Experimental status of neutrino scattering physics and needed measurements

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Knowledge of neutrino interactions with a nuclear target at the neutrino energy around sub-GeV is recently getting more and more important as necessary information for accelerator based neutrino oscillation experiments. A study of neutrino interactions contains rich physics of neutrinos with nucleus, and is used to reveal the properties of neutrinos in the oscillation measurements. We review the recent neutrino scattering experiments addressing the physics of neutrino interactions with a nucleus. We list the recent unresolved problems in neutrino interactions, especially modeling of the quasi-elastic scattering process and the neutrino induced signle pion production process. We present the recent status and new results from the ν-scattering experiments: K2K, MiniBooNE, MINOS, SciBooNE, T2K and MINERνA. At the end, we summaries the future outlook.

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1. Introduction

After the discovery of neutrino oscillations in atmospheric neutrinos [1], the neutrino mass and mixing are intensively studied by many experiments with solar neutrinos, reactor anti-neutrinos, atmospheric neutrinos and accelerator neutrinos. The study of neutrino oscillation with the accelerator neutrinos is one of the most promising approaches to reveal the unknown properties of neutrinos, a whole scheme of the neutrino mixing and the particle and anti-particle (CP) asymmetry in neutrinos, and to provide precise information on the neutrino mass. A next generation accelerator neutrino oscillation experiment, T2K [2], attracts many attentions to provide the new information. At the same time, we recognize that the further precision studies in the accelerator neutrino oscillation experiments request more accurate information on interactions of neutrinos with a nuclear target which is the target material of massive neutrino detectors for neutrino detection. From the view point, recently, many attentions are drew to understand and improve the knowledge of neutrino interactions with a nuclear target at the energy around sub-GeV. In order to address these issues, several neutrino scattering experiments are conducted to study the neutrino interactions with a nuclear target. The neutrino scattering experiments are introduced in Section 3.

The charged-current (CC) quasi-elastic (QE) scattering with a nuclear target is the primary channel in neutrino interactions which must be well-understood and properly modeled because it is a dominant process for sub-GeV neutrinos and is often used to reconstruct the neutrino energy in experiments. Although it looks like a straight-forward process with a nucleon of which many data exists, complicated phenomena are involved by treating a nuclear target. It is explained in Section 2 and many recent experiments are focused on understanding of the CC-QE process.

The single pion (1π) production by neutrino interactions is also the most important channel in neutrino interactions because it is a dominant process for sub-GeV neutrinos and it is a severe background in neutrino oscillation experiments. A search for $\nu_\mu \to \nu_e$ oscillation is one of the most interesting subjects in future experiments, and the neutral-current (NC) $1\pi^0$ production is the background in K2K and T2K [2, 3]. So, it is important to understand the NC-$1\pi^0$ process and to measure the cross section itself and the momenta of the final produced π^0 which potentially suffers with the effects of nuclear medium. For a precise study of neutrino oscillation in the $\nu_\mu \to \nu_\mu$ oscillation channel, a dominant background is the CC-1π process where we miss the pion either by nuclear effects or by the detection technique. In addition to study neutrino oscillation, this channel is equally important to search for a proton-decay, $p \to e^+(\mu^+)\pi^0$, because the CC-$1\pi^0$ is a dominant background by atmospheric neutrinos [4, 5]. We know that the understanding of this process is important to develop a next generation proton decay experiment with a Megaton-size Water Cherenkov detector [6].

Finally, the experimental data of anti-neutrino interactions around sub-GeV are not rich and no data exists on the CC-QE process below 1 GeV. The future CP violation study on neutrino oscillations in the accelerator experiments [7] requests equal knowledge of neutrinos and anti-neutrino interactions where the probability of $\nu_\mu \to \nu_e$ oscillation is compared with that of $\overline{\nu}_\mu \to \overline{\nu}_e$ after carefully subtraction of the background processes. The anti-neutrino interactions must be well-understood with the same level as neutrino interactions although it has lower cross sections. In addition, an anti-neutrino beam in low energy has typically a contamination of neutrinos, which make the background understanding somehow complicated. Currently, the MiniBooND and Sci-

BooNE experiments described in Section 3 collect anti-neutrino data and under analysis.

2. Puzzles

When modern neutrino oscillation experiments, K2K and MiniBooNE, started, it was found that our knowledge of neutrino interactions was not well satisfied to describe the experimental data. For the simulation of neutrino interactions, the K2K collaboration used the NEUT program library [8, 9] and the MiniBooNE collaboration used the NUANCE [10]. Both NEUT and NU-ANCE adopt the similar theoretical models with the nuclear effects, and it is not a clear guide which simulator is better to describe the data. Both K2K and MiniBooNE collaborations intensively studied the neutrino interactions, and found some hints why the experimental data do not match well with the MC prediction. Here, we introduce the unforeseen results in the CC-QE scattering and the single pion production.

2.1 Quasi-Elastic scattering

The CC-QE process is thought to be well described in the vector and axial-vector form factors which are expressed with the dipole formula. The vector form factor is well known by data of electron scattering experiments. The axial-vector form factor with the dipole formula has only one parameter, called M_A, and the M_A was measured by many past experiments. The mean value of M_A is 1.03 GeV/c^2 with the error of a few percent. The observed Q^2 distributions in K2K and MiniBooNE tend to be more energetic than the MC model prediction with $M_A = 1.03$. The measurements of K2K with a water target is $M_A = 1.20 \pm 0.12$ GeV/c^2 [11] and the measurement of MiniBooNE with a carbon target is $M_A^{eff} = 1.23 \pm 0.20$ GeV/c^2 [12]. Here, the MiniBooNE collaboration defines a new interpretation for M_A as an effective M_A because our observation is not a scattering with a nucleon, but with a nuclear target. Therefore, the observation might be suffered by the nuclear effect. Furthermore, the MiniBooNE collaboration also introduces the Pauli-suppression parameter, $\kappa = 1.019 \pm 0.011$. It is very interesting to test the CC-QE modeling proposed by the MiniBooNE collaboration by upcoming new experiments.

2.2 Single pion production

As introduced in Section 1, the single pion production is the second dominant channel at the sub-GeV neutrino energy. One interesting subject is again the form factors of this process because even the simpler model of CC-QE is claimed to modify the axial form factor for the nuclear target as described in Section 2.1. It looks natural that the similar effect could be observed in the CC-1π channel as CC-QE. However, the existing data for the CC-1π process is very limited and the clear extraction of signal is not as easy as for CCQE. Therefore, we have no conclusion yet.

Another interesting subject is the process of coherent pion production by neutrinos. The K2K experiments reported the null result of the CC coherent π production [13] although the clear observation was expected by the Rein and Sehgal model [14]. Rein and Sehgal updated their models by including the lepton mass effect [15]. Recently the MiniBooNE collaboration finds the evidence of NC coherent π^0 production [16]. It is interesting to check the consistency between the null K2K

result on CC coherent π and the positive signal of NC coherent π^0 together by comparing with several theoretical models. Recently, the SciBooNE collaboration looks for the signal of CC coherent π production [17].

Finally, another most important quantity is the momentum distribution of pions because it directly affects the background level in neutrino oscillation experiments. So far, K2K and Mini-BooNE measured the π^0 momentum distribution in NC-1π^0 production [16, 18]. The observed π^0 momentum looks softer than the MC predictions, which may indicate that the treatment of the nuclear effects is not good enough. For future neutrino oscillation experiments, the better estimation of the pion momentum distributions by the MC simulations are necessary to accurately predict the background. To improve the prediction, further experimental data are important to resolve the issues.

2.3 Low energy electron excess

The last puzzle in neutrino interactions is the low energy elecron excess observed by Mini-BooNE [19]. This phenomena is only observed by the MiniBooNE experiment because Mini-BooNE has the best sensitivity to identifying ν_e in the muon neutrino beam. Although the Mini-BooNE collaboration intensively investigates the source of the events, the origin of the excess is not identified yet. Although the impact of this background to T2K was concerned, it may be marginal because the sensitivity of T2K around 0.4% in ν_e appearance is not severe to take matter of this background by comparing with the sensitivity of MiniBooNE around 0.1 %.

3. Neutrino Scattering Experiments

Physics with neutrino scattering is conducted by using the detectors in neutrino oscillation experiments and a few dedicated neutrino scattering experiments. The former case is the neutrino detectors located close to the neutrino beam source in the K2K, MINOS and T2K experiments and the detector in MiniBooNE. The latter case is the SciBooNE and MINERνA experiments. The experiments are summarized in Table 1 for the mean neutrino beam energy ($< E_\nu >$), the detector type, the fiducial mass of the detector, and the target material and the number of neutrino events interacted in the detector (#ν events). The "#ν" events is shown as a guide to know roughly how many events are occurred in the detector with the full running time of the experiment. Those experiments cover the neutrino energy from a few hundred MeV up to 30 GeV with various nuclear targets: H_2O, CH_2, CH, Fe, Pb, C. In addition, several different detector technologies are used for the studies.

3.1 K2K

K2K is the first generation long-baseline neutrino oscillation experiments from KEK to Kamioka. The K2K neutrino beam was produced by the KEK 12-GeV Proton Synchrotron and had the mean energy of 1.3 GeV for neutrinos. K2K has the near and far detectors, and the far detector is Super-Kamiokande. The K2K near detector system consisted of 1 kiloton Water Cherenkov detector and sets of the fine-grained detectors (SciFi, SciBar) with the electro-magnetic calorimeter (EC) and the muon range detector (MRD). The K2K experiment and the near detectors are well described in

Table 1: Summary of Neutrino Scattering Experiments

	$<E_\nu>$ (GeV)	Detector	Fiducial mass (ton)	Target Target	#ν events (as reference)
K2K (Near)	~ 1.3	Water Cherenkov, FGD	$5 \sim 50$	H_2O, CH, Fe	$50k \sim 100k$
MiniBooNE	~ 0.7	Oil Cherenkov	~ 440	CH_2	$\sim 1M$
MINOS (Near)	$2 \sim 30$	Iron/Plastic sandwich	33	Fe	$\sim 5M$
SciBooNE	~ 0.7	FGD	10	CH	$\sim 100k$
T2K (Near)	~ 0.7	FGD	$2 \sim 10$	Fe, Pb, CH, H_2O	$\sim 500k$
MINERνA	$2 \sim 30$	FGD	~ 3	Fe, Pb, C	$\sim 10M$

the reference [20]. The K2K near detectors located inside KEK have rich data on neutrino scattering, and provided several important results on the neutrino scattering physics [5, 11, 13, 18, 21]. In addition to the published results, K2K recently shows the preliminary results on the CC-QE M_A with a carbon target [22] and the CC single π^0 production [23] by using the SciBar detector [24]. The results on the CC-QE M_A has the value of $M_A = 1.144 \pm 0.077 (fit)^{+0.078}_{-0.072} (syst.)$ higher by comparing with the mean value of old experiments. The new value of M_A is consistent with the former result of K2K with the water target [11] and the result of MiniBooNE with the carbon target [12]. The result on the cross section of the CC single π^0 production is found to be slightly higher than the prediction by models implemented in NEUT [8, 9] by (39 ± 15) %. Those new results are under preparation for publication.

3.2 MiniBooNE

MiniBooNE is a short-baseline neutrino oscillation experiment to test the evidence of neutrino transition claimed by LSND. MiniBooNE reported the result not supporting the LSND signal [19]. The MiniBooNE detector is a mineral oil Cherenkov detector of $\sim 1,000$ tons with 1,520 PMTs [25]. MiniBooNE has very high statistics data of neutrino interactions with 450 ton fiducial mass. MiniBooNE collected data of 6.6×10^{20} POT (Protons-On-Target) with a neutrino beam configuration and 2.5×10^{20} POT with an anti-neutrino beam. By using 5.6×10^{20} POT neutrino beam data, MiniBooNE measured the CC-QE scattering on Carbon with an effective axial mass of $M_A^{eff} = 1.23 \pm 0.20$ GeV/c^2 [12]. In addition, MiniBooNE find a deficit of low Q^2 events which is accounted by introducing the Pauli-suppression parameter, $\kappa = 1.019 \pm 0.011$. MiniBooNE detected 28,600 π^0 events and find an evidence of NC coherent π^0 production [16]. With an advantage of high statistics data, the MiniBooNE collaboration extends various physics analysis including the anti-neutrino interactions.

3.3 MINOS

MINOS is the long-baseline neutrino oscillation experiment to confirm the neutrino oscillation and to measure neutrino oscillation parameters precisely. The NuMI (Neutrinos at the Main Injector) neutrino beam for MINOS has the tunability for the neutrino energy and flux, and is typically

operated with the low energy configuration which produces the neutrinos at the peak energy of $3 \sim 4$ GeV and with the flux tail extending up to 30 GeV. The MINOS experiments collected data of more than 4×10^{20} POT. The MINOS front detector (FD) is located 1 km away from the target and has the total mass of 1 kilo-ton. The detector is a sandwich type of magnetized iron and plastic scintillators with the magnetic field of 1.2 T. Because of the high intensity NuMI neutrino beam, the MINOS FD collected 5,500,000 CC neutrino interactions in the fiducial mass of 33 tons with 3×10^{20} POT. The MINOS collaboration can study the CCQE scattering, a low energy neutrino flux extraction, an inclusive CC cross-section shape, DIS and structure function, and CC and NC coherent pion production although they have not get the preliminary results yet. MINOS expects to have 800,000 CC-QE events at 3×10^{20} POT, 2,600,000 ν-DIS events and 300,000 $\overline{\nu}$-DIS events at 7.4×10^{20} POT, 1,700 NC coherent π^0 events and 2,700 CC coherent π^+ events at 3×10^{20} POT.

3.4 SciBooNE

SciBooNE is a dedicated neutrino scattering experiment to study neutrino interactions physics at FNAL-BNB [26]. The SciBooNE beam is FNAL-BNB and the detector located 100 m downstream from the proton target. The SciBooNE detector is the K2K SciBar detector [24] and Electron-Catcher (EC) together with the newly built muon range detector. SciBooNE collected data of 0.99×10^{20} POT with a neutrino beam configuration and 1.54×10^{20} POT with an anti-neutrino beam. The first results from SciBooNE were presented in this conference [27, 28]. The SciBooNE collaboration studies the CC-QE process, CC-1π process, NC-1π^0 process, and NC elastic process with neutrino beam data. The SciBooNE collaboration search for the CC-coherent π process and the preliminary result was presented at ICHEP2008 [17]. The analysis of anti-neutrino beam data is on-going and is expected to be available in 2009.

3.5 T2K

T2K is the next generation long-baseline neutrino oscillation experiments from Tokai to Kamioka. The T2K neutrino beam will be produced by the J-PARC MR accelerator with the initial energy of 30 GeV. The narrow-band neutrino beam with the mean energy of 0.7 GeV is produced by the off-axis technique with the off-axis angle of 2.5 degree. The far detector is Super-Kamiokande, and the near detector consists of so-called neutrino beam monitor (named INGRID) and off-axis neutrino detector (ND280-offaxis) located 280 m downstream from the target. INGRID is a modular type sandwich detector of iron and plastic scintillators. INGRID consists of 16 modules with 10 ton each. The primary purpose of INGRID is not to study the neutrino interactions, but to monitor the neutrino beam. For this purpose, experimental inputs of the neutrino interactions with iron is important for INGRID. The ND280-offaxis is the fine grained tracking detectors mounted inside of the UA1 dipole magnet with the magnetic field of 0.2 T. The ND280-offaxis consists of a dedicated π^0 detector (P0D), two fine-grained scintillator vertex detectors (FGD) with a water target, three large-volume TPCs sitting side by side of FGDs, Electron-Calorimeter (ECAL), and a side muon range detector (SMRD). The uniqueness of T2K ND280-offaxis is the finer granuality of $1 \times 1 \text{cm}^2$ scintillators, momentum measurement with the magnetic field and fine-segmented ECAL. Therefore, it is expected to provide the most precise information on neutrino interactions once it starts the operation. The first T2K beam is expected to be shot in April 2009. The installation of ND280 is

scheduled in summer 2009 and data taking will start around the end of 2009. So, in the near future, we expect more rich data on neutrino interactions for a precision neutrino oscillation experiment.

3.6 MINERνA

MINERνA is a high precision neutrino scattering experiment at the FNAL Main Injector. The MINERνA will use the NuMI neutrino beam. The detector will locate in front of the MINOS front detector. The MINERνA detector is a finely segmented, fully active, scintillator tracking chamber, surrounded by Electro-magnetic and Hadron calorimeters. The uniqueness of MINERνA is a wide variety of nuclear targets to measure the *A* dependence of neutrino interactions. The target nuclei are *He*, *C*, *Fe*, and *Pb*. They plan to run for four years with the NuMI low energy beam configuration for 4×10^{20} POT and the medium energy configuration for 12×10^{20} POT. With a typical beam exposure, it is expected to collect ~ 14 Million neutrino interactions which are used to study the CC-QE process, the resonance meson production, the transition region of the resonance dominance to DIS, the DIS low Q^2 region, the structure functions, the coherent pion production and the charm and strange production. The experiment is planed to finish installation and commissioning in 2009, and to start taking data in 2010.

4. Summary and Outlook

The experimental aspects of neutrino scattering physics are reviewed in this paper. Although the neutrino scattering physics are getting more and more important, there is no special virtue to resolve the current situation of poor understanding and no perfect modeling of many neutrino interaction processes with a nuclear target. It is a only way to settle the puzzles one by one by improving the quality of experimental data. Since several modern experiments are attacking these puzzles to improve the sensitivity of neutrino oscillations, we are looking forward to the breakthrough of neutrino scattering physics in the near future.

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