Study of neutrino charged current interactions on iron in the NINJA experiment

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Abstract. Emulsion Cloud Chamber with 65kg iron target was exposed to the neutrino beam at J-PARC neutrino beam line in 2016. It is capable of detecting short proton tracks down to 200 MeV/c. Data presented in this document corresponds to $0.40 \times 10^{20}$ POT. The 194 neutrino-iron charged current interactions were successfully reconstructed in the target. Numbers of protons and charged pions in the final state of each event were measured and compared with those of a Monte Carlo simulation.

1. Introduction
Overall view of neutrino-nucleus interactions around 1 GeV is not clear due to final state interactions. In this energy region, when the protons emitted from vertex could not be detected or the charged pions re-scattered, absorbed and caused charge exchange in nucleus, it is difficult to select an interaction mode for each event. We introduce an emulsion-based detector, Emulsion Cloud Chamber (ECC), which has sub-micron resolution with wide angle acceptance as a neutrino detector. We can measure charged hadron final states with low energy threshold. In this document, the numbers of protons and charged pions in the final state of each event were measured and compared with those of a Monte Carlo simulation. These measurements are useful for the understanding of neutrino-nucleus interactions.

2. NINJA experiment
The Neutrino Interaction research with Nuclear emulsion and J-PARC Accelerator (NINJA) experiment studies neutrino-nucleus interactions in the energy range of hundreds of MeV to a few GeV by using an emulsion-based detector. Since 2014, we have carried out test experiments to evaluate our detector performance so far. In this document, we report results of the NINJA iron target run in 2016.

3. Detector
An detector structure of NINJA iron target run in 2016 is shown in Fig. 1. The detector consists of ECC(Emulsion Cloud Chamber)[1], shifter(emulsion multi-stage shifter)[2] and INGRID(Interactive Neutrino GRID)[3] from the upstream side of the neutrino beam. ECC is a tracking detector and is made of emulsion films interleaved with iron plates(SUS304). ECC can detect the charged particles from neutrino interactoin with sub-micron position resolution.
and low energy detection threshold. We can measure not only track angle and position but also Volume Pulse Height (VPH) and momentum with nuclear emulsion film. VPH is a measure of dE/dx. VPH is the sum of the number of pixels associated with each recognized track in all sixteen layers of CMOS censer images. We can measure momentum by using the range - energy relation for a short track or measurement of Multiple Coulomb Scattering by the coordinate method [6] or the angular method[7]. Shifter gives timing information to each track of ECC. After time stamping, ECC tracks and INGRID tracks are matched using timing information. We use INGRID, which is a near detector for the T2K experiment, as a muon range detector. We can select neutrino - iron CC interactions by INGRID.

Figure 1. Detector structure and muon ID scheme of the NINJA iron target run in 2016.

Figure 2. Image of a neutrino interaction in an emulsion layer taken by a microscope system, FTS[4, 5]. The Black tracks are due to heavily ionizing particles emitted from the vertex.

4. Particle ID
Neutrino induced muons are selected by matching between ECC and INGRID. In regard to charged hadrons, we can separate proton or charged pion for those tracks by likelihood using VPH and momentum. Likelihood function $L$ is defined as

$$L = \frac{1}{\sqrt{2\pi}\sigma_{p^\beta,angle}} \exp\left[-\frac{(VPH - \mu_{p^\beta,angle})^2}{2\sigma_{p^\beta,angle}^2}\right], \quad (1)$$

where $\mu_{p^\beta,angle}$ and $\sigma_{p^\beta,angle}$ are mean and sigma of VPH gaussian fitting. Likelihood ratio $LR$ is defined as

$$LR = \frac{L_{\text{mip like}}}{L_{\text{mip like}} + L_{\text{proton like}}}, \quad (2)$$

where $L_{\text{mip like}}$ and $L_{\text{proton like}}$ are likelihood functions of minimum ionizing particle and proton. Fig.3 shows a evaluation of likelihood ratio by the Monte Carlo simulation. Fig. 4 shows a correlation of VPH and momentum. Protons and charged pions are well separated at VPH of 150 in p$^\beta$ less than 0.6 GeV/c.

5. Event selection
Data were taken from the exposure of iron target ECC to the neutrino and the anti neutrino beam corresponding to integrated POT $0.40 \times 10^{20}$ and $3.53 \times 10^{20}$, respectively. In this document, we only analyze events in the neutrino beam mode. Neutrino charged current interaction candidates
are selected with the following procedure. First, CC induced muon candidates were selected by INGRID. By tracing back to a vertex in ECC from INGRID via shifter, CC interaction candidates were selected. We get the 47,901 muon ID tracks. Of that muon ID tracks, 1,318 tracks are neutrino or anti-neutrino CC candidates and the other tracks are charged particles tracks from neutrino interaction at the detector hall, or fiducial volume out tracks of ECC. Finally, we obtain 194 neutrino-iron CC events of neutrino beam mode.

6. Results
We measure number of protons and charged pions emitted from each neutrino interaction event and compare the measurement data and the Monte Carlo simulation data based on NEUT\[8, 9\] version 5.4.0. The number of MC events are normalized by POT and target mass. In detector response, we use true value for angle and smeared value for momentum. Detection angle region of each $\tan\theta_x$ and $\tan\theta_y$ are less than 1.7 and the number of emulsion layers more than 2 layers. That corresponds to momentum threshold about 200 MeV/c for proton and about 50 MeV/c for charged pion. PID of proton and charged pion are performed using likelihood ratio which is defined in Sec.4. Fig. 5-(a) shows the number of protons and fig. 5-(b) shows the number of charged pions from neutrino charged current interactions on iron. In the number of protons distribution, for 0 proton, the number of events in data are larger than that in NEUT, on the other hand, for 1 proton, the number of events in data are smaller than that in NEUT. Similar tendency was observed in a previous measurement of T2K[10]. Tab.1 shows correlation of number of protons and charged pions emitted from each neutrino interaction event. This measurement used emulsion’s sub-micron spatial resolution is one of the advantage over other detectors.

7. Summary
Study of neutrino-nucleus interactions in sub-multi GeV energy region is very important for current and future neutrino oscillation experiments. A 65kg iron ECC target was exposed to the neutrino beam with a mean energy of 1.5 GeV at J-PARC in 2016. From this exposure of $0.40\times10^{20}$ POT, neutrino-iron CC interactions of 194 were located in the target. We can detect charged hadrons in the final state with low momentum thresholds, 200 MeV/c for protons and 50 MeV/c for charged pions. We compare the measurement of number of protons and charged pions and those of the Monte Carlo simulation.
Figure 5. Measurements of number of protons and charged pions.

Table 1. Correlation of number of protons and charged pions emitted from each event. The column represents the number of protons and the row represents the number of charged pions. The number outside the parentheses is the number of measured events, and the number inside the parentheses is the number of simulated events. The elements of the matrix means the number of events of CCNπN' events.

|        | 0 p  | 1 p  | 2 p  | 3 p  | ≥ 4 p | Total |
|--------|------|------|------|------|-------|-------|
| 0 π    | 64(50.0) | 45(66.6) | 18(21.7) | 7(8.1) | 2(2.9) | 136(149.3) |
| 1 π    | 20(21.0) | 14(16.3) | 0(4.5) | 4(1.7) | 2(1.0) | 40(44.5) |
| 2 π    | 3(2.9) | 4(3.1) | 1(1.0) | 1(0.5) | 2(0.3) | 11(7.8) |
| 3 π    | 2(0.9) | 1(0.6) | 0(0.2) | 2(0.1) | 1(0.1) | 6(1.9) |
| ≥ 4 π  | 0(0.2) | 1(0.2) | 0(0.1) | 0(0.0) | 0(0.1) | 1(0.6) |
| Total  | 89(75.0) | 65(86.8) | 19(27.5) | 14(10.4) | 7(4.4) | 194(204.1) |

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