Proposal of test experiment to measure the atmospheric and T2K beam related background at the ND280 site ground level using nuclear emulsion detector

S. Aoki[1], D. Barčot[2], C. Bronner[3], T. Fukuda[4], Y. Furuta[4], M. Ghosh[2], L. Halić[2], S. Han[5], T. Hayakawa[4], Y. Hayasaka[4], Y. Hayato[6], H. Inamoto[4], M. Jakkapu[2,*], C. Jesus-Yalls[7], A. Kasumi[4], T. Katori[8], T. Kawahara[4], T. Kikawa[5], B. Kliček[2,**], H. Kobayashi[4], R. Komatani[4], M. Komatsu[4], B. Kovač[2], T. Matsuo[4], S. Mikado[9], A. Minamino[3], Y. Morimoto[4], K. Morishima[4], N. Naganawa[4], Y. Nakamura[4], T. Nakano[4], T. Nakaya[5], T. V. Ngoc[5], S. Ogawa[10], H. Oshima[6], N. Otani[5], H. Rokujo[4], O. Sato[4], T. Sato[11], H. Shibuya[12], S. Shimizu[4], K. Sugimura[4], L. Suzui[4], A. Suzuki[1], M. Suzuki[3], S. Takeshita[4], I. Usuda[4], S. Yamamoto[4], and M. Yoshimoto[13]

[1]Kobe University, Kobe 657-8501, Japan
[2]Center of Excellence for Advanced Materials and Sensing Devices, Ruđer Bošković Institute, Zagreb, Croatia
[3]Yokohama National University, Yokohama 240-8501, Japan
[4]Nagoya University, Nagoya 464–8602, Japan
[5]Kyoto University, Kyoto 606-8502, Japan
[6]ICRR, The University of Tokyo, Kashiwa 277-8582, Japan
[7]Kavli IPMU (WPI), The University of Tokyo, Kashiwa 277-8583, Japan
[8]King's College London, London, WC2R 2LS, UK
[9]Nihon University, Narashino 275-8576, Japan
[10]Toho University, Funabashi 274-8510, Japan
[11]RCNP, Osaka University, Osaka 567-0047, Japan
[12]Kanagawa University, Yokohama 221-8686, Japan
[13]RIKEN, Wako 351-0198, Japan
[*]Email: mahesh.jakkapu@irb.hr
[**]Email: budimir.klicek@irb.hr

Abstract

The NINJA experiment is measuring the neutrino interaction cross-section at J-PARC in the T2K neutrino beam using nuclear emulsions. The plan for one of

the future measurement campaigns is to position NINJA at the ground level at J-PARC to achieve a large off-axis angle. In preparation for this, we propose a test experiment to measure background coming from atmospheric muons and gammas, and sky-shine from the T2K beam, using a small emulsion detector placed in the Neutrino Assembly building at J-PARC. For this we plan to have two exposures: one when the T2K beam is OFF and one when the T2K beam is ON. The duration of each exposure is roughly two weeks. This test experiment will have a small footprint and minimal requirements for power and infrastructure. We propose to conduct it immediately before and after the T2K beam commissioning in the fourth quarter of 2025.

1 Introduction

1.1 NINJA experiment

Precise measurements of neutrino-nucleus cross sections are crucial to understand neutrino interactions and oscillations by reducing systematic uncertainties. The NINJA experiment aims to measure these cross sections using a nuclear emulsion detector, which provides high spatial resolution and tracking capabilities. NINJA's detectors have submicrometer positional resolution with a capability to detect low-momentum protons near the neutrino interaction vertex, which provides us with an opportunity to study interaction with multiple nucleons in the final state.

The NINJA experiment [1] has successfully taken data with various configurations of nuclear emulsion detectors in the Neutrino Monitoring (NM) Building of the J-PARC underground site during the J-PARC neutrino beam periods. The data taking periods and detector configurations are summarized in Table 1.

2 Proposal of the test experiment

2.1 Motivation for the test experiment

NINJA utilizes the nuclear emulsion detector with iron plates and water as targets. As part of the latest Letter of Intent [2], NINJA will conduct a measurement at a large off-axis angle at the ground level of the ND280 site. This will be the first NINJA measurement campaign to be conducted at the ground level, as opposed to an underground location, so the background contribution of the atmospheric muons and gammas, together with sky-shine from T2K beam, is expected to play a more significant role. In preparation for such a measurement, it is imperative to measure these backgrounds using the same detector technology as the proposed ground-level NINJA and at the similar location. Therefore, we propose to use an emulsion detector for this measurement, even though it might not be the optimal choice for stand-alone measurements of atmospherics and sky-shine. The detector would be placed in the Neutrino Assembly (NA) building at J-PARC, close to the ND280 site. The data will be used as an input to the design of the ground-level NINJA detector: it will allow us to conclude to which degree these backgrounds have an effect on the emulsion detector placed at the surface level, allowing us to optimize the detector shielding and configuration for maximal neutrino interaction cross-section sensitivity.

Table 1: Emulsion detector exposure history

Period	POT	Detector	Site
Oct. 2014-Dec. 2014	1.3 x 10^{20}	2 kg iron detector, Emulsion shifter, INGRID	SS floor at NM
Jan. 2015-Apr. 2015	1.4 x 10^{20}	2 kg iron detector, Emulsion shifter, INGRID	SS floor at NM
May 2015-Jun. 2015	0.8 x 10^{20}	1.5 kg water target ECC	SS floor at NM
Jan. 2016-May. 2016	4.0 x 10^{20}	60 kg water target ECC, Medium emulsion shifter, INGRID	SS floor at NM
Dec. 2016-Apr. 2017	5.9 x 10^{20}	1.5 kg water target ECC	SS floor at NM
Nov. 2017-May. 2018	7.1 x 10^{20}	3 kg water target ECC, Scintillator fiber tracker, INGRID	SS floor at NM
Nov. 2019-Feb. 2020	4.8 x 10^{20}	75 kg water, 130 kg iron and 15 kg CH target ECC, Large emulsion shifter, Scintillator fiber tracker, Baby MIND	B2 floor at NM
Mar. 2021-Apr. 2021	1.8 x 10^{20}	9 kg heavy water ECC	B2 floor at NM
Nov. 2023-Feb. 2024	2.9 x 10^{20}	75 kg water, 130 kg iron and 15 kg CH target ECC, Large emulsion shifter, Scintillator fiber tracker, Baby MIND	B2 floor at NM

We propose two experimental runs (exposures): one while the T2K beam is OFF, and one while the T2K beam is in nominal operation mode. It is important to avoid exposure during the T2K beam commissioning because of the high variability of the beam during that time and the fact that the emulsion has no timing information; to obtain the best quality data, the beam exposure must be done during the stable and nominal T2K beam operation. On the other hand, it is favourable to have the beam OFF and beam ON measurements as close in time as possible to minimize the effect of seasonal variations, so we propose to have the beam OFF exposure just before the T2K beam commissioning and beam ON exposure immediately when the beam reaches the nominal operation. For these reasons, the timeline of the experiment depends on the T2K beam schedule, and the one presented in this document is tentative and subject to change with regard to T2K schedule.

2.2 Experimental setup

The experimental setup consists of two Emulsion Cloud Chamber (ECC) bricks, one along the beam direction (vertical brick) and the other facing upward (horizontal brick). The emulsion brick for this test experiment consists of nuclear emulsion films interleaved with lead plates (30 lead plates tentatively), similar to the emulsion bricks in the OPERA experiment [3]. The size of such a brick is approximately $10 \times 13 \times 5$ cm^3. The ECC is vacuum-packed to prevent light contamination and to prevent any humidity from entering the detector. In addition, a muon counter made of scintillator bars will be arranged to measure the approximate number of muons passing through our emulsion brick. This muon counter will be used as a cross-check for the emulsion data. The detector setup is shown in Figure 1. The emulsion film consists of a plastic base coated with a thin emulsion layer on both sides. Emulsion layers act as sensitive material to produce micrometer-level tracks of activated AgBr crystals. The lead plates are used as a target for atmospheric gammas and to reconstruct the muon momentum using multiple Coulomb scattering. We expect to record $\sim$ 450000 cosmic muon tracks in each horizontal and $\sim$ 150000 in each vertical emulsion brick. The exact expected number of detected events will be obtained from a full Monte Carlo simulation, which is under preparation. The exposure time for horizontal bricks has been tuned to achieve optimal track density for data analysis, while for vertical we opted for an exposure of 12 days to keep the experiment within a reasonable time limit while still recording a significant number of tracks.

Apart from the cosmics study, we will perform a dedicated data analysis to search for signal of cosmic gamma ray interactions and neutron interactions coming from sky-shine. This will be compared to the Monte Carlo estimate, which we plan to obtain/develop by the end of data analysis. If these turn out to be negligible, this will be good news for the future NINJA surface experiment.

Two sets of the aforementioned detectors are going to be placed orthogonal to each other, one along the J-PARC neutrino beam and the other facing the vertical direction. To maintain the nominal temperature of emulsion films ($\sim$10°C), the emulsion detectors will be placed in a freezer box (410 mm $\times$ 525 mm $\times$ 810 mm) that can maintain the temperature in the range of +4°C to +20°C range.

2.3 Momentum reconstruction

A particle passing through matter undergoes multiple Coulomb scattering, and lead plates are utilized to measure the momentum of the tracks passing through the detector. The momentum of the particle can be reconstructed using the standard deviation of the scattering angles due to multiple Coulomb scattering [4] as shown in Equation 1. Where $\Delta\theta$ is the standard deviation of the scattering angle, z is the charge of the scattered particle, βc is the velocity of the particle, p is the momentum of the particle, x is the thickness of the lead layer, and X_0 is the radiation length of lead. In this case, we assume that lead plates contribute primarily to the multiple Coulomb scattering of muons. The radiation length of the lead is approximately 0.56 cm. The thickness of the lead layer is chosen to be 0.1 cm.

$$\Delta\theta = \frac{13.6\ \text{MeV}}{\beta c p} z \sqrt{\frac{x}{X_0}} \left(1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right) \tag{1}$$

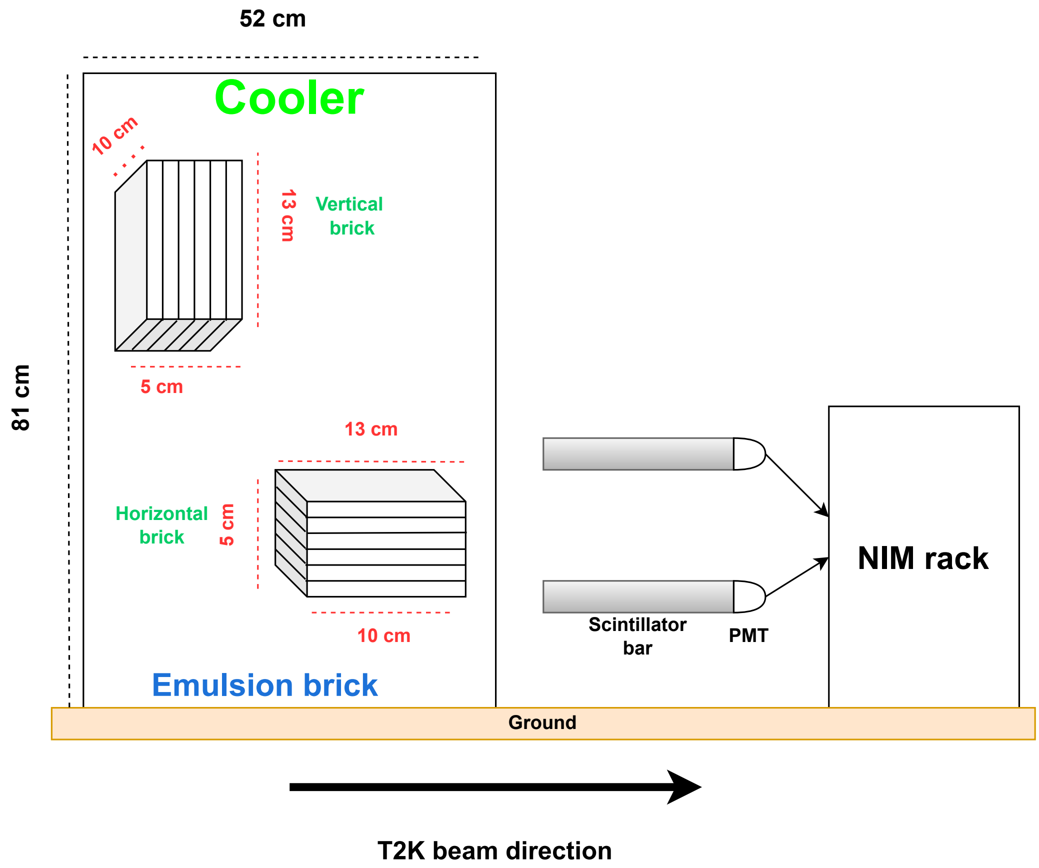

Figure 1: Schematic diagram of the nuclear emulsion detector setup. The emulsion films are interleaved with lead plates and vacuum packed. Scintillator trackers are used to measure the muon rate using PMTs, discriminator and coincidence modules in a NIM.

2.4 GEANT4 simulation

A GEANT4 simulation of the emulsion brick was performed to study the effect of the number of lead layers in the emulsion brick on the reconstructed momentum resolution. Muon tracks are simulated with varying momentum and lead layers. Figure 2 shows the GEANT4 simulation of the emulsion brick and a muon track undergoing multiple Coulomb scattering.

An example of the reconstructed muon momentum distribution using the standard deviation of the scattering angle is shown in Figure 3. The true momentum of the muon is 1 GeV simulated along the Z axis and the number of lead layers is 30. The reconstructed momentum distribution shows a peak around the true momentum value and a standard deviation of $\sim 30\%$.

3 Schedule

The schedule is tentative and depends on the T2K beam commissioning schedule. We plan to finish scanning the emulsion films early in 2026 and have the data analysis in a mature state by the end of 2026.

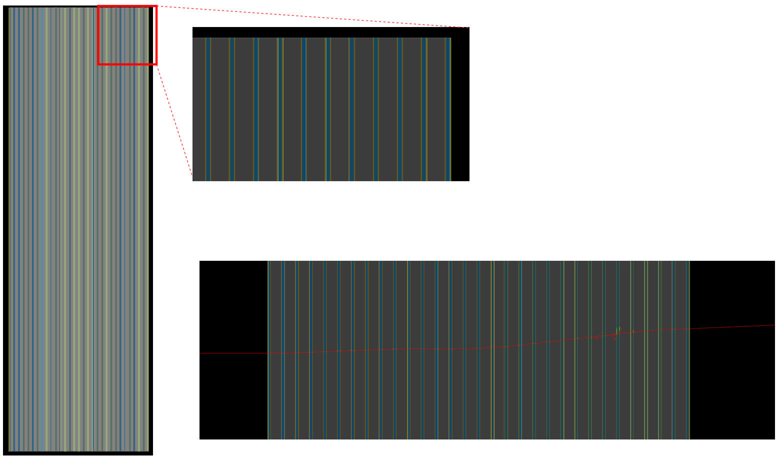

Figure 2: GEANT4 simulation of the emulsion brick (left) and muon track undergoing multiple coulomb scattering (right).

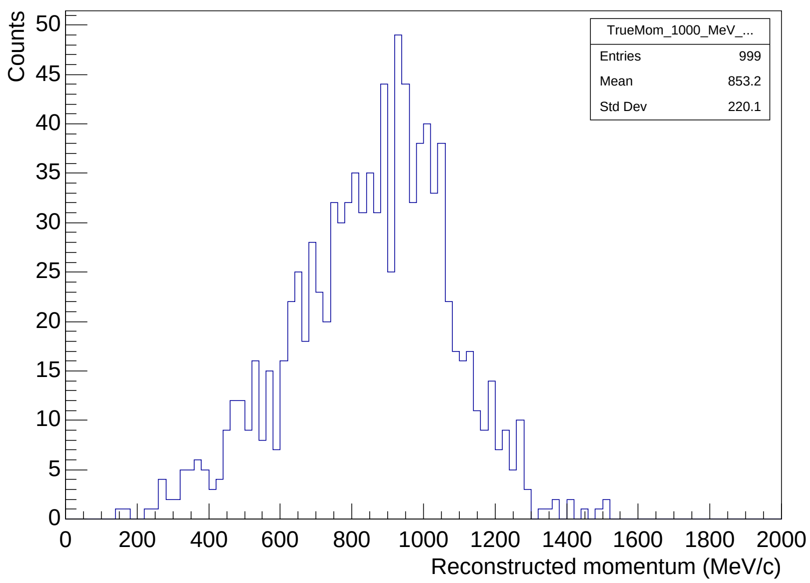

Figure 3: Reconstructed muon momentum distribution using the standard deviation of the scattering angle. True momentum is 1 GeV and number of lead layers are 30.

4 Requests

- Site: Inside the NA building at ground level with freezer, 1.5 x 1.5 m^2 area for the freezer box and the NIM rack.
- Power supply: For the freezer box (freezers specifications 100V, 100W), PMTs and NIM rack.
- Preparation: Use the existing NINJA dark room to pack and unpack the emulsion bricks before and after data collection.

Table 2: Test experiment schedule @ J-PARC

Run	Period	Task	Site
Run 1	Nov. 05 - 07	Construct emulsion bricks	NINJA dark room
Run 1	Nov. 08 - 19	Beam OFF exposure	NA building ground floor
Run 1	Nov. 11 - 12	Unpack horizontal emulsion brick	NINJA dark room
Run 1	Nov. 20 - 21	Unpack vertical emulsion brick	NINJA dark room
Run 2	Dec. 03 - 04	Construct emulsion bricks	NINJA dark room
Run 2	Dec. 05 - 16	Beam ON exposure	NA building ground floor
Run 2	Dec. 08 - 09	Unpack horizontal emulsion brick	NINJA dark room
Run 2	Dec. 17 - 18	Unpack vertical emulsion brick	NINJA dark room

5 Summary

This proposal outlines a test experiment to measure the atmospheric muon and gamma background, together with sky-shine from T2K beam at the ground level in the NA building using nuclear emulsion detector and scintillator trackers. The aim is to understand the way these backgrounds affect the emulsion detector. The experiment will have a 1.5 x 1.5 m^2 footprint and minimal requirements for electrical power and infrastructure.

References

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