Proposal for precise measurement of neutrino-water cross-section in NINJA physics run

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The NINJA Collaboration

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Abstract

We propose a neutrino experiment which aims at measuring neutrino-water cross-sections with nuclear emulsion based detector at J-PARC neutrino beamline. Precise measurement of neutrino-water interactions is important to reduce systematic uncertainties in current and future neutrino oscillation experiments which search for

the CP violation in the lepton sector and decide the neutrino mass hierarchy. We have demonstrated the detector performance through several test experiments (J-PARC T60/T66/T68) from 3 years ago. On the basis of these previous experiences, this document presents the details of the experimental plan using a large scale water target emulsion detector to measure the neutrino-water cross-sections with accuracy of 10 %.

1. Introduction

1.1 Motivation

Current and future neutrino oscillation experiments have been in progress or planed to find the CP violating phase in the PMNS matrix or decide the neutrino mass hierarchy [1-9]. The T2K (Tokai-to-Kamioka) experiment, one of long-baseline neutrino oscillation experiments, discovered $\nu_\mu \rightarrow \nu_e$ oscillations with appearance mode in 2013 [10]. This fact opened the possibility of observing CP violation in the lepton sector. Recently T2K reported to exclude CP-conservation in neutrino sector at 2σ [11]. Currently J-PARC MR is also upgrading the proton beam power to more than 1 MW in order to observe CP violation at 3σ level [12]. Furthermore extra large size of water cherenkov detector, Hyper-Kamiokande was proposed to achieve 5σ discovery of CP violation [2]. Toward these goals, it is essential to reduce systematic uncertainties in order to discover such rare effect. Currently the systematic uncertainty of the neutrino oscillation analysis in T2K is estimated to be approximately 5 % as shown in Table 1. It is the most significant factor in total systematic uncertainty. For future neutrino oscillation analysis, the systematic uncertainty has to be reduced to less than 3 %. This is achieved by measuring the neutrino-nucleus cross-sections exclusively with accuracy of 10 %.

Table 1: Systematic errors in the T2K experiment [12]

Error type	ν_μ	$\overline{\nu}_\mu$	ν_e	$\overline{\nu}_e$
SK Detector	3.9	3.3	2.5	3.1
SK Final State & Secondary Interaction	1.5	2.1	2.5	2.5
ND280 Constrained Flux & Cross-section	2.8	3.3	3.0	3.3
$\sigma\nu_e/\sigma\nu_\mu, \sigma\overline{\nu}_e/\sigma\overline{\nu}_\mu$	0.0	0.0	2.6	1.5
NC 1γ Cross-section	0.0	0.0	1.5	3.0
NC Other Cross-section	0.8	0.8	0.2	0.3
Total Systematics Error	5.1	5.2	5.5	6.8

※ SK: Super Kamiokande; T2K far detector, ND280: T2K near detector

The main neutrino interaction process is Charged-Current Quasi-Elastic (CCQE: $\nu + n \rightarrow \mu^- + p$: Fig.1-left) interactions in sub-GeV energy region at J-PARC neutrino beamline. The CCQE process is two-body current and the energy of incident neutrinos is measured easily. Therefore CCQE process is used as main signal mode for the neutrino oscillation analysis in T2K because the oscillation function depends on neutrino energy. However our understanding of neutrino-nucleus interactions in this energy region is not enough for the future projects. For example, the presence of multi-nucleon correlation process, known as two-particle-two-hole (2p2h) [13,14], is suggested from disagreement between previous measurements and theoretical prediction. In 2p2h process, two protons are emitted besides muon as shown in Fig.1-right. But this process is not distinguished from CCQE process in final state because slow protons from the interactions are not able to detect with current T2K detectors. As a result, the energy of incident neutrinos in 2p2h process is miscalculated in the case of assuming two-body current (CCQE) as shown in Fig.2. There is no clearly experimental evidence of 2p2h process in the neutrino interactions [15] up to now. So it's important to study the neutrino interactions with low energy threshold detector. Additionally it's also important to measure exclusive hadronic final states of neutrino-nucleus interactions in not only muon-neutrinos but also electron-neutrinos to reduce systematic uncertainties in future neutrino oscillation analysis. Furthermore, one possible explanation of LSND and MiniBooNE anomaly [16,17] is a result of existence of so-called sterile neutrino. The MiniBooNE anomaly was observed as an excess of the ν_e events in sub-GeV region. So the precise ν_e measurement will give an useful information to the interpretation of such phenomena.

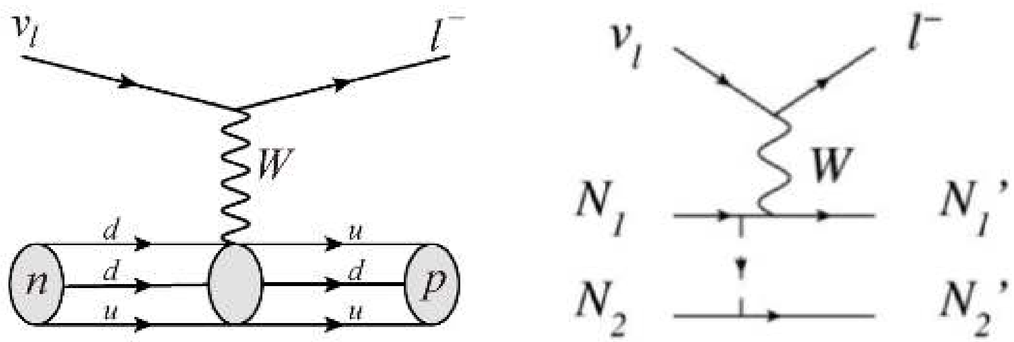

Figure 1: Diagram of neutrino-nucleus interactions in CCQE (left) and 2p2h (right)

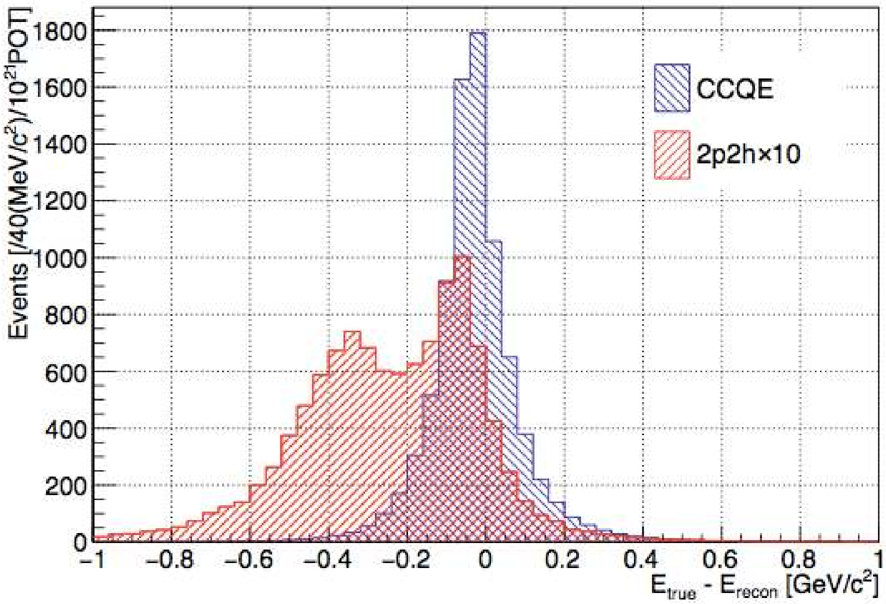

Figure 2: Neutrino energy reconstructed assuming CCQE mode

1.2 The NINJA Experiment

NINJA means "**N**eutrino **I**nteraction research with **N**uclear emulsion and **J**-PARC **A**ccelerator". The NINJA Collaboration proposes a new neutrino experiment to study neutrino-nucleus interactions with nuclear emulsion as a main detector at J-PARC in this document. We have demonstrated the detector performance through several test experiments (J-PARC T60/T66/T68) from 3 years ago. The experimental plan is based on the previous experiences.

Nuclear emulsion is a three-dimensional solid tracking detector with sub-micron resolution. The emulsion technique has played an important role in fundamental particle physics relating to short life-time particle, such as the observation of $\pi \rightarrow \mu$ decay [18], discovery of charmed particle in cosmic-ray [19], first observation of ν_τ [20], discovery of $\nu_\mu \rightarrow \nu_\tau$ appearance [21] and so on. Thanks to its high spatial resolution, emulsions can measure hadronic final states with low energy threshold in neutrino-nucleus interactions. For example, slow protons (~20 MeV) from primary interaction can be detected with wide angle acceptance (< 3.4 π) through offline scanning [22][23]. Fig.3 shows the comparison of proton detection capability from CCQE and 2p2h process in the emulsion detector and the current T2K near detector.

Additionally emulsion can also measure ν_e CC interactions with low background from ν_μ NC (Neutral Current) interactions with π^0 production by separating one electron from ν_e CC from electron-positron pair from π^0 with sub-micron position accuracy. Furthermore the detector using nuclear emulsion films has a lot of flexibility for target material selection since the detector, so-called Emulsion Cloud Chamber (ECC), is constructed as a sandwich structure of thin films and the target material, not only carbon or iron plates but also water. Since far detector of T2K (SK) is water cherenkov detector, the contributions from nuclear effect in the neutrino-nucleus cross-section measurement can be avoided by choosing same material as far detector (water) to target material. In summary, nuclear emulsion is one of ideal detectors for investigating neutrino-nucleus interactions.

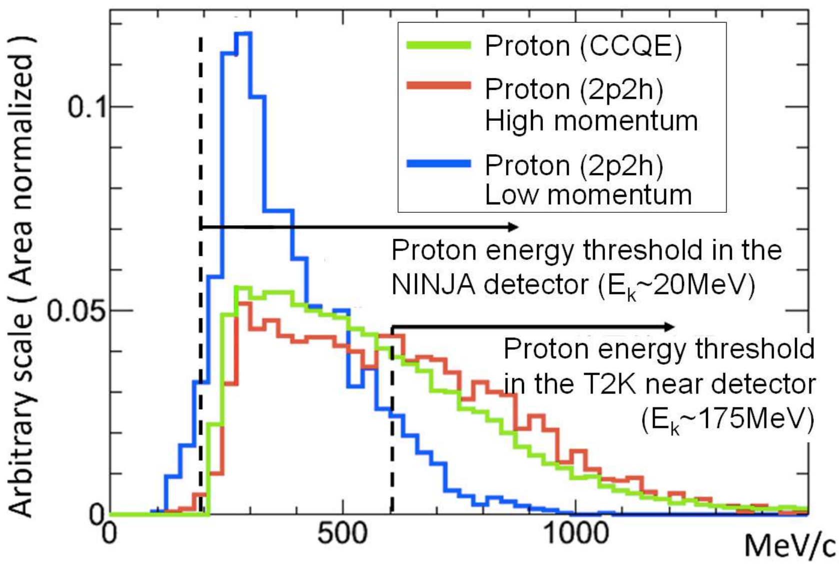

Figure 3: Proton detection capability from CCQE and 2p2h in the emulsion detector and the current T2K near detector.

2. Experimental method

2.1 J-PARC neutrino beam

High-intensity 30 GeV protons from the J-PARC accelerator are exposed to a graphite target every ~2.5 seconds and produce charged pions and kaons. These hadrons are focused to the forward direction by three horn magnets and decay in the 96 m long decay volume. Neutrinos (anti-neutrinos) are produced from decays of positively (negatively) charged pions. Horn magnets select charged sign of pions by reversing the current direction. Fig.4 –left shows the energy distribution of neutrino beam at on-axis and each off-axis angles. Thanks to its high intensity of neutrino beam (anti-neutrino beam), we have implemented to study feasibility and check the detector performance sufficiently with small size of emulsion detector so far.

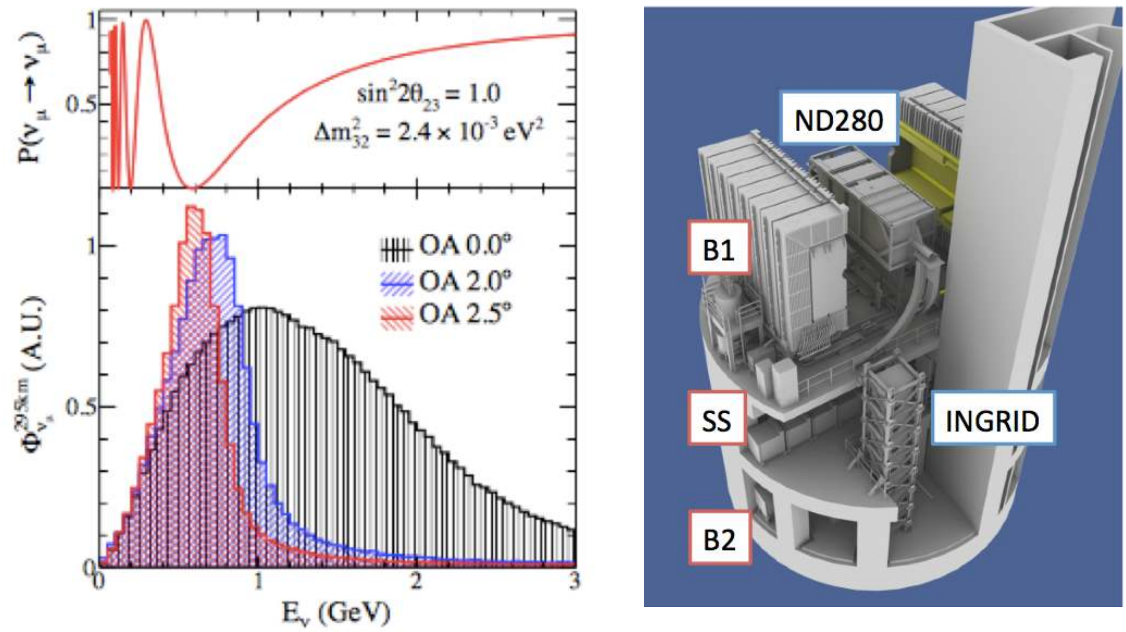

Figure 4: (left-bottom) shows the energy spectrum of neutrino beam at on-axis and each off-axis angles. (left-top) shows the energy dependence of neutrino oscillation probability. On-axis angle and off-axis angle (2.5° from On-axis) is corresponding to the central position at SS-floor and ND280 which is one of the T2K near detectors at B1 floor in (right) view, respectively. The direction to SK is off-axis angle (2.5° from On-axis). The energy spectrum in B2 floor is similar to one in B1 floor.

2.2 Conceptual design for the detectors

The ECC technique has a proton identification capability from high energy charged particles using dE/dx, momentum measurement [24]. However π/μ separation at more than sub-GeV in ECC is difficult, except in the very huge emulsion detector as the OPERA detector [25]. So we have used one of the T2K near detector, INGRID [26] as shown in Fig.4 (right) to identify the muon tracks in the NINJA experiment. Additionally precise tracking detectors with timing information have been applied to connect tracks between ECC and INGRID as given in a later section. Fig. 5 shows the schematic view of the detector setup.

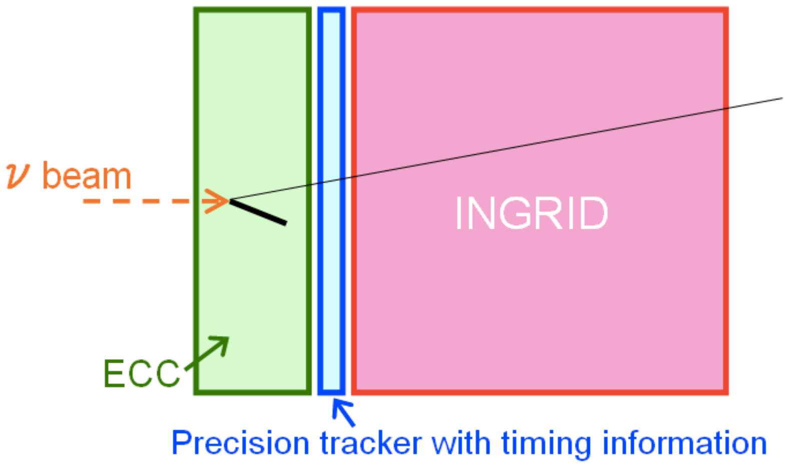

Figure 5: Detector concept

2.3 Status of the NINJA experiment

We have performed J-PARC T60, T66, T68 experiment. Table 2 shows the exposure history in the NINJA experiment. We successfully confirmed the following points through the test experiments.

- Confirmation of the long-term stability of the newly developed emulsion films
- Establishment of the emulsion handling and operating method at the T2K near detector hall
- First detection of neutrino events with nuclear emulsion detector at J-PARC neutrino beamline [27]
- Evaluation of hybrid analysis between ECC and INGRID with the emulsion shifter to identify the muons from neutrino interactions in the ECC with INGRID [28]
- Performance check of the water target ECC and observation of neutrino-water interactions with the emulsion detector [29]

- Building and operating of Scintillating Fiber Tracker (SFT) [30] and evaluating of hybrid analysis between ECC and INGRID with SFT (ongoing)

Table 2: Exposure history

	Period	POT (main mode)	Detector	Site
1	Oct.2014－Dec.2014	1.3×10^{20} (anti-neutrino)	2kg iron target ECC Emulsion shifter INGRID	SS floor at NM
2	Jan.2015－Apr.2015	1.4×10^{20} (anti-neutrino)	2kg iron target ECC Emulsion shifter INGRID	SS floor at NM
3	May 2015－Jun.2015	0.8×10^{20} (anti-neutrino)	1.5kg water target ECC	SS floor at NM
4	Jan.2016－May 2016	4.0×10^{20} (anti-neutrino)	60kg iron target ECC Large emulsion shifter INGRID	SS floor at NM
5	Dec.2016－Apr.2017	5.9×10^{20} (neutrino)	1.5kg water target ECC	SS floor at NM
6	Oct.2017－Dec.2017 (ongoing)	*** $\times 10^{20}$ (anti-neutrino)	4kg water target ECC SFT INGRID	SS floor at NM

2.3.1 Overview of the installed detectors

Fig.6, 7, 8 and 9 shows the detector setups so far. Nuclear emulsion gel was produced at the facility of Nagoya University. High-sensitive emulsion gels, containing 55 % or 45 % AgBr crystal by volume ratio was produced in this time. Two emulsion layers, each 50-70 μm-thick, were formed on both faces of a 180 μm-thick polystyrene plate. Newly developed emulsion gels were investigated the sensitivity and the noise accumulating for a half of year and were confirmed to be kept at safety level for the physics analysis.

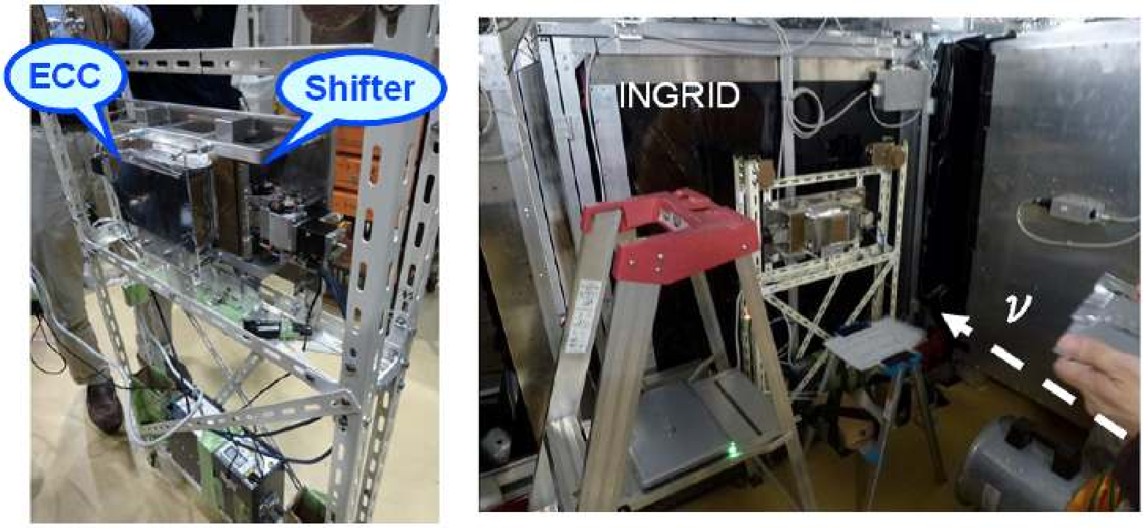

Figure 6: 2kg iron target ECC + Emulsion shifter +INGRID

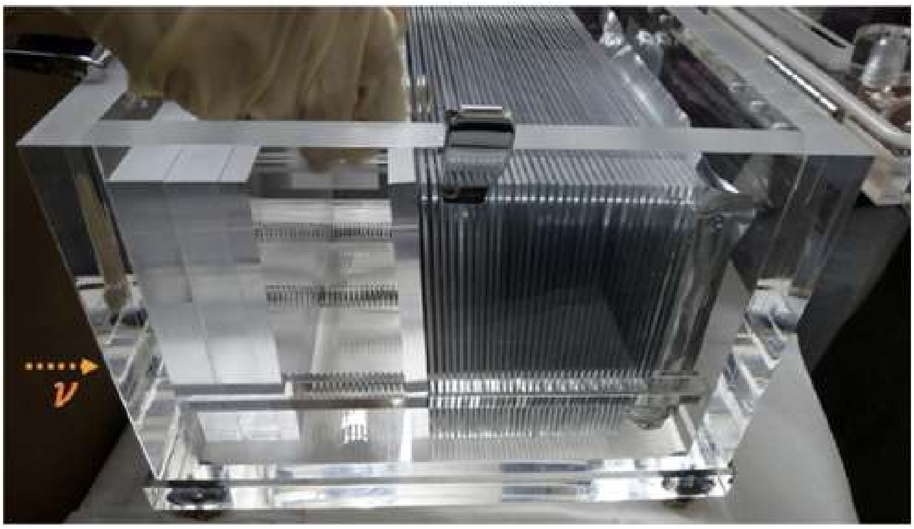

Figure 7: 1.5kg water target ECC

Figure 8: 60kg iron target ECC + Large emulsion shifter + INGRID

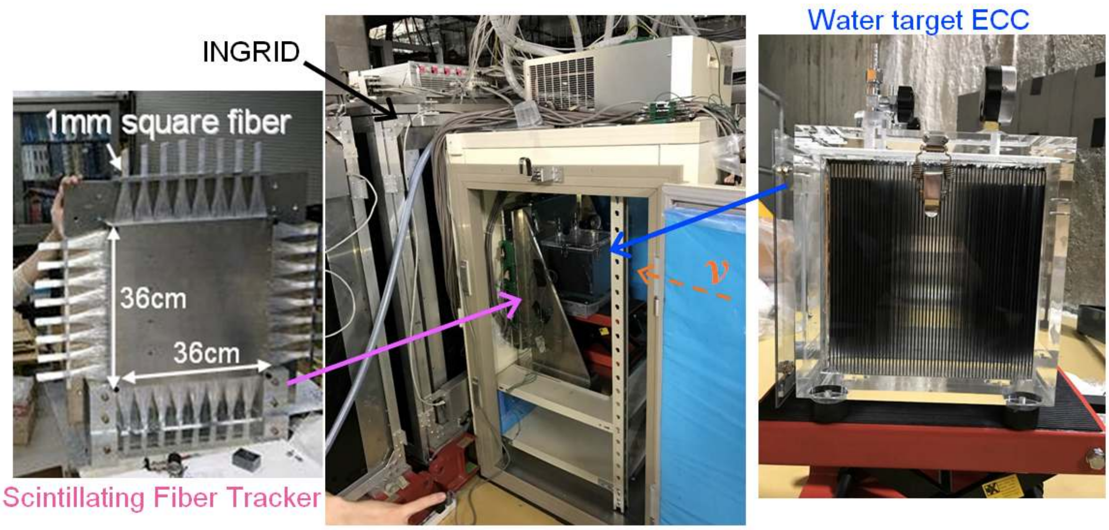

Figure 9: 4kg water target ECC + SFT + INGRID

2.3.2 Establishment of the analysis procedure with the iron target ECC

The iron target ECC consisted of the emulsion films and 500 μm-thick iron plates. After beam exposure, all of emulsion films were developed in a dark room prepared at Nihon University as shown in Fig. 10. Then the emulsion films were scanned by the high-speed automatic emulsion scanning system, HTS [31] at Nagoya University (Fig. 11). Then the tracks were reconstructed and neutrino event vertex was searched. Fig 12 shows detected neutrino events in one of analysis area in the ECC. The proton tracks were also identified with dE/dx and momentum or range measurement in the ECC as shown in Fig. 13.

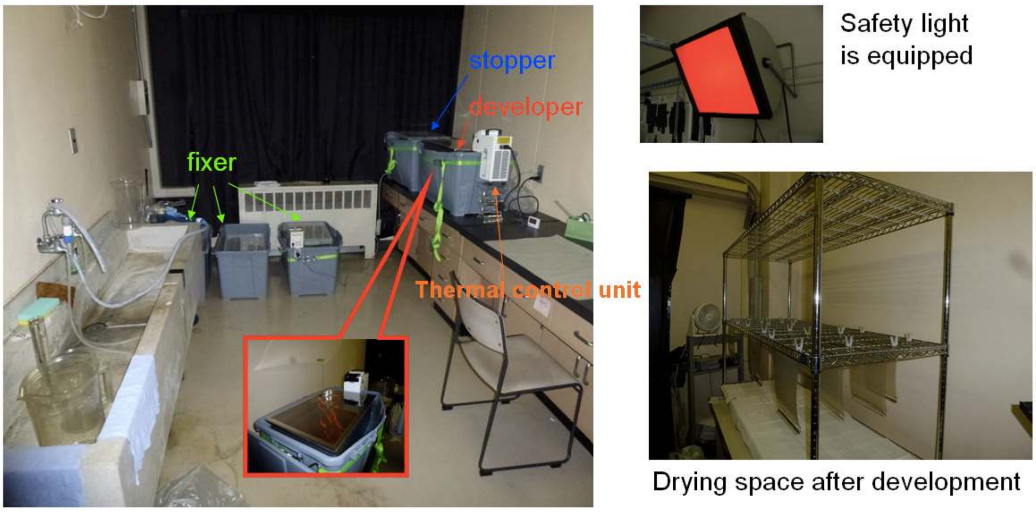

Figure 10: Developing room in Nihon University

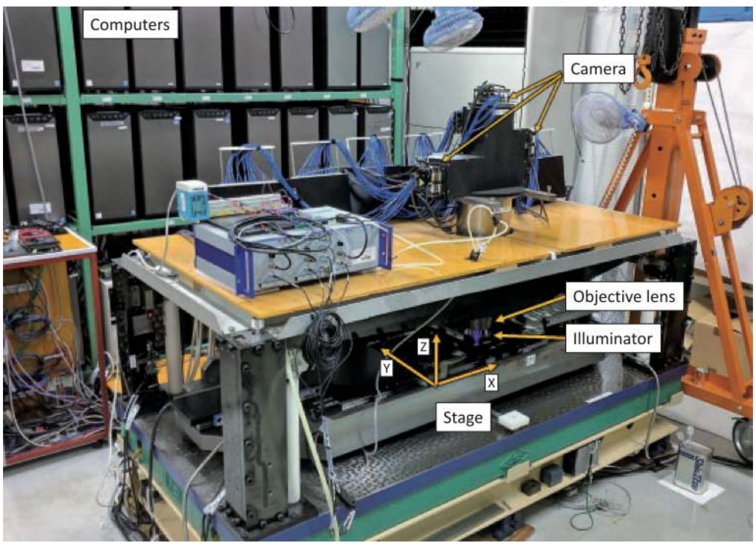

Figure 11: HTS in Nagoya University

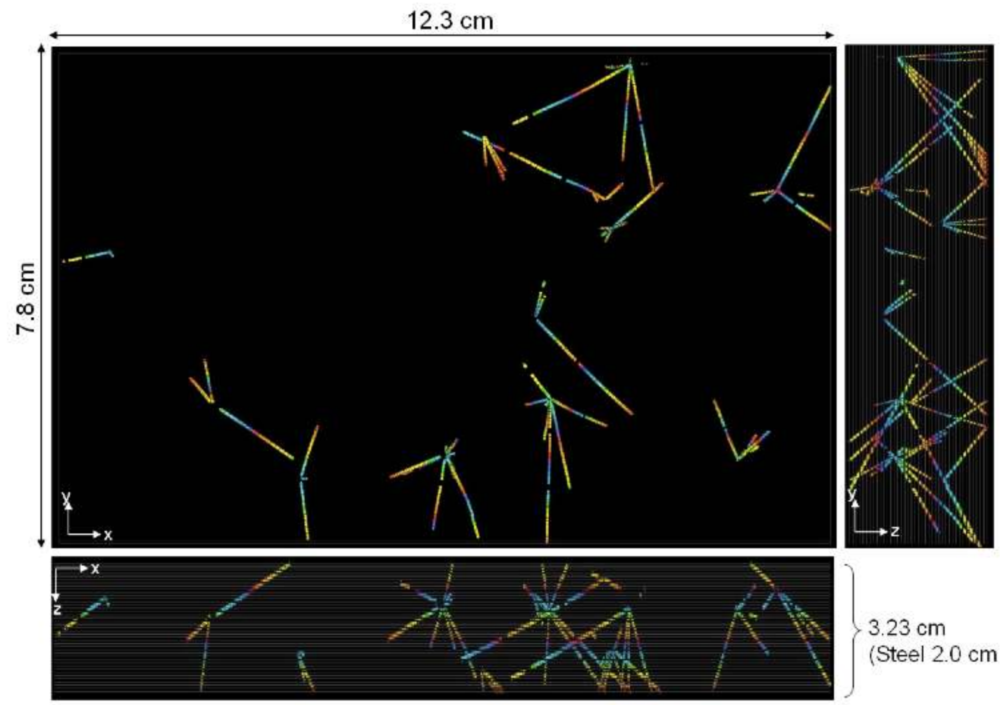

Figure 12: Detected neutrino candidate events in the iron target ECC

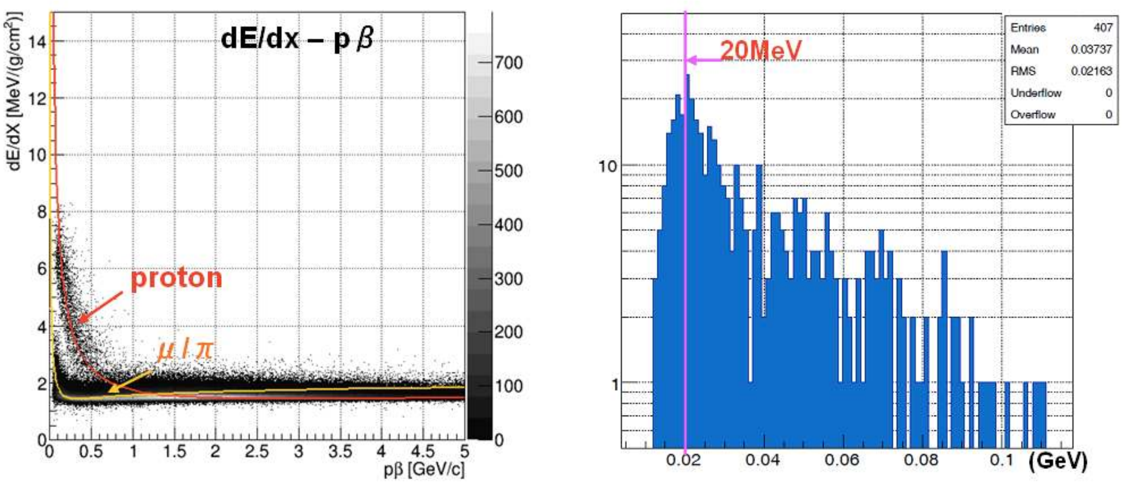

Figure 13: Proton identification by dE/dx-momentum (left) and range (right) measurement in the ECC

2.3.3 R & D for the water target ECC

The water target ECC has a sandwich structure of vacuum packed emulsion films and 2.0-mm-thick frame type acrylic spacers to fill water in the space as shown in Fig.14. In the package, there are two emulsion films and a support plate between these two films. We tested 250 μm, 500 μm-thick iron plates and 300 μm, 400 μm, 2 mm-thick acrylic plates for the support plate so far. As a result, 500 μm-thick iron plates is adopted as a support plate in latest water target ECC since the standard deviation of the distance between the films across the water was suppressed most effectively (below a few tens of μm). Fig.15 shows some neutrino-water interactions detected in the ECC.

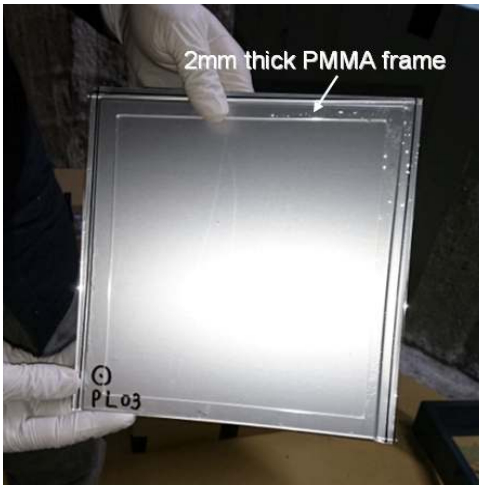

Figure 14: A vacuum packed film and a frame type spacer in the water target ECC

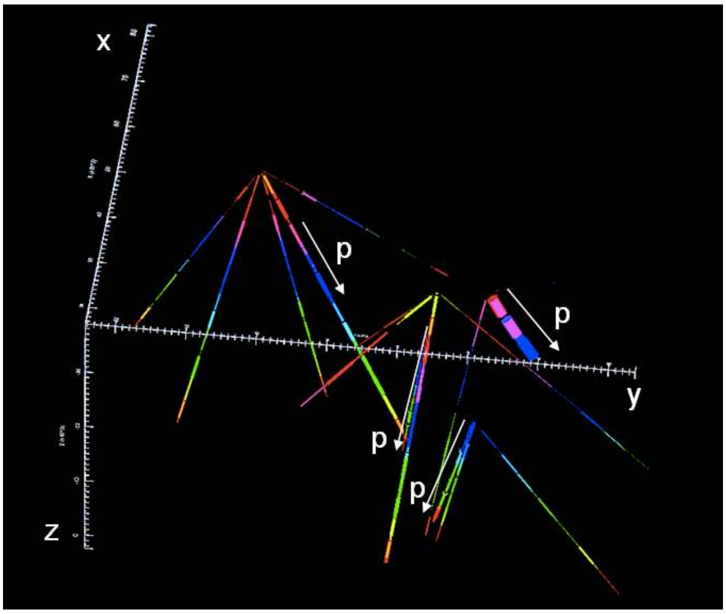

Figure 15: Neutrino-water interactions detected in the water target ECC.

2.3.4 R & D for muon identification

As noted in previous section, we used the INGRID for μ identification. The INGRID is one of the T2K near detectors. The tracking device of INGRID is a 1 cm-thick plastic scintillator (5 cm width) read out with wave length-shifting fibers. The constitution of the detector is a sandwich structure of the tracking planes and 6.5 cm-thick iron blocks. The detector assembled from a total of nine iron layers (58.5 cm) and 11 vertical and horizontal tracking planes.

It's difficult to connect the ECC tracks with INGRID tracks directly because the ECC intrinsically has no timing resolution and the position resolution of the INGRID is not fine enough to connect uniquely. Therefore it is necessary that a precise tracker with timing information is installed to connect between the ECC and the INGRID. We have demonstrated the hybrid analysis between the iron target ECC and the INGRID with the existing emulsion shifters which have been used for balloon experiment. The details for this device are written in [28]. Fig. 16 shows an example of neutrino events identified muon tracks. Furthermore we have developed a new type of scintillating fiber tracker (SFT) for latest exposure using water target ECC as shown in Fig.9. The details for this equipment are described in [30,32]. Currently data taking and the SFT-INGRID matching is going well. Fig.17 shows a part of matched events. The ECC-SFT matching will be started on next January after film development.

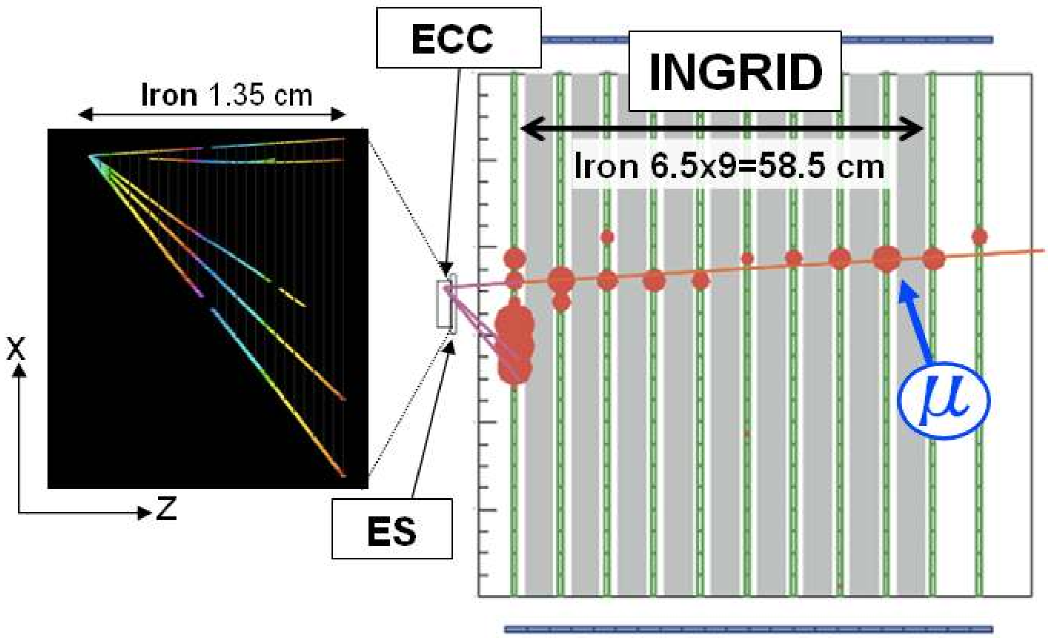

Figure 16: An example of hybrid analysis with the emulsion shifter. The event topology is well matched between the ECC and the INGRID.

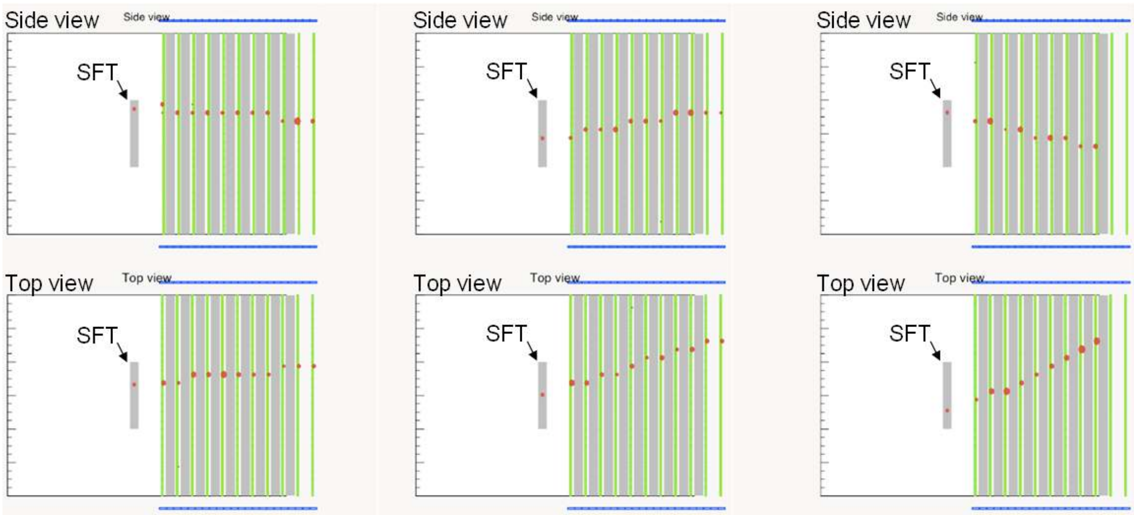

Figure 17: A part of matched events between the SFT and the INGRID

2.4 Physics Run

We have demonstrated the basic performance and analysis of each component in the emulsion based experiment at J-PARC through previous test experiments as explained above. In this section, we propose a new experiment (NINJA—Physics Run) to study neutrino-water interactions precisely and create physics outputs as mentioned in the Sec. 1.1 based on the experiences so far.

2.4.1 Aim

The aim of NINJA – Physics Run is to measure the neutrino-water cross-section for CCQE, CC1π and 2p2h reaction mode in neutrino interactions with accuracy of 10 %. That deepens our understanding for neutrino-nucleus interactions. Fig. 18 shows the expected number of neutrino-water interactions for each reaction mode at 1.0° off axis (a candidate site as described below) in 1 × 10^{21} POT (Protons On Target). The neutrino cross-section of 2p2h mode has a large ambiguity (approximately 10-30 % of CCQE). Additionally the number of 2p2h mode is fewer than the number of CCQE and CC1π mode. To achieve the goals, we request 1 × 10^{21} POT in neutrino mode. In this case, we will detect more than one hundred 2p2h events with 200 kg water target (assuming 10 % detected efficiency estimated conservatively), even if in worst case. Then we can also analyze the electron neutrino events and will achieve to measure the ν_e CCQE, CC1π cross-sections.

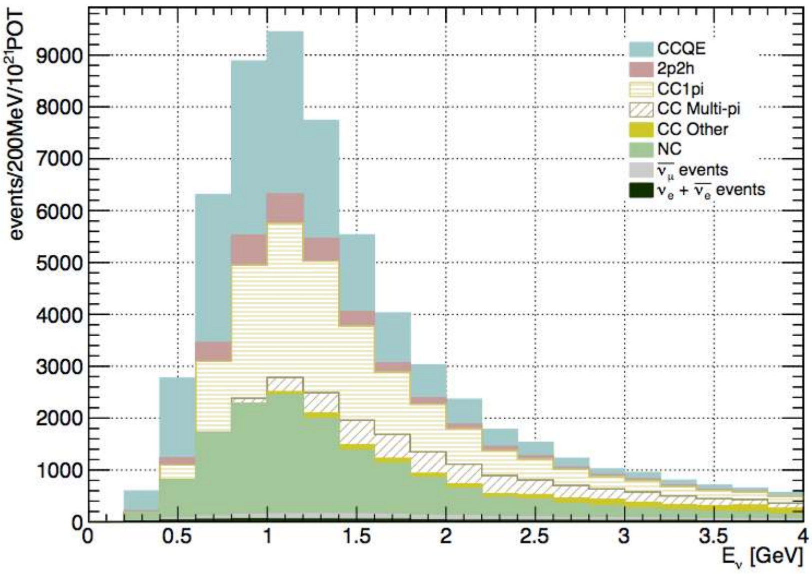

Figure 18: Expected number of neutrino events with 200 kg water target at 1.0° off-axis in 1 × 10^{21} POT.

2.4.2 Experimental site and beam request

The experimental site is B2 floor in Neutrino Monitor building (NM) at J-PARC. Fig. 19 shows the candidate site in B2 floor (1.0° off-axis) to install our detectors. This experiment can run parasitically with T2K, therefore we request no dedicated beam time nor beam condition.

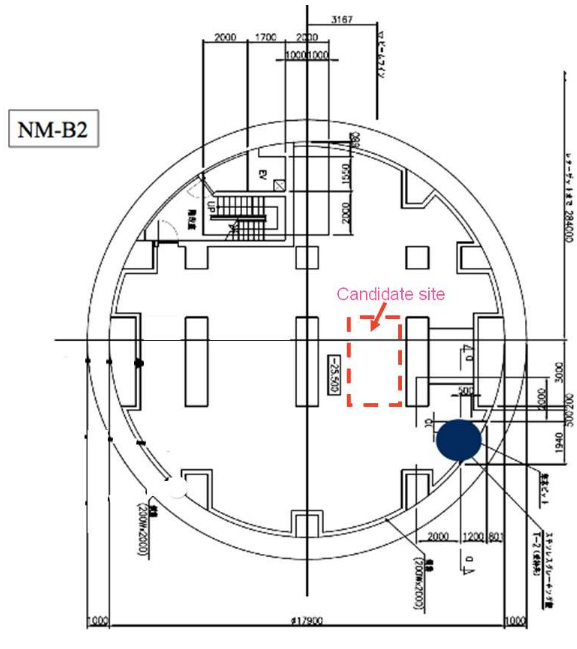

Figure 19: Candidate site for NINJA Physics Run at B2 floor

2.4.3 Detector

The main detector is a 200 kg large scale of water target ECC. The detector unit is same type of water target ECC which has been used in current beam exposure. In this run, we use 48 units (4 × 4 × 3 walls) for the detector as shown in Fig.20. Additionally an INGRID is used to identify muon from the neutrino interactions in the ECCs. So we will develop a large scale SFT to use as the precise tracker with timing information for connection between the ECCs and the INGRID.

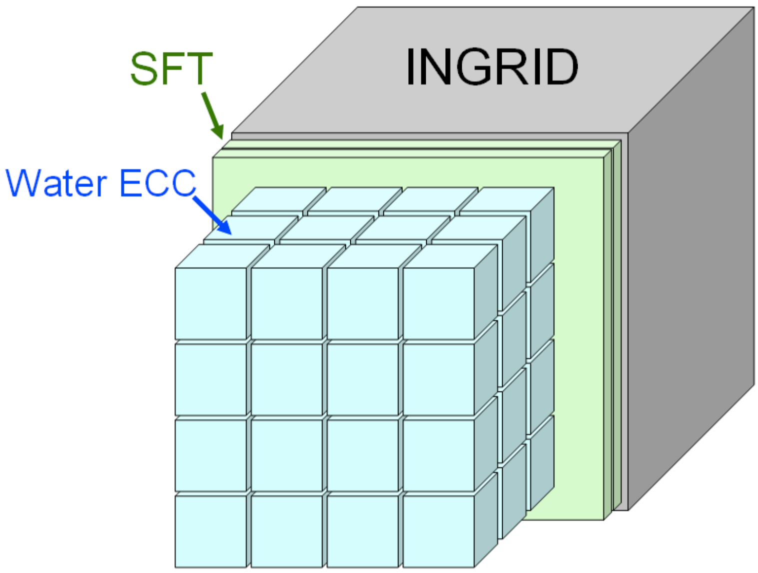

Figure 20: Large scale water target ECC, SFT and INGRID.

2.4.4 Future advanced upgrade

In NM, many neutrino detectors were installed or planned to install in near future. We have possibility to build a hybrid detector with other detectors, e.g. BabyMIND [33] or WAGASCI [34] (B2), or ND280 [35-39] (B1) in the future. Since water target ECC can be surrounded by these detectors in the case of making hybrid detector with these detectors, the identification efficiency of muon which is emitted at large angle is expected to improve. Additionally, charged sign information is obtained with the magnetized detector as BabyMIND or ND280. In the case of hybrid with ND280, the information of gamma (π^0) from neutrino interactions can be also obtained. These possibilities are currently under discussion with related people. Although we plan to realize such advanced upgrades in 2020, that is not include in this proposal.

3. Schedule and cost estimation

3.1 Schedule

In 2018,

- Apr.－Sep.: production of emulsion films at Nagoya University
- Apr.－Sep.: development of large scale SFT
- Aug.－Nov.: noise track reduction of emulsion film and assembling of water target ECC at J-PARC
- Sep.－Dec.: commissioning of SFT

In 2019,

- Jan.－May: neutrino beam exposure (1×10^{21} POT. tentative plan because beam exposure schedule is not fixed yet) and data taking of SFT.
- Jun.－Jul.: development of emulsion films at Nihon University
- Aug.－Dec.: scanning and track data reconstruction of emulsion films at Nagoya University
- Sep.－Dec.: pilot analysis

In 2020,

- Jan.－Jul.: physics analysis

The described schedule is a tentative one because it depends on the plan of neutrino beam exposure and the budget approval that we requested in this year.

3.2 Cost estimation

Table.3 shows roughly estimated cost for the detectors. We will try to suppress total cost by optimizing the detector structure.

Table.3: Estimated cost

Item		Cost [kJY]
Water target ECC :	Emulsion film	30,000
	Iron plate	4,500
	Container	2,100
	Chemicals for development	5,000
SFT system :	Fiber	3,600
	MPPC	4,000
	Electronics	2,300

4. Summary

We (NINJA Collaboration) proposed a new neutrino experiment with nuclear emulsion as a main detector to measure the neutrino-water cross-sections exclusively with accuracy of 10 % in this document. The detector consists of water target ECCs, SFT and INGRID. The detector performance of each component has been demonstrated through several test experiments. In this experiment, we request to install the detectors at B2 floor and the neutrino beam exposure at 1×10^{21} POT are also requested. The precise measurement data of neutrino-water cross-section obtained in this experiment will strongly contribute to current and future neutrino oscillation analysis which search for the CP violation in the lepton sector and the decision of the neutrino mass hierarchy.

5. References

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