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CHARGED CURRENT INTERACTIONS OF ν_μ AND $\bar{\nu}_e$ IN SUPERNOVA

Andreas Lohs[*1], [†]
[1]*Institut für Kernphysik (Theoriezentrum), Technische Universität Darmstadt, Schlossgartenstraße 2, D-64289 Darmstadt, Germany*
E-mail: alohs@theorie.ikp.physik.tu-darmstadt.de

Gabriel Martínez-Pinedo[1,2], **Tobias Fischer**[3]
[2]*GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, D-64291 Darmstadt, Germany*
[3]*Institute for Theoretical Physics, University of Wroclaw, Plac Maksa Borna 9, 50-204 Wroclaw, Poland*

Accurate neutrino transport is among the main ingredients to understand core-collapse supernovae and to perform numerical simulations of these events. The large amount and energy emitted in the form of neutrinos affects various distinct processes in supernovae. Neutrinos might trigger the explosion but they are also responsible for nucleosynthesis in neutrino driven wind. It is therefore necessary to study which neutrino reactions are relevant for which conditions. Here we explore the possible impact of additional reaction channels that are not included in current supernovae simulations. In particular we have investigated charged-current weak interactions for muon neutrinos and inverse neutron decay for electron antineutrinos at densities above $10^{12}\,\mathrm{g\,cm^{-3}}$. It is shown that these reactions might affect the formation of neutrino spectra and neutrino signals from the interior of the protoneutron star. This could have further consequences especially for nucleosynthesis conditions in the neutrino driven wind.

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1. Introduction

The collapse of a massive star at the end of its lifetime and the subsequent explosion in a core-collapse supernova releases an enormous amount of energy, roughly 10^{53} erg. Most of this energy, up to 99 %, is released in the form of neutrinos. This is due to their weak coupling to matter, allowing them to escape from the surface of the protoneutron star (PNS). Hence, the deleptonization and cooling of a PNS creates a characteristic neutrino signal. For a galactic supernova it can be detected on earth, as for supernova SN1987A. In the interior of the PNS weak interactions become large and neutrinos are trapped in the high density matter. They are then in thermal and chemical equilibrium with their environment. As the density decreases so do the ν-opacities until the neutrinos eventually decouple and their spectra form. The shape of these spectra depends on the behaviour of weak interactions in the decoupling region. Predicting reliable neutrino spectra therefore requires knowledge of all relevant reaction channels. They need to be evaluated consistently with the underlying equation of state (EOS) and the thermodynamical conditions. In particular the effect of the strong interactions in the nuclear matter must be considered in the computation of neutrino transport for densities above $\sim 10^{12}\,\mathrm{g\,cm^{-3}}$ [1 – 3]. A good review on core collapse supernovae in general and the explosion mechanism (and the role of neutrinos therein) in particular is given in [4]. In this work we will focus on the role of neutrinos after the explosion has been launched. Once decoupled from matter, most of the neutrinos leave the PNS without further interactions. Only a small fraction gets reabsorbed. Yet, due to the larger neutrino flux, this small fraction still deposits a considerable amount of energy. This creates low-mass ejecta from the surface of the PNS, the so called neutrino driven wind (NDW). The NDW has long been studied as a possible site for heavy-element nucleosynthesis [5]. Current understanding is that a weak r-process [6] and the ν-p-process [7 – 9] might take place here. The exact path of nucleosynthesis is very sensitive to the composition i.e. the ratio of neutrons to protons in the NDW. This is again determined by the properties of the neutrino spectra. Hence, neutrino transport couples neutrino driven wind nucleosynthesis to nuclear physics at high densities. In the next section we will discuss this concept in more detail. In section 3 we will discuss the importance of inverse neutron decay for electron antineutrinos at high densities. In section 4 we will do the same for charged-current weak interactions for muon neutrinos. All of these reactions have to our knowledge not yet been studied in the context of core-collapse supernovae.

2. Neutrino transport

As the PNS cools and deleptonizes, the density from which neutrinos escape rises continuously. One can define the concept of a region of last interaction, the so called neutrinosphere [10]. In general, the position of this sphere depends on the neutrino energy. Furthermore, two different definitions have to be distinguished. One is the scattering sphere, where neutrinos are deflected for the last time. The other is the energy sphere, where the neutrinos exchange energy for the last time with the matter i.e. where they are emitted. For ν_e these regions are mostly the same, since their total opacity for the main cooling phase during the first seconds post bounce is dominated by absorption on neutrons. For $\bar{\nu}_e$ and heavy neutrino flavours ν_x, the dominant reaction is scattering on nucleons, especially neutrons. Yet, due the large mass of the nucleons, these reactions have almost no impact on the energy of the neutrinos. One can therefore think of these neutrinos as decoupling at the scattering sphere but of their spectra as being formed at the energy sphere. This concept is widely used in studying neutrino transport and we will apply it, too. However, it is challenged by the argument that scatterings with nucleons outside of the energy sphere still happen so frequently that they might modify the neutrino spectra considerably[11]. In any event, it is very important to understand the dominant reaction channels for ν's around the energy sphere in order to predict the spectra. Further outside, reactions are too rare to really affect the spectra; further inside, neutrinos are in equilibrium. Other than scattering on nucleons, the dominant reactions at the energy sphere are absorption on protons and scattering on electrons for $\bar{\nu}_e$ and scattering on electrons and inverse bremsstrahlung for ν_x. Only absorption on protons and bremsstrahlung can change the number of the respective neutrinos.

As stated before, after decoupling some of the neutrinos will eject matter in the neutrino driven wind. The relevant reactions here are just

$$\nu_e + n \to e^- + p \qquad \text{and} \qquad \bar{\nu}_e + p \to e^+ + n.$$

The composition of the NDW will be determined by the condition of equilibrium between these reactions for the given ν-spectra [12, 13]. For the electron fraction Y_e to be below 0.5 the average energy $\varepsilon_{\bar{\nu}_e}$ of $\bar{\nu}_e$ must be considerably higher than ε_{ν_e}. $\bar{\nu}_e$ have to overcome the mass difference between neutrons and protons while ν_e release this energy. However, if Y_e is above 0.5 then r-process can not take place in NDW nucleosynthesis. Simulations are currently predicting that the NDW might initially be slightly below $Y_e = 0.5$ and then become proton-rich, allowing only for a weak r-process. However, a possible change in the neutrino spectra due to improved neutrino transport in the decoupling region could easily affect this prediction.

The study of additional reactions is based on profiles from a 1-dimensional spherical symmetric core-collapse supernova of a $15M_\odot$ progenitor star with Boltzmann neutrino transport [14]. The underlying equation of state is the DD2-EOS [15, 16] which agrees very well with constraints on the nuclear symmetry energy from experiment (e.g. multifragmentation reactions[17]), theory (chiral EFT[18]), and observation (neutron star radii and masses[19]).

3. Inverse neutron decay

As opposed to ν_e, $\bar{\nu}_e$-absorption has to overcome the energy difference between neutrons and protons. At densities above $10^{12}\,\mathrm{g\,cm^{-3}}$ strong interactions become relevant. Below $10^{14}\,\mathrm{g\,cm^{-3}}$ nucleons can be described by a relativistic mean field (RMF) EOS that can be approximated to the nonrelativistic limit. Hence nucleons follow the dispersion relation

$$E_{n,p} = \frac{p^2}{2m^*} + M_{n,p} + U_{n,p} \tag{3.1}$$

where m^* denotes the effective mass and U the mean field potential. The inclusion of U is modifying the Q-value for charged-current neutrino-matter interactions. This is because $U_n \neq U_p$, mostly $U_n > U_p$ for the relevant conditions (see Figure 1). The opacity for absorption of $\bar{\nu}_e$ will be more suppressed the larger $U_n - U_p$. In addition, absorption of $\bar{\nu}_e$ with energies significantly lower than the threshold is practically not possible since they cannot convert the protons into neutrons. However this is not the case for the decay of a neutron and it's inverse process.

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

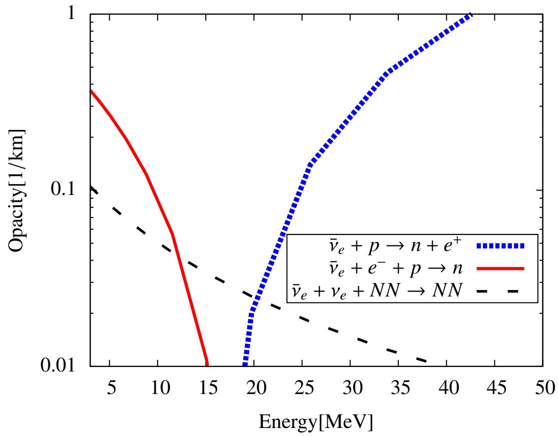

Figure 1: Inverse mean free path for several $\bar{\nu}_e$-reactions. Conditions correspond to decoupling region for low energy $\bar{\nu}_e$ at ~ 1 s. $T = 8$ MeV, $\rho = 3.4 \cdot 10^{13}$ g cm^{-3}, $Y_e = 0.42$

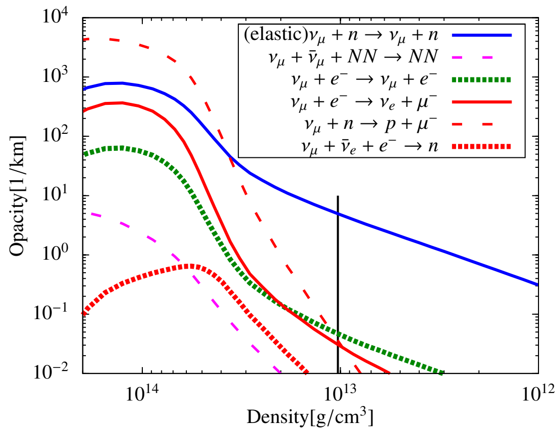

Figure 2: Spectrally averaged inverse mean free path for ν_μ at 720 ms postbounce. The black line denotes the energy sphere. Absorption of ν_μ with e^- and n is comparable to scattering on e^-.

Electron chemical potentials are generally large in the decoupling region so the additional electron in the incoming channel can supply the required energy to convert the proton. Also, emission from neutron decay becomes relevant at high densities due to the large number of free neutrons and the shorter lifetime due to the increased Q-value. On the other hand, three particle reactions are inherently less likely than two particle reactions. Another point in favour of neutron decay is that low energy $\bar{\nu}_e$ decouple further inside the PNS than high energy $\bar{\nu}_e$, so nuclear interaction is more important. Despite these arguments neutron decay was not considered in supernova simulations up to now.

One can calculate the respective opacity and emissivity of $\bar{\nu}_e$ in close analogy to neutrino absorption. In the so called elastic approximation [20] the $\bar{\nu}_e$-opacity or inverse mean free path for inverse neutron decay becomes

$$\chi\left(E_{\bar{\nu}}\right) \simeq \frac{G_F^2 \cos^2\theta_C}{\pi\left(\hbar c\right)^4}\left(g_V^2 + 3g_A^2\right)\left(M_n + U_n - M_p - U_p - E_{\bar{\nu}}\right)^2 f_e\left(M_n + U_n - M_p - U_p - E_{\bar{\nu}}\right) \times \frac{n_p - n_n}{1 - \exp\left[\beta\left(\phi_n - \phi_p\right)\right]} \tag{3.2}$$

with $\phi_i = \mu_i - M_i - U_i$. Figure **1** compares $\bar{\nu}_e$ opacities for inverse neutron decay and absorption on proton at large densities in a PNS. One can see that the opacity for absorption on protons drops sharply below the threshold energy. In the same region the inverse neutron decay becomes important and grows towards even smaller antineutrino energies. It can be concluded that the inverse neutron decay is a major contributing factor to the overall opacity for low energy antineutrinos at high densities. This is especially interesting, since the same neutrinos decouple at the highest densities, making the effect of strong interactions even more relevant. Preliminary results from a new simulation with inverse neutron decay included show a reduction in the average energy of $\bar{\nu}_e$. This would lead to larger Y_e and make r-process even more difficult. That would be in agreement with observations of metal-poor stars which are deficient in heavy neutron-capture elements beyond Z > 45 [21].

4. Charged current reactions for muon neutrinos

For the transport of μ- and τ-flavour neutrinos only neutral current interactions are usually taken into account. Charged-current interactions for these particles need to overcome the huge barrier of producing one of the heavy leptons. Therefore these reactions are considered to be extremely suppressed. The neutral-current interactions are exactly the same for μ- and τ neutrinos and the difference between neutrinos and antineutrinos is rather small. Thus in simulations all the heavy flavour neutrinos are often considered as one four-fold degenerate heavy neutrino ν_x. However, in the deep interior of a hot PNS one finds that the electron chemical potential μ_e, the neutron-minus-proton chemcial potential $\mu_n - \mu_p$ and the temperature are of the order of several 10 MeV and higher. Under this condition muon production is surely possible. It is further apparent that only muons can be produced, as antimuons would require proton rich matter and τ-leptons are too heavy. With respect to neutino transport, the question arises whether these charged-current muonic reactions contribute significantly to the overall opacity of μ-type neutrinos especially close to the energy sphere.

We then derived and calculated the mean free path for the following reactions:

$$(1)\, \nu_\mu + n \rightarrow \mu^- + p \qquad (2)\, \nu_\mu + e^- \rightarrow \nu_e + \mu^-$$

$$(3)\, \nu_\mu + \bar{\nu}_e + e^- \rightarrow \mu^- \qquad (4)\, \bar{\nu}_e + e^- \rightarrow \bar{\nu}_\mu + \mu^-$$

The ν_μ absorption on neutrons (1) was calculated again in analogy to ν_e absorption [1]. All the leptonic reactions (2)-(4) were calculated similar to $\nu_e - e^-$ scattering [22, 23, 25, 26]. Figure **2** shows the (spectrally averaged) inverse mean free path of the relevant reactions for ν_μ, including (1)-(3). For almost all densities the dominant channel is scattering on neutrons. Before, the dominant energy changing neutral current reaction was scattering on electrons (NES). Now one can see that the absorption of ν_μ on neutrons and the flavour conversion on electrons are comparable to NES in the region of decoupling. This manifests in an outward shift of the neutrinosphere when including the new reactions. Furthermore, the opacity for the absorption grows steeply towards higher densities. It eventually becomes the overall dominant opacity at densities close to $10^{14}\,\mathrm{g\,cm^{-3}}$.

5. Summary

We studied inverse neutron decay for electron antineutrinos and charged-current weak interactions for μ-type neutrinos in the context of neutrino transport in core-collapse supernovae. We find that these reactions contribute significantly to the respective opacities once the energy spheres have moved to densities where strong interaction becomes important in the nuclear matter. We therefore expect their inclusion in dynamical simulations to modify the respective neutrino spectra and fluxes. In particular the average energy of $\bar{\nu}_e$ will decrease. The spectra of ν_μ will evolve differently from $\bar{\nu}_\mu$ and τ-flavour neutrinos. This might open up the channel for neutrino flavor oscillations between ν_μ and ν_τ. Also a dynamical simulation will tell to which extent the spectral modifications can be observable from a next nearby galactic supernova.

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