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Asymmetry in the neutrino and anti-neutrino reactions in a nuclear medium

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ABSTRACT

We study the effect of the density-dependent axial and vector form factors on the electron–neutrino (ν_e) and anti-neutrino ($\bar{\nu}_e$) reactions for a nucleon in nuclear matter or in ^{12}C. The nucleon form factors in free space are presumed to be modified for a bound nucleon in a nuclear medium. We adopt the density-dependent form factors calculated by the quark–meson coupling (QMC) model, and apply them to the ν_e and $\bar{\nu}_e$ induced reactions with the initial energy $E = 8$–80 MeV. We find that the total ν_e cross sections on ^{12}C as well as on a nucleon in nuclear matter are reduced by about 5% at the nuclear saturation density, ρ_0. This reduction is caused by the modification of the nucleon structure in matter. Although the density effect for both cases is relatively small, it is comparable with the effect of Coulomb distortion on the outgoing lepton in the ν-reaction. In contrast, the density effect on the $\bar{\nu}_e$ reaction reduces the cross section significantly in both nuclear matter and ^{12}C cases, and the amount maximally becomes of about 35% around ρ_0. Such large asymmetry in the ν_e and $\bar{\nu}_e$ cross sections, which seems to be nearly independent of the target, is originated from the differences in the helicities of $\bar{\nu}_e$ and ν_e. It is expected that the asymmetry influences the r-process and also the neutrino-process nucleosynthesis in core-collapse supernovae.

In the core-collapse supernova explosion, the neutrino (ν) heating was suggested as one of the main mechanisms for the explosion, leading to the so-called ν driven explosions. The central object formed at the core bounce is expected to be a hot and lepton-rich proto-neutron star (PNS). Therefore, the shock propagation by the initial bounce from the contraction of heavy nuclei crosses the ν-sphere, *i.e.* the neutrino energy- and flavor-dependent sphere, and releases vast numbers of neutrinos [1].

These neutrinos propagate through the PNS, whose density is believed to be of about a few times of the nuclear saturation density, $\rho_0 \sim 0.15$ fm^{-3}. During the propagation, the neutrinos interact with nucleons in a dense nuclear medium. For example, the asymmetry in ν scattering and absorption in a magnetized PNS may account for the pulsar kick of neutron stars, according to the detailed study of the ν transport in dense matter by a relativistic mean field theory [2,3].

Outside of the PNS, the emitted neutrinos also interact with nucleons and the nuclei already produced by the s-process in the progenitor and/or the r-process in the explosion. Around the Si layer, the anti-neutrino ($\bar{\nu}$) absorption in the proton-rich environment may produce neutrons immediately captured by the neutron-deficient nuclei, which affect the proton process, dubbed as the νp process [4]. In the O–Ne–Mg layer, the ν induced reactions may play an important role for producing some p-nuclei which are odd–odd neutron-deficient nuclei. For example, ^{180}Ta and ^{138}La in the cosmos are believed to be produced from the ν process [5,6]. Other light nuclei abundances are also closely associated with the neutrino interactions in the He–C layer [7]. Of course, the density of the medium outside the PNS is not so high compared to that of the PNS. However, the nucleons interacting with the neutrinos are strongly bound in a nucleus, and the interactions should thus be different from those in free space.

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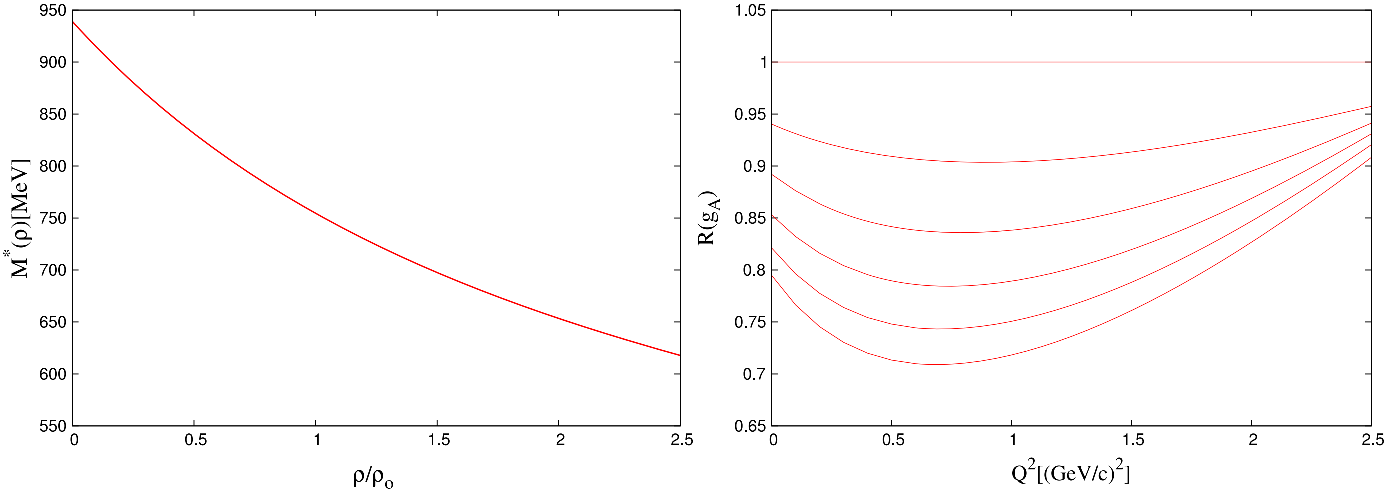

Fig. 1. (Color online.) Effective nucleon mass $M^*(\rho)$ versus the nuclear density ratio ρ/ρ_0 (left), and the in-medium axial coupling constant normalized to that in free space (right), $R(g_A) = g_A(\rho, Q^2)/g_A(\rho = 0, Q^2)$, as a function of Q^2. In the right panel, from the uppermost (for vacuum), the density increases by $0.5\rho_0$ in order. The lowermost curve is for $\rho = 2.5\rho_0$.

Recently, strong evidence for the modification of the nucleon structure in nuclear matter has been reported from the proton electromagnetic form factors measured in the polarized $(\vec{e}, e'\vec{p})$ scattering off ^{16}O [8] and ^{4}He [9–12] at MAMI and Jefferson Lab., and also from the study of the neutron properties in a nuclear medium through the polarized $(\vec{e}, e'\vec{n})$ scattering off ^{4}He [13]. Therefore, it is quite interesting to investigate the possible change in the ν and $\bar{\nu}$ induced reactions due to the variation of the nucleon properties, in order to pin down the ambiguity inherent in the nucleon and/or nuclear structure in the interpretation of various ν reactions in the cosmos.

In this Letter, we adopt the density-dependent weak form factors calculated in the quark–meson coupling (QMC) model [14–16]. The quark mass in a hadron can be related to the quark condensate $\langle\bar{q}q\rangle$ in vacuum. The mass (or $\langle\bar{q}q\rangle$) in nuclear matter may then be reduced from the value in vacuum because of the condensed scalar (σ) field depending on the nuclear density ρ, namely the Lorentz-scalar, attractive interaction in matter. The decrease of the quark mass in matter leads to the variation of the baryon internal structure at the quark level. Such an effect is considered self-consistently in the QMC model. As an alternative approach, Smith and Miller have studied the modification of the nucleon structure in nuclear matter using the chiral quark–soliton model [17]. The QMC model has been successfully applied in studying the properties of hadrons in a nuclear medium [18], finite nuclei [19], quasi-elastic (QE) electron scattering off nuclei [20] and hypernuclei [21]. (For a review, see Ref. [22].)

There have been many studies on the neutrino–nucleus interactions so far. In particular, the cross sections in the quasi-elastic (QE) and/or Δ production region, where the energy transfer is more than 100 MeV, have intensively been investigated [23] to analyze the recent MiniBooNE data [24]. Furthermore, the neutrino propagation in hot neutron matter has been studied within the framework of the random phase approximation [25].

But, in this Letter, we focus on the energy region of importance in the supernova neutrinos. Therefore we study the ν reactions relevant to the energy range of the LSND experiments [26], where the initial neutrino energy is less than 80 MeV. An initial study for the effect of the density-dependent weak-current form factors on the neutrino scattering can be found in Ref. [27]. However, in that paper, the simple, relativistic Fermi gas model has been used to study the ^{12}C(ν_μ, μ^-)X reaction, for which only the ν-flux averaged data have been measured. In contrast, in the present calculation, we treat the nuclear structure of ^{12}C in terms of quasi-particle random phase approximation (QRPA) [28,29], which enables us to carry out more realistic calculations. We then compare the result with the observed, energy-dependent cross section for the ^{12}C$(\nu_e, e^-)^{12}$N$_{g.s.}$ reaction [26]. For more thorough understanding of the density effect, the ν_e and $\bar{\nu}_e$ reactions on a nucleon in nuclear matter are also examined in detail, as well as the $\bar{\nu}_e$ reaction on ^{12}C, because the elementary process may be convenient and useful to see how the variation of the form factors affects the ν_e and $\bar{\nu}_e$ reactions in matter.

The weak current operator W^μ for the ν induced reaction takes a form of $V^\mu - A^\mu$ in the standard electro-weak theory. For a free nucleon, the weak current operator respectively comprises the vector, the axial vector and the pseudo scalar form factors, $F^V_{i=1,2}(Q^2)$, $F_A(Q^2)$ and $F_P(Q^2)$:

$$W^\mu = F^V_1(Q^2)\gamma^\mu + F^V_2(Q^2)\frac{i}{2M}\sigma^{\mu\nu}q_\nu + F_A(Q^2)\gamma^\mu\gamma^5 + \frac{F_P(Q^2)}{2M}q^\mu\gamma^5, \tag{1}$$

where M is the nucleon mass in free space, and $Q^2(= -q^2)$ is the four-momentum transfer squared. Because of the conservation of the vector current (CVC) and nonexistence of the second class current, we here ignore the scalar form factor in the vectorial part and the axial-tensor form factor in the axial part. By the CVC hypothesis, the vector and axial form factors for the charged current (CC) are respectively expressed as [30,31]

$$\begin{aligned} F^{V,CC}_i(Q^2) &= F^p_i(Q^2) - F^n_i(Q^2), \\ F^{CC}_A(Q^2) &= -g_A/(1 + Q^2/M^2_A)^2, \end{aligned} \tag{2}$$

where $F^{p(n)}_i$ is the proton (neutron) form factor, and g_A and M_A are the axial coupling constant and the axial cut off mass, respectively.

Before applying to the ν reaction, we briefly discuss the change of the in-medium nucleon properties calculated by the QMC model [14–16]. In Fig. 1 the effective nucleon mass is illustrated in the left panel, which shows a monotonic decrease of the mass while the nuclear density increases. The modification of the axial coupling constant in nuclear matter is also shown in the right panel as a function of Q^2. Even in the region of small momentum transfer, where most of the ν reactions expected in the cosmos