HTML ABSTRACT + LINKS

Screening effects on neutrino-nucleus reactions

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Abstract. We discuss effects of the electron plasma on charged-current neutrino-nucleus reaction, (ν_e, e^-) in a core-collapse supernova environment. We first discuss the electron screening effect on the final state interaction between the outgoing electron and the daughter nucleus. To this end, we solve the Dirac equation for the outgoing electron with the screened Coulomb potential obtained with the Thomas-Fermi approximation. In addition to the screening effect, we also discuss the Pauli blocking effect due to the environmental electrons on the spectrum of the outgoing electron. We find that both effects hinder the cross section of the charged-current reaction, especially at low incident energies.

Keywords: neutrino-nucleus reaction, electron screening effect, Pauli blocking effect, r-process nucleosynthesis
PACS: 23.40.Bw,26.30.+k,26.50.+x,98.80.Ft

A large number of neutrinos are emitted from a core-collapse supernova. These neutrinos interact with nuclei through the weak interaction. Although their cross sections are small, it is agreed that their contribution to nucleosynthesis (that is, r-, ν- and p-processes) is not negligible due to the large neutrino luminosity [1]. Neutrinos may even play a leading role in some cases. For instance, Yoshida *et al.* recently argued that the abundance ratio between ^{7}Li and ^{11}B is sensitive to the ν-process and thus can be used to extract information on the neutrino mass hierarchy [2]. Also, the abundance ratio between U and Th elements, which has been used as a cosmochronometer, may be affected by the ν-process. It is thus important to calculate with high accuracy the cross section of the neutrino-nucleus reactions in a dense star.

In the supernova nucleosynthesis, only the charged current reactions of the electron neutrinos, ν_e, and the electron anti-neutrinos, $\overline{\nu}_e$, are relevant, since those of ν_μ and ν_τ (and their antineutrinos) are suppressed due to the threshold effects. The outgoing electron and positron produced by the weak interaction feel the Coulomb interaction from the daughter nucleus as they leave. This final state interaction affects the neutrino-nucleus reaction rate [3, 4]. In the supernova environment, the motion of the outgoing electron is further perturbed by environmental electrons. Such effects have been considered in Ref. [5] for electron capture rates in a dense star. Furthermore, in a high electron density, the charged-current reaction is suppressed because low energy electron states are Pauli blocked. It is crucial to take into account those two effects in order to accurately estimate the neutrino-nucleus reaction rate for nucleosynthesis. In this contribution, we present such calculations, taking into consideration both the electron screening and Pauli blocking effects [6].

CP891, *Tours Symposium on Nuclear Physics VI, Tours 2006*
edited by M. Arnould, M. Lewitowicz, H. Emling, H. Akimune, M. Ohta, H. Utsunomiya, T. Wada, and T. Yamagata
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Let us first discuss how we implement the electron screening and the Pauli blocking effects in our calculations. We assume that the electron charge distribution is homogeneous with density ρ_e^0 in the absence of the daughter nucleus. This charge distribution of the environmental electrons is modified to $\rho_e(\vec{r})$ due to the presence of the daughter nucleus. The Coulomb field $\phi(\vec{r})$ at $\vec{r}$ from the daughter nucleus reads

$$\phi(\vec{r}) = \int d\vec{r}' \frac{e\rho_{\rm N}(\vec{r}') - e\,\delta\rho_e(\vec{r}')}{|\vec{r}-\vec{r}'|}, \tag{1}$$

where $\delta\rho_e(\vec{r}) \equiv \rho_e(\vec{r}) - \rho_e^0$ is the polarization charge. In order to evaluate this function, we assume a sharp-cut charge distribution for the nuclear charge density $\rho_{\rm N}$, that is, $\rho_{\rm N}(\vec{r}) = [3Z/(4\pi R^3)]\cdot\theta(R-r)$ with a nuclear radius of R. Here, Z is the atomic number of the daughter nucleus. For the electron density ρ_e, we use the Thomas-Fermi theory. The polarization charge then reads $\delta\rho_e(\vec{r}) = (2m\varepsilon_F(\vec{r}))^{3/2}/(3\pi^2\hbar^3) - \rho_e^0$. Here, m is the electron mass, and the local Fermi energy $\varepsilon_F(\vec{r})$ is given by $\varepsilon_F(\vec{r}) = \varepsilon_F^0 + e\phi(\vec{r})$ with $\varepsilon_F^0 = (3\pi^2\hbar^3\rho_e^0)^{2/3}/2m$. The boundary condition is imposed so that the Coulomb potential vanishes at the radius where the net negative charge inside is equal to the charge number of the daughter nucleus. Once the Coulomb field ϕ is obtained, we solve the Dirac equation for the outgoing election with the potential $V_C(r) = -e\phi(r)$. Using the solution of the Dirac equation, we estimate the cross sections of neutrino-nucleus reactions with the DWBA method [7]. In order to take into account the Pauli blocking effect for electrons, we multiply a factor $(1 - f_e(E_e, T_e, \mu_e))$ to the cross section, where E_e is the energy of the outgoing electron and f_e is the distribution function of the environmental electrons given by $f_e(E, T_e, \mu_e) = 1/(1+\exp[(E-\mu_e)/T_e])$. For a given electron density ρ_e^0, we estimate the Fermi energy μ_e using the relativistic Fermi gas model,

$$\rho_e^0 = \frac{m^3c^6}{\pi^2\hbar^3}\int_0^\infty \frac{\sinh^2 x \cosh x}{\exp(\beta(mc^2\cosh x - \mu_e)) + 1}\,dx, \tag{2}$$

where $\cosh x = p/mc^2$, p being the momentum of the electron.

We now evaluate numerically the electron screening and the Pauli blocking effects on the charged current ^{56}Fe$(\nu_e, e^-)^{56}$Co and ^{208}Pb$(\nu_e, e^-)^{208}$Bi reactions. We set the electron temperature to be T_e = 0.5 MeV. We consider the Fermi type transition to the $J^\pi = 0^+$ state at $E_{\rm x}$ = 3.5 MeV in ^{56}Co [8] and $E_{\rm x}$ = 15.0 MeV in ^{208}Bi [9]. For simplicity, we follow Ref. [7] and assume the transition density which is proportional to $\rho_{fi} \propto \delta(r-R)Y_{JM}(\theta,\phi)$. The differential cross sections $d\sigma/dE_e$ for the ^{56}Fe$(\nu_e, e^-)^{56}$Co and the ^{208}Pb$(\nu_e, e^-)^{208}$Bi reactions are shown in Figure 1. The solid line shows the results in the absence of the environmental electrons. The top, middle and bottom panels are for the electron density of ρ_e^0 = $10^{32}, 10^{33}$, and 10^{34} cm^{-3}, respectively. The dotted line denotes the results with the electron screening effects, while the dashed line takes into account both the screening and the Pauli blocking effects. For the electron density smaller than 10^{31} cm^{-3}, we find that both the effects are marginal. The screening effect is larger in the ^{208}Pb$(\nu_e, e^-)^{208}$Bi than in the ^{56}Fe$(\nu_e, e^-)^{56}$Co reaction, as is expected. We confirm that Pauli blocking effects are important below the Fermi energies and that the screening and the Pauli blocking effects disappear in the high E_e limit.

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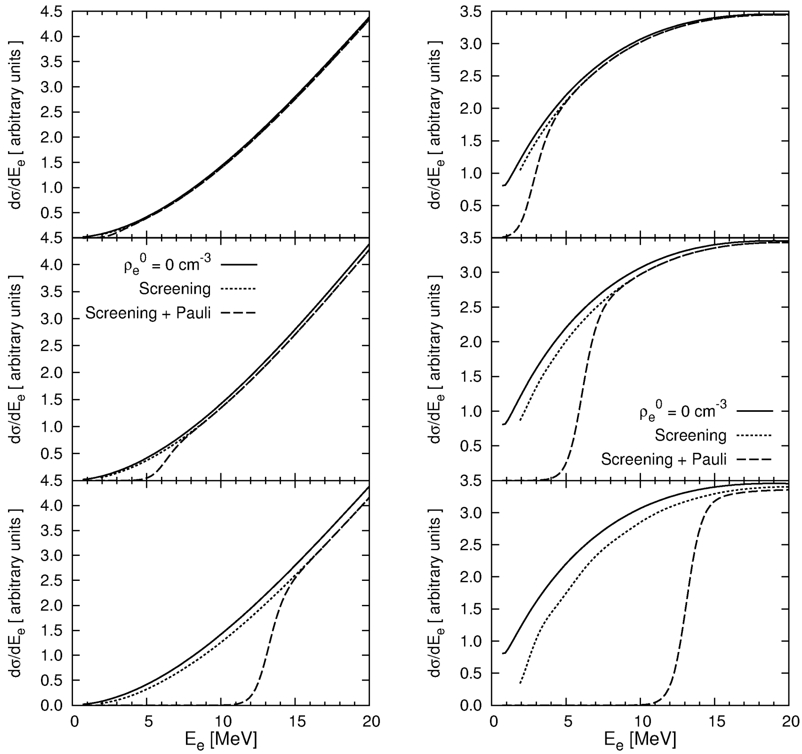

FIGURE 1. The cross sections for the charged current $\nu_e+^{56}\mathrm{Fe} \rightarrow e^-+^{56}\mathrm{Co}$ (left panel) and $\nu_e+^{208}\mathrm{Pb} \rightarrow e^-+^{208}\mathrm{Bi}$ (right panel) as a function of the energy of the outgoing electron. ρ_e^0. The top, middle, and bottom panels are for $\rho_e^0 = 10^{32}, 10^{33}$, and 10^{34} cm^{-3}, respectively.

We next discuss the total cross sections. In order to compute the total cross sections, we integrate the differential cross sections with a weight factor given by the energy distribution for the incident neutrino $n_\nu(E_\nu)$ [10]. Figure 2 shows the total cross sections for the $^{56}\mathrm{Fe}(\nu_e,e^-)^{56}\mathrm{Co}$ and the $^{208}\mathrm{Pb}(\nu_e,e^-)^{208}\mathrm{Bi}$ reactions as a function of the density of the environmental electrons, respectively. These are plotted as the ratio to the total cross sections in the absence of the environmental electrons, σ_0. The neutrino temperature T_ν is set to be 4 MeV. The dotted line takes into account only the screening effects, while the dashed line includes both the screening and the Pauli blocking effects. We see that the Pauli blocking effect influences the $^{208}\mathrm{Pb}(\nu_e,e^-)^{208}\mathrm{Bi}$ reaction much more significantly than the $^{56}\mathrm{Fe}(\nu_e,e^-)^{56}\mathrm{Co}$ reaction. This is due to the differences of the energy of the outgoing electron produced in each reactions.

In summary, we have discussed the electron screening as well as the Pauli blocking effects due to the environmental electrons on cross sections of the neutrino-nucleus reaction. For this purpose, we used the Thomas-Fermi theory for the screening potential,

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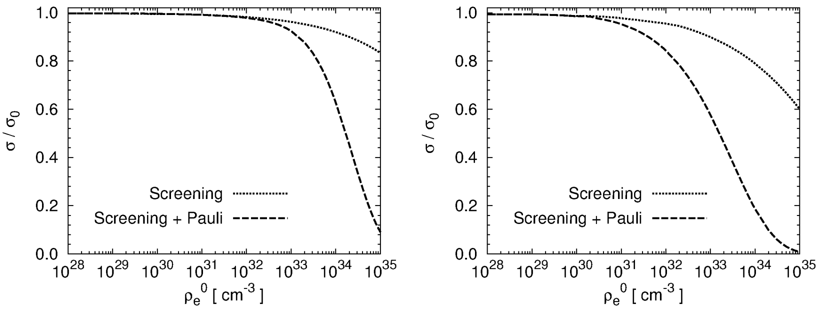

FIGURE 2. The total cross sections for the ν_e+^{56}Fe $\rightarrow e^-$+^{56}Co reaction (left panel) and ν_e+^{208}Pb $\rightarrow e^-$+^{208}Bi reaction (right panel) as a function of the density of the environmental electrons.

and the DWBA with the Pauli blocking factor for the cross sections. Our results for the ^{208}Pb$(\nu_e, e^-)^{208}$Bi and ^{56}Fe$(\nu_e, e^-)^{56}$Co reactions show that both the effects hinder the cross sections, especially at high electron densities. We have also shown that the Pauli blocking effect is more significant in the former reaction than in the latter reaction. The screening effect is also larger in the former reaction because of the larger atomic number.

We thank Y. Kato for useful discussions on electron screening. F. M. also acknowledges the 21st Century for Center of Excellence (COE) Program "Exploring New Science by Bridging Particle-Matter Hierarchy" and "Initiatives of Attractive Education in Graduate Schools" program at Tohoku University for financial support. This work was supported in part by the Grant-in-Aid for Scientific Research, Contract No. 16740139 from the Japanese Ministry of Education, Culture, Sports, Science, and Technology, in part by the U.S. National Science Foundation Grant No. PHY-0555231, and in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation.

REFERENCES

1. A. B. Balantekin and G. M. Fuller, J. Phys. G **29**, 2513 (2003).
2. T. Yoshida, T. Kajino, H. Yokomakura, et. al, Phys. Rev. Lett. **96**, 091101 (2006).
3. J. D. Walecka, *Theoretical Nuclear and Subnuclear Physics* (Oxford University Press, New York, 1995), Sec. 45.
4. M. Morita, *Beta decay and muon capture* (W.A. Benjamin Inc., Reading, 1973).
5. N. Itoh, N. Tomizawa, M. Tamamura and S. Wanajo, Astrophys. J. **579**, 380 (2002).
6. F. Minato, K. Hagino, N. Takigawa, A. B. Balantekin, Ph. Chomaz, arXiv:nucl-th/0608045.
7. J. Engel, Phys. Rev. C **57**, 2004 (1998).
8. T. Murakami, S. Nishihara and T. Nakagawa, Nucl. Phys. **A403**, 317 (1983).
9. A. Krasznahorkay, H. Akimune, M. Fujiwara et. al., Phys. Rev. C **64**, 067302 (2001).
10. Y.-Z. Qian and G. M. Fuller, Phys. Rev. D **51**, 1479 (1995).

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