Study of Charged-Current neutrino interactions on water with nuclear emulsion in the NINJA experiment

A.Hiramoto[a], Y.Suzuki[b], T.Fukuda[b], T.Nakaya[a] for the NINJA collaboration

[a]Kyoto University, Department of Physics, Kyoto, Japan
[b]Nagoya University, Department of Physics, Nagoya, Japan

E-mail: hiramoto@scphys.kyoto-u.ac.jp

Abstract. Neutrino-nucleus interaction is one of the major sources of the uncertainty for neutrino oscillation experiments. The NINJA experiment aims to measure neutrino-water interactions containing low-momentum secondary particles using a nuclear emulsion detector. Since the nuclear emulsion has sub-micron position resolution, it allows us to observe the interaction vertices clearly. Short proton tracks down to 200 MeV/c momentum are expected to be observed, which are hardly reconstructed in plastic scintillator based detectors. A series of test experiments has been carried out with prototype detectors at J-PARC. In a test run in 2017-2018, a 3 kg water target detector was exposed to anti-neutrino beam corresponding to 0.7×10^{21} POT (protons on target). We have successfully detected low momentum protons above 200 MeV/c threshold from neutrino-water interactions.

1. Introduction

Neutrino interaction on nucleus is one of the major uncertainties for neutrino oscillation experiments. Especially, understanding of multi-nucleon interaction represented by 2p2h (2 particle - 2 hole) is important since it mimics the CCQE (Charged Current Quasi Elastic) signals and affects the reconstruction of incoming neutrino energy. Although direct measurement of outgoing protons from neutrino interactions is very important to understand the multi-nucleon interactions, there haven't been sufficient measurements so far because most proton tracks are too short to be detectd in scintillator-based trackers.

2. The NINJA experiment

The NINJA experiment stands for "Neutrino Interaction research with Nuclear emulsion and J-parc Accelerator". We measure neutrino interactions on water target for the T2K experiment. We use nuclear emulsion as our tracker, which is a three-dimensional tracking device having sub-micron position resolution. Because of this resolution, the emulsion detector can measure above 200 MeV/c protons even from neutrino interactions on water target by constructing an alternative structure of water layers and emulsion films. So far, liquid argon time projection chambers have achieved the lowest detection threshold for detection of low momentum protons from neutrino-argon interactions[1]. On the other hand, a measurement of low momentum protons from neutrino-water interactions is necessary for T2K since the water Cerenkov detector, Super-Kamiokande, is used as the far detector.

NINJA detector is separated into three parts. The main emulsion detector, so called ECC (Emulsion Cloud Chamber), is placed in front of a muon range detector (MRD), which has a sandwich structure of iron plates and scintillator trackers. Since the emulsion doesn't have time resolution, all tracks including cosmic rays are accumulated. To select beam-timing tracks, a scintillating fiber tracker which has both good position and time resolutions is placed between ECC and MRD as a time-stamper.

ECC has been used in several neutrino experiments, but NINJA is the first experiment using a water target ECC. Figure 1 is a top view of the water ECC. It has a sandwich structure of 2 mm water target layers and tracking layers. A tracking layer contains two emulsion films and one iron plate. The emulsion provides us position, angle and energy deposit of all charged particles at each plate. $P\beta$ (momentum) of each track is measured by multiple Coulomb scattering on the iron plates. In addition, separation of proton and pion is performed using energy deposit of the tracks.

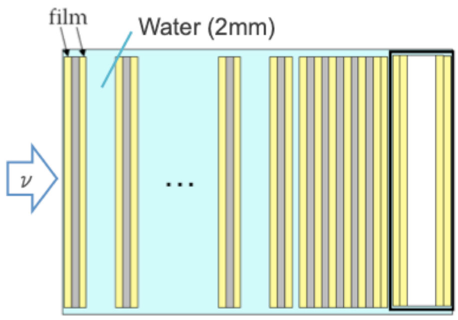

Figure 1. Structure of the water target ECC

So far, we had a series of test runs. The first run in 2014 confirmed detection of neutrino interactions using a small iron target ECC[2][3]. Then, two test runs were carried out. One is 65 kg iron target run in 2016, and the other is 3 kg water target run in 2017-2018. In this article, outcomes from the water target run are shown using 70% of all data which includes a anti-neutrino beam exposure of 0.7×10^{21} POT. Monte Carlo simulation is performed using NEUT (v5.4.0) and a GEANT4-based detector simulation.

3. Event selection

Neutrino event candidates are selected based on following procedures. First, track matching between ECC and MRD is performed. Although 10,741 tracks are identified as muons, most of them are muons from neutrino interactions in upstream wall of the detector hall. Only 250 tracks have vertices in the ECC fiducial volume. We have both water and iron in our detector, however, only water interaction candidates are selected. Some candidates are excluded because they interacted on emulsion gel or plastic base of the films. Then, muon tracks which have consistency between momentum measured by multiple scattering and that measured by the MRD range are selected to reduce track mismatching between ECC and MRD. Finally, we get 62 water neutrino event candidates while the Monte Carlo simulation expects 66 events.

4. Results

4.1. Track multiplicity

Figure 2 shows track multiplicity of the neutrino event candidates. Our detector acceptance is currently limited up to $|\tan\theta| < 1.3$. Tracks which penetrate two or more emulsion plates are selected.

4.2. Muon kinematics

Figure 3 shows muon angle and momentum distributions. The muon momentum is estimated from the MRD range. Muons are limited by the acceptance of the MRD. We require to penetrate at least two iron plates, but most muons have momentum more than 1 GeV and penetrate MRD. Muon angle and MRD range have a good agreement with the Monte Carlo simulation.

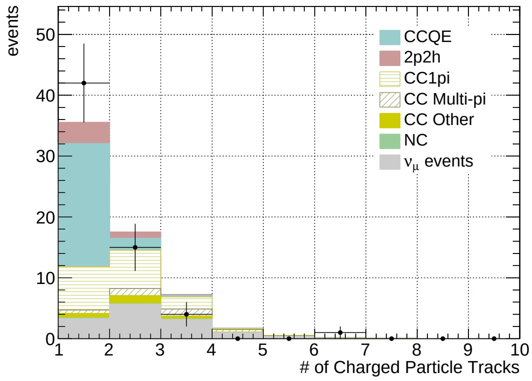

Figure 2. Track multiplicity of water interactions

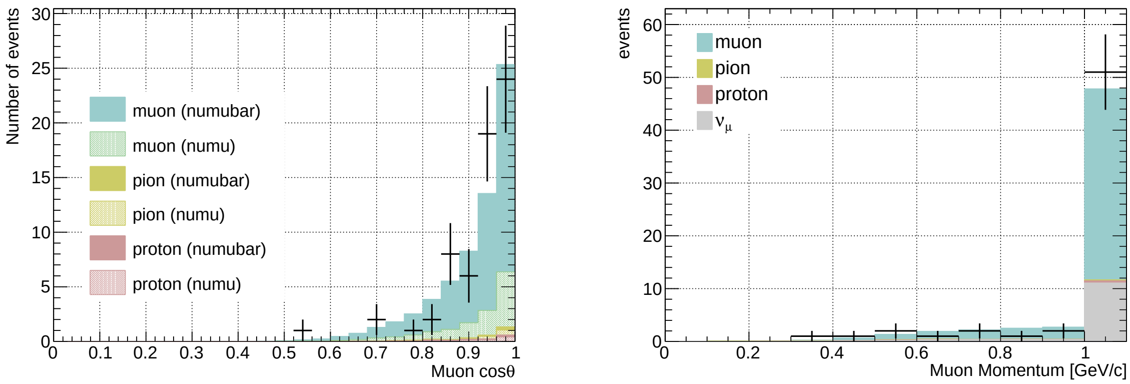

Figure 3. Muon angle (left) and muon momentum estimated from the MRD range (right).

4.3. Proton and pion kinematics

After the muon identification, protons and pions are identified using a likelihood calculated by blackness of tracks in emulsion, which corresponds to energy deposit. Angle and momentum distributions of proton and pion tracks are shown in Figure 4 and Figure 5. Two-dimensional distribution of proton angle and momentum is also shown in Figure 6. We have successfully detected protons down to 200 MeV/c from neutrino interactions on water target.

5. Future prospects

We will start physics run from November 2019. Detectors are placed among T2K-WAGASCI detectors at the neutrino detector hall in J-PARC. A 75kg water target ECC will be exposed to neutrino beam corresponding to 0.5×10^{21} POT, and 3000 charged current neutrino events are expected to be detected. Our first goal is a measurement of the number of proton, pion and their momentum and angle distributions. The cross section measurement divided by number of protons and pions will also be performed. Furthermore, we plan to have another physics run after J-PARC Main Ring upgrade.

6. Conclusion

NINJA measures neutrino interactions on water with 200 MeV/c proton threshold. First measurements of muon, proton and pion kinematics using water target ECC are shown, and protons above 200 MeV/c are successfully detected on water target. We will update our results with full data including all systematic uncertainties.

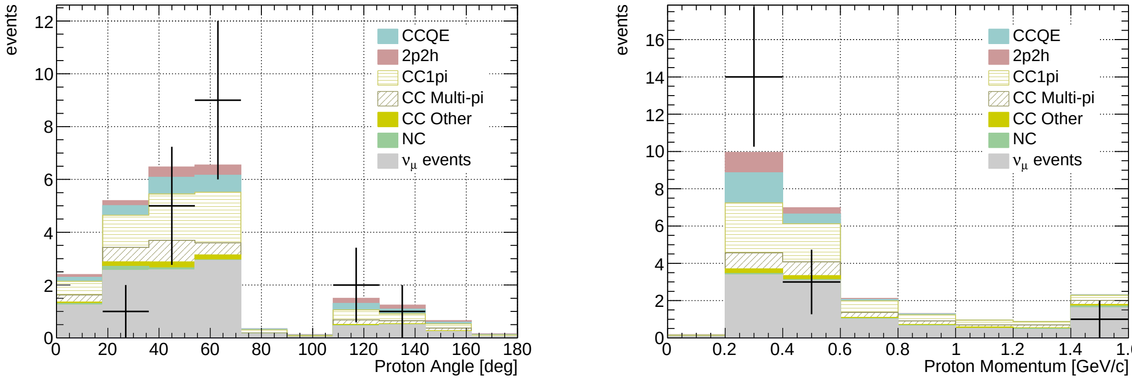

Figure 4. Proton angle (left) and momentum (right).

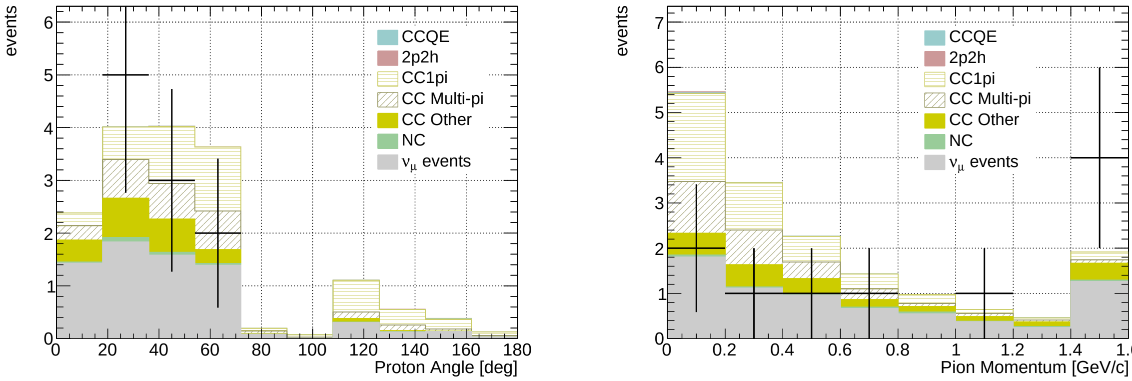

Figure 5. Pion angle (left) and momentum (right).

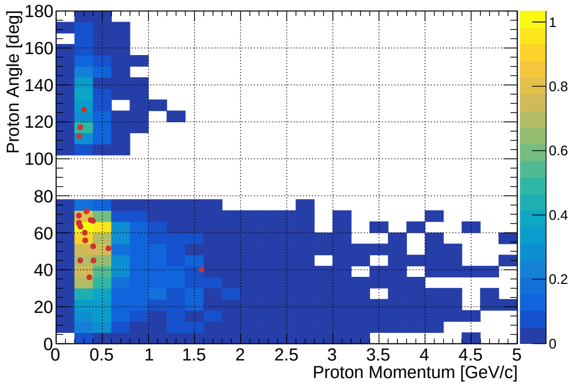

Figure 6. Proton angle-momentum distribution.

References

[1] R. Acciarri *et al,* Phys. Rev. D 90, 012008 (2014)
[2] T. Fukuda *et al.*, Prog. Theor. Exp. Phys. 063C02 (2017)
[3] K. Yamada *et al.*, Prog. Theor. Exp. Phys. 063H02 (2017)