Sterile neutrinos in supernovae

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Abstract. Motivated by the recent hints for sterile neutrinos from reactor anomalies, we discuss active-sterile conversions in an electron-capture supernova using a (2 active + 1 sterile) scenario. By including the feedback effect on the electron abundance due to neutrino oscillations, we study the impact of sterile neutrinos on both the oscillated neutrino fluxes and Y_e.

1. Introduction
Sterile neutrinos are hypothetical gauge-singlet fermions that mix with one or more of the active states and thus show up in active-sterile flavor oscillations. Our study is motivated by the most recent indication for the possible existence of eV-mass sterile neutrinos coming from a new analysis of reactor $\bar{\nu}_e$ spectra [1, 2]. The data suggest a $\nu_e-\nu_s$ mixing of $\sin^2 2\theta \sim 0.14$ with mass splitting of $\Delta m^2 > 1.5 \text{ eV}^2$.

Assuming that the sterile state is heavier than the active ones because of cosmological mass limits, in supernovae (SNe) such parameters imply $\nu_e-\nu_s$ MSW conversions close to the SN core. Therefore, the $\nu_e$ flux arriving at Earth from the next SN explosion would be significantly modified by the presence of sterile neutrinos.

We here focus on a different aspect of $\nu_e-\nu_s$ oscillations that could have an interesting impact during the SN cooling phase. The neutrino-driven matter outflow is a candidate site for r-process nucleosynthesis. It requires a neutron-rich environment, i.e. $Y_e < 0.5$, large entropy to favor lighter nuclei at high temperatures, and fast timescales to lower the efficacy of converting alpha particles to heavier nuclei. We discuss whether sterile neutrinos might trigger the r-process or somehow affect the nuclei formation.

2. Neutrino and Y_e evolutions in electron-capture supernovae
We use long-term simulations for an electron-capture SN of a representative progenitor with mass 8.8 $M_\odot$ [3] and we discuss here two representative cooling times ($t = 0.5, 2.9 \text{ s}$). In table 1, for each flavor $\nu_\beta$, the neutrino-sphere radius, the luminosity $L_{\nu_\beta}$ and the average energies $\langle E_{\nu_\beta} \rangle$ are reported.

We consider a $2+1$ flavor scenario ($\nu_e, \nu_\mu, \nu_s$) with mass differences $\delta m^2_S = 2.35 \text{ eV}^2 > 0$ and $\delta m^2_{\text{atm}} = -2 \times 10^{-3} \text{ eV}^2 < 0$. The mixing is driven by $\sin^2 \Theta_{13} = 10^{-4}$ and $\sin^2 2\Theta_S = 0.165$ assuming negligible the other mixing angles. The flavor evolution is described by matrices of densities for each energy mode $E$ for $\nu$ and $\bar{\nu}$, the diagonal entries being the usual occupation numbers. The evolution of $\rho_E$ is governed by the Liouville equations

$$i \partial_t \rho_E = [H_E, \rho_E] \quad \text{and} \quad i \partial_t \bar{\rho}_E = [\bar{H}_E, \bar{\rho}_E],$$

(1)
The Hamiltonian matrix contains vacuum, matter, and neutrino–neutrino terms \( H_E = H_E^{\text{vac}} + H_E^{\text{m}} + H_E^{\nu\nu} \). Because of the presence of sterile neutrinos, the matter term includes both the charge-current (CC) and the neutral-current (NC) contributions: \( H_E^{\text{m}} = \sqrt{2} G_F \text{diag}(N_e - N_n/2, -N_n/2, 0) \), with \( N_e \) the electron number density and \( N_n \) the neutron one in the medium. Note that being \( Y_e = N_e(r)/(N_e(r) + N_n(r)) \), \( H_E^{\text{m}} \) is a function of \( Y_e \) and it changes as \( Y_e \) changes. \( H_E^{\nu\nu} \) has all the terms involving sterile neutrinos identically equal to zero, as proved in [4]. The electron fraction, on the other hand, is altered by the charged-current weak interactions by converting neutrons to protons and vice-versa. Assuming \( \beta \)-equilibrium is reached, the electron abundance is set by the competition between \( \nu_e + n \rightarrow p + e^- \) and \( \bar{\nu}_e + p \rightarrow n + e^+ \) and the associated reversed processes. The rate of change of \( Y_e \) on an outflowing mass element may be written as [5]

\[
\frac{dY_e}{dt} = v(r) \frac{dY_e}{dr} \approx (\lambda_{\nu_e} + \lambda_{e^-})Y_n^f - (\lambda_{\bar{\nu}_e} + \lambda_{e^+})Y_p^f,
\]

where \( v(r) \) is the velocity of the outflowing mass element, \( t \) is the time parameter, \( \lambda_{\nu_e} (\lambda_{\bar{\nu}_e}) \) is the forward rate of (anti-)neutrinos and \( \lambda_{e^-} (\lambda_{e^+}) \) the electron (positron) capture rate on free nucleons [5]. Since \( Y_e \) is a function of the neutrino-capture rates, it depends on the neutrino flavor evolution. Therefore, we have to consider the double feedback effect due to both these effects.

### 3. Results: early-cooling phase

Figure 1 shows the spectra without (with) oscillations on the top (bottom) for \( \Delta m_{\text{atm}}^2 < 0 \). Neutrino refractive contribution on the \( \nu_e-\bar{\nu}_e \) conversion is minimal. After the \( \nu_e-\nu_\mu \) MSW conversion, the \( e-x \) difference spectrum is very asymmetric between neutrinos and antineutrinos and collective conversions are suppressed.

Figure 2 shows \( Y_e \) as a function of the radius for the cases without and with neutrino oscillations. The MSW flavor conversions lower the electron abundance.

### 4. Results: intermediate-cooling phase

Figure 3 shows the energy fluxes for \( \Delta m_{\text{atm}}^2 < 0 \). In this case, collective oscillations sensitively modify the spectra. In fact, after the \( \nu_e-\nu_\mu \) MSW conversion, the neutrino background is responsible for increasing the \( \bar{\nu}_e \) flux with respect to the case with only matter and for averaging out the \( \nu_x \) and \( \bar{\nu}_x \) fluxes.

In figure 4 the electron abundance is plotted as a function of the radius. The oscillations are responsible for an asymptotic value of \( Y_e \) lower than in the case without oscillations, and in particular collective effects make it even lower. The smaller value of \( Y_e \) due to sterile neutrinos could sensitively affect the nucleosynthesis in SNe.

### 5. Conclusions

Motivated by the recent hints on sterile neutrinos, we assume the existence of one sterile family with the reactor anomaly mixing parameters and discuss for the first time the impact of \( \bar{\nu}_s \) on two active flavor evolution and on nucleosynthesis.
Figure 1. Spectra for $\nu$ (left) and $\bar{\nu}$ (right) in arbitrary units (a.u.) for the 0.5 s model. Top: No oscillations (spectra at neutrino sphere). Middle: Oscillated spectra, including only the matter effect. Bottom: $\nu-\nu$ interactions are also included, but cause no visible difference.

Figure 2. Electron abundance as a function of the radius at $t = 0.5$ s for the case with and without oscillations.

The sterile neutrino production is triggered by the MSW resonance between the active and the sterile sector. However for $t = 0.5$ s, no further flavor conversion is caused by $\nu-\nu$ interactions because collective oscillations are suppressed. For $t = 2.9$ s, the $\nu-\nu$ interactions do trigger further flavor conversions. For both time slices discussed, $Y_e$ is lower than in the case without oscillations and it could affect the nuclei formation.

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**Figure 3.** Energy spectra for $t = 2.9$ s, as in figure 1.

**Figure 4.** Electron abundance for $t = 2.9$ s, as in figure 2.

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