Effects of Medium Modifications of Nucleon Form Factors on Neutrino Scattering in Dense Matter

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Effects of the in-medium modifications of nucleon form factors on neutrino interaction in dense matter are presented by considering both the weak and electromagnetic interactions of neutrinos with the constituents of the matter. A relativistic mean field and the quark-meson coupling models are respectively adopted for the effective nucleon mass and in-medium nucleon form factors. We calculate the cross section of neutrino scattering as well as the neutrino mean free path. We found the cross sections of neutrino scattering in cold nuclear medium decrease when the in-medium modifications of the nucleon weak and electromagnetic form factors are taken into account. This reduction results in the enhancement of the neutrino mean free path, in particular at the baryon density of around a few times of the normal nuclear matter density.

KEYWORDS: neutrino interactions, electroweak interactions, nucleon form factors, differential cross section, mean free path

1. Introduction

The majority of neutrinos in the universe are produced in the core collapse supernova explosion. The final stage of the explosion creates a hot dense proto-neutron star, which emits bursts of neutrinos \cite{1}. Then the produced neutrinos propagate through the neutron star and affect the evolution of neutron stars. Inside the neutron star, neutrinos scatter with the constituents of matter, mostly neutrons and protons, and this process determines the propagation of neutrinos, namely, the neutrino mean free path (NMFP). The NMFP is an important input in simulations of neutron star evolution as well as those of compact stars.

The electromagnetic form factors of nucleons reflect their internal structure. Recent experimental observations in electron-nucleus scatterings suggest the in-medium modifications of the nucleon electromagnetic (EM) form factors. There are several issues related with the interpretation of the experimental observations in connection with the in-medium effects, nucleon correlations, and so on. More detailed discussions can be found, for example, in Refs. \cite{2, 3}. In the present article, following the point of view that the properties of the quark and gluon substructure of nucleons change in nuclear medium and can be estimated by effective theories of quantum chromodynamic (QCD). We reported the effects of in-medium modified weak and EM form factors of the nucleon on the NMFP in dense nuclear medium. This report is based on the recent article \cite{4}.
2. Neutrino scatterings with constituents of matter

Before discussing the in-medium modifications of the nucleon weak and EM form factors, we briefly discuss the free space neutrino scatterings with constituents of the matter. With the effective Lagrangian of Ref. [4], the differential cross section per volume of the neutrino scattering with a target particle can be calculated as

\[
\frac{1}{V} \frac{d^3\sigma}{d^2\Omega dE_f} = - \frac{1}{16\pi^2 E_f} \left[ \left( \frac{G_F}{\sqrt{2}} \right)^2 (L^{\alpha\beta}_f \Pi_{\alpha\beta}^{\text{IM}})^{(W)} + \left( \frac{4\pi\alpha_{\text{em}}}{q^2} \right)^2 (L^{\alpha\beta}_f \Pi_{\alpha\beta}^{\text{EM}})^{(INT)} + \frac{8\pi G_F \alpha_{\text{em}}}{q^2 \sqrt{2}} (L^{\alpha\beta}_f \Pi_{\alpha\beta}^{\text{IM}})^{(INT)} \right],
\]

where \( E_f \) is the final (initial) energy of the neutrino. For the details on the analytic formulas of the polarization tensors for the weak and EM interactions and all the corresponding quantities in Eq. (1), we refer to Refs. [5, 6]. The inverse mean free path of the neutrino is straightforwardly obtained by integrating the differential cross section of Eq. (1) over the energy transfer \( q_0 \) and the three-momentum transfer \( |\vec{q}| \). The final expression for the NMFP as a function of the initial energy at a fixed baryon density can be obtained as [4, 7]

\[
\frac{1}{\lambda(E_f)} = \int_{q_0}^{2E_f-q_0} dq_0 \int_0^{2E_f} dE_f \frac{d^3\sigma}{d\Omega dE_f},
\]

where the final and initial neutrino energies are related as \( E_f = E_i + q_0 \). More detailed explanations for the determination of the lower and upper limits of the integral can be found in Ref. [7].

3. Models for matter

Following Ref. [8], we write the interactions of the nucleon in matter as described by an effective chiral Lagrangian \( \mathcal{L} = \mathcal{L}_N + \mathcal{L}_M \). Here the Lagrangian \( \mathcal{L}_N \) of the nucleon part is given by

\[
\mathcal{L}_N = \bar{\psi} \left[ \gamma^\mu \left( \partial_\mu + i v_\mu + i g_A \rho_\mu + i g_{\omega} \omega_\mu \right) + g_A \gamma^\mu \gamma^5 \sigma_\mu - M_N + g_\sigma \sigma \right] \psi,
\]

where \( \psi \) is the nucleon isodoublet field defined as \( \psi = \left( \begin{array}{c} n \\ p \end{array} \right) \) with \( M_N \) being the nucleon mass. The Lagrangian \( \mathcal{L}_M \) of the mesonic part reads [8]

\[
\mathcal{L}_M = \frac{f_\pi^2}{4} \text{Tr} \left( \partial_\mu U \partial_\nu U^\dagger \right) + \frac{f_\pi^2 m_\pi^2}{4} \text{Tr} \left( U + U^\dagger - 2 \right) + \frac{1}{2} \partial_\mu \sigma \partial_\nu \sigma - \frac{1}{2} \text{Tr} \left( \rho_\mu \rho_\nu \right) - \frac{1}{4} \omega_\mu \omega_\nu + \frac{1}{2} \omega_\omega \omega_\omega + m_p^2 \text{Tr} \left( \rho_\mu \rho_\mu \right) - \frac{b}{3} M_N (g_\sigma \sigma)^3 - \frac{c}{4} (g_\omega \sigma)^4,
\]

where \( \omega_\mu = \partial_\mu \omega - \partial_\omega \partial_\mu \), and \( \rho_\mu = \partial_\mu \rho - \partial_\rho \partial_\mu \). In the Hartree mean field approximation, the \( \pi \) meson makes no contribution because of its negative intrinsic parity. Throughout the present calculation, we use \( M_N = 939 \text{ MeV} \), \( m_p = 770 \text{ MeV} \), \( m_\omega = 783 \text{ MeV} \), and \( m_\sigma = 520 \text{ MeV} \). We use the coupling constants determined in Ref. [9], i.e., \((g_\sigma/m_\sigma)^2 = 9.148 \text{ fm}^2 \), \((g_\omega/m_\omega)^2 = 4.820 \text{ fm}^2 \), \((g_\rho/m_\rho)^2 = 4.791 \text{ fm}^2 \), \( b = 3.478 \times 10^{-3} \), and \( c = 1.328 \times 10^{-2} \). (We note that similar approaches were used successfully in Ref. [6].)

4. Medium modifications of the nucleon form factors

For the estimates of the in-medium nucleon form factors, we make use of the quark-meson coupling (QMC) model [10]. Referring the further details of the QMC model to Refs. [11, 12], the ratios
of the in-medium to free-space nucleon form factors $G_{E,M,A}^{\text{QMC}}/(G_{E,M,A}^{\text{ICBM}})_{\text{free}}$ are then calculated so that the in-medium nucleon form factors can be estimated, where the superscript ICBM stands for the improved cloudy bag model. The ratios of the in-medium to free-space nucleon form factors are then obtained as shown in Fig. 2 as functions of $\rho_B/\rho_0$. It would be worthwhile to emphasize again that the form factor ratios presented in Fig. 1 are calculated based on the quark substructure of nucleons.

Fig. 1. Ratios of the in-medium to free-space nucleon weak and EM form factors at the four-momentum transfer squared $q^2 = 0$ versus $\rho_B/\rho_0$ with $\rho_0 = 0.15$ fm$^{-3}$.

5. Numerical results

We calculate the differential cross sections of neutrino scatterings with the constituents of matter at zero temperature as functions of the energy transfer $q_0$ at $|\vec{q}| = 2.5$ MeV with the initial neutrino energy $E_\nu = 5$ MeV, which is the typical kinematics for the cooling phase of a neutron star. Our numerical results are shown in Fig. 2, which shows the total sum of the differential cross sections in vacuum (thin solid lines) and those in nuclear medium (thick solid lines) as well as the contributions from each target to the total sum of the differential cross sections (see the caption of Fig. 2 for details). In the present calculation, we set the charge radius of the neutrino $R_{V,A} = 0$ and neutrino magnetic moment $\mu_\nu = 0$ in order to focus on the different role of the nucleon form factors in vacuum and in medium. As a result, the shape and magnitude of the differential cross section depend on the modifications of the form factors and effective nucleon mass. One can verify that the impact of the in-medium nucleon weak and EM form factors is pronounced at higher densities. Although the nucleon weak and EM form factors at the four-momentum transfer squared $q^2 = 0$, i.e., $F_2^W(0)$ and $F_2^{EM}(0)$, respectively, are enhanced in nuclear medium, the quenched axial-vector coupling constant $G_A^\ast(0)$ gives a dominant contribution to reduce the cross section, which results in the enhancement of NMFP (See Fig. 4 of Ref. [4]).

6. Summary

To summarize, we have revisited our previous work on the impact of the in-medium modifications of the nucleon weak and electromagnetic form factors on the neutrino scattering of Ref. [4] in the
calculation of differential cross sections and the neutrino mean free path in dense matter using the results from a relativistic mean field model. The in-medium nucleon form factors are estimated by the quark-meson coupling model that is based on the quark degrees of freedom of the nucleon and nuclear matter enjoying successful applications to describing the hadron and nuclear properties in nuclear medium.

The differential cross sections of the neutrino scatterings with the constituents of cold matter were found to slowly decrease with increasing baryon density, which results in the increase of the neutrino mean free path. This feature is sensitive to the in-medium modifications of the nucleon weak and electromagnetic form factors (in particular, that of the axial-vector form factor) as well as effective nucleon mass, and that the effect is pronounced for higher baryon densities.

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