Neutrino Emissivities from Deuteron-Breakup and Formation in Supernovae

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Abstract. Recently it was pointed out that there are abundant light clusters, such as deuteron, triton and helium, in supernova environment. An interesting question is how much neutrino emissions from these light clusters affect supernova explosion mechanism. To address this question through a supernova simulation, neutrino emissivities from these light clusters are necessary input. The deuteron is the simplest cluster, and occupy a substantial portion of the light cluster abundance. Thus in this work, we study neutrino emissions from electron/positron capture on the deuteron and the nucleon-nucleon fusion processes in the surface region of a supernova core. We evaluate these weak processes using one-nucleon impulse current supplemented by two-nucleon exchange-currents, and nuclear wave functions generated by a high precision nucleon-nucleon potential. We present the neutrino emissivities from the deuteron calculated for typical profiles of core-collapsed supernovae. These novel neutrino emissivities are compared with the standard neutrino emission mechanisms.

1. Introduction

Neutrino reactions in the dense matter of a supernova core are crucial for understanding the supernova explosion mechanism. The emission of neutrinos acts as a cooling mechanism of the central core, and a portion of the emitted neutrinos are subsequently absorbed by the material behind the shock wave and thereby act as a heating agent.

Recent supernova simulations have shown that all of light clusters can appear copiously in the regions between the supernova core and the shockwave [1, 2]. The light clusters with mass number $A=2$ and $3$ can be abundant in hot and moderately dense matter ($< 10^{13}$ g/cm$^3$) under nuclear statistical equilibrium [1, 3] and should be considered in studying the supernova explosion mechanism. Their appearance gives a new contribution to the neutrino emission and absorption. For example, the neutrino absorption on deuterons as an additional heating mechanism on top of the neutrino reactions on nucleons and $^{4}$He was studied in Ref. [4].

In this work [5], we study neutrino emissions from deuteron breakup/formation processes (DBF for short) in the surface region of a proto-neutron star, where neutrino emissions act as a cooling mechanism. We present the first evaluation of the neutrino emissivities from electron/position-capture on the deuteron (deuteron breakup) and from the nucleon-nucleon weak fusion processes (deuteron formation); see (1)-(5) below. The neutrino emissivities arising from these deuteron reactions will be compared with those coming from the “conventional” processes; by “conventional” processes we mean the neutrino emission processes which have been previously considered in the literature. The neutrino emissivities reported here are expected to be useful for numerical simulations of supernova explosion and proto-neutron star cooling.
Theoretical treatments of electroweak processes in two-nucleon systems have been well developed. One approach is the standard nuclear physics approach (SNPA) that involves nuclear wave functions derived from high-precision phenomenological nuclear potentials, and one-nucleon and two-nucleon electroweak currents. SNPA has been well tested by analyses of photo-reactions, electron scattering, and muon capture on the two-nucleon systems. We adopt SNPA in this work.

This article is arranged as follows. The theoretical framework for calculating the neutrino emissivities due to DBF is outlined in section 2, and the numerical results are presented in section 3. A summary is given in section 4.

2. Calculation of neutrino emissivities

We consider neutrino emissions via deuteron breakup/formation (DBF):

\[ d + e^- \rightarrow n + n + \nu_e , \]  
(1)

\[ d + e^+ \rightarrow p + p + \bar{\nu}_e , \]  
(2)

\[ n + n \rightarrow d + e^- + \bar{\nu}_e , \]  
(3)

\[ p + p \rightarrow d + e^+ + \nu_e , \]  
(4)

\[ p + n \rightarrow d + \nu + \bar{\nu} . \]  
(5)

The reactions (1) and (2) are deuteron breakup via \( e^- / e^+ \)-capture, whereas the reactions (3), (4) and (5) are deuteron formation through nucleon-nucleon scattering. The first four reactions that are caused by the charged-current (CC), can only emit \( \nu_e \) or \( \bar{\nu}_e \), whereas the last reaction occurring via the neutral-current (NC) gives rise to \( \nu \bar{\nu} \) pair-emission of all three flavors. The Hamiltonian for low-energy semi-leptonic weak processes is, to good accuracy, given by the product of the hadron current and the lepton current with the Fermi weak coupling constant. The hadronic weak currents are combinations of the vector current and the axial-vector current.

The nuclear weak currents consist of one-nucleon [impulse-approximation (IA)] terms and two-nucleon meson-exchange current (MEC) terms. In this work we consider the pion and rho meson-exchange currents. The validity of this approach has been well tested for the vector current by comparing the model predictions with, e.g., the measured \( n + p \rightarrow d + \gamma \) reaction data. As for the strength of the axial-vector exchange current, we follow the standard practice to adjust its strength to reproduce the experimental triton beta decay rate [6]. Detailed descriptions of the model for the nuclear currents used in the present work are given in Refs. [7, 8], where the basic formulation and relevant input parameters are explained.

In this article, we evaluate the emissivities for the DBF processes, (1) - (5). The emissivities for neutrinos and anti-neutrinos are denoted by \( Q_\nu \) and \( Q_{\bar{\nu}} \), respectively. They are given by integrating the transition probability over the momenta \( \vec{p}_{i,k} \) and \( \vec{p}_{f,l} \) with a weighting factor representing the momentum distributions:

\[
Q^\alpha_{\nu(\bar{\nu})} = \frac{(2\pi)^4}{s_is_f} \int \prod_k \frac{d\vec{p}_{i,k}}{(2\pi)^3} \prod_l \frac{d\vec{p}_{f,l}}{(2\pi)^3} \langle 4 \rangle \sum_{p_{f,l'}} \sum_{k'} p_{f,l'} - \sum_{k'} p_{i,k'} \rangle \omega_{\nu(\bar{\nu})} \sum_{i,f} | f | H^\alpha_{\nu(\bar{\nu})} | i > |^2 \Xi \tag{6}
\]

where \( \omega_{\nu(\bar{\nu})} \) is the energy of the emitted neutrino (anti-neutrino) and \( s_i \) and \( s_f \) are symmetry factors when two-nucleons in the initial or final state are identical particles. The summation \( \sum_{i,f} \) is taken over the spin states of the final particles and the average over the initial spin states. The momenta of the initial (final) particles, labeled by \( k \) (\( l \)), are \( \vec{p}_{i,k} \) (\( \vec{p}_{f,l} \)). \( \Xi \) represents the occupation probability of incoming particles and the Pauli blocking of outgoing particles:

\[
\Xi = \prod_{k=\text{initial particle}} f_k(p_k) \prod_{l=\text{final fermion}} (1 - f_l(p_l)) \tag{7}
\]
with \( f_k(p_k) = 1/(\exp((e_k(p_k) - \mu_k)/k_B T) \pm 1) \) where one should use “+” (“−”) for a fermion (boson); \( e_k \) (\( \mu_k \)) is the energy (chemical potential) of the particle of the \( k \)-th kind, and \( k_B T \) is the temperature multiplied by the Boltzmann constant. Note that we have not included the Pauli blocking factor for the final-state neutrino (anti-neutrino) in \( \Xi \), and that we have ignored the bose enhancement factor \((1 + f_d)\) for deuterons, because \( f_d \) is sufficiently small. More explicit expressions for the emissivities for the various processes under consideration are given in Ref. [5].

3. Neutrino emissivities

3.1. Supernova profiles

In order to study the consequences of neutrino emissions due to DBF for the supernova-explosion mechanism, we calculate neutrino emissivities for a given profile of a core-collapse supernovae, and compare the emissivities due to DBF with those arising from the conventional processes. To this end, we consider two representative profiles of a supernova core, Compositions I and II.

Composition I is the one obtained in Ref. [9] in simulating gravitational collapse and core bounce for a 15 \( M_\odot \) star (\( M_\odot \): solar mass). This composition, which represents a typical situation of the post-bounce phase with a stalled shock wave, has been obtained from a numerical simulation adopting the Shen equation of state (EOS) [10]. Composition I includes only nucleons, \(^4\text{He}\) and a single heavy nucleus in the Shen EOS. Figure 1 shows the temperature (\( T \)), the density (\( \rho \)) and the electron fraction (\( Y_e \)) as functions of the distance \( r \) from the supernova center, pertaining to a snapshot at 150 ms after the core bounce.

To assess the significance of the new additional emissivities due to DBF, we consider Composition II, which includes the mass fractions of the light clusters obtained from the nuclear statistical equilibrium model [1], i.e., nucleons, deuterons, tritons, \(^3\text{He}\), \(^4\text{He}\) and other nuclei are taken into account. We remark that Compositions I and II share the same data for the profiles of \( \rho, T \) and \( Y_e \) shown in Fig. 1. The nucleon chemical potentials needed to calculate the emissivities are also taken from the Shen EOS. We consider the surface region of a proto-neutron star (\( r > 20 \text{ km}, \rho < 10^{13} \text{ g/cm}^3 \)) where the neutrino-sphere exists between the surface of the nascent proto-neutron star and the shock wave, and neutrino cooling and heating are important.

3.2. Emissivity from the surface region of a proto-neutron star

To set the stage for examining the possible influences of \( \nu_e \)-emissivities due to DBF, we first present \( \nu_e \)-emissivities due to the conventional reactions calculated for Composition II. Nucleon-nucleon bremsstrahlung is calculated for Composition I. The left panel in Fig. 2 shows the emissivities arising from \( e^- p \) capture and \( e^- e^+ \) annihilation, while the right panel gives the emissivities due to nucleon-nucleon bremsstrahlung. The figure indicates that \( e^- p \) capture gives
The $\nu_e$-emissivities are shown as functions of the distance $r$ from the center of the supernova evaluated with composition II except NN bremsstrahlung. In the left panel, the neutrino emissivities due to $e^-$ captures on deuteron (1) and proton, and $e^+e^-$ annihilation are shown in solid, dashed and dash-dotted curves, respectively. In the right panel, the emissivities due to the $pp$ and $np$ fusion processes, (4) (5), and NN bremsstrahlung are shown in long-dash, solid and dotted curves, respectively. The emissivities due to the $NN$ bremsstrahlung and $e^+e^-$-annihilation are taken from Ref. [9].

Figure 2. The $\nu_e$-emissivities are shown as functions of the distance $r$ from the center of the supernova evaluated with composition II except NN bremsstrahlung. In the left panel, the neutrino emissivities due to $e^-$ captures on deuteron (1) and proton, and $e^+e^-$ annihilation are shown in solid, dashed and dash-dotted curves, respectively. In the right panel, the emissivities due to the $pp$ and $np$ fusion processes, (4) (5), and NN bremsstrahlung are shown in long-dash, solid and dotted curves, respectively. The emissivities due to the $NN$ bremsstrahlung and $e^+e^-$-annihilation are taken from Ref. [9].

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4. Summary

Neutrino emissions from $e^\mp$-capture on the deuteron and from deuteron formation in nucleon-nucleon weak-fusion processes have been studied as new neutrino emission mechanisms in supernovae. These weak processes are evaluated with the standard nuclear physics approach,
Figure 3. Left panel: Mass fraction of proton (solid curve) and deuteron (long dashed curve) for Composition II and that of proton (short dashed curve) for Composition I. Right panel: The ratio of the neutrino emissivity due to $e^-$-capture (solid curve) and $e^+$-capture (short dashed curve) calculated for Composition II (emissivity from deuterons and nucleons) to that calculated for Composition I (emissivity from nucleons only).

which consists of the one-nucleon impulse current and two-nucleon exchange current and nuclear wave functions derived from high-precision phenomenological $NN$ potentials. It is found that the contribution of the two-nucleon meson-exchange current is only a few % for the $e^\mp$-capture reactions, while it can be as large as the one-nucleon current contribution for the $NN$ fusion reaction at higher energies. The consequences of these new neutrino-emission channels have been examined for representative profiles of core-collapse supernovae at 150 ms after core bounce. The cross section due to the $e^\mp$capture reaction on the deuteron is smaller than that on the free nucleon. Therefore, as Fig. 3 indicates, the total neutrino emissivity due to electron capture on protons and deuterons is suppressed when an appreciable amount of protons in a supernova are bound inside deuterons. This results in a smaller neutrino luminosity and the lower efficiency of neutrino heating behind a stalled shock wave. Therefore, this new process may contribute unfavorably towards a successful supernova explosions. It might lead to a slower speed of the deleptonization and, hence, a slower evolution of nascent proto-neutron stars. On the other hand, as seen in Fig. 2, neutrino emission via deuteron formation can be comparable to nucleon-nucleon bremsstrahlung in the outer region. This implies that there might exist situations in which the deuteron-formation weak processes are the main channels for neutrino emission.

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