Neutrino-Nucleus Reactions for Nucleosynthesis

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Abstract. We calculated neutrino-induced reactions in the energy range below the quasi-elastic region for nuclei of astrophysical importance. Neutrino-induced reactions have been found to be important for nucleosynthesis in core collapsing supernovae because the expected neutrino flux is sufficiently high enough to excite many relevant nuclei in spite of the small cross section of the weak interaction. Our calculation is carried out with the Quasi-particle Random Phase Approximation (QRPA), which has been successfully applied for the nuclear β and double β decay of relevant nuclei. Our QRPA takes neutron-proton as well as neutron-neutron and proton-proton pairing correlations into account. To describe neutrino reactions, general multipole transitions by the weak interaction with finite momentum transfers are calculated for neutral and charged current reactions. Both reactions are described in a theoretical framework. Our results, which are compared with other theoretical calculations, are shown to well reproduce the sparse experimental data, in specific, for $^{12}\text{C}$ and $^{56}\text{Fe}$ targets. Therefore our results for $^{40}\text{Ar}$, $^{56}\text{Ni}$, $^{138}\text{La}$ and $^{180}\text{Ta}$ targets could be valuable data for predicting yields of future measurements of neutrino-induced reactions and further applications to the neutrino-process in the nucleosynthesis.

1. Introduction

Neutrino ($\nu$) (antineutrino ($\bar{\nu}$)) reactions on complex nuclei play important roles on understanding not only the nuclear structure probed by the weak interaction [1, 2] but also $\nu$-parameters relevant to the $\nu$-physics [3, 4]. For example, mass hierarchies and mixing angle $\theta_{13}$ may be constrained through detailed analysis of light-element nuclear abundances in core collapsing supernova (SN) explosions [4]. Recently, lots of interests have been focused on the $\nu$-process [3, 4, 5] in the nucleosynthesis of medium and medium heavy nuclei because emitted neutrino flux in the core collapsing SN is expected to be sufficiently high enough to excite related nuclei in dense matter in spite of small cross sections of the weak interaction. Therefore, cross sections for neutrino(antineutrino)-nucleus ($\nu(\bar{\nu})-A$) reactions are to be treated as important input data for network calculations estimating relevant nuclear abundances, in specific, for the weak rapid process [6].

In this report, we show numerical results for neutrino reactions via charged current (CC) and neutral current (NC) on $^{12}\text{C}$, $^{40}\text{Ar}$ and $^{56}\text{Fe}$, and $^{138,139}\text{La}$ and $^{180,181}\text{Ta}$, and discuss their general
physical properties. Our QRPA, which includes neutron-neutron (nn), proton-proton (pp) and neutron-proton (np) pairing correlations, has successfully described the relevant nuclear $\beta$, $2\nu\beta\beta$ and $0\nu2\beta$ decays [7].

2. Theoretical Frameworks

For the reaction on even-even nuclei, our QRPA takes the ground state of a target nucleus as the BCS vacuum for quasi-particles composed of various short range correlations [7]. Excited states, $|m; J^P M\rangle$, in a compound nucleus, are generated by operating the following one phonon operator to the initial ground state

$$Q_{JM}^m = \sum_{k_i\ell_i} [X_{m}^{k_i\ell_i\nu'} J^+(k_i\ell_i
u'; J M) - Y_{m}^{k_i\ell_i\nu'} \tilde{C}(k_i\ell_i\nu'; J M)] ,$$

where

$$C^+(k_i\ell_i\nu'; J M) = \sum_{m_i} C_{jm_i}^{JM} a_{m_i}^{+\nu} a_{k_i\ell_i}^{\nu} , \tilde{C}(k_i\ell_i\nu'; J M) = (-)^{J-M} C(k_i\ell_i\nu'; J - M) ,$$

where $a_{k_i\ell_i}^{\nu}$ is a quasi-particle creation operator and $C_{jm_i}^{JM}$ is the Clebsh-Gordan coefficients. If the np pairing correlation is neglected, the phonon operator decouples to two different phonon operators. The first is for the charge changing reaction such as beta decays and CC neutrino reactions. The second is for the charge conserving reaction like electro-magnetic and NC neutrino reactions. Amplitudes $X_{a\alpha,b\beta}$ and $Y_{a\alpha,b\beta}$, which stand for forward and backward going amplitudes from state $aa$ to $b\beta$, are obtained from the QRPA equation, whose detailed derivation was done at Ref. [7, 9, 10].

Based on the initial and final nuclear states, cross section for $\nu(\bar{\nu}) - A$ reactions through the relevant transition operators (longitudinal, Coulomb, electric and magnetic) is given as

$$\frac{d\sigma_{\nu}}{d\Omega}(\nu/\bar{\nu}) = \frac{G_F^2 e k}{\pi (2J_i + 1)} \left[ \sum_{J=0} \left| (1 + \hat{\bar{\nu}} \cdot \hat{\beta}) < J_f | \hat{\Delta}_J | J_i > \right|^2 + (1 - \hat{\bar{\nu}} \cdot \hat{\beta} + 2(\hat{\bar{\nu}} \cdot \hat{q})(\hat{\beta} \cdot \hat{q})) < J_f | \hat{\Delta}_J | J_i > \right]^2 $$

$$-\hat{q} \cdot (\hat{\bar{\nu}} + \hat{\beta}) 2Re < J_f | \hat{\Delta}_J | J_i > < J_f | \hat{\Delta}_J | J_i >^* + \sum_{J=1} (1 - (\hat{\bar{\nu}} \cdot \hat{q})(\hat{\beta} \cdot \hat{q})) | < J_f | \tilde{F}_j^m | J_i > |^2$$

$$+ | < J_f | \tilde{F}_j^{mag} | J_i > | \sum_{J=1} \hat{q} \cdot (\hat{\bar{\nu}} - \hat{\beta}) 2Re | < J_f | \tilde{F}_j^{mag} | J_i > | < J_f | \tilde{F}_j^l | J_i >^* | ,$$

where (±) means cases of $\nu(\bar{\nu})$, respectively. $\hat{\bar{\nu}}$ and $\hat{k}$ are 3-momenta of incident and final leptons, and $\hat{q} = \hat{k} - \hat{\nu}$, $\hat{\beta} = \hat{k}/\epsilon$ with the final lepton’s energy $\epsilon$. Of course, the extremely relativistic limit (ERL) may yield more simple formula, but we use the general expression for further application to $\nu_\mu - A$ reactions. For CC reaction we multiplied Cabibbo angle $\cos^2\theta_c$ and include the Coulomb distortion of outgoing leptons due to residual nuclei [2, 8].

Since the Fermi function, $F(Z \pm 1, \epsilon_f)$, which was deduced from the spectra of outgoing electrons in the nuclear $\beta$ decay, usually assumes s-wave electrons, one needs more deliberate approach for $\nu(\bar{\nu}) - A$ reactions because outgoing leptons’ energies in the reaction are higher rather than those of the $\beta$ decay. To exactly describe the Coulomb distortion, one has to solve the Dirac equation of outgoing leptons under the Coulomb potential due to residual interactions with daughter nuclei.

But, since the exact solution needs time consuming computations, one usually exploits an averaged momentum of the outgoing particles. Typical approach is the effective momentum approach (EMA), which was shown to reproduce results from exact treatments of the Coulomb distortion [8]. Here we use both approaches, the Fermi function and the EMA approach. By
following the prescriptions on Refs.[8, 10], we choose the energy on which both approaches predict same values, and take the Fermi function below the energy and adopt the EMA above the energy.

Cross sections for $\nu$-A reactions are usually sensitive on the treatment of the Coulomb correction as well as the np pairing correlations and the $g_A$ quenching. In specific, the Coulomb correction becomes the most important factor in the high energy region. Since detailed discussions will be appeared elsewhere, in this report, we explicitly indicate the approach used for the Coulomb correction for each reaction.

3. Results

3.1. Light Nuclei

In Fig.1, we showed results for $\nu^{-}{^{12}}C$. Our results for the Gamow Teller (GT) transition reproduce very well the exclusive reaction data $^{12}C(\nu_e,e^-)^{12}N_{g.s.(1^+)}$ [11]. Fair agreement of our theoretical calculations with this energy dependent experimental data could be accounted to be a reliable guideline for further predictions of any $\nu-A$ reactions. Other $J^p$ states’ contributions including spin dipole resonances are verified to become also important for understanding the reaction $^{12}C(\nu_e,e^-)^{12}N_{^j\pi}$ [2, 8]. In specific, contributions from $1^-$ and $2^-$ states become more prominent beyond 60 MeV region. We used $g_A = 1.23$ from Ref. [10], which reproduces half lives of $\beta^-$ and $\beta^+(EC)$ decays of relevant nuclei [9]. For $^{12}C$, cross sections are not so sensitive on the Coulomb correction, whose ambiguity is within 5 %.

3.2. Medium Nuclei

Results for $^{40}Ar(\nu_e,e^-)^{40}K^+$ and $^{40}Ar(\nu_e,\nu_e')^{40}Ar^+$ reactions are shown in Fig. 2. These reactions are used for ICARUS detectors [12, 13] for SN neutrinos, which is originally developed for the detection of the solar neutrino from $^{8}B$. Since the Q value for the $\bar{\nu}_e$ CC reaction on $^{40}Ar$ is 7.48 MeV, $\bar{\nu}_e$ reactions are kinematically disfavored. Moreover $\nu_e$ reactions in the low energy region is dominated by the Fermi and GT transitions. But for the SN neutrinos whose energy may go up to 100 MeV, contributions from other higher multipole play significant roles for the reactions, as shown in Fig.2. Results for $^{56}Fe$ and $^{56}Ni$ reactions are shown in Fig. 3. In specific, the cross section, $^{56}Fe(\nu_e,e^-)^{56}Co^*$, averaged by the neutrino spectrum from the decay at rest (DAR) is
measured as $256\pm 108\pm 43 \times 10^{-42} cm^2$ [10]. If the np pairing is switched off, we obtain $< \sigma > = 141.8 \times 10^{-42} cm^2$. But the np pairing enhanced it to $173.5 \times 10^{-42} cm^2$ which is located within the experimental data.

### 3.3. Heavy Nuclei

In Figs. 4-5, we show results for one of the heaviest odd-odd nuclei $^{138}$La and $^{180}$Ta. Their cosmological origins are believed to be closely related to the neutrino ($\nu$) process [14]. Results for CC reactions show that the GT $1^+$ transition is still dominant in the lower energy region. But remained contributions are ascribed to other transitions, such as Isobaric Analogue State (IAS) and spin dipole transitions, $(1^-, 0^\pm, 3^\pm$ and $2^+)$. These roles of the GT and other transitions are typical of CC neutrino reactions on even-even nuclei, for example, in the left hand sides of Figs. 1-3 for $^{12}$C, $^{40}$Ar and $^{56}$Ni [9, 10].

But, NC reaction is fully dominated by the GT transition in the lower energy region. This is contrast to the CC reaction cases. Since NC reactions on these nuclei occur on odd-even nuclei, one need a special approach to describe the odd-even nuclei. We used the Quasi-particle Shell Model (QSM). Detailed discussions for the approach will be appeared elsewhere.
3.4. Temperature dependence
For the supernovae application, in Fig. 6, we show the cross sections averaged by the SN neutrino spectrum, which is presumed as Fermi-Dirac distribution. The heavier nuclei we go to, the larger cross sections are obtained. On the even-even nuclei in the light and medium heavy nuclei, such as \( ^{12}C \), \( ^{56}Fe \) and \( ^{56}Ni \), cross sections via CC are mainly dominated by the GT, IAS and SDR transitions, while those by NC are dominated by the GT transition. Magnitude of CC reactions are 5 times larger than those by NC. Applications to the \( \nu \)-process for the relevant nuclei are in progress.

4. Summary and Conclusions
The QRPA is a very efficient method to consider multi-particle and multi-hole interactions and their configuration mixing and successfully described nuclear reactions sensitive on the nuclear structure, such as \( 2\nu/2\beta \) and \( 0\nu/2\beta \) decays. Therefore feasible ambiguities due to the nuclear structure can be pinned down by reproducing the data related to the nuclear \( \beta \) decay and forthcoming GT transitions by \( (^3He, t) \) or \( (p, n) \) reactions. Based on these stocked results [7], we calculated neutrino reactions on light, medium and medium heavy nuclei by including multipole transitions up to \( J^\pi = 4^\pm \) with explicit momentum dependence. Parts of the results are shown in this report. Available experimental data were reproduced very well. Our QRPA includes neutron-proton (np) pairing as well as neutron-neutron and proton-proton pairing correlations.
Figure 6. Temperature dependence of the energy weighted cross section for $\nu - A$ reactions, where neutrino spectrum for the SN is exploited. Results for $^{12}$C, $^{56}$Fe and $^{56}$Ni are referred from our previous calculations [9, 10].

Since energy gaps between proton and neutron energy spaces in heavy nuclei are adjacent to each other, the np pairing may affect significantly the nuclear weak interaction. One more point to be noticed is that we exploited the quasi-particle shell model (QSM) to the NC reactions for odd-even nuclei, for example, $^{139}$La.

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