THERMAL ENHANCEMENT OF NUCLEAR (ANTI)NEUTRINO EMISSION DURING PRE-SUPERNOVA STAGE

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International Workshop

Infinite and Finite Nuclear Matter (INFINUM-2025)

May 12–16, 2025, Dubna, Russia

Motivation

ν_x, $\bar{\nu}_x$ ($x = e, \mu, \tau$) emission plays important role in massive star evolution at $\rho \gtrsim 10^7$ g/cm^3:

- keeps temperature low $T \lesssim 10^{10}$ K;
- carries away 99% of gravitational energy $\sim 10^{53}$ erg released in core collapse (SN1987A);
- neutrino heating mechanism for CCSN

Neutrino luminosity grows by orders of magnitude in last hours/days before collapse.

Can we see ν_e and $\bar{\nu}_e$ from pre-SN ?

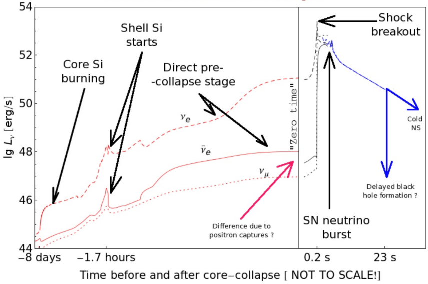
- alarm for an upcoming SN explosion
- direct observation of stellar interiors

Detector	Mass [kton]	Reactions	Number of Targets	Flux at 1 kpc [$cm^{-2}\,day^{-1}$]	Event rate [day^{-1}]
		$\nu_x + d \to \nu_x + p + n$	$6.00 \cdot 10^{[illegible]}$	$3.8 \cdot 10^{[illegible]}$	0.038
		$\bar{\nu}_x + d \to \bar{\nu}_x + p + n$	$6.00 \cdot 10^{31}$	$3.8 \cdot 10^{11}$	0.032
Super-K	32 (H_2O)	$\bar{\nu}_e + p \to e^+ + n$	$2.14 \cdot 10^{33}$	$2.8 \cdot 10^{11}$	41
UNO	440 (H_2O)	$\bar{\nu}_e + p \to e^+ + n$	$2.94 \cdot 10^{34}$	$2.8 \cdot 10^{11}$	560
Hyper-K	540 (H_2O)	$\bar{\nu}_e + p \to e^+ + n$	$3.61 \cdot 10^{34}$	$2.8 \cdot 10^{11}$	687

Event rate per day in selected neutrino detectors from silicon burning stage in neutrino-cooled star at distance of 1 kpc.

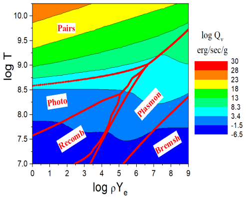
Odrzywolek, Misiaszek, and Kutschera Astropart. Phy. 21, 303 (2004)

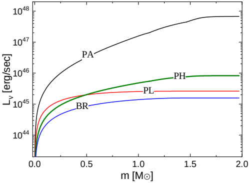
Neutrinos BEFORE and AFTER collapse



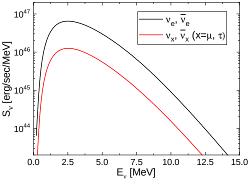
Odrzywolek and Heger Acta Physica Polonica B41(2010) 1611

Emission of $\nu\bar{\nu}$ pairs in thermal processes





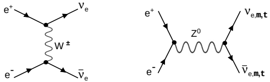
Spectra of ν and $\bar{\nu}$ from the PA process



Thermal processes produce all flavors of neutrinos

- Electron-positron pair annihilation (PA process)

$$\gamma + \gamma \leftrightarrows e^- + e^+ \to \nu + \bar{\nu},$$



- Plasmon decay (PL process)

$$\gamma^* \to \nu + \bar{\nu}$$

- Electron-nucleus bremsstrahlung (BR process)

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

- Photo-neutrino (PH process)

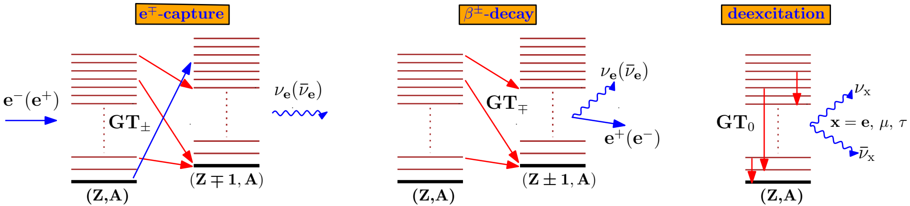
$$e^- + \gamma \to e^- + \nu + \bar{\nu}$$

Emission of ν and $\bar{\nu}$ in nuclear weak-interaction processes

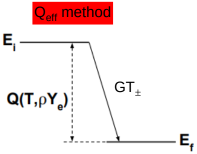
- Iron-group nuclei ($A = 50 - 60$) dominate in the central part of the star.
- Nuclei are completely ionized and electrons (positrons) form a (non)degenerate gas ($\mu_{e-} \sim \rho^{1/3}$, $\mu_{e+} = -\mu_{e-}$).
- Nuclear excited states are thermally populated in accordance with Boltzmann distribution

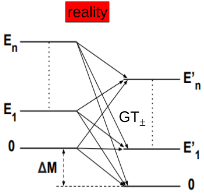
$$p_i(T) = \frac{\exp(-E_i/T)}{Z(T)}.$$

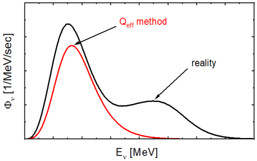
At $T \approx 1$ MeV, for iron-group nuclei mean excitation energy is $\langle E \rangle = \frac{AT^2}{8} \approx 6 - 8$ MeV .



Emission of ν and $\bar{\nu}$ in nuclear processes is dominated by GT$_{\pm,0}$ transitions ($\vec{\sigma}t_{\pm,0}$ operator).







For a single nucleus, the neutrino spectra from charge-exchange weak reactions are parameterized as follows

$$\phi^{\text{EC,PC}}(E_\nu) = N_{\text{EC,PC}} \frac{E_\nu^2 (E_\nu - Q)^2}{1 + \exp\left(\dfrac{E_\nu - Q \mp \mu_e}{kT}\right)} \Theta(E_\nu - Q - m_e c^2),$$

$$\phi^{\beta^\pm}(E_\nu) = N_{\beta\pm} \frac{E_\nu^2 (Q - E_\nu)^2}{1 + \exp\left(\dfrac{E_\nu - Q \mp \mu_e}{kT}\right)} \Theta(Q - E_\nu - m_e c^2),$$

The effective Q-value and normalization factors N_i are fit parameters, and they are adjusted to the average (anti)neutrino energy and weak reaction rates

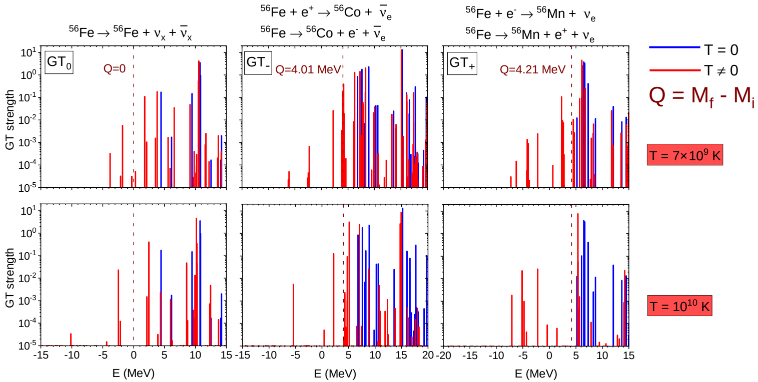
$$\langle E_{\nu,\bar\nu} \rangle = \frac{\int_0^\infty (\phi^{\text{EC,PC}} + \phi^{\beta^\pm}) E_\nu dE_\nu}{\int_0^\infty (\phi^{\text{EC,PC}} + \phi^{\beta^\pm}) dE_\nu},$$

$$\lambda^i = \int_0^\infty \phi^i (E_\nu) dE_\nu \quad i = \text{EC, PC, } \beta^\pm.$$

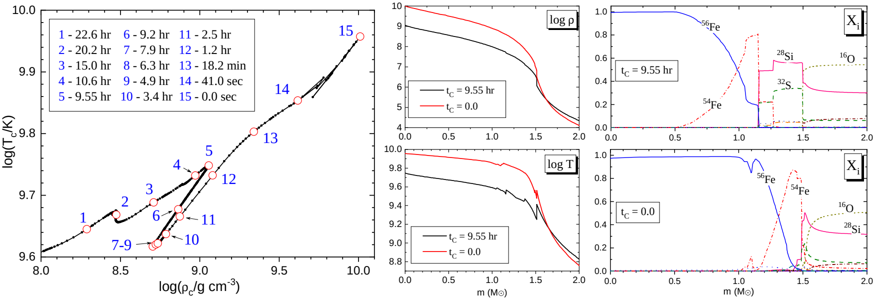
For iron-group nuclei weak-interaction rates for hot nuclei in stellar matter were obtained within Large-scale Shell Model Calculations (Langanke&Martínez-Pinedo).

- Temperature dependent strength functions $S(E,T)$ for GT$_{\pm,0}$ transitions in a hot nucleus;
- GT$_{\pm,0}$ transitions are treated within the TQRPA;
- The detailed balance is fulfilled: $S(-E,T) = \exp\left(-\frac{E}{T}\right) S(E,T)$;
- Self-consistent calculations with the Skyrme energy-density functional SkM*.

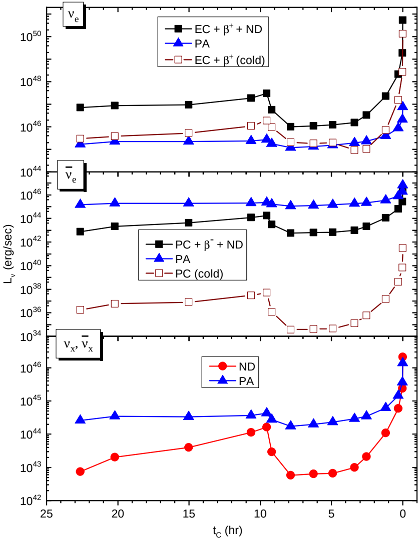
Thermal effects on GT strength functions in ^{56}Fe



- Pre-supernova model with $M = 14\,M_\odot$;
- Realistic pre-supernova conditions via **MESA** (Modules for Experiments in Stellar Astrophysics);
- **MESA** outputs: $\rho(t,r)$, $T(t,r)$, $X_i(t,r)$ and $Y_e(t,r)$.

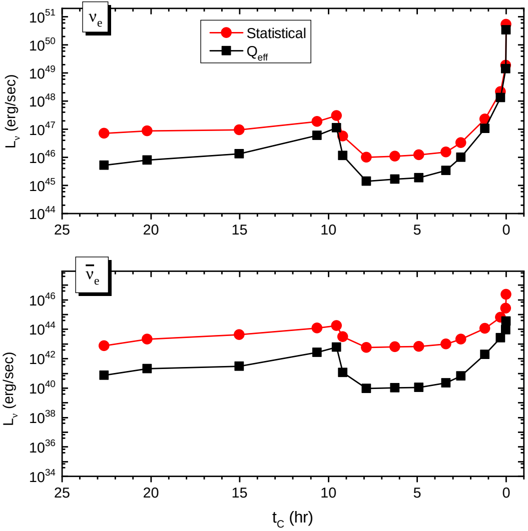


Energy luminosity

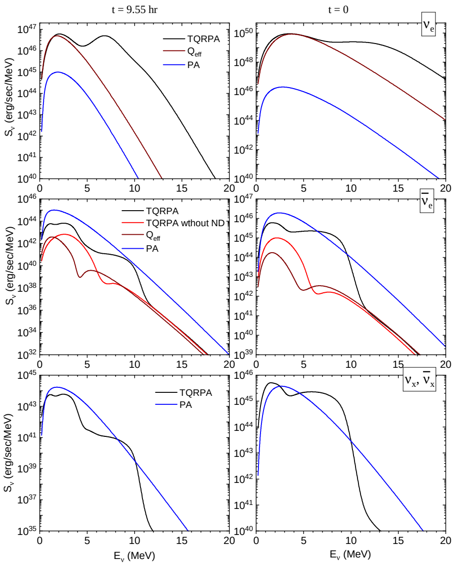


EC - electron capture
PC - positron capture
ND - nuclear charge-neutral deexcitation
PA - pair annihilation

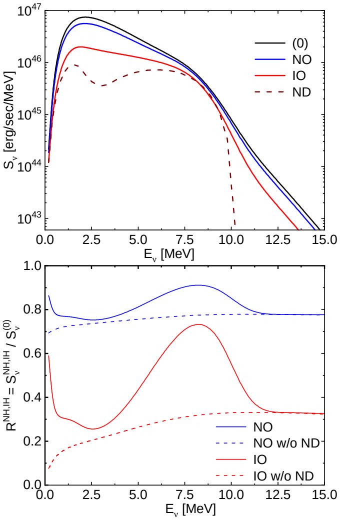
Energy luminosity from nuclear processes



(Anti)neutrino spectra from nuclear and thermal processes



Influence of the ND process on oscillated $\bar{\nu}_e$ spectra



Flavor neutrinos are a linear combination of mass neutrinos

$$\nu_\alpha = \sum_{i=1,2,3} U_{\alpha i}\nu_i, \quad (\alpha = e,\, \mu,\, \tau).$$

The probabilities of oscillations in a vacuum

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i<j} \text{Re}[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}] \sin^2 \frac{\Delta m^2_{ij} L}{4E}$$
$$+ 2\sum_{i<j} \text{Im}[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}] \sin^2 \frac{\Delta m^2_{ij} L}{2E}.$$

Mikheev-Smirnov-Wolfenstein effect amplifies oscillations.

The final $\bar{\nu}_e$ flux reaching the Earth can be written as

$$S_{\bar{\nu}_e} = pS^{(0)}_{\bar{\nu}_e} + (1-p)S^{(0)}_{\bar{\nu}_x}, \quad (x = \mu,\, \tau),$$

where p is the survival probability

- $p \approx 0.68$ for the **normal mass ordering (NO)** ($m_1 < m_2 < m_3$);
- $p \approx 0.02$ for the **inverted mass ordering (IO)** ($m_3 < m_1 < m_2$).

Influence of the ND process on $\bar{\nu}_e$ detection

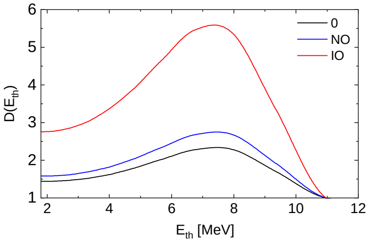
The dominant detection process for $\bar{\nu}_e$ is the inverse β-decay:

$$\bar{\nu}_e + p \to n + e^+.$$

The cross section for IBD is $\sigma_{\text{IBD}}(E_\nu) \sim p_{e^+} E_{e^+}$, where $E_{e^+} = E_{\bar{\nu}_e} - (M_n - M_p)$. The minimum energy required to induce IBD is $E_{\bar{\nu}_e}^{\text{min}} = M_n - M_p + m_e \approx 1.8\,\text{MeV}$.

We assume the detection efficiency 100% above the threshold $E_{\text{th}} \geq E_{\bar{\nu}_e}^{\text{min}}$. Then the number of detected events is

$$N(E_{\text{th}}) \sim \int_{E_{\text{th}}}^{\infty} \sigma_{\text{IBD}}(E_\nu) \Phi_{\bar{\nu}_e}(E_\nu) dE_\nu.$$



Detection rate enhancement factor due to the ND process:

$$D(E_{\text{th}}) = \frac{N(E_{\text{th}})}{N^*(E_{\text{th}})},$$

where $N^*(E_{\text{th}})$ is computed without the ND contribution.

Conclusions

- A new method for calculating spectra and luminosities for (anti)neutrinos produced in the pre-supernova environment by weak processes with hot nuclei is proposed. The method is based on the thermal quasiparticle random phase approximation (TQRPA), that allows microscopic thermodynamically consistent calculations of GT strength functions at finite temperatures.
- It is found that the TQRPA approach produces not only a higher total luminosity of electron neutrinos (mainly born in the electron capture reaction), compared to the standard technique based on the Q_{eff} method, but also a harder neutrino spectrum. Both these effects are due to a larger strength of low- and negative-energy GT transitions in thermally excited nuclei predicted by the TQRPA.
- It is shown that in the context of electron antineutrino generation, the nuclear de-excitation (ND) process via neutrino-antineutrino pair emission is at least as important as the electron-positron pair annihilation process.
- It is found that flavor oscillations enhance the high-energy contribution of the ND processes to the electron antineutrino flux. This could potentially be important for pre-supernova antineutrino registration by the Earth's detectors.