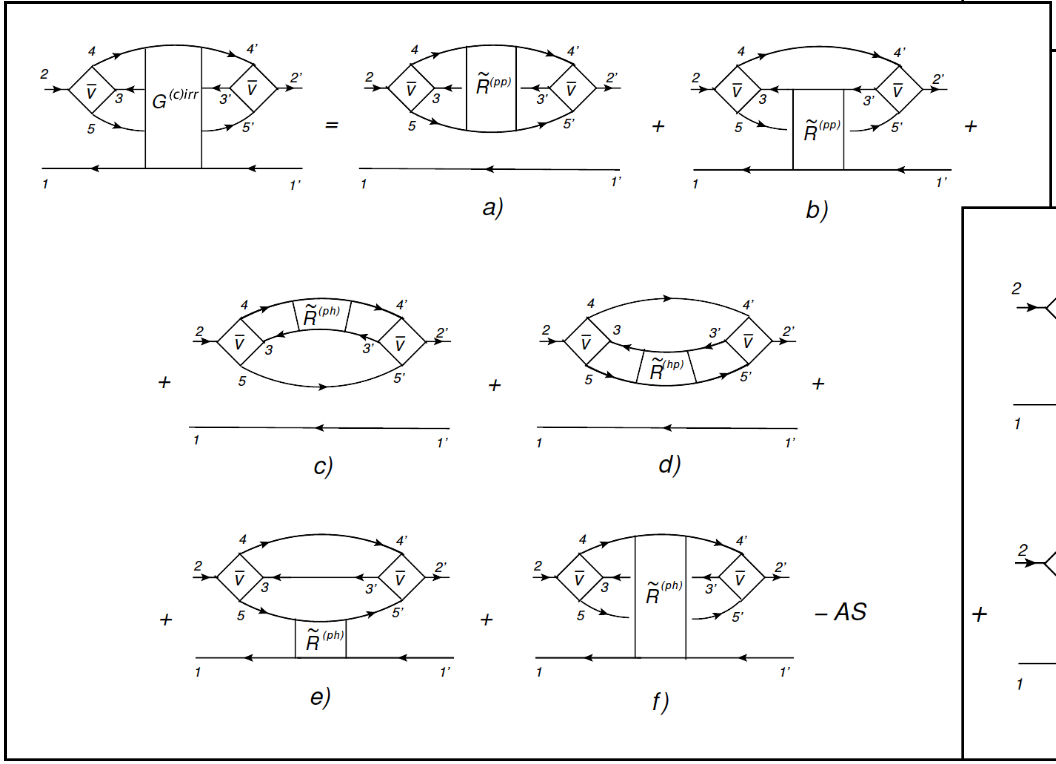
P. Schuck and M. Tohyama:
Irreducible part of $G^{(4)}$ is decomposed into uncorrelated, singly-correlated and doubly-correlated terms (approximation, but very accurate):

$$G^{irr}(543'1',5'4'31) = G^{(0)irr}(543'1',5'4'31) + \\ + G^{(c)irr}(543'1',5'4'31) + G^{(cc)irr}(543'1',5'4'31)$$

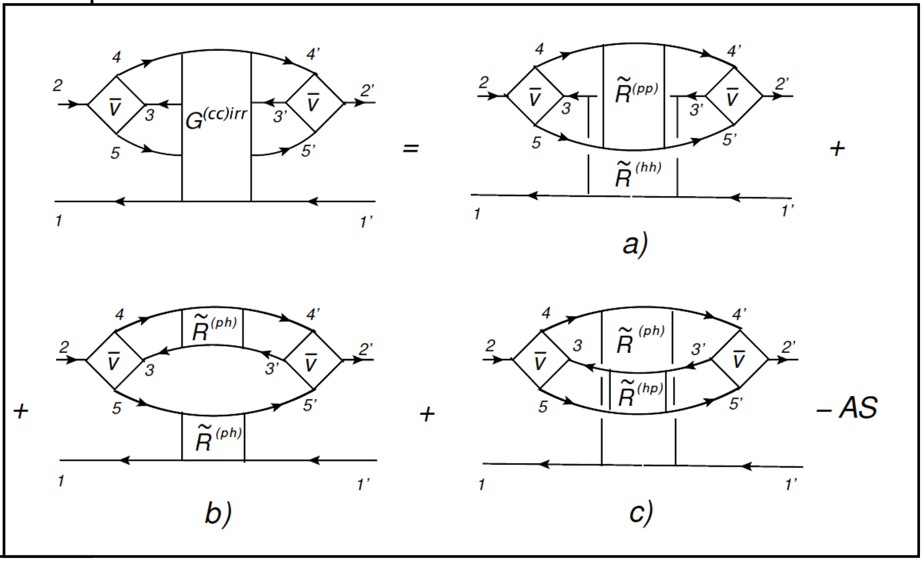
(i) Uncorrelated terms ("Second RPA"):



(ii) Singly-correlated terms, up to phases (PVC, QVC, …):

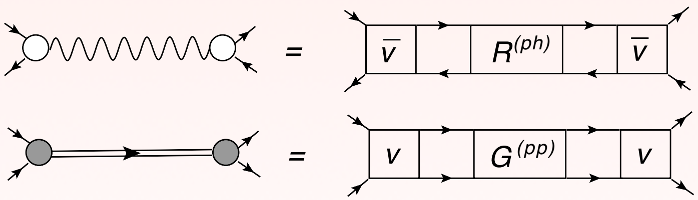


(iii) Doubly-correlated terms, up to phases (generalized QVC):



Model-independent mapping to the QVC-TBA:

$$\sum_{343'4'} \tilde{V}^{*}_{12,34} R_{34,3'4'}(\omega) \tilde{V}_{3'4'1'2'} = \sum_m g^{m*}_{12} D_m(\omega) g^{m}_{1'2'}$$



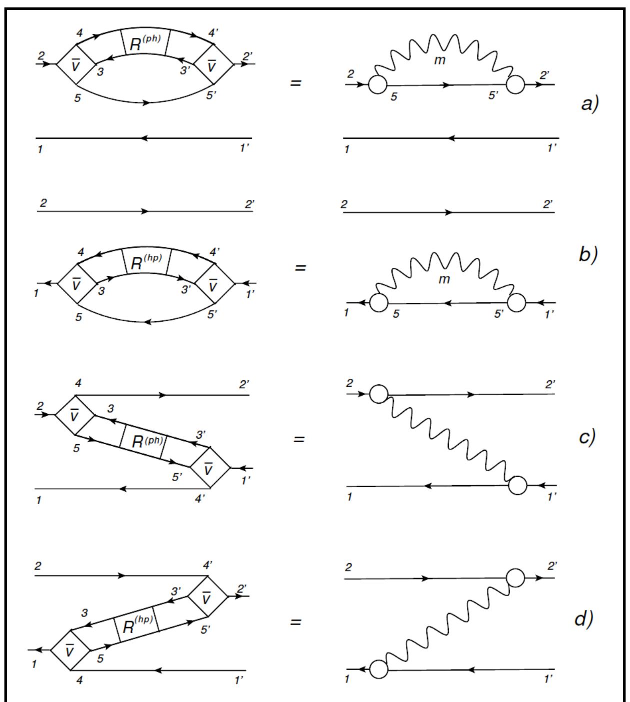
$$R_{12,1'2'}(\omega) = \sum_m \Big(\frac{\rho^{m*}_{12}\rho^{m}_{1'2'}}{\omega - \Omega_m + i\delta} - \frac{\rho^{m}_{21}\rho^{m*}_{2'1'}}{\omega + \Omega_m - i\delta} \Big)$$

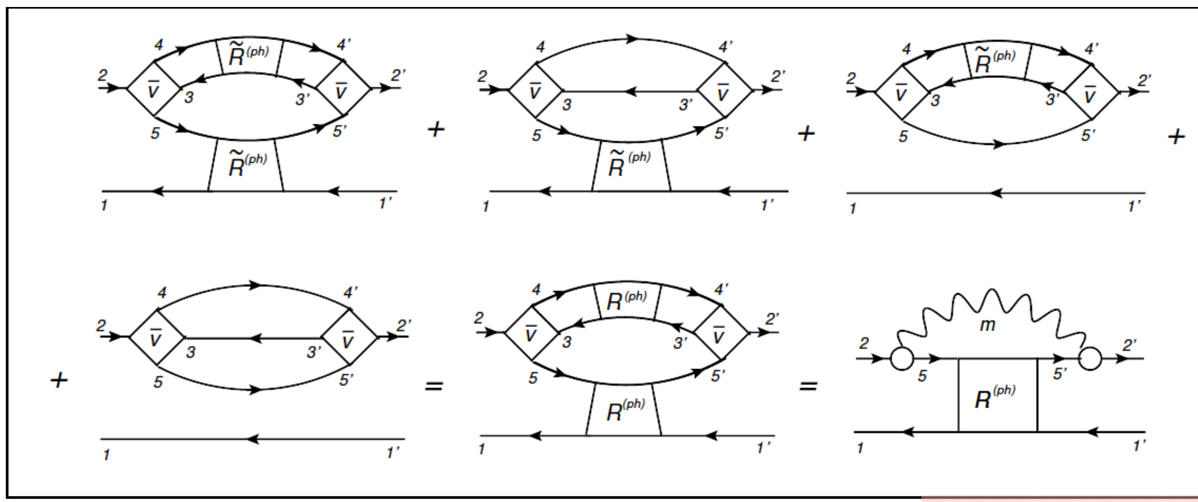
$$g^{m}_{12} = \sum_{34} \tilde{V}_{12,34}\rho^{m}_{34}$$ *"phonon" vertex*

$$D_m(\omega) = \frac{1}{\omega - \Omega_m + i\delta} - \frac{1}{\omega + \Omega_m - i\delta}$$ *"phonon" propagator*

Original QVC (NFT, R(Q)TBA): non-correlated and main singly-correlated terms:

Generalized R(Q)TBA (E.L. PRC91, 034332 (2015): *meets EOM: ALL correlated terms*





Self-consistent closed system of equations

$$\boxed{\hat{R}(\omega) = \hat{R}^{(0)}(\omega) + \hat{R}^{(0)}(\omega) W[\hat{R}(\omega)]\hat{R}(\omega)}$$

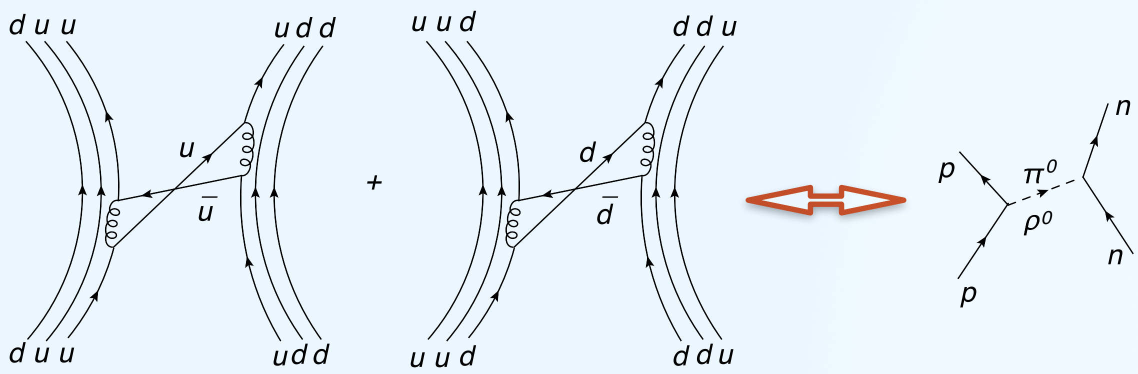
All channels are coupled in W[R(ω)]

E.L., P. Schuck, in progress

The underlying NN-interaction: meson exchange (ME)

Neutral mesons σ, ω, π, ρ…:

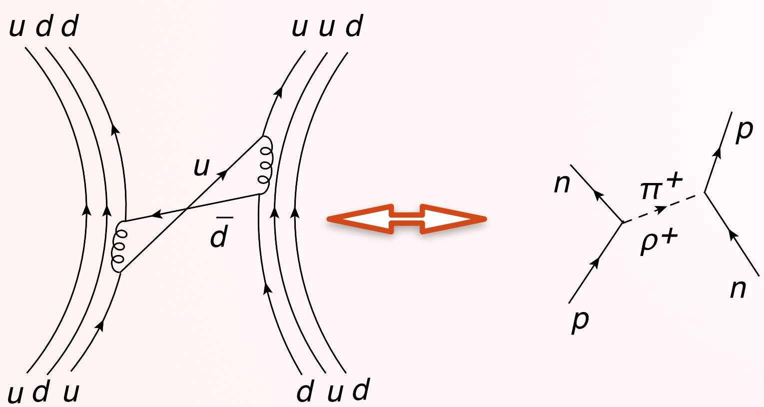
QCD   QHD



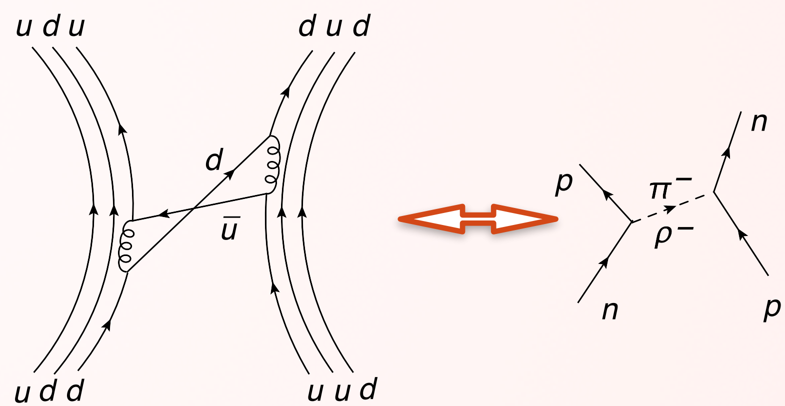
- *The full many-body scheme has not been (yet) executed neither for the bare meson-exchange (ME) interaction nor for any other bare interaction.*
- *A good starting point - the use of effective ME interactions adjusted to nuclear bulk properties on the mean-field level (J. Walecka, M. Serot, …, P. Ring) and to supplement the many-body correlation theory with proper subtraction techniques (V. Tselyaev), in the covariant framework.*

Charged mesons: π, ρ,…

QCD   QHD

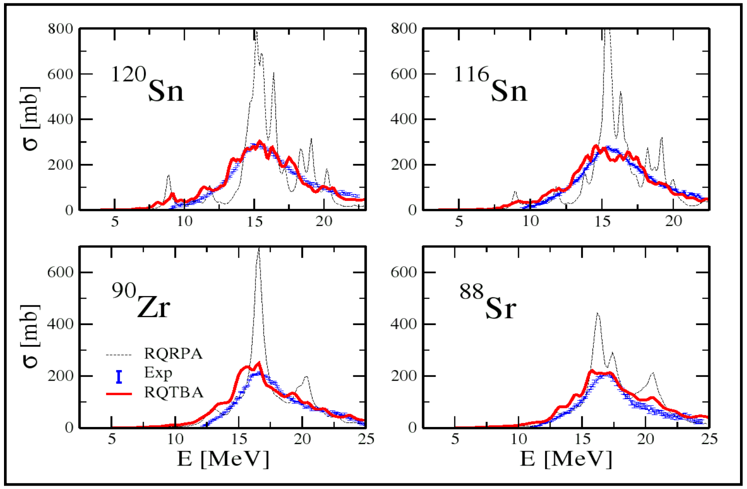


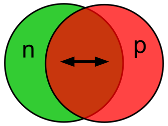
QCD   QHD



Response of medium-mass and heavy nuclei within Relativistic (Quasiparticle) Time Blocking Approximation (R(Q)TBA)

Giant dipole resonance (GDR) in stable nuclei



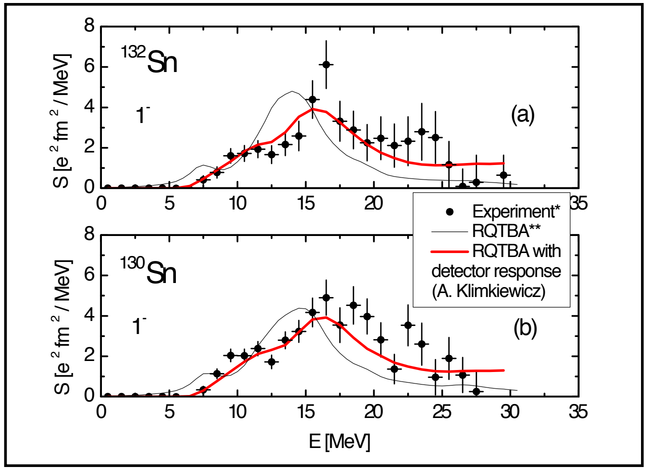


**E. L., P. Ring, and V. Tselyaev et al.,
Phys. Rev. C 78, 014312 (2008).
Phys. Rev. C 79, 054312 (2009).
Phys. Rev. Lett. 105, 022502 (2010).
Phys. Rev. C 88, 044320 (2013).

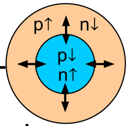
J. Endres, E. Litvinova, D. Savran et al., Phys. Rev. Lett. 105, 212503 (2010).

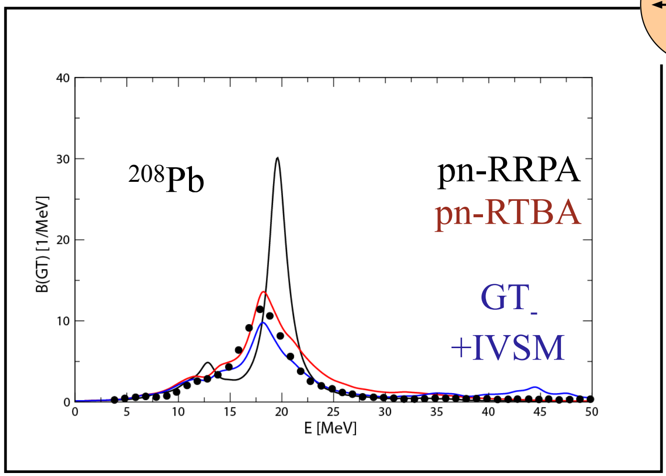
…

GDR in neutron-rich Sn



Gamow-Teller resonance





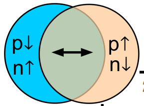
E.L., B.A. Brown, D.-L. Fang, T. Marketin, R.G.T. Zegers,
Phys. Lett. B 730, 307 (2014).

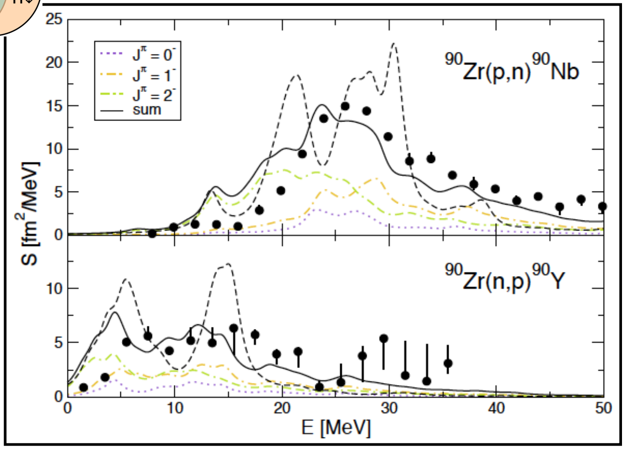
T. Marketin, E.L., D. Vretenar, P. Ring,
Phys. Lett. B 706, 477 (2012).

C. Robin and E. Litvinova,
Eur. Phys. J. A 52, 205 (2016).

E. Litvinova, C, Robin, and I.A. Egorova,
Phys. Lett. B 776, 72 (2018).

Spin-dipole resonance

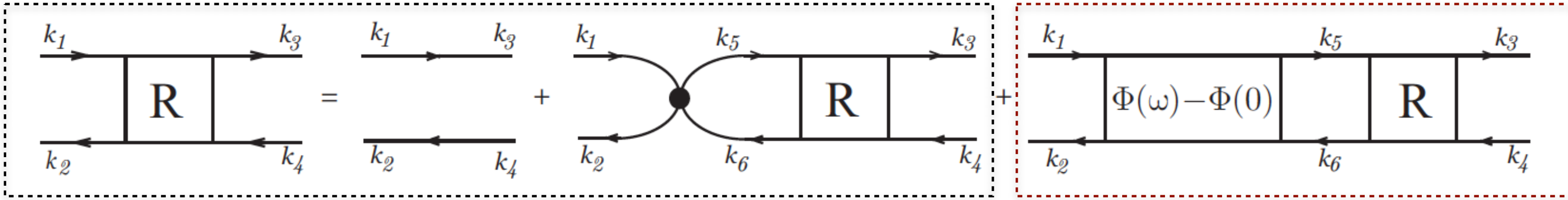




The dynamical part of the interaction kernel (quasiparticle-vibration coupling) brings a significant overall improvement to the description of both high-frequency and low-lying strengths.

Higher orders: toward a "complete" theory

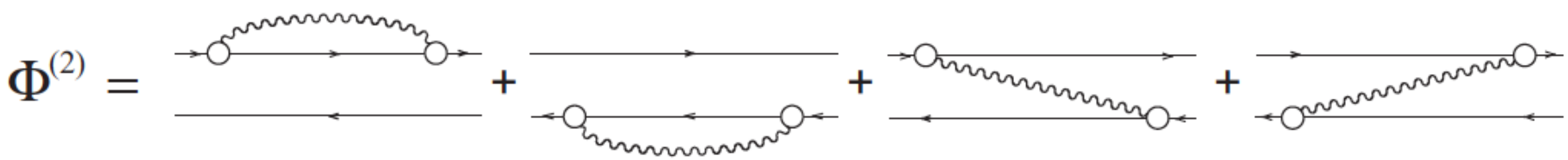
Bethe-Salpeter (Dyson) Equation for the ph-response:



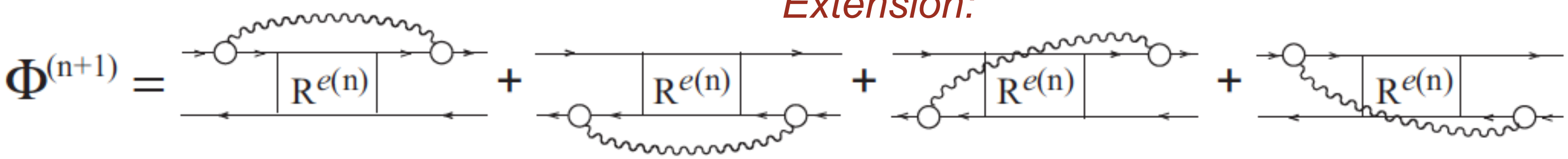
(Q)RPA

(Q)PVC

"Conventional" Nuclear Field Theory and Time Blocking Approximation:

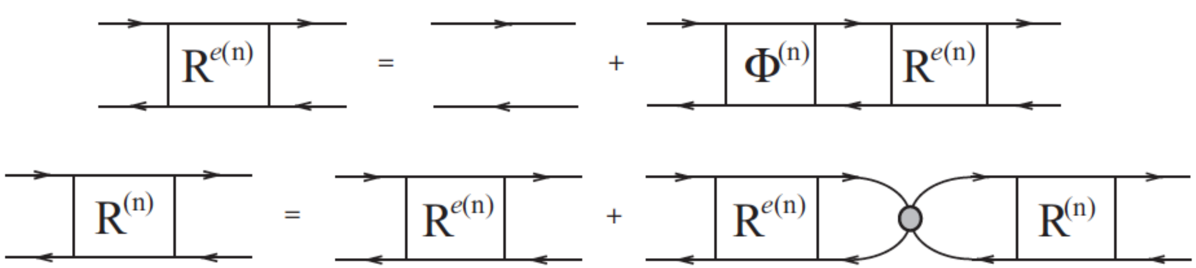


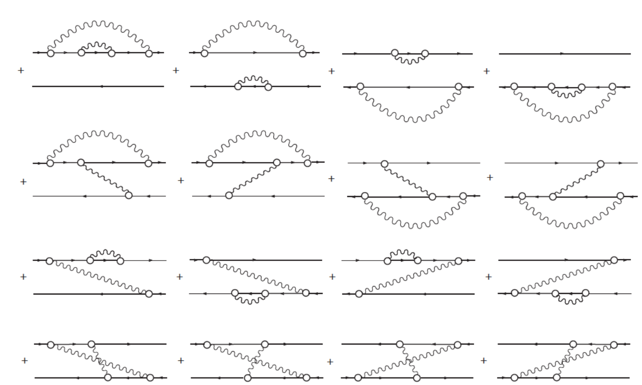
Extension:



n = 3: 3p3h (3-body effects)

n-th order correlated propagator:

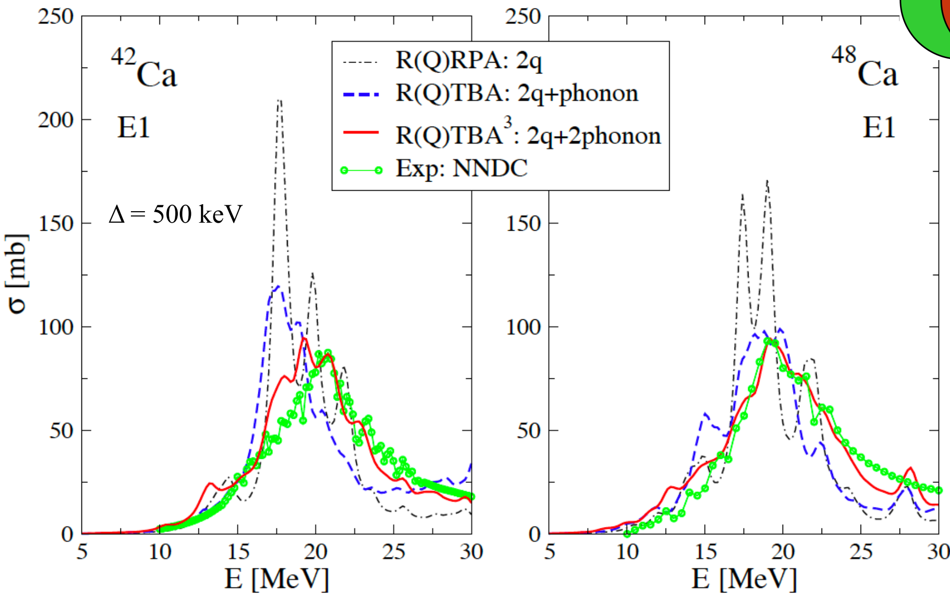


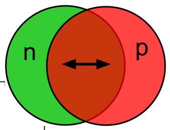


E.L. PRC 91, 034332 (2015)

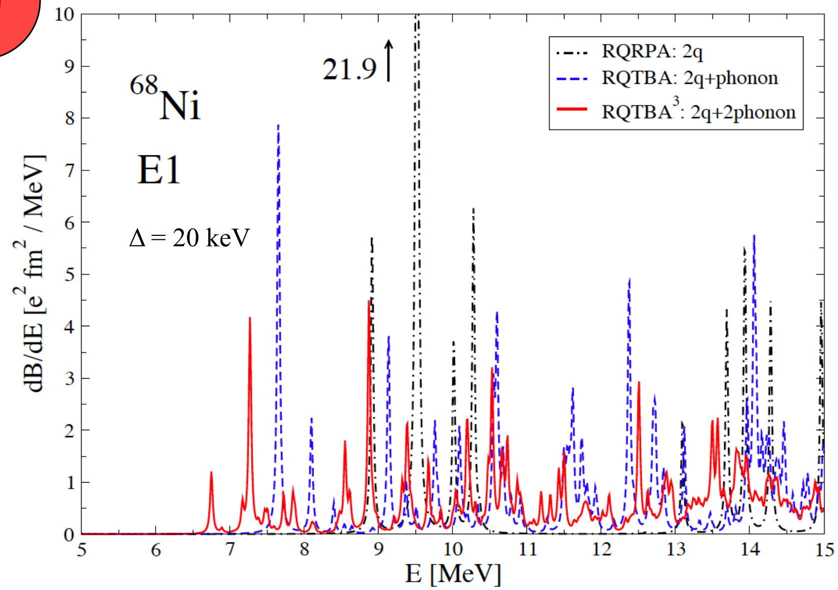
RQTBA^3: partly correlated 3p3h configurations (preliminary results)

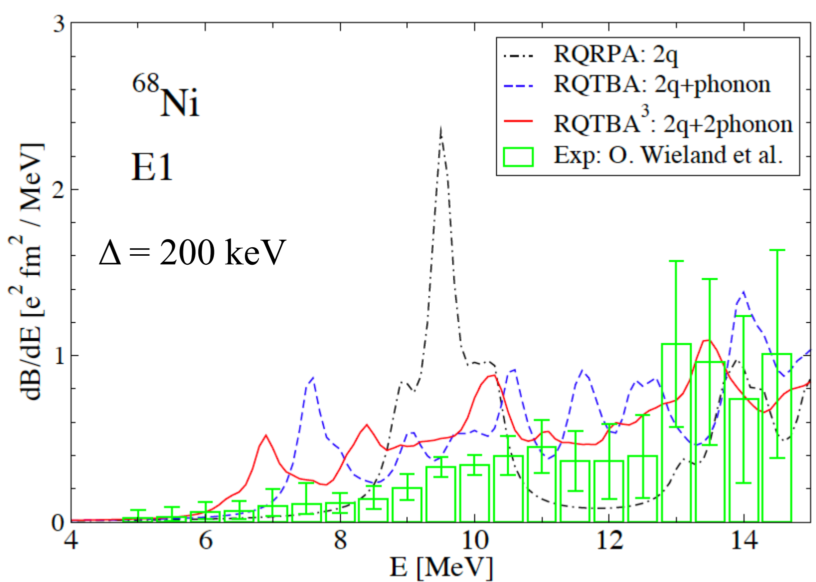
Giant Dipole Resonance in Ca isotopes





Pygmy Dipole Resonance in ^{68}Ni

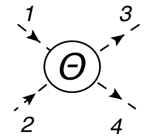


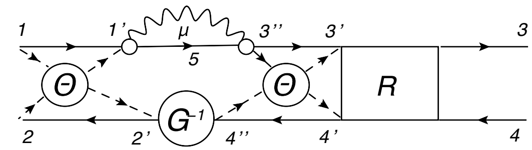


- *The new complex configurations 2q+2phonon included for the first time enforce fragmentation and spreading toward higher and lower energies, thus, modifying both giant and pygmy dipole resonances;*
- *Exp. Data: V.A. Erokhova et al., Bull. Rus. Acad. Phys. 67, 1636 (2003) O. Wieland et al., Phys. Rev. C 98, 064313;*
- *RQTBA^3 demonstrates an overall systematic improvement of the description of nuclear excited states heading toward spectroscopic accuracy without strong limitations on masses and excitation energies.*

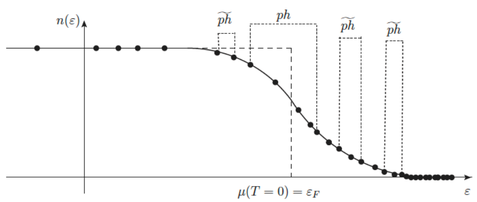
Time blocking (diagram ordering) at T>0: 2q+phonon case

$$\Theta(14,23;T) = \delta_{\sigma_1,-\sigma_2}\theta(\sigma_1 t_{14})\theta(\sigma_1 t_{23})$$
$$\times\left[n(\sigma_1\varepsilon_2,T)\theta(\sigma_1 t_{12}) + n(-\sigma_1\varepsilon_1,T)\theta(-\sigma_1 t_{12})\right]$$





$$\sigma_1 = sign(\varepsilon_1 - \varepsilon_2)$$



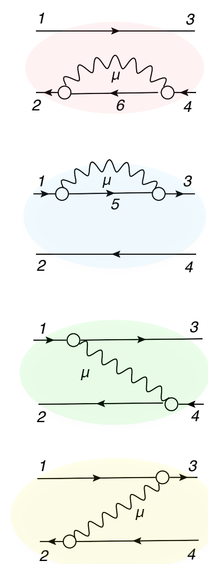
"Soft" time blocking at T>0 leads to a single-frequency variable equation for the response function

$$\mathcal{R}_{14,23}(\omega,T) = \tilde{\mathcal{R}}^0_{14,23}(\omega,T) +$$
$$+\sum_{1'2'3'4'}\tilde{\mathcal{R}}^0_{12',21'}(\omega,T)\left[\tilde{V}_{1'4',2'3'}(T) + \delta\Phi_{1'4',2'3'}(\omega,T)\right]\mathcal{R}_{3'4,4'3}(\omega,T)$$
$$\delta\Phi_{1'4',2'3'}(\omega,T) = \Phi_{1'4',2'3'}(\omega,T) - \Phi_{1'4',2'3'}(0,T)$$

T > 0:

$$\Phi^{(ph)}_{14,23}(\omega,T) = \frac{1}{n_{43}(T)}\sum_{\mu}\sum_{\boxed{\eta_\mu=\pm1}}\eta_\mu\Big[\delta_{13}\sum_6\gamma^{\eta_\mu}_{\mu;62}\gamma^{\eta_\mu *}_{\mu;64}\times$$
$$\times\frac{\big(N(\eta_\mu\Omega_\mu)+n_6(T)\big)\big(n(\varepsilon_6-\eta_\mu\Omega_\mu,T)-n_1(T)\big)}{\omega-\varepsilon_1+\varepsilon_6-\eta_\mu\Omega_\mu} +$$
$$+\,\delta_{24}\sum_5\gamma^{\eta_\mu}_{\mu;15}\gamma^{\eta_\mu *}_{\mu;35}\times$$
$$\times\frac{\big(N(\eta_\mu\Omega_\mu)+n_2(T)\big)\big(n(\varepsilon_2-\eta_\mu\Omega_\mu,T)-n_5(T)\big)}{\omega-\varepsilon_5+\varepsilon_2-\eta_\mu\Omega_\mu} -$$
$$-\,\gamma^{\eta_\mu}_{\mu;13}\gamma^{\eta_\mu *}_{\mu;24}\times$$
$$\times\frac{\big(N(\eta_\mu\Omega_\mu)+n_2(T)\big)\big(n(\varepsilon_2-\eta_\mu\Omega_\mu,T)-n_3(T)\big)}{\omega-\varepsilon_3+\varepsilon_2-\eta_\mu\Omega_\mu} -$$
$$-\,\gamma^{\eta_\mu *}_{\mu;31}\gamma^{\eta_\mu}_{\mu;42}\times$$
$$\times\frac{\big(N(\eta_\mu\Omega_\mu)+n_4(T)\big)\big(n(\varepsilon_4-\eta_\mu\Omega_\mu,T)-n_1(T)\big)}{\omega-\varepsilon_1+\varepsilon_4-\eta_\mu\Omega_\mu}\Big],$$

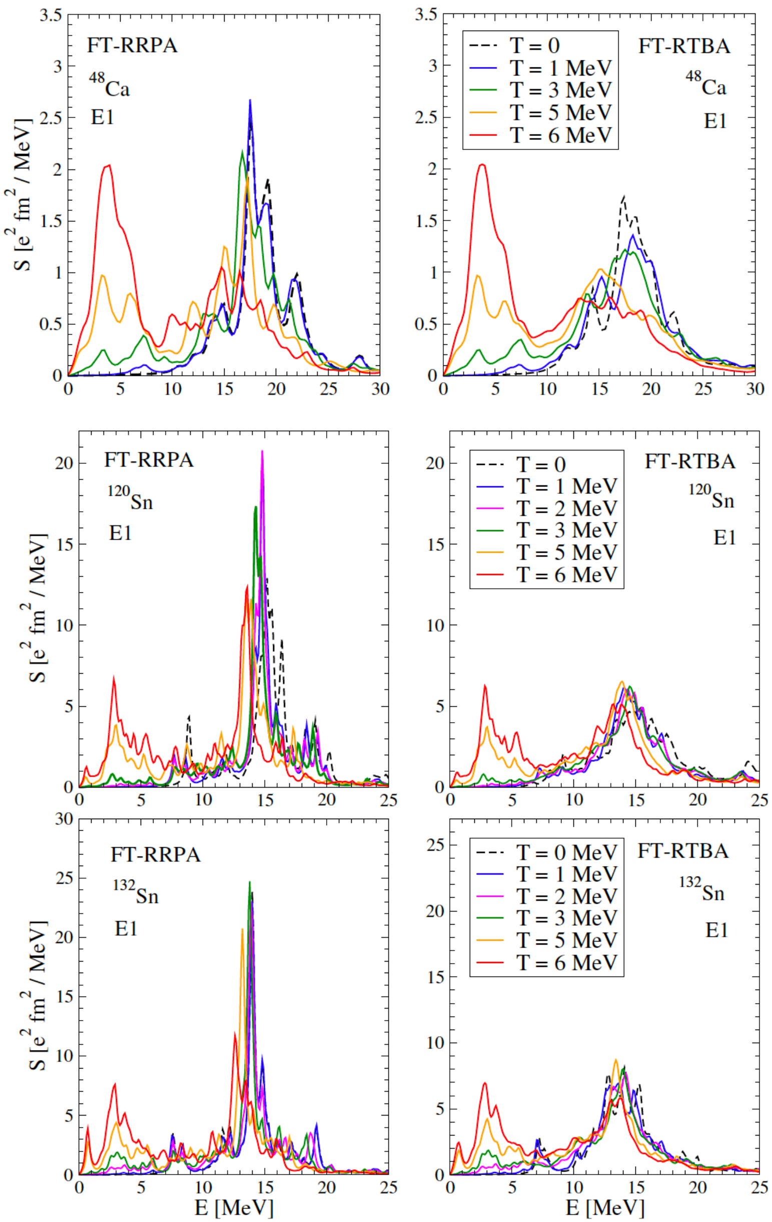
Dynamical kernel:



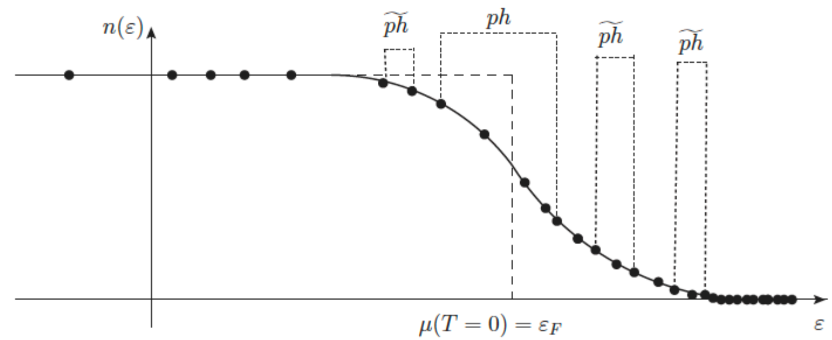
T = 0:

$$\Phi^{(ph,ph)}_{14,23}(\omega) = \sum_\mu\times$$
$$\times\Big[\delta_{13}\sum_6\frac{\gamma^{\mu}_{62}\gamma^{\mu *}_{64}}{\omega-\varepsilon_1+\varepsilon_6-\Omega_\mu} +$$
$$+\delta_{24}\sum_5\frac{\gamma^{\mu}_{15}\gamma^{\mu *}_{35}}{\omega-\varepsilon_5+\varepsilon_2-\Omega_\mu} -$$
$$-\frac{\gamma^{\mu}_{13}\gamma^{\mu *}_{24}}{\omega-\varepsilon_3+\varepsilon_2-\Omega_\mu} -$$
$$-\frac{\gamma^{\mu *}_{31}\gamma^{\mu}_{42}}{\omega-\varepsilon_1+\varepsilon_4-\Omega_\mu}\Big]$$

Giant Dipole Resonance in ^{48}Ca and ^{120,132}Sn at T>0



Thermal unblocking:



Uncorrelated propagator:

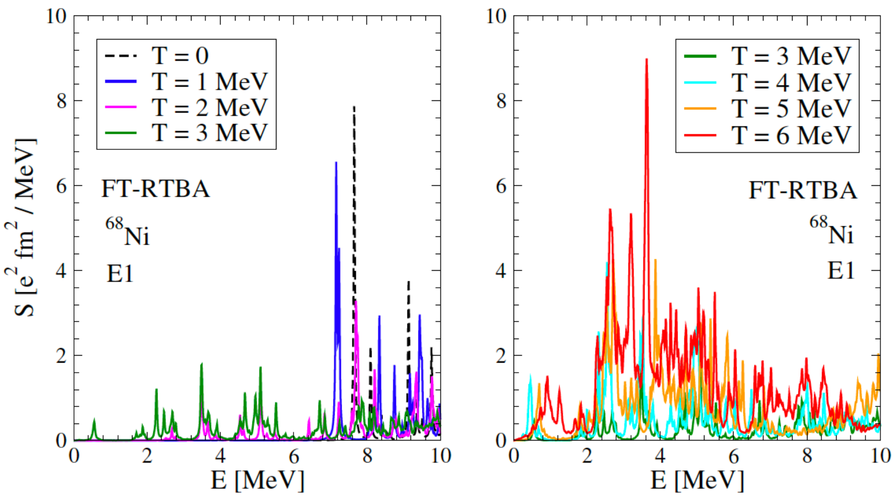
$$\tilde{R}^{0}_{14,23}(\omega) = \delta_{13}\delta_{24}\frac{n_2 - n_1}{\omega - \varepsilon_1 + \varepsilon_2}$$

- *New transitions due to the thermal unblocking effects*
- *More collective and non-collective modes contribute to the PVC self-energy (~400 modes at T=5-6 MeV)*
- *Broadening of the resulting GDR spectrum*
- *Development of the low-energy part => a feedback to GDR*

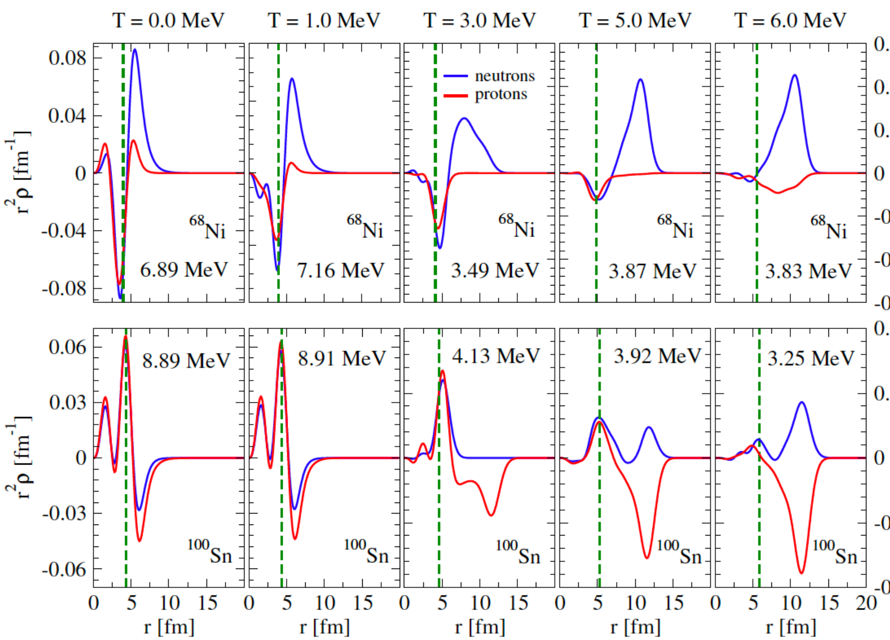
- *The spurious translation mode is properly decoupled as the mean field is modified consistently*
- *The role of the new terms in the Φ amplitude increases with temperature*
- *A very little fragmentation of the low-energy peak (cancellations in the Φ amplitude, possibly due to the absence of GSC/PVC)*

Evolution of the pygmy dipole resonance (PDR) at T>0

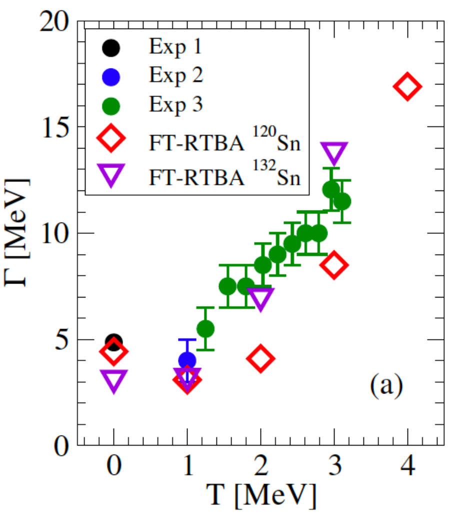
Low-energy strength distribution in ^{68}Ni



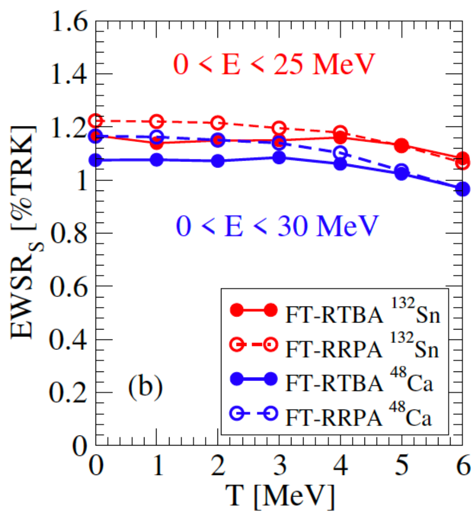
Transition density for the low-energy peak in ^{68}Ni, ^{100}Sn



GDR's width



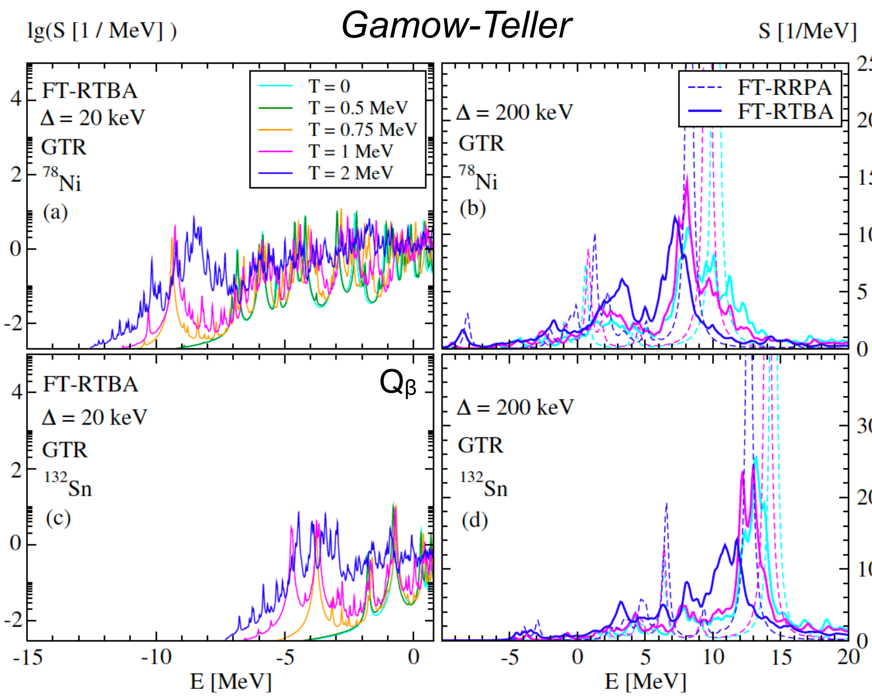
Energy-weighted sum rule

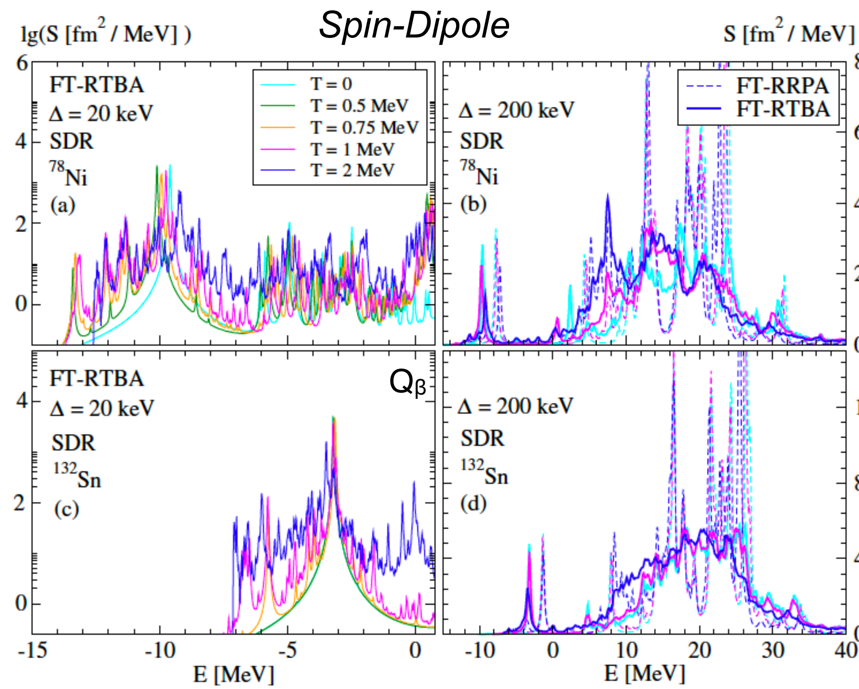


- *The low-energy peak (PDR) gains the strength from the GDR with the temperature growth: EWSR ~ const*
- *The total width $\Gamma \sim T^2$ (as in the Landau theory); shape fluctuations are missing for T~2-3 MeV*
- *The PDR develops a new type of collectivity originated from the thermal unblocking*
- *The same happens with other low-lying modes (2+, 3-, …) => strong PVC => "destruction" of the GDR at high temperatures*

E.L., H. Wibowo, Phys. Rev. Lett. 121, 082501 (2018).
H. Wibowo, E.L., arXiv:1810.01456, Phys. Rev. C (2019).

Gamow-Teller and Spin Dipole Resonances at T>0: ^{78}Ni and ^{132}Sn

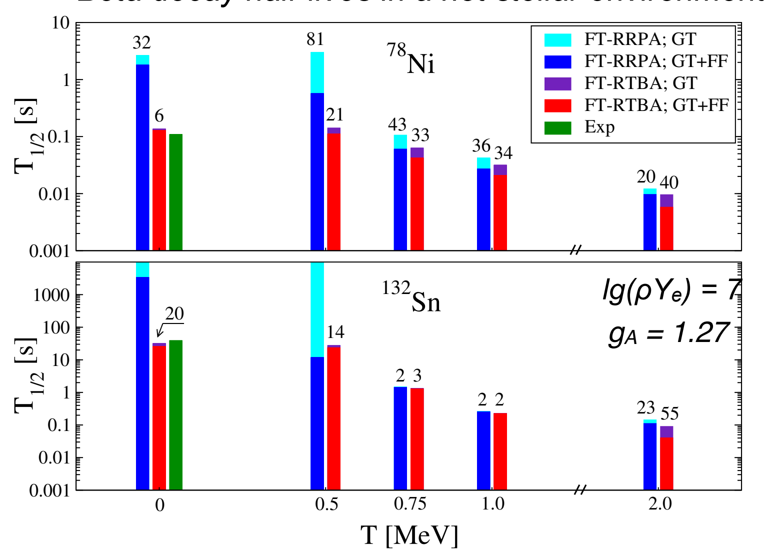




- *The thermally unblocked transitions enhance both the GTR and the SDR strengths within the Q_β window. This causes the decrease of the $T_{1/2}$ with temperature.*
- *The contribution from SDR-like (first-forbidden transitions) increases with temperature.*
- *At the typical r-process temperatures T~0.2-0.3 MeV the thermal unblocking is still suppressed by the large shell gaps, however, the effect should be stronger in open-shell nuclei.*

E.L., C. Robin, H. Wibowo, arXiv:1808.07223

Beta decay half-lives in a hot stellar environment



Outlook

Summary:

- Relativistic NFT offers a powerful framework for an accurate solution of the nuclear many-body problem.
- The non-perturbative response theory based on QHD and including high-order correlations is available now for a large class of nuclear excited states in even-even (and odd-odd nuclei).
- The time blocking approximation to the nuclear response beyond RPA is generalized to finite temperature and applied to neutral and charge-exchange response.

Current and future developments:

- An approach to nuclear response including both continuum and PVC at finite temperature, for both neutral and charge-exchange excitations;
- Inclusion of the superfluid pairing at $T>0$ to extend the application range (r-process);
- Inclusion of 3p3h-configurations (ongoing for $T=0$);
- Applications to neutron stars and other QFT cases;
- Toward an "ab initio" description: realization of the approach based on the bare relativistic meson-exchange potential (CD-Bonn etc.).

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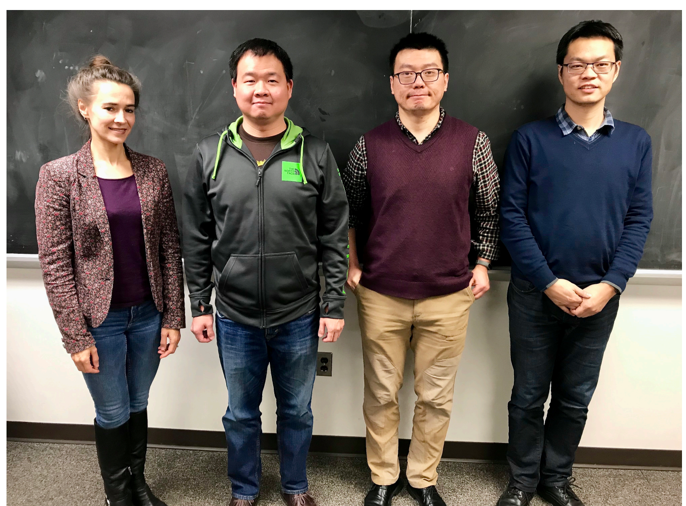
WMU Nuclear Theory group in 2017

…in fall 2018



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Backup