The Quantum Dancing of Hot Atomic Nuclei: a New Theoretical Approach

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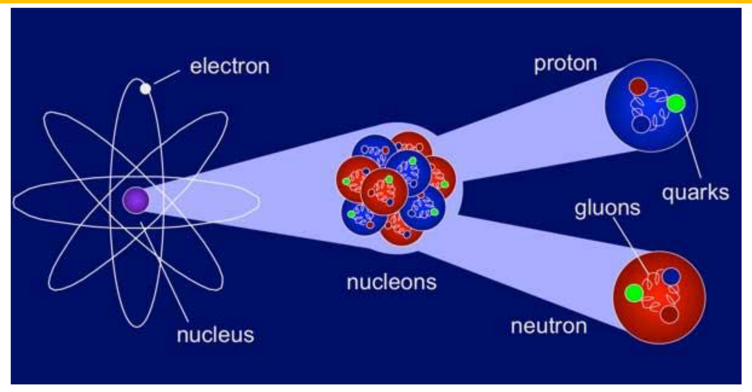
Abstract

We study the nuclear excitation spectra in the two energy domains: the low energy region (below 10 MeV) and giant resonance (GR) region (10-30 MeV). In the low energy region, the experimentally discovered upbend of the radiative dipole strength function is very important as it has an impact on the rapid neutron capture cross sections, which are used, in particular, for the r-process nucleosynthesis studies.

Thermal continuum quasiparticle random-phase approximation (TCQRPA) is one of the models which attempts to explain this phenomenon. The deficiency of TCQRPA is the absence of quasiparticle vibration coupling (QVC) mechanism, which is already included in relativistic time-blocking approximation (RTBA).

In this poster, we provide the brief description of TBA and present the preliminary results of the finite temperature generalization of RTBA using the Matsubara Green's function formalism.

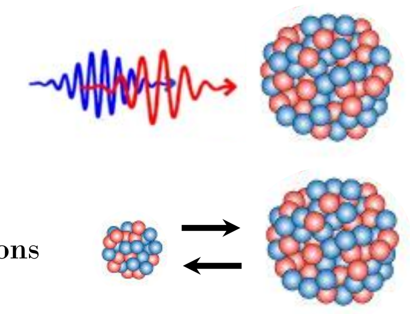
Background



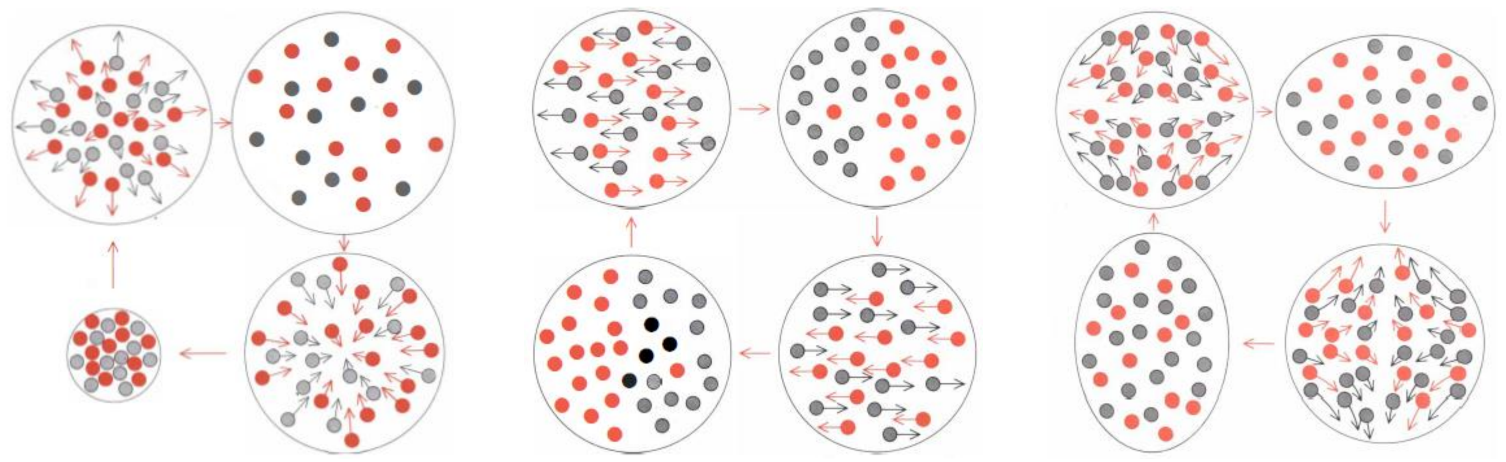
Credit: Nuclear Science and Technology School

Photoexcitation

Heavy ion collisions



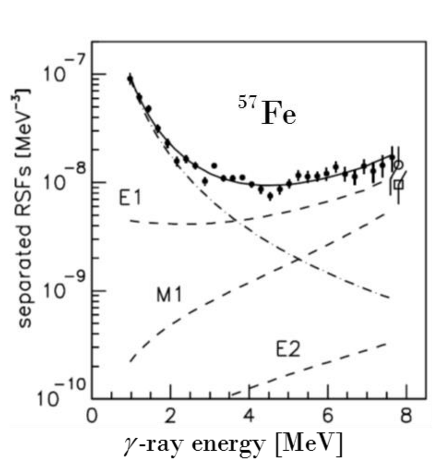
We can make "hot nuclei" using various ways!



Giant Monopole Resonance | Giant Dipole Resonance | Giant Quadrupole Resonance

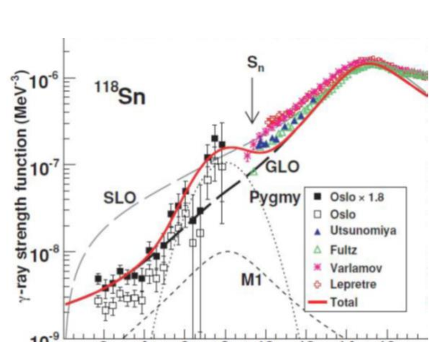
G. F. Bertsch, *Vibrations of the Atomic Nucleus*, Scientific American, Inc., 1983

Experimental Results in Low Energy Region



Voinov *et al.*, PRL 93, 142504, 2004

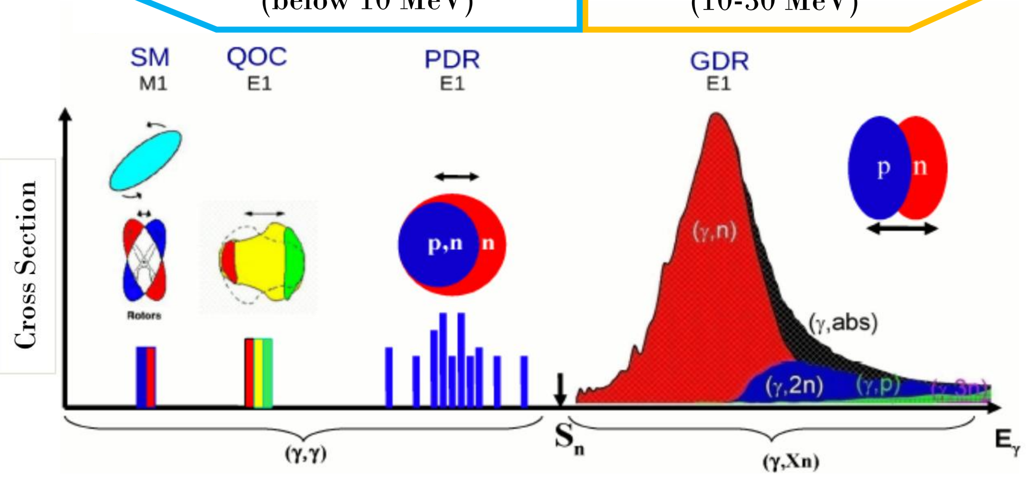
(Upbend structure of RSF)



Toft *et al.*, PRC 81, 064311, 2010

(No upbend structure of RSF)

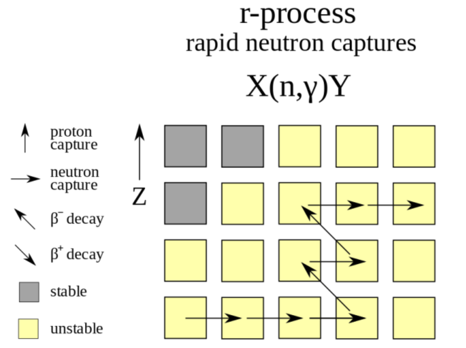
Low Energy Region (below 10 MeV) | Giant Resonance Region (10-30 MeV)



Habs et.al., Nuclear Photonics, arXiv: 1201.4466v1

r-process

rapid neutron captures



synthesis of neutron-rich nuclei

A > 60

https://commons.wikimedia.org/wiki/File:R-process.svg

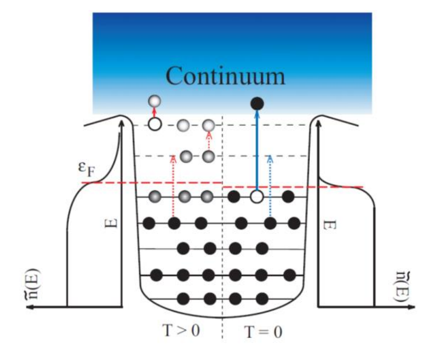
Relation to the R-Process Nucleosynthesis:

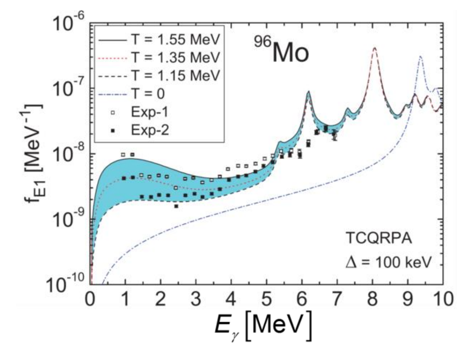
"For the exotic neutron-rich nuclei, the upbend structure of low-energy RSF can enhance rapid neutron capture reaction rates by one or two orders of magnitude."

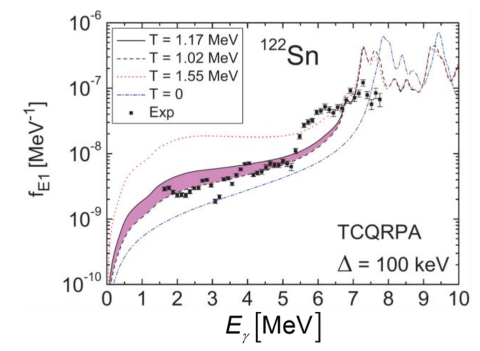
[Larsen and Goriely, PRC 82, 014318, 2010]

We need a microscopic model that can give the accurate prediction of low-energy strength function!

Thermal Continuum QRPA (TCQRPA): One possible explanation for phenomena in low-energy region







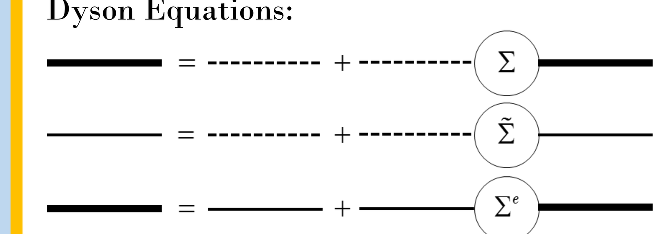
Litvinova and Belov, PRC 88, 031302, 2013

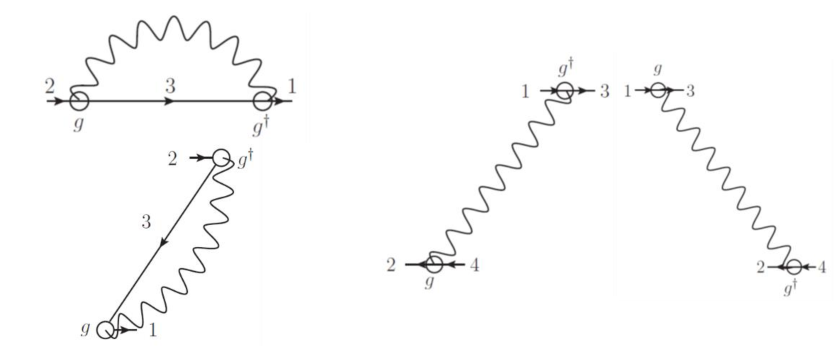
Deficiency: The absence of quasiparticle vibration coupling (QVC) mechanism, which is included in relativistic time-blocking approximation (RTBA).

Particle Vibration Coupling (PVC)

Kamerdzhiev, Tertychnyi, and Tselyaev, Phys. Part. Nucl. 28, 134, 1997

Dyson Equations:





$$\Sigma(\varepsilon)=\tilde{\Sigma}+\Sigma^e(\varepsilon)$$

$$g_{12}^{m(\sigma)}=\delta_{\sigma,+1}g_{12}^m+\delta_{\sigma,-1}g_{21}^m$$

$$\tilde{G}_{12}(\varepsilon)=\delta_{12}\tilde{G}_1(\varepsilon)$$

$$\tilde{G}_1(\varepsilon)=\frac{1}{\varepsilon-\tilde{\varepsilon}_1+i\sigma_1\delta}$$

$$\Sigma_{12}^e(\varepsilon)=\sum_{3,m}\frac{g_{13}^{m(\sigma_3)*}g_{23}^{m(\sigma_3)}}{\varepsilon-\tilde{\varepsilon}_3-\sigma_3(\omega_m-i\delta)}$$

$$U_{12,34}^e=\sum_{\sigma,m}\frac{\sigma g_{31}^{m(\sigma)*}g_{42}^{m(\sigma)}}{\varepsilon-\varepsilon'+\sigma(\omega_m-i\delta)}$$

Research Objectives

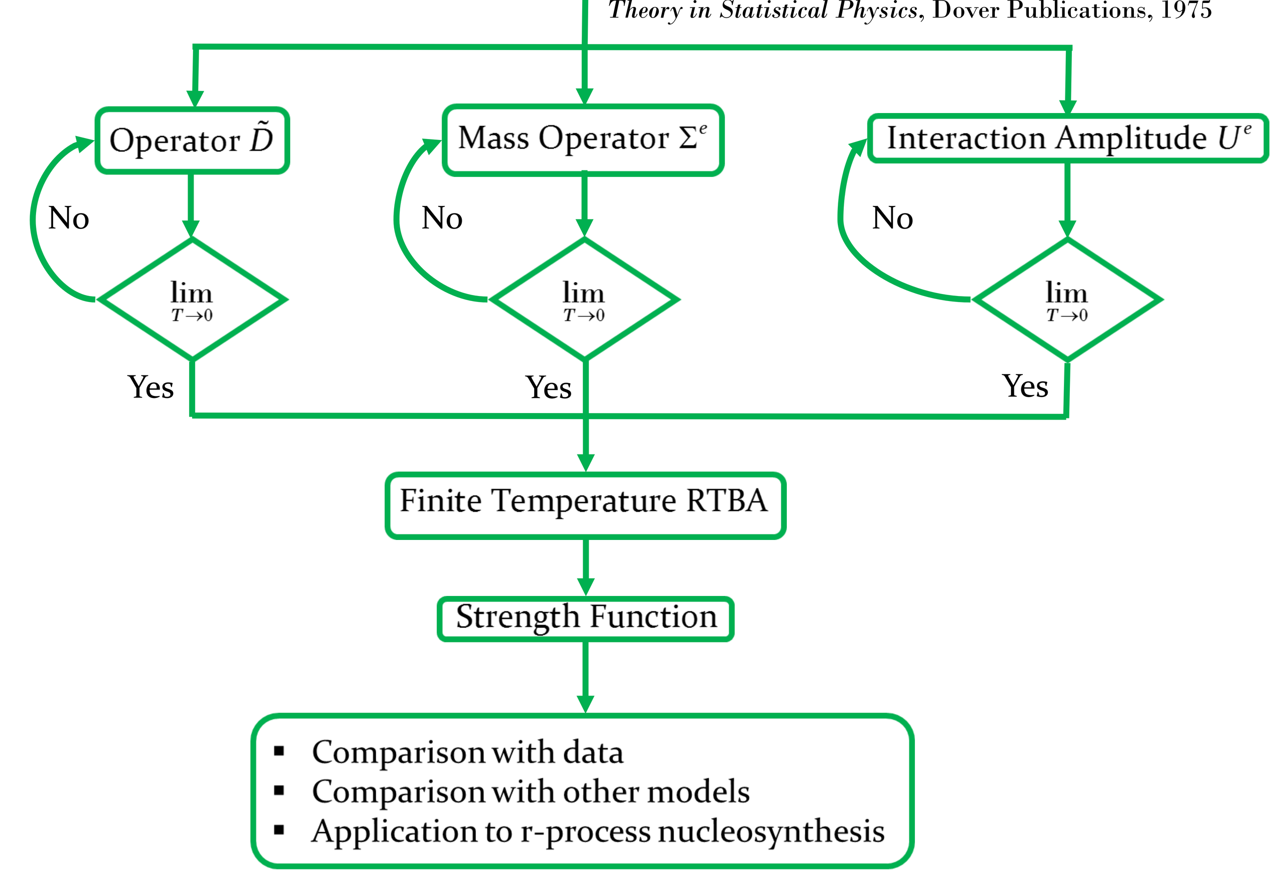
1. To formulate finite temperature RTBA model.
2. To obtain the E1 and M1 strength functions from the finite temperature RTBA model.
3. To calculate the gamma strength function, rapid neutron capture reaction rates, possibly Gamow-Teller strengths, and beta decay rates relevant for r-process nucleosynthesis.

Research Design

Matsubara Green's Function

Objects	Time Representations	Fourier Transforms
Free Fermion	$\mathscr{G}_{13}^{(0)}(\tau_{13}>0)=-\delta_{13}[1-n_1]e^{-(\varepsilon_1-\mu)\tau}$ $\mathscr{G}_{13}^{(0)}(\tau_{13}<0)=\delta_{13}n_1e^{-(\varepsilon_1-\mu)\tau}$	$\mathscr{G}_{13}^{(0)}(\omega_n)=\frac{\delta_{13}}{i\omega_n-\varepsilon_1+\mu}$ $n_1=\frac{1}{e^{(\varepsilon_1-\mu)/T}+1}$ $\omega_n=(2n+1)\pi T$
Free Phonon	$\mathscr{D}_{\lambda}^{(0)}(\tau>0)=-\{(1+N_\lambda)e^{-\omega_\lambda\tau}+N_\lambda e^{\omega_\lambda\tau}\}$ $\mathscr{D}_{\lambda}^{(0)}(\tau>0)=-\{N_\lambda e^{-\omega_\lambda\tau}+(1+N_\lambda)e^{\omega_\lambda\tau}\}$	$\mathscr{D}_{\lambda}^{(0)}(\omega_n)=\frac{2\omega_\lambda}{(i\omega_n)^2-\omega_\lambda^2}$ $N_\lambda=\frac{1}{e^{\omega_\lambda/T}-1}$ $\omega_n=2n\pi T$

Abrikosov, Gorkov, and Dzyaloshinski, *Method of Quantum Field Theory in Statistical Physics*, Dover Publications, 1975



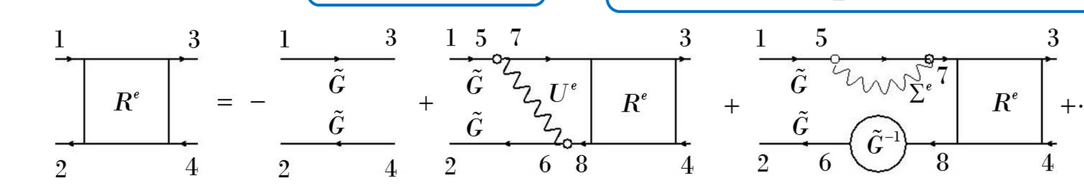
Time Blocking Approximation

V. I. Tselyaev, Yad. Fiz. 50, 1252 (1989)

Bethe-Salpeter Equation:

$$R=R^e+iR^e\tilde{U}R$$

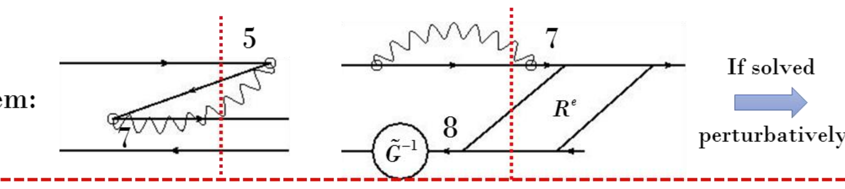
$$R^e=-\tilde{G}\tilde{G}-i\tilde{G}\tilde{G}\left[U^e+i\Sigma^e\tilde{G}^{-1}+i\tilde{G}^{-1}\Sigma^e-i\Sigma^e\Sigma^e\right]R^e$$



Strength Function:

$$S(E)=\frac{1}{\pi}\lim_{\Delta\to+0}\mathrm{Im}\sum_{1234}V_{21}^{0*}R_{12,34}(E+i\Delta)V_{43}^{0}$$

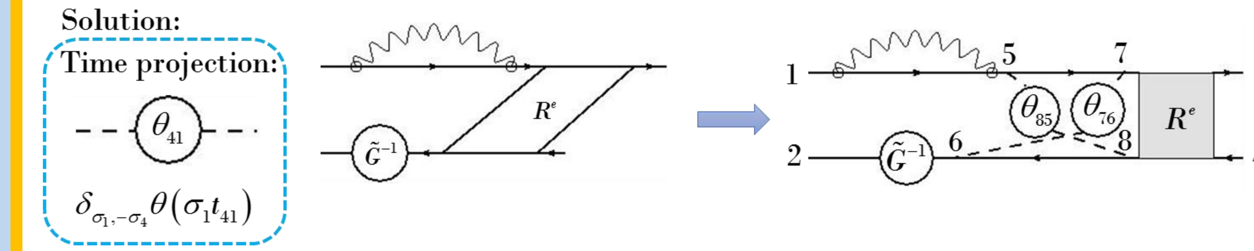
Problem:



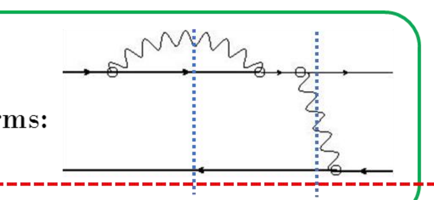
If solved perturbatively ⇒ Negative strength! Negative cross section!

Solution:

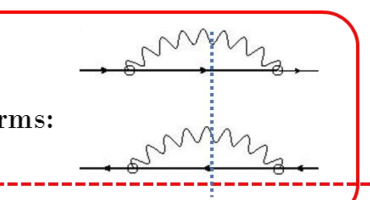
Time projection:



Allowed terms:



Blocked terms:



Preliminary Results

Finite temperature $\tilde{D}$ operator:

$$\tilde{\mathcal{D}}_{12,34}^{\sigma_1,\sigma_2}=\delta_{\sigma_1,-\sigma_2}\mathcal{G}^{\sigma_1}(3,1)\mathcal{G}^{\sigma_2}(2,4)\theta(\sigma_1\tau_{41})\theta(\sigma_1\tau_{32})$$

Fourier transform:

$$\tilde{\mathcal{D}}_{12,34}^{(+1,-1)}(\omega_\ell,\varepsilon_\ell,\varepsilon_{\ell'})=\frac{1}{8}\delta_{13}\delta_{24}(\omega_\ell-\varepsilon_1+\varepsilon_2)\mathcal{G}_1(\varepsilon_\ell)\mathcal{G}_2(\varepsilon_{\ell'})\mathcal{G}_2(\omega_\ell+\varepsilon_{\ell'})\mathcal{G}_1(\omega_\ell+\varepsilon_\ell)$$

$$\tilde{\mathcal{D}}_{12,34}^{(-1,+1)}(\omega_\ell,\varepsilon_\ell,\varepsilon_{\ell'})=-\frac{1}{8}\delta_{13}\delta_{24}(\omega_\ell-\varepsilon_1+\varepsilon_2)\mathcal{G}_1(\varepsilon_\ell)\mathcal{G}_2(\varepsilon_{\ell'})\mathcal{G}_2(\omega_\ell+\varepsilon_{\ell'})\mathcal{G}_1(\omega_\ell+\varepsilon_\ell)$$

Zero temperature $\tilde{D}$ operator:

$$\tilde{D}_{12,34}=\delta_{\sigma_1,-\sigma_2}\theta(\sigma_1t_{41})\theta(\sigma_1t_{32})\tilde{G}(3,1)\tilde{G}(2,4)$$

$$\tilde{D}_{12,34}(\omega,\varepsilon,\varepsilon')=-i\delta_{\sigma_1,-\sigma_2}\delta_{13}\delta_{24}\sigma_1(\omega-\tilde{\varepsilon_1}+\tilde{\varepsilon_2})\tilde{G}_1(\varepsilon)\tilde{G}_2(\varepsilon')\tilde{G}_1(\omega+\varepsilon)\tilde{G}_2(\omega+\varepsilon')$$

Finite temperature mass operator:

$$\mathcal{M}_{12}(\xi_\ell,T)=-T\sum_{3,m}\sum_{\xi_{\ell'}}g_{13}^{m*}g_{23}^{m}\mathcal{G}_3^{(0)}(\xi_{\ell'})\mathcal{D}_m(\xi_\ell-\xi_{\ell'})$$

$$\mathcal{M}_{12}(\xi_\ell,T)=\sum_{3,m}g_{13}^{m*}g_{23}^{m}\left\{\frac{n_3(\varepsilon_3,T)+N(\omega_m)}{\xi_\ell-\varepsilon_3+\omega_m}+\frac{N(\omega_m)+1-n_3(\varepsilon_3,T)}{\xi_\ell-\varepsilon_3-\omega_m}\right\}$$

Zero temperature mass operator:

$$\Sigma_{12}^e(\varepsilon)=\sum_{3,m}\frac{g_{13}^{m(\sigma_3)*}g_{23}^{m(\sigma_3)}}{\varepsilon-\tilde{\varepsilon}_3-\sigma_3(\omega_m-i\delta)}$$

Status

1. Direct application of the Matsubara Green's functions for calculating operator $\tilde{D}$ and mass operator shows a promising results since it gives approximately the correct limit of $T=0$.
2. There are still some unanswered questions related to the correct definition of finite temperature operator $\tilde{D}$, such as the origin of factor 1/8 and the requirement to add minus sign so that it gives the correct limit for $T=0$.

Acknowledgments

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