Neutral Current ν Induced Reactions in Nuclei at Supernova Neutrino Energies

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In the late phase of stellar evolution the gravitational collapse of the core of a massive star takes place in which a huge amount of energy is released over a period of few tens of seconds. The energy carriers are mainly neutrinos and thus called supernova neutrinos. This constitutes almost equal proportion of all the flavor of neutrinos. The interaction of these neutrinos with the dense neutron rich matter in the stellar core results in the difference in energy distribution for various neutrino flavors, for example the average energy for electron type of neutrino: $\langle E_{\nu_e}\rangle = 12MeV$, for electron type antineutrino $\langle E_{\bar\nu_e}\rangle = 15MeV$ and for all other flavors $\langle E_{\nu_\mu}\rangle = \langle E_{\bar\nu_\mu}\rangle = \langle E_{\nu_\tau}\rangle = \langle E_{\bar\nu_\tau}\rangle = 25MeV$. It is expected that these neutrinos may provide valuable information about the stellar core, its equation of state and the dynamics of core collapse and supernova explosion mechanism. These neutrino burst from a galactic supernova can be detected in terrestrial detectors. There are presently various detectors like Super-K, MiniBooNE, IceCube which are capable of detecting supernova neutrinos. The various detectors[1] like HALO, Icarus, LBNE LAr, LBNE WC, MEMPHYS, Hyper-K, LENA, GLACIER are planned in future which will also be sensitive to supernova neutrino detection. Most of these detectors are using nuclear targets like ^{16}O, ^{40}Ar and ^{208}Pb. Though charged current interactions take place only for the ν_e and $\bar\nu_e$ components, the neutral current weak interaction is possible for all the flavors of neutrinos. In this paper we have calculated event rates for neutral current neutrino induced reaction

$$\nu_l(k) + N(p) \rightarrow \nu_l(k') + N(p') \qquad (1)$$

on nuclear targets ^{16}O, ^{40}Ar and ^{208}Pb. These events are presented for 1kT of target material. When these processes take place inside the nucleus various nuclear medium effects come into play. We have calculated the cross section in the Fermi gas model using the local density approximation and took into account Pauli blocking, Fermi motion, renormalization of the weak transition strength in the nuclear medium [2]. The effects of Fermi motion and Pauli blocking are taking into account through the imaginary part of the Lindhard function for the particle hole excitations in the nuclear medium. The renormalization of the weak transition strengths are calculated in the random phase approximation(RPA) through the interaction of the p-h excitations as they propagate in the nuclear medium using a nucleon-nucleon potential described by pion and rho exchanges. The expression of total scattering cross section in the local density approximation(LDA) inside the nucleus is given by [2]

$$\sigma(E_\nu) = -2{G_F}^2 \int_{r_{min}}^{r_{max}} r^2 dr \int_{k'_{min}}^{k'_{max}} k' dk' \times \int_{Q^2_{min}}^{Q^2_{max}} dQ^2 \frac{1}{E^2_{\nu_l} E_l} L_{\mu\nu} J^{\mu\nu} Im U_N(\mathbf{q_0}, \mathbf{q})$$

where $q = k - k'$. $\mathcal{M}$ is the matrix element which is defined as $\mathcal{M} = \frac{G_F}{\sqrt{2}} L_\mu J^\mu$ with G_F as Fermi coupling constant, L_μ is the leptonic current: $L_\mu = \bar u(k')\gamma_\mu(1-\gamma_5)u(k)$ and J^μ is the hadronic current given by

$$J^\mu = \bar u(p')[\left(\gamma_\mu - \frac{\not q q_\mu}{q^2}\right)\tilde F_1^N + \frac{i}{2M_N}\sigma_{\mu\nu}q^\nu \tilde F_2^N + \gamma_\mu\gamma_5 \tilde F_A^N + \frac{q_\mu}{M_N}\gamma_5 \tilde F_P^N]u(p)$$

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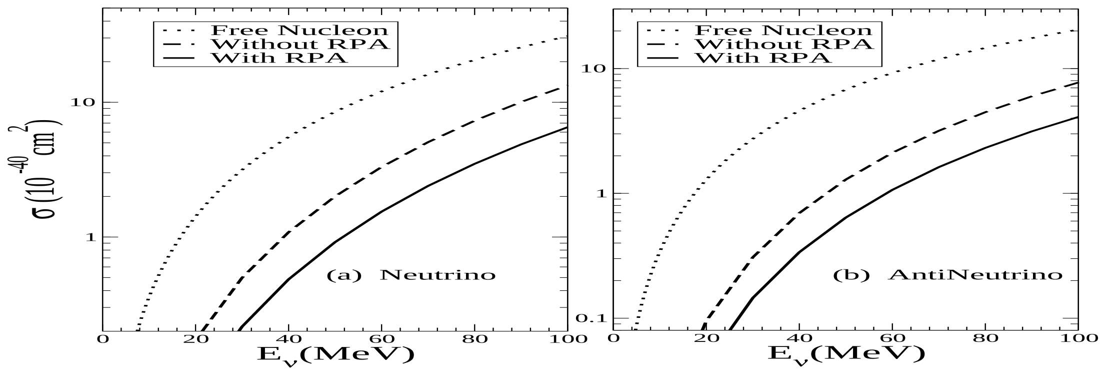

FIG. 1: $\nu_l(k) + N(p) \rightarrow \nu_l(k') + N(p')$ scattering cross section $\sigma(E)$ vs E.

where $\tilde{F}^N_{1,2}$, $\tilde{F}^N_A$ and $\tilde{F}^N_P$ are the vector, axial and pseudoscalar form factors, respectively. These form factors are in turn defined in terms of the standard Dirac and Pauli form factors of the nucleon $F_1^{p,n}$ and $F_2^{p,n}$ and a strange component $F^s_{1,2}$, in the following way

$$\tilde{F}^p_{1,2} = (\frac{1}{2} - 2sin^2\theta_W)F^p_{1,2} - \frac{1}{2}F^n_{1,2} - \frac{1}{2}F^s_{1,2}$$

$$\tilde{F}^n_{1,2} = (\frac{1}{2} - 2sin^2\theta_W)F^n_{1,2} - \frac{1}{2}F^p_{1,2} - \frac{1}{2}F^s_{1,2}$$

with θ_W as the weak mixing angle.

For simplicity we have taken $F^s_{1,2}(0)$=0 in our calculation.

$$\tilde{F}^{p,n}_A = \pm\frac{1}{2}F_A - \frac{1}{2}F^s_A; F^s_A(q^2) = \frac{\Delta s}{(1+\frac{q^2}{M_A^2})^2}$$

where M_A(=1.1GeV) is axial dipole mass, Δs denotes the strange contribution to the nucleon spin taken as Δs = -0.15. The expression for the $F^p_{1,2}$, $F^n_{1,2}$, F_A and F_P are taken from the Ref.[2]. The consideration of renormalization of weak transition strengths in the nuclear medium leads to modified hadronic tensor $J^{\mu\nu}_{RPA}$, the expression for which is given in Ref. [2]. In Fig.1, we have presented the results for the scattering cross section σ as a function of neutrino and antineutrino energies, for the free case as well as in ^{16}O obatined using the LDA with and without RPA effects.

For the event rate calculation we have used these cross sections and averaged over the supernova neutrino flux $\phi(E)$ provided at the web site[3]:

$$\langle\sigma\rangle = \int \sigma(E)\phi(E)dE$$

We find that the total averaged cross section for 1kT water Cerenkov target when we calculate the events in the local Fermi gas model without RPA effects for ν_e is 11.3 events, for $\bar{\nu}_e$ is 26.1 events, for $\nu_\mu + \bar{\nu}_\mu + \nu_\tau + \bar{\nu}_\tau$ is 124.2 events. While when RPA effects are taken into account, these events become 5.7 events for ν_e, 14.7 events for $\bar{\nu}_e$ and 64.2 events for $\nu_\mu + \bar{\nu}_\mu + \nu_\tau + \bar{\nu}_\tau$. In the symposium, we shall discuss the dependence of these event rates on the different supernova fluxes that exist in literature, for example given in Refs. [4, 5] and also we shall present the results for the event rates in ^{40}Ar and ^{208}Pb with and without the RPA effects.

References

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