Theoretical Status of Neutrino Cross Sections

T. Sato

Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan

Abstract. Recent theoretical studies on the neutrino nucleus reactions in the quasi elastic and the single pion production region are briefly reviewed.

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INTRODUCTION

The understanding of the neutrino-nucleus reaction around 1 GeV neutrino energy is of great importance in analyzing neutrino oscillation experiment. In this energy region, the main reaction mechanisms are quasielastic scattering and single pion production reaction through the Δ excitation. The energy spectrum of the neutrino may be extracted from the quasielastic data by using the kinematics of single nucleon knockout, which is only valid for the plane wave impulse approximation. Therefore one needs a good control of the nuclear effects such as initial state and final state nuclear correlations. In analyzing the experimental data, those nuclear effects are parametrized keeping the single particle picture of reaction mechanism by modifying the axial vector form factor of nucleon. There have been intense theoretical efforts on the quasi elastic reaction with various approaches. We will report on the recent discussions in comparison with the new double differential cross section data[1].

The pion production reaction becomes a background in neutrino oscillation experiments. Precise understanding of the reaction requires knowledge of complex meson propagation and interaction within nuclei. The coherent pion production reaction, which is essentially a elastic scattering for the nucleus, is of considerable interest. As far as the nuclear transition density is concerned, nuclear structure is rather well controlled theoretically. Therefore one may able to test the theoretical approaches of weak pion production mechanism and pion interaction by analyzing the coherent pion production process. The theoretical model based on PCAC[2] failed to explain K2K, SciBooNE, MiniBooNE data below a few GeV neutrino and this triggered theoretical studies on the reaction.

In this report we will discuss the neutrino-nucleon interaction which is an input for the nuclear reaction study, the neutrino nucleus reaction at the quasielastic region and the coherent pion production reaction.

NEUTRINO-NUCLEON INTERACTION

The neutrino-nucleus reaction in the quasielastic region can be described by the impulse approximation. The impulse current is given by the on-mass shell matrix element of weak current as

$$\begin{aligned} < N|V^{\mu,\alpha}|N > &= \bar{u}[g_V^\alpha(q^2)\gamma^\mu + \frac{g_M^\alpha(q^2)}{2M_N} i\sigma^{\mu\nu}q_\nu]u \\ < N|A^{\mu,\alpha}|N > &= \bar{u}[g_A^\alpha(q^2)\gamma^\mu + \frac{g_P^\alpha(q^2)}{2m_\mu} i\sigma^{\mu\nu}q_\nu]\gamma_5 u \end{aligned} \tag{1}$$

for $\alpha = CC, NC$. The form factors of the vector current g_V, g_M can be obtained from the electromagnetic form factors of proton and neutron. The axial vector form factor g_A, which plays important role in neutrino-nucleus reaction, is usually parametrized as $g_A(q^2) = g_A(0)/(1 - q^2/M_A^2)^2$. Here $g_A(0)$ is determined from neutron beta decay and the mass parameter $M_A \sim 1.026 \pm 0.021$ GeV extracted from the analysis of the neutrino reaction on proton and deuteron. This M_A is in good agreement with 1.069 ± 0.016 GeV obtained from the E_{0+} multipole amplitude of the pion electroproduction by using the heavy baryon chiral perturbation theory[3]. The induced pseudoscalar form factor g_P determined from muonic hydrogen can be understood well in chiral perturbation theory[4].

The neutrino-nucleon reaction in the nucleon resonance region has been studied in dispersion theory[5], isobar model[6]. Here we concentrate on the single pion production reaction in the delta resonance ($\Delta_{33}(1232)$) region, which is the main mechanism of pion production around the 1 GeV neutrino. The resonance model shown Fig. 1 (a) successfully explains the charged current νp process. On the other hand, the analysis of νn suggests the need for an extra reaction mechanism. Recently model is improved by including the non-resonant mechanism shown in Fig. 1 (b) based on the effective chiral Lagrangian[7, 8, 9, 10] in addition to the resonant amplitude (a). The contribution of the non-resonant mechanism can be about 50% of the total cross section depending on the model. The mechanism of pion production can be tested from the electron scattering data which are available over the wide center of mass energy W and momentum transfer Q^2 regions including polarization observables. The model of Refs. [11, 12] takes into account the rescattering of the pion (Fig. 1 (c)) by solving the Lippmann-Schwinger equation and the model is extensively tested from the electron scattering data. Though various theoretical approaches have been developed, the axial vector transition form factors $g_{N\Delta}$ are not constrained well from the current data of neutrino induced pion production reactions on a nucleon.

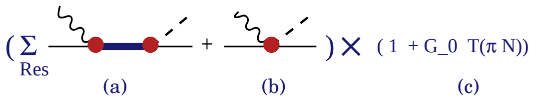

FIGURE 1. Mechanism of the neutrino induced pion production reaction.

QUASI ELASTIC NEUTRINO SCATTERING

The inclusive cross section of the neutrino-nucleus reaction is given by using the hadron tensor $W_{\mu\nu}$ expressed as

$$W^{\mu\nu} \quad \sim \quad Im[<0|J^{\nu\dagger}\frac{1}{E-H+i\varepsilon}J^{\mu}|0>]. \qquad (2)$$

Here J^μ, H and $|0>$ represent nuclear weak current, nuclear Hamiltonian and the nuclear ground state. Impulse current is usually used for J^μ. However, it is known from the analysis of electron-nucleus scattering that the many-body nuclear current (meson exchange current MEC) becomes important in the energy region away from the quasielastic peak. So far, the role of MEC for the neutrino-nucleus reaction has not been explored fully. The hadron tensor is evaluated from various theoretical approaches. In the Green function approach[13], the nuclear Hamiltonian is written in terms of single particle Hamiltonian with optical potential. In Refs. [14, 15], the initial state correlation of the ground state is taken into account using the spectral function. The long range particle-hole and delta-hole correlation is included in RPA approach[16, 17, 18]. The final state interactions are included with coupled-channel transport model in Ref. [19], where within the framework the inclusive reaction in the pion production region and the quasielastic region can be studied.

In those theoretical approaches, the experimental double differential cross section of the electron-nucleus inclusive reaction (fixed electron angle and varying energy transfer to the nucleus) around the QE peak is well explained. It is noted that some of those approaches underestimate the strength at the 'dip region' between QE and Δ peak, where the 2p-2h and meson-exchange current are expected to play role[20]. Once a theoretical model is constrained from the data of the QE peak of electron scattering, the model dependence of the predictions on the QE neutrino-nucleus reaction is small.

Recent MinoBooNE data[1] allows us for the first time to test the theoretical double differential neutrino-nucleus cross section. In Ref. [15], it was shown that the theory which reproduces well the QE peak of electron scattering fails the neutrino scattering data at almost the same scattering angle and the incident lepton energy. The theory underestimates the peak of the neutrino-nucleus cross section when one uses the free nucleon current given in Eq. (1). It is also shown it is difficult to repair the discrepancy by tuning the mass of axial vector form factor M_A. It is noticed that the distribution of the incident neutrino energy spreads over a relatively large energy region. The structure like the quaielastic peak as a function of final muon energy will include contributions off the QE kinematics. Therefore theoretical approaches should have the ability to predict a rather wide region of nuclear excitation energy below QE to above QE to account for the data. It is shown in Ref. [18] that one obtains enough strength of the total cross section in the RPA approach including the two-particle two-hole configuration, which may offer a possible solution. Further theoretical efforts are necessary for the full understanding of QE neutrino-nucleus reactions with a model which can account for the cross section in a wide energy region and which is well tested from the electron scattering data.

COHERENT PION PRODUCTION

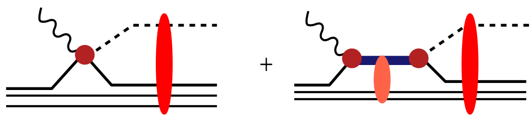

FIGURE 2. The neutrino induced coherent pion production amplitude

The charged current ($CC\pi^+$) and neutral current ($NC\pi^0$) neutrino induced coherent pion production reactions are

$$A+\nu_\mu \quad \rightarrow \quad A+\pi^+ +\mu^- \quad CC\pi^+ \qquad (3)$$

$$A+\nu_x \quad \rightarrow \quad A+\pi^0+\nu_x - \quad NC\pi^0, \qquad (4)$$

where A is nuclear ground state.

The PCAC relates the matrix element of the axial vector current to the pion production amplitude $\alpha +$

$A^{\mu} \to \beta + \pi$[21]

$$q_{\mu} < \beta | A^{\mu} | \alpha > \quad = \quad \frac{M_N g_A}{g_r} \frac{M_{\pi}^2}{M_{\pi}^2 - q^2} T(\pi^+ + \alpha \to \beta) \tag{5}$$

With this relation, the forward amplitude of the coherent pion production can be related to the half-off shell elastic pion scattering amplitude. The above relation is used for the nucleon in the original PCAC approach[2]. The relation is now used for the nucleus ($\alpha =$ nucleus) in Ref. [22], where the nuclear effects are effectively included by using an empirical pion-nucleus elastic scattering amplitude.

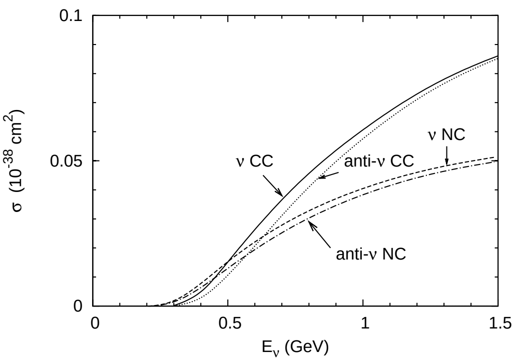

FIGURE 3. E_{ν} dependence of the total cross section for CCπ^+ and NCπ^0 reactions on ^{12}C

In the dynamical approaches[23, 24, 25], the coherent pion production amplitude is constructed from the weak pion production amplitude of the nucleon (t), nuclear ground state wave function ($|0>$) and the distorted wave of the pion (ϕ_{π}) written schematically as

$$T_{fi} = < 0, \phi_{\pi} | t_{N+J \to N+\pi} | 0 > . \tag{6}$$

The medium modification of the pion production mechanism and interaction of the produced pion while propagating inside nuclei can be included in $t_{N+J \to N+\pi}$ and ϕ_{π} as shown in Fig. 2. In the delta-hole model[25], the medium propagation of the delta and the final state rescattering of the pion is included in a unified way with the delta-hole Hamiltonian. Furthermore the effect of the non-local propagation of Δ pointed out in Ref. [26] can be taken into account, which was indeed important. To construct a dynamical model, it is crucial to control the parameters of the model such as the spreading potential of the delta-hole Hamiltonian by investigating the pion-nucleus reactions and also test the model against the data of coherent pion photo production reaction before applying the model to the neutrino induced reaction.

The energy dependence of the total cross section of the neutrino and anti-neutrino induced coherent pion production (CCπ^+, NCπ^0) on ^{12}C calculated in Ref. [25] is shown in Fig. 3. For the higher incident energies, the ratio σ_{CC}/σ_{NC} approaches 2 a value expected from the isospin factor with Δ_{33} dominance. For low energy $E_{\nu} <$ 0.5 GeV, the ratio decreases because of the reduction of the phase space for CCπ^+ due to muon mass. The results indicate the theoretical result is not compatible with the recent report on the CC/NC ratio[27].

In Table 1, the recent theoretical results on the total cross section of the coherent pion production reaction are summarized. The second(third) row shows the flux averaged cross section for CC(NC), where K2K[28] reports $\sigma_{CC} < 7.7 \times 10^{-40} cm^2$ (MiniBooNE[29] reports $\sigma_{NC} = 7.7 \pm 1.6 \pm 3.6 \times 10^{-40} cm^2$). The theoretical results from dynamical models and PCAC approaches agrees reasonably well for the integrated cross sections. It is noticed however remaining discrepancies among them in the differential observables such as the energy distribution of pion should be resolved in a future study.

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TABLE 1. The flux averaged total cross section of CCπ^+ and NCπ^0 in $10^{-40} cm^2$.

	Alvarez-Ruso[23]	Hernandez[24]	Nakamura[25]	Berger[22]	Martini[17]
CCπ^+	10.8 / 5.7	6.1 ± 1.3	6.3	0.62×12	
NCπ^0	5.6 / 2.6	2.6 ± 0.5	2.8		2.8

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