THERMAL EFFECTS ON NEUTRAL-CURRENT NEUTRINO-NUCLEUS INELASTIC SCATTERING CROSS SECTIONS

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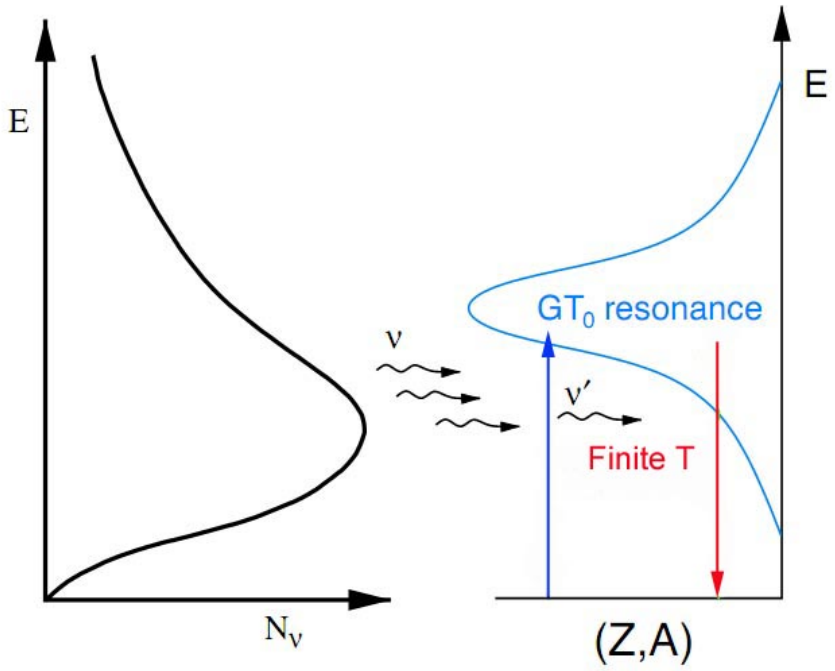
Motivation

- Important process for supernova physics – neutrino inelastic scattering

$$(A, Z) + \nu_e \rightarrow (A, Z)^* + \nu'_e.$$

- W.C. Haxton, PRL 60 (1988) 1999: the reaction is dominated by GT_0 transitions ($\vec{\sigma}\tau_0$ operator);
- J.M. Sampaio et al., PLB 529 (2002) 11: shell-model calculations for iron group nuclei, thermal effects in the low-energy cross sections;
- Astrophysical conditions: $T = 10^9 \div 2 \times 10^{10}$ K (10^9 K ≈ 0.1 MeV).



Determining inelastic neutrino-nucleus cross section

The $(A,Z)+\nu_e \to (A,Z)^* + \nu'_e$ cross section at $T \neq 0$ is given by

$$\sigma_\nu(E_\nu) = \frac{G_F^2}{\pi} \sum_{i\,f} E^2_{\nu',if} B_{if}(GT_0) g_i(T),$$

where $E_{\nu',if} = E_\nu + (E_i - E_f)$, $\quad B_{if}(GT_0) = \left(\frac{g_A}{g_V}\right)^2 |\langle i|\vec{\sigma}\tau_0|f\rangle|^2$,

and $g_i(T) \sim (2J_i+1)\exp\left(-\frac{E_i}{T}\right)$.

To simplify the calculations within the SM diagonalization approach the cross section is splitted into two parts:

$$\begin{aligned}
\sigma_\nu(E_\nu) &= \sigma^d_\nu(E_\nu) + \sigma^{up}_\nu(E_\nu) \\
&= \frac{G_F^2}{\pi}\left[\sum_{E_i<E_f} E^2_{\nu',if} B_{if}(GT_0) g_i(T) + \sum_{E_i>E_f} E^2_{\nu',if} B_{if}(GT_0) g_i(T)\right] \\
&= \frac{G_F^2}{\pi}\left[\sum_{f} E^2_{\nu',0f} B_{0f}(GT_0) + \sum_{E_i>E_f} E^2_{\nu',if} B_{if}(GT_0) g_i(T)\right].
\end{aligned}$$

The TFD formalism (1)

The Liouville-von Neumann equation

$$i\frac{\partial}{\partial t}\rho = [H, \rho]\ , \qquad \text{where} \quad H|n\rangle = E_n|n\rangle.$$

The thermal average of an arbitrary operator A is given by

$$\langle\langle A\rangle\rangle = \mathrm{Tr}[\rho A]/\mathrm{Tr}[\rho] = Z^{-1}(T)\sum_n \mathrm{e}^{-E_n/T}\langle n|A|n\rangle.$$

A thermal vacuum state in TFD

$$\langle\langle A\rangle\rangle = \langle 0(T)|A|0(T)\rangle\ .$$

Let $|0(T)\rangle = \sum_n c_n(T)|n\rangle$. Then

$$c_n^*(T)c_m(T) = Z^{-1}(T)e^{-E_n/T}\delta_{nm}$$

which is impossible for mere numbers $c_n(T)$.

The TFD formalism (2)

To construct the thermal vacuum we introduce the "tilde" Hamiltonian $\widetilde{H}$ acting in the independent Hilbert space and having the same eigenvalues as H:

$$\widetilde{H}|\widetilde{n}\rangle = E_n|\widetilde{n}\rangle, \quad \langle m|\widetilde{n}\rangle = 0.$$

In the doubled Hilbert space the thermal vacuum is given by

$$|0(T)\rangle = Z^{-1/2}(T)\sum_n e^{-E_n/2T}|n\rangle \otimes |\widetilde{n}\rangle.$$

and

$$\begin{aligned}\langle 0(T)|A|0(T)\rangle &= Z^{-1}(T)\sum_{n,m} \mathrm{e}^{-(E_n+E_m)/2T}\langle n,\widetilde{n}|A|m,\widetilde{m}\rangle \\ &= Z^{-1}(T)\sum_n \mathrm{e}^{-E_n/T}\langle n|A|n\rangle = \langle\langle A\rangle\rangle\ ,\end{aligned}$$

since the physical operator A acts only on non-tilde states.

The TFD formalism (3)

Tilde-conjugation rules:

$$\widetilde{(A_1 A_2)} = \widetilde{A}_1 \widetilde{A}_2, \quad \widetilde{(c_1 A_1 + c_2 A_2)} = c_1^* \widetilde{A}_1 + c_2^* \widetilde{A}_2,$$
$$(\widetilde{A})^\dagger = \widetilde{A^\dagger}, \quad [\widetilde{A}, B]_\mp = 0, \quad \widetilde{\widetilde{A}} = A.$$

The thermal vacuum meets the following conditions:

- $\mathcal{H}|0(T)\rangle = 0$, where $\mathcal{H} = H - \widetilde{H}$ is the thermal Hamiltonian;
- $\widetilde{|0(T)\rangle} = |0(T)\rangle$
- the thermal state condition is valid:

$$A|0(T)\rangle = \sigma \exp\left(\frac{\mathcal{H}}{2T}\right) \widetilde{A^\dagger}|0(T)\rangle,$$

where $\sigma = 1$ for bosonic A and $\sigma = i$ for fermionic A.

The Kubo-Martin-Schwinger relation

$$\langle 0(T)|A(t)B(t')|0(T)\rangle = \langle 0(T)|B(t')A(t + iT^{-1})|0(T)\rangle.$$

results from the thermal state condition.

The TFD formalism (4)

The Schrödinger equation for a hot system in the doubled Hilbert space:

$$i\frac{\partial}{\partial t}|\Psi(t,T)\rangle = \mathcal{H}|\Psi(t,T)\rangle, \qquad (\mathcal{H} = H - \widetilde{H}).$$

If we can diagonalize the thermal Hamiltonian by some operators

$$\mathcal{H} \approx \sum_n \varepsilon_n(T)[\mathcal{O}_n^\dagger \mathcal{O}_n - \widetilde{\mathcal{O}}_n^\dagger \widetilde{\mathcal{O}}_n] \ ,$$

then the strength distribution for a transition operator $\mathcal{A}$ is given by

$$S_{\mathcal{A}}(E) = -i\int_0^\infty \mathrm{d}t\, \mathrm{e}^{iEt}\langle\langle \mathcal{A}^\dagger(t)\mathcal{A}\rangle\rangle = -i\int_0^\infty \mathrm{d}t\, \mathrm{e}^{iEt}\langle 0(T)|\mathcal{A}^\dagger(t)\mathcal{A}|0(T)\rangle$$

$$= \sum_{n,m} \frac{|g_{nm}|^2}{E - (\varepsilon_n(T) - \varepsilon_m(T))}, \quad \text{where} \quad g_{nm} = \langle n, \widetilde{m}|\mathcal{A}|0(T)\rangle \ .$$

Main advantages of the TFD

- TFD is a real time formalism;
- the whole machinery of operator technique at $T = 0$ may be applied at $T \neq 0$ within TFD.

QPM Hamiltonian

$$H_{QPM} = H_{sp} + H_{pair} + H^{ph}_{M} + H^{ph}_{SM} \ ,$$

$$H_{sp} = \sum_{\tau=p,n} \sum_{jm} (E_{\tau j} - \lambda_{\tau}) a^{\dagger}_{\tau jm} a_{\tau jm} \ , \quad (jm \equiv n, l, j, m),$$

$$H_{pair} = -\frac{1}{4} \sum_{\tau=p,n} G_{\tau} \sum_{jm\, j'm'} a^{\dagger}_{\tau jm} a^{\dagger}_{\tau \overline{jm}} a_{\tau \overline{j'm'}} a_{\tau j'm'}, \quad (a_{\tau \overline{jm}} = (-1)^{j-m} a_{\tau j-m}),$$

$$H^{ph}_{M} = -\frac{1}{2} \sum_{\lambda} (\kappa^{(\lambda)}_{0} + \kappa^{(\lambda)}_{1} \vec{\tau}_1 \vec{\tau}_2) \sum_{\mu} M^{\dagger}_{\lambda\mu} M_{\lambda\mu},$$

$$H^{ph}_{SM} = -\frac{1}{2} \sum_{L\lambda} (\kappa^{(L\lambda)}_{0} + \kappa^{(L\lambda)}_{1} \vec{\tau}_1 \vec{\tau}_2) \sum_{\mu} S^{\dagger}_{L\lambda\mu} S_{L\lambda\mu},$$

$$M^{\dagger}_{\lambda\mu} = \sum_{jm\, j'm'} \langle jm | i^{\lambda} R_{\lambda}(r) Y_{\lambda\mu} | j'm' \rangle a^{\dagger}_{jm} a_{j'm'} \ , \quad S^{\dagger}_{L\lambda\mu} = \sum_{jm\, j'm'} \langle jm | i^{L} R_{L}(r) [Y_L \vec{\sigma}]^{\lambda}_{\mu} | j'm' \rangle a^{\dagger}_{jm} a_{j'm'} \ .$$

Thermal Hamiltonian: $\mathcal{H} = H_{QMP} - \widetilde{H}_{QPM} = \mathcal{H}_{sp} + \mathcal{H}_{pair} + \mathcal{H}^{ph}_{M} + \mathcal{H}^{ph}_{SM}$.

Thermal quasiparticles (1)

Bogoliubov transformation

$$\alpha^\dagger_{jm} = u_j a^\dagger_{jm} - v_j a_{\jmath m},$$
$$\widetilde{\alpha}^\dagger_{jm} = u_j \widetilde{a}^\dagger_{jm} - v_j \widetilde{a}_{\jmath m}, \quad (u_j^2 + v_j^2 = 1)\ .$$

Thermal Bogoliubov transformation

$$\beta^\dagger_{jm} = x_j \alpha^\dagger_{jm} - i y_j \widetilde{\alpha}_{jm},$$
$$\widetilde{\beta}^\dagger_{jm} = x_j \widetilde{\alpha}^\dagger_{jm} + i y_j \alpha_{jm}, \quad (x_j^2 + y_j^2 = 1)\ .$$

We rewrite $\mathcal{H}_{sp} + \mathcal{H}_{pair}$ in terms of the thermal quasiparticles

$$\mathcal{H}_{sp} + \mathcal{H}_{pair} = \mathcal{H}_{11} + \mathcal{H}_{20} + \ldots,$$

where $\mathcal{H}_{11} \sim (\beta^\dagger_{jm}\beta_{jm} - \widetilde{\beta}^\dagger_{jm}\widetilde{\beta}_{jm})\ , \qquad \mathcal{H}_{20} \sim (\beta^\dagger_{jm}\beta^\dagger_{\jmath m} - \widetilde{\beta}^\dagger_{jm}\widetilde{\beta}^\dagger_{\jmath m}) + \text{(h.c.)}$

and demand $\mathcal{H}_{20} = 0$. Then $\begin{pmatrix} u_j \\ v_j \end{pmatrix} = \frac{1}{\sqrt{2}} \left(1 \pm \frac{E_j - \lambda_\tau}{\sqrt{(E_j - \lambda_\tau)^2 + \Delta_\tau^2}} \right)^{1/2}\ .$

Here $\Delta_\tau(x_j, y_j)$ is the gap parameter , $\lambda_\tau(x_j, y_j)$ is the chemical potential:

$$\Delta_\tau = \frac{G_\tau}{2} \sum_j^\tau (2j+1)(x_j^2 - y_j^2) u_j v_j, \quad N_\tau = \sum_j^\tau (2j+1)(v_j^2 x_j^2 + u_j^2 y_j^2).$$

Thermal quasiparticles (2)

The thermal BCS Hamiltonian:

$$\mathcal{H}_{BCS} = \mathcal{H}_{sp} + \mathcal{H}_{pair} \simeq \sum_{\tau} \sum_{jm}^{\tau} \varepsilon_j(T)(\beta^{\dagger}_{jm}\beta_{jm} - \widetilde{\beta}^{\dagger}_{jm}\widetilde{\beta}_{jm}),$$

$$\varepsilon_j(T) = \sqrt{(E_j - \lambda_\tau)^2 + \Delta^2_\tau}, \quad \beta_{jm}|0(T); qp\rangle = \widetilde{\beta}_{jm}|0(T); qp\rangle = 0.$$

The coefficients x_j, y_j can be found from the TS condition:

$$a_{jm}|0(T); qp\rangle = i \exp\left(\frac{\mathcal{H}_{BCS}}{2T}\right) \widetilde{a}^{\dagger}_{jm}|0(T); qp\rangle.$$

Then

$$y_j = \left[1 + \exp\left(\frac{\varepsilon_j}{T}\right)\right]^{-1/2}, \quad x_j = \left(1 - y_j^2\right)^{1/2},$$

and

$$\langle 0(T); qp|\alpha^{\dagger}_{jm}\alpha_{jm}|0(T); qp\rangle = y_j^2;$$

Thermal quasiparticles (3)

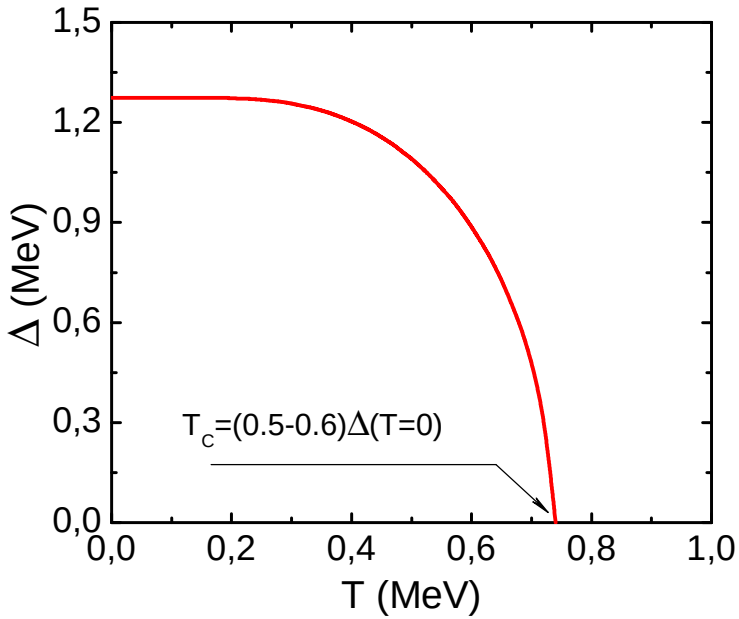
BCS equations at finite temperature

$$y_j^2 = \left[1+\exp\left(\frac{\varepsilon_j}{T}\right)\right]^{-1}, \quad \varepsilon_j = \sqrt{(E_j-\lambda_\tau)^2+\Delta_\tau^2},$$

$$\Delta_\tau = \frac{G_\tau}{2}\sum_j^\tau (2j+1)(x_j^2 - y_j^2)u_j v_j,$$

$$N_\tau = \sum_j^\tau (2j+1)(v_j^2 x_j^2 + u_j^2 y_j^2),$$

$$\begin{pmatrix} u_j \\ v_j \end{pmatrix} = \frac{1}{\sqrt{2}}\left(1 \pm \frac{E_j-\lambda_\tau}{\varepsilon_j}\right)^{1/2}.$$



Physical interpretation:

$$\alpha^\dagger_{jm}|0(T);\mathrm{qp}\rangle = x_j\beta^\dagger_{jm}|0(T);\mathrm{qp}\rangle, \quad \alpha_{\overline{jm}}|0(T);qp\rangle = -i\,y_j\widetilde{\beta}^\dagger_{\overline{jm}}|0(T);qp\rangle.$$

Thermal phonons (1)

The thermal Hamiltonian

$$\mathcal{H}_{\rm QPM} = \sum_{\tau} \sum_{jm}^{\tau} \varepsilon_j (\beta^\dagger_{jm}\beta_{jm} - \widetilde{\beta}^\dagger_{jm}\widetilde{\beta}_{jm})$$

$$- \frac{1}{2} \sum_{\lambda\mu} \sum_{\tau\rho=\pm 1} (\kappa_0^{(\lambda)} + \rho\kappa_1^{(\lambda)}) \left\{ M^\dagger_{\lambda\mu}(\tau) M_{\lambda\mu}(\rho\tau) - \widetilde{M}^\dagger_{\lambda\mu}(\tau) \widetilde{M}_{\lambda\mu}(\rho\tau) \right\}$$

$$= \mathcal{H}_{\rm QRPA} + \mathcal{H}_{\rm qph} \quad .$$

To diagonalize $\mathcal{H}_{QRPA}$ we introduce a thermal phonon creation operator (spherical even-even nuclei)

$$Q^\dagger_{\lambda\mu i} = \frac{1}{2} \sum_{\tau} \sum_{j_1 j_2}^{\tau} \left(\psi^{\lambda i}_{j_1 j_2} [\beta^\dagger_{j_1} \beta^\dagger_{j_2}]^\lambda_\mu + \widetilde{\psi}^{\lambda i}_{j_1 j_2} [\widetilde{\beta}^\dagger_{\overline{j}_1} \widetilde{\beta}^\dagger_{\overline{j}_2}]^\lambda_\mu + 2i\, \eta^{\lambda i}_{j_1 j_2} [\beta^\dagger_{j_1} \widetilde{\beta}^\dagger_{\overline{j}_2}]^\lambda_\mu \right)$$

$$+ \left(\phi^{\lambda i}_{j_1 j_2} [\beta_{\overline{j}_1} \beta_{\overline{j}_2}]^\lambda_\mu + \widetilde{\phi}^{\lambda i}_{j_1 j_2} [\widetilde{\beta}_{j_1} \widetilde{\beta}_{j_2}]^\lambda_\mu + 2i\, \xi^{\lambda i}_{j_1 j_2} [\beta_{\overline{j}_1} \widetilde{\beta}_{j_2}]^\lambda_\mu \right) .$$

The new thermal vacuum $|0(T); ph\rangle$ is the vacuum for thermal phonons

$$Q_{\lambda\mu i} |0(T); ph\rangle = 0, \quad \widetilde{Q}_{\lambda\mu i} |0(T); ph\rangle = 0 \ .$$

Thermal phonons (2)

Thermal phonon operators commute like bosonic ones:

$$[Q_{\lambda'\mu'k'},\ Q^{\dagger}_{\lambda\mu k}] = \delta_{\lambda'\lambda}\delta_{\mu'\mu}\delta_{k'k}, \quad [\widetilde{Q}_{\lambda'\mu'k'},\ Q^{\dagger}_{\lambda\mu k}] = 0, \quad \text{etc.}$$

This imposes the following ortonormalization constraint

$$\frac{1}{2}\sum_{\tau}\sum_{j_1 j_2}{}^{\tau}(\psi^{\lambda k'}_{j_1 j_2}\psi^{\lambda k}_{j_1 j_2} + \widetilde{\psi}^{\lambda k'}_{j_1 j_2}\widetilde{\psi}^{\lambda k}_{j_1 j_2} + 2\eta^{\lambda k'}_{j_1 j_2}\eta^{\lambda k}_{j_1 j_2}$$
$$- \phi^{\lambda k'}_{j_1 k_2}\phi^{\lambda k}_{j_1 j_2} - \widetilde{\phi}^{\lambda k'}_{j_1 k_2}\widetilde{\phi}^{\lambda k}_{j_1 j_2} - 2\xi^{\lambda' k'}_{j_1 j_2}\xi^{\lambda k}_{j_1 j_2}) = \delta_{k'k}.$$

The energy and the structure of thermal phonons can be found from the variational principle:

$$\delta\Big\{\langle Q_{\lambda\mu k}|\mathcal{H}_{QRPA}|Q_{\lambda\mu k}\rangle - \frac{\omega_{\lambda k}}{2}\left[\langle 0(T); ph|[Q_{\lambda\mu k}, Q^{\dagger}_{\lambda\mu k}]|0(T); ph\rangle - 1\right]\Big\} = 0$$

The thermal state condition for the phonon vacuum

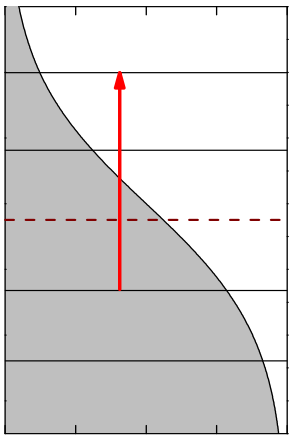
$$A|0(T); ph\rangle = \exp\left(\frac{\mathcal{H}_{QRPA}}{2T}\right)\widetilde{A^{\dagger}}|0(T); ph\rangle.$$

Thermal phonons (3)

Equation for thermal phonon energies reads ($\kappa_1^{(L,\lambda)} \neq 0$)

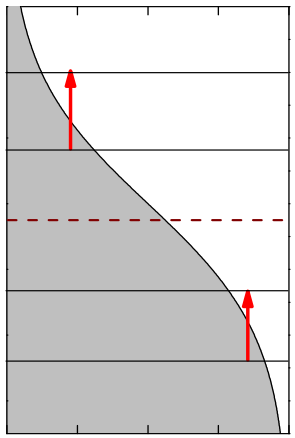
$$\frac{2\lambda+1}{\kappa_1^{(L,\lambda)}} = \sum_{\tau}\sum_{j_1\, j_2}{}^{\tau} (f_{j_1 j_2}^{(L,\lambda)})^2 \left[\frac{(u_{j_1 j_2}^{(-)})^2 \varepsilon_{j_1 j_2}^{(+)} (1 - y_{j_1}^2 - y_{j_2}^2)}{(\varepsilon_{j_1 j_2}^{(+)})^2 - \omega^2} - \frac{(v_{j_1 j_2}^{(+)})^2 \varepsilon_{j_1 j_2}^{(-)} (y_{j_1}^2 - y_{j_2}^2)}{(\varepsilon_{j_1 j_2}^{(-)})^2 - \omega^2} \right]$$

and $\varepsilon_{j_1 j_2}^{(\pm)} = \varepsilon_{j_1} \pm \varepsilon_{j_2}$, $u_{j_1 j_2}^{(-)} = u_{j_1} v_{j_2} - v_{j_1} u_{j_2}$, $v_{j_1 j_2}^{(+)} = u_{j_1} u_{j_2} + v_{j_1} v_{j_2}$.



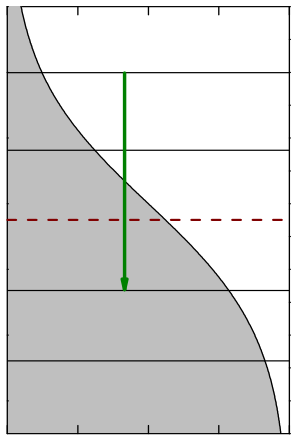
$\varepsilon_{j_1 j_2}^{(+)} > 0$

$\beta_1^\dagger \beta_2^\dagger$



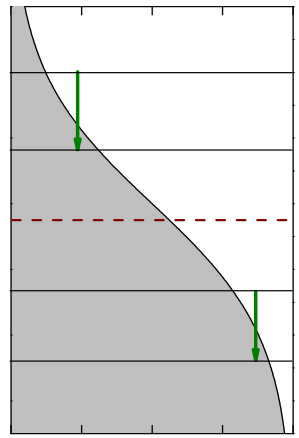
$\varepsilon_{j_1 j_2}^{(-)} > 0$

$\beta_1^\dagger \widetilde{\beta}_2^\dagger$



$-\varepsilon_{j_1 j_2}^{(+)} < 0$

$\widetilde{\beta}_1^\dagger \widetilde{\beta}_2^\dagger$



$-\varepsilon_{j_1 j_2}^{(-)} < 0$

$\widetilde{\beta}_1^\dagger \beta_2^\dagger$

Thermal phonons (4)

Thermal phonon amplitudes:

$$\begin{pmatrix} \psi \\ \phi \end{pmatrix}^{\lambda i}_{j_1 j_2} = \frac{1}{\sqrt{\mathcal{N}^{\lambda i}_{\tau}}} \frac{f^{(L,\lambda)}_{j_1 j_2} u^{(-)}_{j_1 j_2}}{\varepsilon^{(+)}_{j_1 j_2} \mp \omega_{\lambda i}} \left(x_{j_1} x_{j_2} X_{\lambda i} - y_{j_1} y_{j_2} Y_{\lambda i} \right) ,$$

$$\begin{pmatrix} \widetilde{\psi} \\ \widetilde{\phi} \end{pmatrix}^{\lambda i}_{j_1 j_2} = -\frac{1}{\sqrt{\mathcal{N}^{\lambda i}_{\tau}}} \frac{f^{(L,\lambda)}_{j_1 j_2} u^{(+)}_{j_1 j_2}}{\varepsilon^{(+)}_{j_1 j_2} \pm \omega_{\lambda i}} \left(y_{j_1} y_{j_2} X_{\lambda i} - x_{j_1} x_{j_2} Y_{\lambda i} \right) ,$$

$$\begin{pmatrix} \eta \\ \xi \end{pmatrix}^{\lambda i}_{j_1 j_2} = \frac{1}{\sqrt{\mathcal{N}^{\lambda i}_{\tau}}} \frac{f^{(L,\lambda)}_{j_1 j_2} v^{(+)}_{j_1 j_2}}{\varepsilon^{(-)}_{j_1 j_2} \mp \omega_{\lambda i}} \left(x_{j_1} y_{j_2} X_{\lambda i} - y_{j_1} x_{j_2} Y_{\lambda i} \right)$$

where $Y_{\lambda i} = \left[\exp\left(\frac{\omega_{\lambda i}}{T}\right) - 1 \right]^{-1/2}$ and $X_{\lambda i} = [1 + Y^2_{\lambda i}]^{1/2}$.

The thermal QRPA Hamiltonian

$$\mathcal{H}_{QRPA} = \sum_{\lambda \mu i} \omega_{\lambda i}(T) (Q^{\dagger}_{\lambda \mu i} Q_{\lambda \mu i} - \widetilde{Q}^{\dagger}_{\lambda \mu i} \widetilde{Q}_{\lambda \mu i}).$$

Transition amplitudes

Transition amplitudes:

excitation: $\Phi(\omega_{\lambda i}) = \left|\langle Q_{\lambda i} \| D_{\lambda i} \| 0(T); ph\rangle\right|^2$;

de-excitation: $\widetilde{\Phi}(-\omega_{\lambda i}) = \left|\langle \widetilde{Q}_{\lambda i} \| D_{\lambda i} \| 0(T); ph\rangle\right|^2$.

$$\Rightarrow \quad \widetilde{\Phi}_{\lambda i} = \exp\left(-\frac{\omega_{\lambda i}}{T}\right) \Phi_{\lambda i}$$

Inelastic neutrino-nucleus scattering cross section ($E_\nu \leq 15$ MeV):

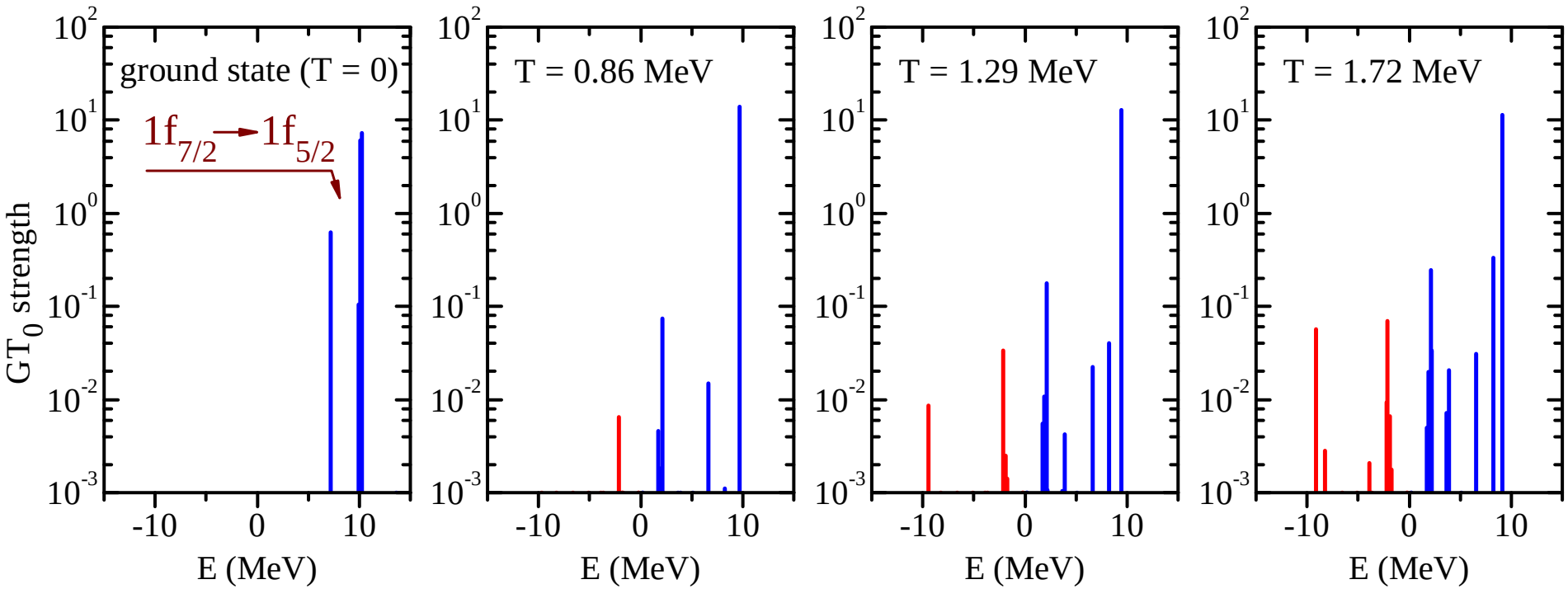
$$\sigma(E_\nu) = \frac{G_F^2}{\pi} \sum_i \left\{ (E_\nu - \omega_{1i})^2 \Phi_{1i} + (E_\nu + \omega_{1i})^2 \widetilde{\Phi}_{1i} \right\}$$

$$= \frac{G_F^2}{\pi} \sum_i \Phi_{1i} \left\{ (E_\nu - \omega_{1i})^2 + \exp\left(-\frac{\omega_{1i}}{T}\right) (E_\nu + \omega_{1i})^2 \right\}.$$

The QPM Hamiltonian parameters for ^{54}Fe

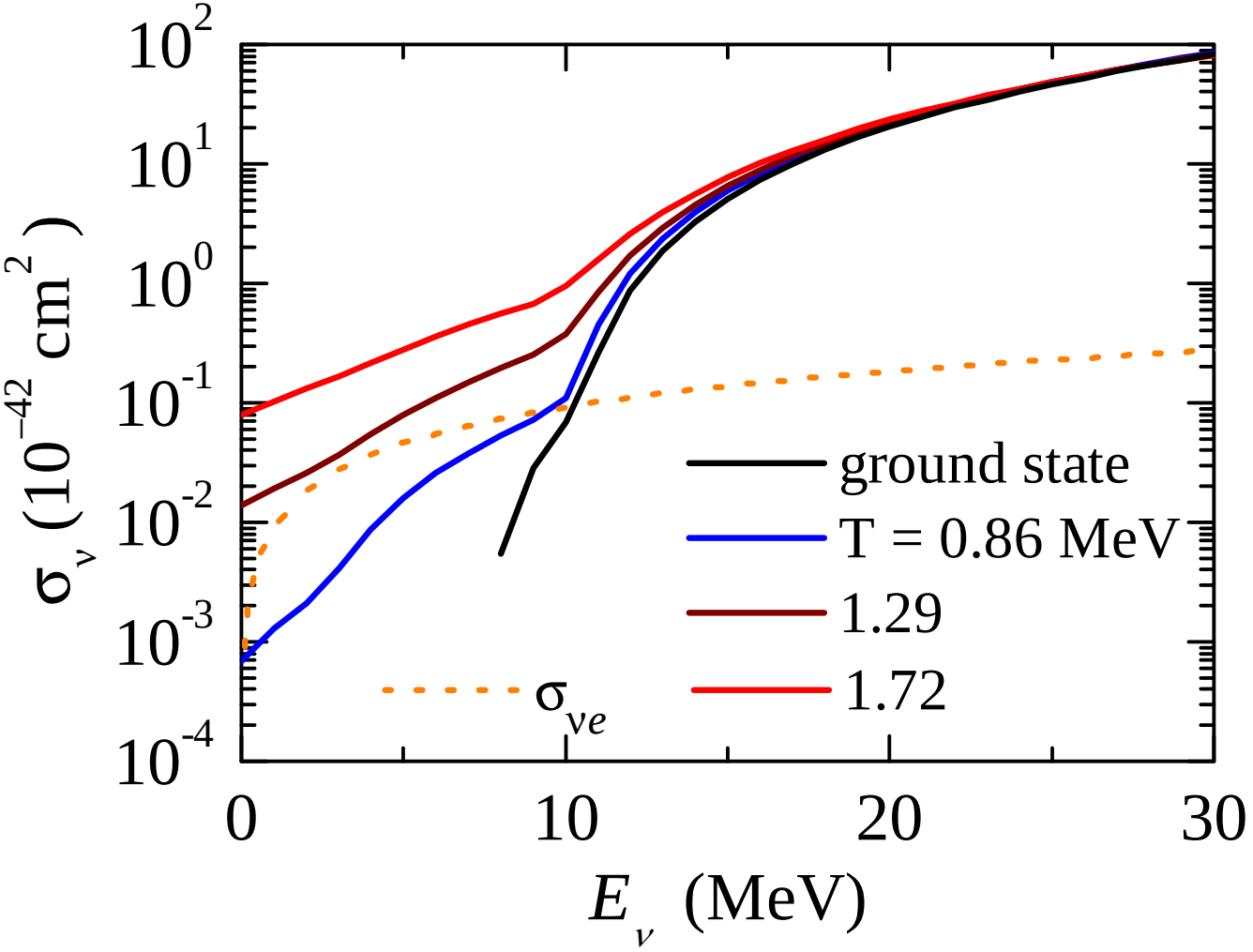
- The proton and neutron single particle energies and wave functions are calculated in the Woods-Saxon potential.
- The pairing constants G_n and G_p are fixed to reproduce the odd-even mass difference. $\Delta_p = 1.52$ MeV, $\Delta_n = 0$, $T_{cr} \simeq \Delta_p/2 = 0.8$ MeV.
- The spin-multipole coupling constants $\kappa^{01}_{0,1}$ and $\kappa^{21}_{0,1}$ are fixed to reproduce the experimental position of $GT_{\mp}$ and M1 resonances in ^{54}Fe.

GT_0 strength distribution in ^{54}Fe at finite temperatures



$1\ \text{MeV} \approx 11.6 \times 10^9 \text{K}$

Neutrino inelastic scattering cross section on ^{54}Fe



Conclusion and perspectives

- The novel approach to study properties of hot nuclei is developed. The approach is based on the thermo field dynamics.
- The approach is applied to study thermal effects on inelastic neutrino-nucleus scattering important for astrophysical applications. It was shown that thermal effects enhance the low-energy neutrino-nucleus cross sections. The enhancement is larger than it is predicted by SM calculations.
- All other conditions being equal, the predicted enhancement leads to a stronger shock wave and favors a supernova explosion.
- The approach can be further extended to include the interaction of one-phonon configuration with two-phonon ones like it was done at $T = 0$ within QPM. Moreover, it is desirable to extend the formalism for a realistic residual interaction.