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Neutrino–nucleus reactions in the delta resonance region

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Abstract

Reliable estimates of neutrino–nucleus reactions in the resonance–excitation region play an important role in many of the on-going and planned neutrino oscillation experiments. We study here neutrino–nucleus reactions in the delta-particle excitation region with the use of neutrino pion-production amplitudes calculated in a formalism in which the resonance contributions and the background amplitudes are treated on the same footing. Our approach leads to the neutrino–nucleus reaction cross sections that are significantly different from those obtained in the conventional approach wherein only the pure resonance amplitudes are taken into account. To assess the reliability of our formalism, we calculate the electron–nucleus scattering cross sections in the same theoretical framework; the calculated cross sections agree reasonably well with the existing data.

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1. Introduction

It is well recognized that the precise knowledge of neutrino–nucleus reaction cross sections is of importance in analyzing neutrino oscillation experiments; for recent reports, see, e.g., Refs. [1–5]. In particular, neutrino–nucleus reactions at incident neutrino energies around 1 GeV play a prominent role in many cases including the experiments at K2K [2]. To obtain estimates of the relevant cross sections, one must at present rely on theory, and much theoretical effort has been invested to provide these estimates [6–11]. In an attempt to make a quantitative estimation of neutrino–nucleus reaction cross sections, it is useful to study simultaneously the related electron–nucleus reactions within the same general theoretical framework, and this strategy has been pursued by many authors. In electron–nucleus scattering in the GeV region, quasi-elastic scattering and pion-production processes are known to be the main reaction mechanisms, and similar features are expected to manifest themselves also in the neutrino–nucleus reactions in the GeV region.

For quasi-elastic scattering, the relevant transition operators are essentially known, so the main theoretical issue is how to incorporate various nuclear effects for the initial and final states. The early works were based on the Fermi gas model [12,13], but recent investigations incorporate the nuclear correlation effects in the initial state with the use of the spectral function and take account of the final-state interactions on the outgoing nucleon [7]. As regards the pion-production process, in addition to these nuclear effects, the structure of the transition operators responsible for pion production needs to be carefully studied. These operators can in principle involve more than one nucleon, but it is in general expected that pion production on a single nucleon should give a dominant contribution. Neutrino-induced pion production on the nucleon in the resonance region has been studied so far mostly with the use of pure resonance excitation amplitudes. In some studies these amplitudes were evaluated in the quark model, see, e.g., Ref. [14]. In recent studies by Paschos and his collaborators [15,16], the resonance excitation amplitudes due to the vector current were directly related to the empirically known electro-excitation amplitudes, while those

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due to the axial–vector current were constrained by invoking PCAC.

Meanwhile, it is to be noted that pion production can take place not only through resonance excitations but also via non-resonant processes. Two of the present authors [17,18] have recently developed a dynamical model for describing photo- and electro-production of pions off the nucleon around the Δ-resonance region, with the view to systematically incorporating both the resonance and non-resonance contributions. Hereafter we refer to this approach as the SL-model (the Sato–Lee model). The development of the SL-model was motivated by recent extensive experimental studies of electron- and photon-induced meson-production reactions on the nucleon in the resonance region. The main objective of these experiments is to study the non-perturbative features of QCD by testing the resonance properties as predicted by QCD-inspired models and/or lattice simulations. The SL-model was subsequently extended to weak-interaction processes [19,20], and it was shown that this model gives a successful description of neutrino-induced pion production in the Δ-resonance region.

As explained in more detail later, the SL-model starts from the non-resonant meson–baryon interaction and the resonance interaction, and the unitary amplitudes are obtained from the scattering equation. It leads to fairly consistent descriptions of all the available data for the electroweak reactions in the Δ-resonance region. It has been shown that treating the resonance and non-resonance amplitudes on the same footing can have significant observable consequences. In particular, the inclusion of the pion cloud effects as considered in SL can resolve a long-standing puzzle that the N–Δ magnetic dipole transition form factor G_M predicted by the quark model is smaller than the empirical value by as much as ∼40%. Furthermore, the electric E2(G_E) and Coulomb C2(G_C) form factors for the N–Δ transition in electron scattering calculated in the SL-model show pronounced momentum dependences due to the pion cloud effects, which suggests non-negligible deformation effects in the N–Δ transition. Regarding the neutrino reactions, a serious problem that has been known for quite some time is that the axial–vector N–Δ transition strength calculated in the constituent quark model [21] is lower than the empirical value [22] by about 35%. It is noteworthy that the dynamical pion cloud effects included in the SL-model [19] can naturally remove this discrepancy.

In view of these successes, it seems worthwhile to study neutrino–nucleus reactions in the resonance region with the use of the SL-model amplitudes for neutrino-induced pion production on the nucleon. We describe here our first attempt at such a study and present the cross sections, the energy spectrum of the final lepton (for charged-current reactions), and the lepton-momentum transfer distribution. Our work is basically of exploratory nature and, as far as the nuclear effects are concerned, we only consider those that can be taken into account with the use of a modified Fermi gas model wherein nuclear correlations are approximately subsumed into the spectral function [7]. Despite these limitations, our investigation is hoped to be informative as the first calculation of neutrino–nucleus reactions in the Δ-resonance region based on the electroweak pion-production amplitudes calculated in SL [17,18], whose validity has been extensively tested by the Jlab data [23,24]. It is understood that, as the experimental precision improves, more detailed calculations will be called for that incorporate higher order effects. In particular, the final-state interaction (FSI) must be treated properly. As discussed in Ref. [7] and many earlier works on inclusive electron scattering, FSI redistributes the inclusive cross sections and, for the incident electron energy around 1 GeV, FSI can reduce the strength at the quasi-free peak by about 10%. We remark that a detailed study [25] indicates that the FSI effects for inclusive reactions, properly treated, can be rather different from those for exclusive processes [26]. Meanwhile, in the pion-production region, we need to take into account pion absorption and medium effects on Δ propagation. To this end, one may profitably use the information obtained in the well-developed Δ-hole model [27]; such a study has been made in Ref. [28] within the framework of the dynamical transport approach. Our present calculation, however, falls short of considering FSI. Since the importance of these FSI effects grows rather fast with the increasing target mass number (this is particularly true for pion absorption), we limit ourselves here to nuclear targets of low mass numbers and concentrate on the $A = 12$ target. Although heavier nuclei such as ^{56}Fe are important in some neutrino-oscillation experiments [5], we can deal with these cases only after FSI is incorporated into our formalism.

2. Sato–Lee (SL) model

As the SL-model has been fully described in Refs. [17–20], we give here only a brief explanation of the model, using as an example the case of pion photoproduction. The effective Hamiltonian H_{eff} in the SL-model for this process is given by

$$H_{\text{eff}} = H_0 + v_{\pi N} + v_{\gamma\pi} + \Gamma_{\pi N\leftrightarrow\Delta} + \Gamma_{\gamma N\leftrightarrow\Delta}, \tag{1}$$

where H_0 is the free Hamiltonian; $v_{\pi N}$ and $v_{\gamma\pi}$ represent the non-resonant pion–nucleon and pion-photoproduction interactions, respectively, while $\Gamma_{\pi N\leftrightarrow\Delta}$ and $\Gamma_{\gamma N\leftrightarrow\Delta}$ are responsible for the creation and annihilation of a bare Δ-resonance. By solving the Lippmann–Schwinger equation based on the above effective Hamiltonian, we obtain the amplitude for pion production on a nucleon as

$$T_{\gamma\pi} = t_{\gamma\pi}(E) + \frac{\bar{\Gamma}_{\Delta\to\pi N}(E)\bar{\Gamma}_{\gamma N\to\Delta}(E)}{E - m_\Delta^0 - \Sigma(E)}, \tag{2}$$

where E is the total energy of the pion and nucleon in the center-of-mass system. The first term $t_{\gamma\pi}$ is the non-resonant amplitude, which arises from the vertices $v_{\pi N}$ and $v_{\gamma N}$ alone, while the second term represents the resonant amplitude involving the dressed vertex $\bar{\Gamma}$. We note that the bare resonance vertex Γ is renormalized into $\bar{\Gamma}$ by the non-resonant meson cloud effects arising from rescattering as

$$\bar{\Gamma}_{\gamma N\to\Delta}(E) = \Gamma_{\gamma N\to\Delta} + \Gamma_{\pi N\to\Delta} G_0 t_{\gamma\pi}(E), \tag{3}$$

and that the renormalized resonance vertex $\bar{\Gamma}$ should exhibit a significant deviation from the bare vertex Γ because of the meson cloud effects. In conventional analyses, however, one dis-