Излучение (анти)нейтрино нагретыми ядрами на стадии предсверхновой

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"Физика фундаментальных взаимодействий",
посвященная 70-летию со дня рождения
Валерия Анатольевича Рубакова

17-21 февраля, 2025, Москва, Россия

Motivation

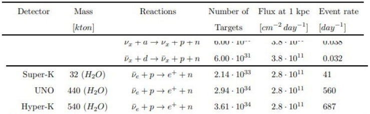
ν_x, $\bar{\nu}_x$ $(x = e, \mu, \tau)$ emission plays an important role in massive star evolution at $\rho \gtrsim 10^7$ g/cm^3:

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

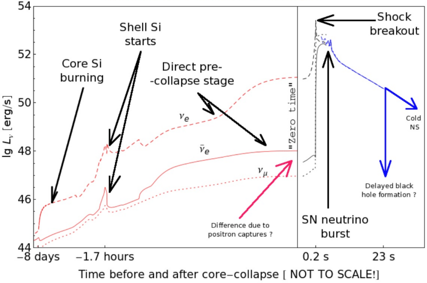


Detector	Mass [$kton$]	Reactions	Number of Targets	Flux at 1 kpc [$cm^{-2}\,day^{-1}$]	Event rate [day^{-1}]
		$\nu_x + a \to \nu_x + p + n$	$6.00 \cdot 10$[illegible]	$3.8 \cdot 10$[illegible]	0.038
		$\bar{\nu}_x + d \to \bar{\nu}_x + p + n$	$6.00 \cdot 10^{31}$	$3.8 \cdot 10^{11}$	0.032
Super-K	32 (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.

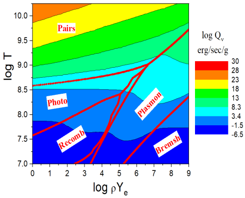
Odrzywolek, Misiaszek, and Kutschera Astropart. Phy. 21, 303 (2004)

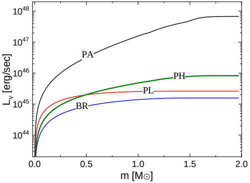
Neutrinos BEFORE and AFTER collapse



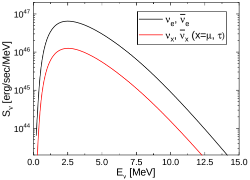
Odrzywolek and Heger Acta Physica Polonica B41(2010) 1611

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





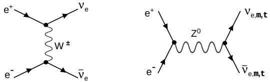
Spectra of ν and $\bar{\nu}$ from the PA process



Thermal processes produce all flavors of neutrinos

- Electron-positron pair annihilation (PA process)

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



- Plasmon decay (PL process)

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

- Electron-nucleus bremsstrahlung (BR process)

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

- Photo-neutrino (PH process)

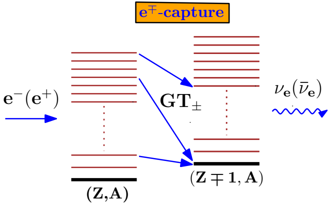
$$e^- + \gamma \rightarrow e^- + \nu + \bar{\nu}$$

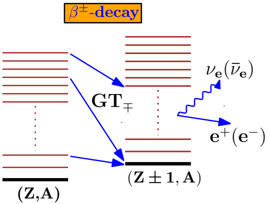
Emission of ν and $\bar{\nu}$ in nuclear weak-interaction processes

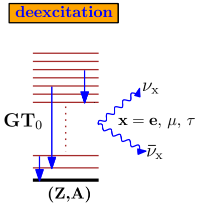
- Iron-group nuclei ($A = 50 - 60$) dominate in the central part of the star.
- Electrons (positrons) form a (non)degenerate gas.
- Nuclear excited states are thermally populated in accordance with Boltzmann distribution

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

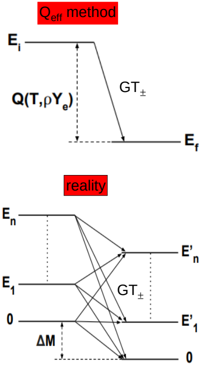
At $T \approx 1\,\text{MeV}$, for iron-group nuclei mean excitation energy is $\langle E \rangle = \dfrac{AT^2}{8} \approx 6 - 8\,\text{MeV}$.

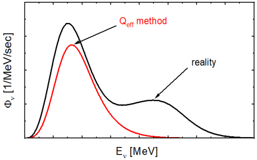






Effective Q-value method





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

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

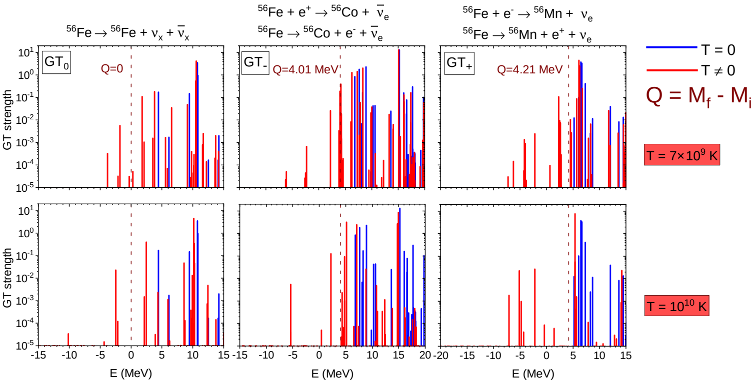
$$\lambda^i = \int_0^\infty \phi^i(E_\nu) dE_\nu \quad i = \text{EC, PC, } \beta^\pm.$$

For iron-group nuclei weak-interaction rates for hot nuclei in stellar matter were obtained within Large-scale Shell Model calculations.

Statistical approach

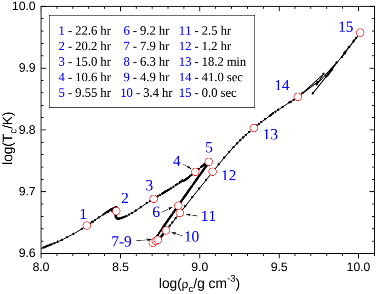
- Temperature dependent strength functions $S(E,T)$ for $\mathrm{GT}_{\pm,0}$ transitions in a hot nucleus;
- $\mathrm{GT}_{\pm,0}$ transitions are treated in one-phonon approximation;
- The detailed balance is fulfilled: $S(-E,T) = \exp\left(-\frac{E}{T}\right) S(E,T)$;
- Self-consistent calculations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

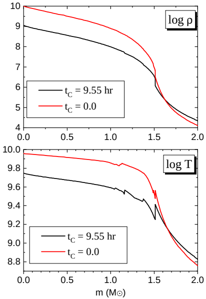
Thermal effects on GT strength functions in ^{56}Fe

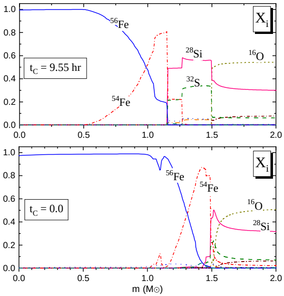


Pre-supernova model

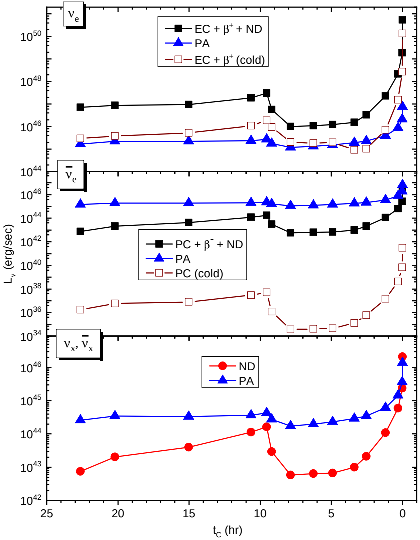
- Realistic pre-supernova conditions via **MESA** (**M**odules for **E**xperiments in **S**tellar **A**strophysics)
- Pre-supernova model with $M = 14\,M_\odot$







Energy luminosity



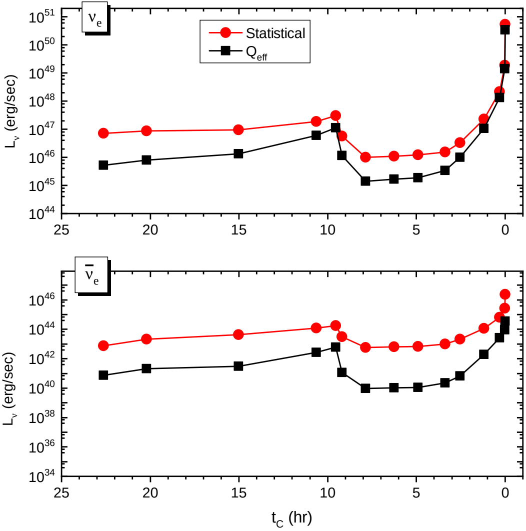
EC - electron capture

PC - positron capture

ND - nuclear charge-neutral deexcitation

PA - pair annihilation

Energy luminosity from nuclear processes



Influence of nuclear processes on oscillated ν_e and $\bar{\nu}_e$ 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

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

Mikheev-Smirnov-Wolfenstein effect amplifies oscillations.

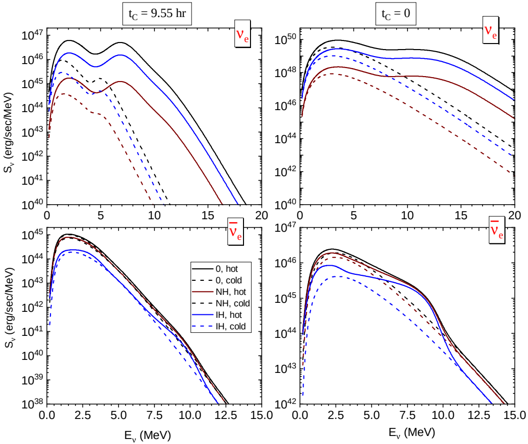
The final ν_e flux reaching the Earth can be written as

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

where p and $\bar{p}$ are the survival probabilities:

- $p \approx 0.02$ and $\bar{p} \approx 0.68$ for the **normal mass ordering (NO)** ($m_1 < m_2 < m_3$);
- $p \approx 0.3$ and $\bar{p} \approx 0.02$ for the **inverted mass ordering (IO)** ($m_3 < m_1 < m_2$).

Influence of nuclear processes on oscillated ν_e and $\bar{\nu}_e$ spectra



Conclusions

- It is shown that a thermodynamically consistent treatment of thermal effects predicts a several times higher luminosity of pre-supernova electron neutrinos and antineutrinos compared to the standard technique based on the effective Q-value method.
- It was found that electron capture on excited nuclear states leads to an increase in the fraction of high-energy electron neutrinos in the spectrum compared to the spectrum formed on a cold nucleus.
- It is shown that the process of neutrino-antineutrino pair emission via de-excitation of a hot nucleus plays the same important role in the generation of electron antineutrinos as the process of electron-positron annihilation.
- We also showed that neutrino oscillations significantly enhance the relative contribution of the nuclear de-excitation process to the flux of high-energy electron antineutrinos.
- The observed effects increase the probability of detecting electron neutrinos and antineutrinos from pre-supernovae by the Earth's detectors.