Gamow-Teller strength distributions at finite temperatures and electron capture rates in stellar environment

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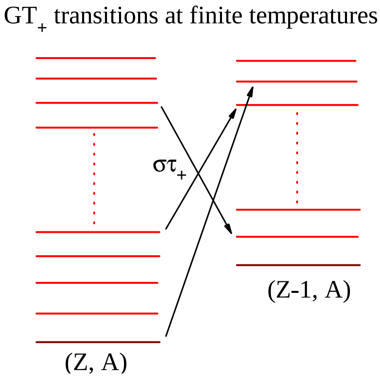
Electron capture on nuclei during the core collapse

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

- Reduses the number of electrons (Y_e) and keeps the core cool;
- Decreases Chandrasekar mass ($M_{Ch} \approx 1.44(2Y_e)^2 M_\odot$);
- Dominated by Gamow-Teller transitions caused by the $\sigma\tau_+$ operator.

In stellar environments EC takes place at finite temperatures $T = 0.2 - 2.0$ MeV ($0.1\text{ MeV} \approx 1.2 \times 10^9$ K) and GT_+ distributions for nuclear excited states are needed.



EC rates are computed by:

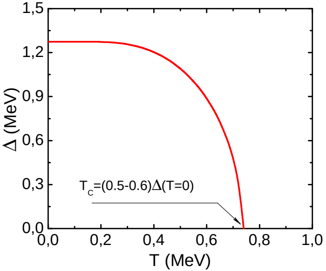
- Shell-Model for $A < 65$;
- Hybrid model (SMMC+RPA) for $A > 65$.

Basic ingredients of the Thermal QRPA (pnQRPA + TFD) approach:

- Thermo Field Dynamics
  - Thermal Hamiltonian: $\mathcal{H} = H - \widetilde{H}$, where $H|n\rangle = E_n|n\rangle$ and $\widetilde{H}|n\rangle = E_n|\widetilde{n}\rangle$;
  - Thermal vacuum: $\mathcal{H}|0(T)\rangle = 0$ and $\ll A \gg = \langle 0(T)|A|0(T)\rangle$;
- The QPM Hamiltonian: $H = H_{W.S.} + H_{BCS} + H_{ph}$.

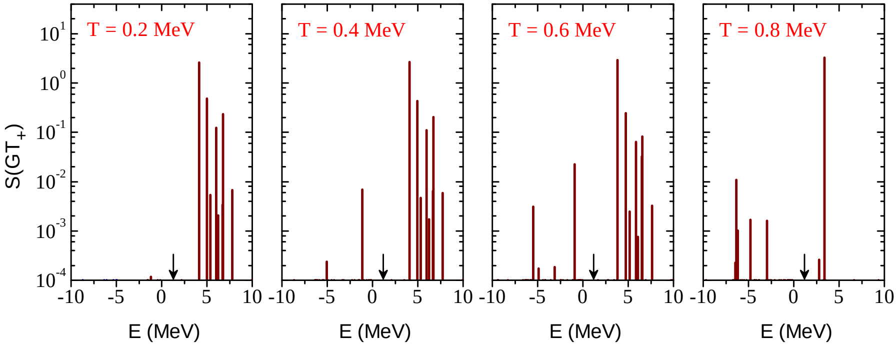
Diagonalization of $\mathcal{H}$ within TQRPA:

- Thermal quasiparticles:
  $\mathcal{H}_{W.S+BCS} \approx \sum_{i,\tau=p,n} \varepsilon_{i\tau}(\beta^\dagger_{i\tau}\beta_{i\tau} - \widetilde{\beta}^\dagger_{i\tau}\widetilde{\beta}_{i\tau})$;
- Thermal phonons:
  $\mathcal{H} \approx \sum_{k\lambda} \omega_{k\lambda}(Q^\dagger_{k\lambda}Q_{k\lambda} - \widetilde{Q}^\dagger_{k\lambda}\widetilde{Q}_{k\lambda})$



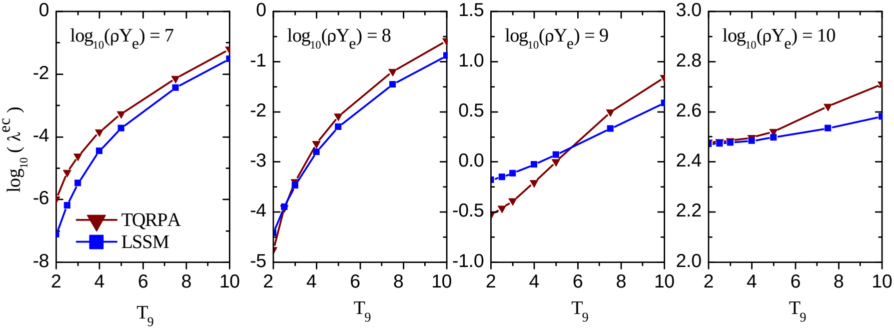
Transition strength: $S_{k\lambda} = \langle Q^\dagger_{k\lambda}|\hat{\mathcal{O}}_\lambda|0(T)\rangle$ and $S_{\widetilde{k\lambda}} = \langle \widetilde{Q}^\dagger_{k\lambda}|\hat{\mathcal{O}}_\lambda|0(T)\rangle$.

Iron group nuclei are essential at the early presupernova collapse,
$T = 0.2 - 0.8$ MeV and $\rho = 10^7 - 10^{10}$ g cm^{-3}.



The black arrows indicate the zero-temperature EC threshold
$Q = M(^{54}\mathrm{Fe}) - M(^{54}\mathrm{Mg}) = 1.21$ MeV.

Electron capture rates for ^{54}Fe

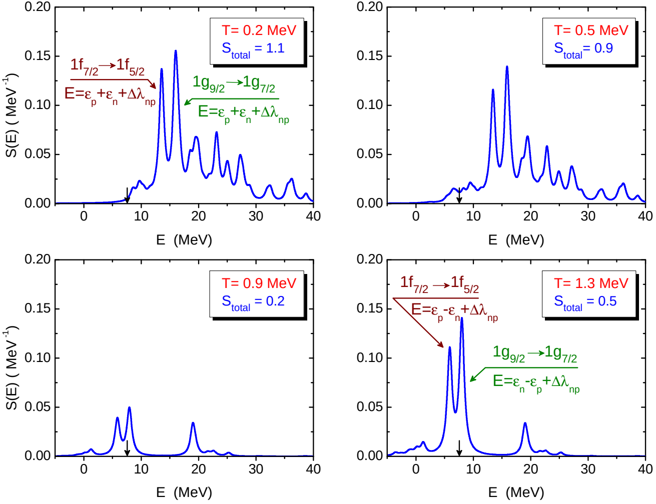


$\lambda^{ec} = \frac{\ln 2}{6150s} \sum_i S_i(GT_+)F_i,$

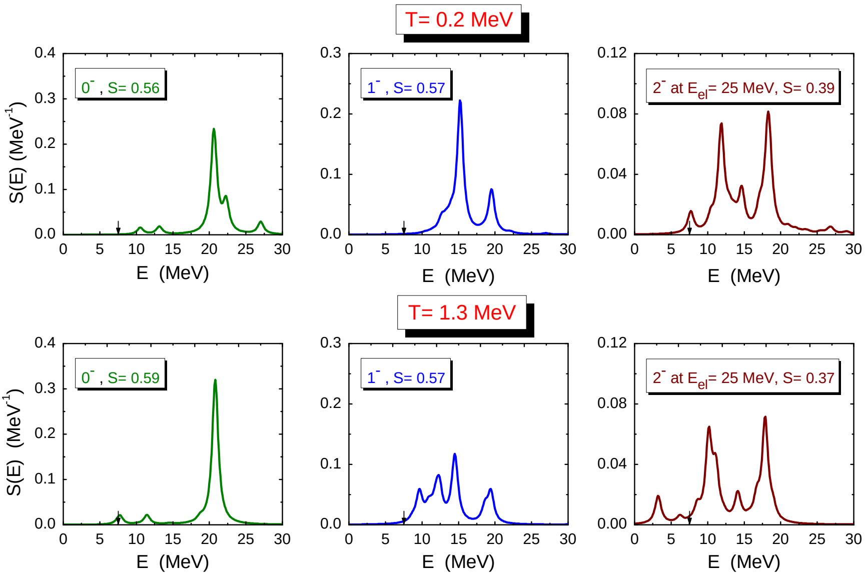
$T_9 = 10^9$ K; density ρY_e in g cm^{-3}.

Strength distributions of GT_+ transitions in ^{76}Ge

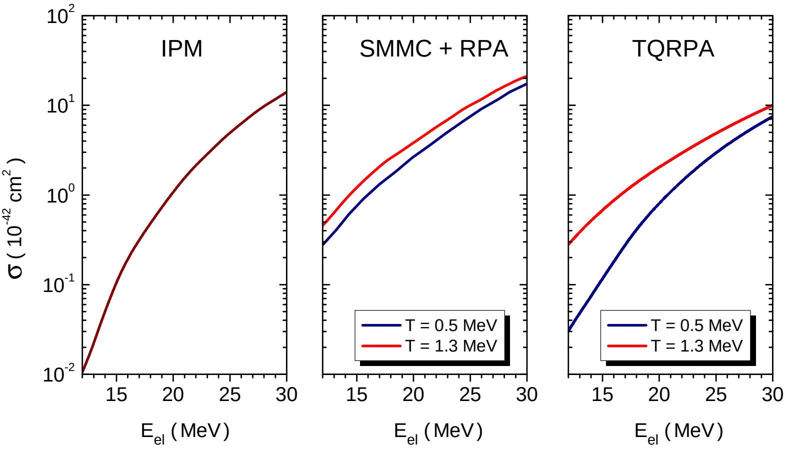
- Neutron-rich nuclei with $N \geqslant 40$ and $Z \leqslant 40$ dominate the nuclear composition for $\rho > 10^{10}$ g cm^{-3} and $T > 0.8$ MeV
- Unblocking mechanisms: thermal excitations and configuration mixing.



Strength distributions of first-forbidden $p \to n$ transitions in ^{76}Ge



Electron capture cross sections for ^{76}Ge



$\sigma(E_{el}, T) = \frac{G_w}{2\pi} F(Z, E_{el}) \sum_{\lambda i} (E_{el} - E_{\lambda i})^2 S_{\lambda i}$, $\lambda = 1^-, 0^+, 1^+, 2^+$.

Summary and Outlook

- The novel approach to study thermal effects on the GT_+ strength distributions and electron captures on nuclei in stellar environment have been presented. It was shown that thermal effects shift GT_+ centroid to lower excitation energies and make possible negative- and low-energy transitions. It was found that the unblocking effect for GT_+ transitions in neutron-rich nuclei is more sensitive to increasing temperature than it was predicted by the hybrid model.
- To improve the predictive power of the approach it is desirable to combine our TFD-based method with self-consistent QRPA calculations based on more realistic effective interactions. Another direction is the inclusion of correlations beyond TQRPA by coupling one-phonon states with more complex configurations like it was done at zero temperature within the QPM.

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