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Research article

Measurement of cosmic muon angular distribution and deposited energy using sFGD prototype in the T2K upgrade ND280

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ABSTRACT

Introduction: The superFGD (sFGD), a scintillator detector, has been chosen as the target for neutrinos in the T2K near detector upgrade. Its design enables nearly 4π coverage for neutrino interactions, leading to lower energy thresholds and reduced systematic errors in the experiment. The sFGD is composed of optically-isolated scintillators measuring $1 \times 1 \times 1$ cm^3, ensuring the necessary spatial and energy resolution to minimize uncertainties in future T2K runs. With close to two million cubes assembled into a volume of $1920 \times 560 \times 1840$ mm^3, the sFGD represents a significant advancement. **Methods**: The sFGD prototype, comprised of 48 cubes, was instrumented. The experiment was conducted in Tokai (36°27'42.8"N 140°35'57.7"E). Additionally, we present the results of the GEANT4 simulation of this prototype, where a cosmic ray muon is simulated by the CRY generator. **Results**: The angular and energy deposition distributions are presented in this paper. **Conclusion**: We hope that our research can contribute to deepening the understanding of neutrino detection technology.

Key words: sFGD, SiPM array, cosmic ray

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INTRODUCTION

T2K (Tokai to Kamioka) is a neutrino experiment conducted in Japan (see Figure 1). The T2K upgrade project was launched in 2017 aiming to investigate CP violation, a phenomenon that breaches the combined conservation laws associated with charge conjugation (C) and parity (P) by the weak force, with a confidence level (CL) of 3σ. A novel concept for a scintillator detector with 3D fine granularity has been introduced as part of this upgrade. This innovative design use 1 x 1 x 1 cm^3 cubes, read out along three orthogonal directions by wavelength-shifting fibers (WLS fibers). This detector serves a a new massive target for neutrino interactions and is named the Super Fine-Grained Detector (sFGD) [1].

The commissioning of the sFGD prototype was motivated by the necessity to study the readout electronics, resembling those of the final detector and developing the reconstruction method, along with the analysis methods to identify cosmic rays.

Muons represent the majority of charged particles in secondary cosmic muon at the ground level. The average energy of cosmic muon reaching the Earth's surface is around 4 GeV at an approximate rate of 1.1 particle cm^{-2}/min [2]. Cosmic ray muon angle distribution and deposited energy have been extensively studied at sea level [3].

The prototype setup was described in Section 2, while Section 3 elaborates on Monte Carlo (MC) simulation utilizing the GEANT4 toolkit and CRY generator. The analysis and reconstruction of data are outlined in Section 4.

PROTOTYPE DESIGN AND SETUP

The prototype consists of 48 cubes of plastic scintillators, each measuring 4cmx4cmx3cm. These plastic scintillators are composed of polystyrene ((C8H8)n doped with 1.5% of para-terphenyl (PTP) and 0.01% of 1,4-bis benzene (POPOP). Each cube has dimemsions of 1 x 1 x 1cm^3, with a reflective layer applied to each surface using a chemical agent, resulting in the formation of a 50 – 80 μm thick white polystyrene micropore deposit [1,4]. These cubes are assembled in the construction of sFGD in the T2K upgrade. We are utilizing the Y-11(200) MS WLS fiber, manufactured by Kuraray Co, which is the same fiber used in ND280's current sFGD. It is a multi-clad, round-shaped fiber of S-type (increased flexibility) with a diameter of 1.0 mm. The scintillation light emitted by the cubes is collected by WLS fibers along two orthogonal directions, X and Y (as illustrated in Figure 2), and read out by an MPPC (Multi-pixel Photon Counter) array model S13361-3050AE-04 to detect the position of cosmic rays. The prototype was placed in a black box, as seen in Figure 2 and Figure 3.

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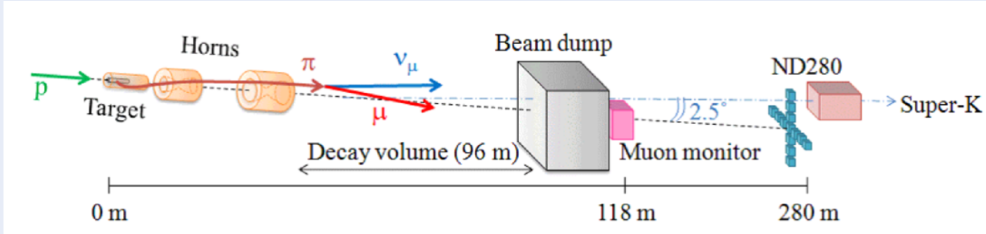

Figure 1: The layout of the T2K experiment.

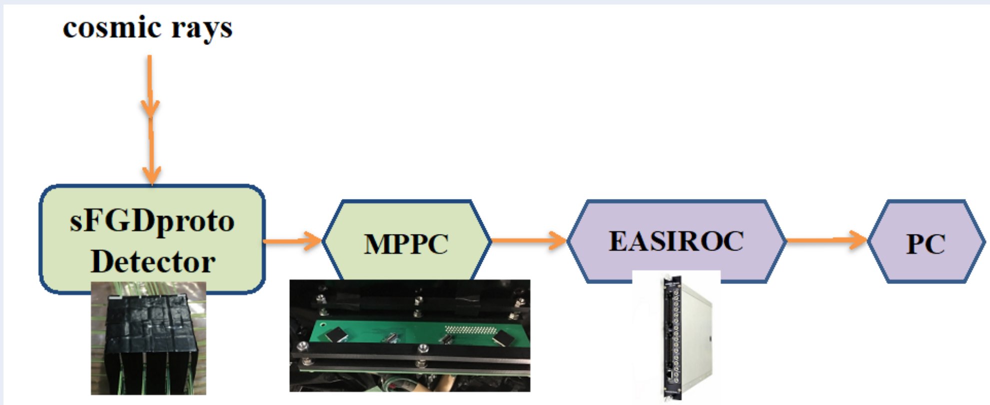

Figure 2: The block diagram.

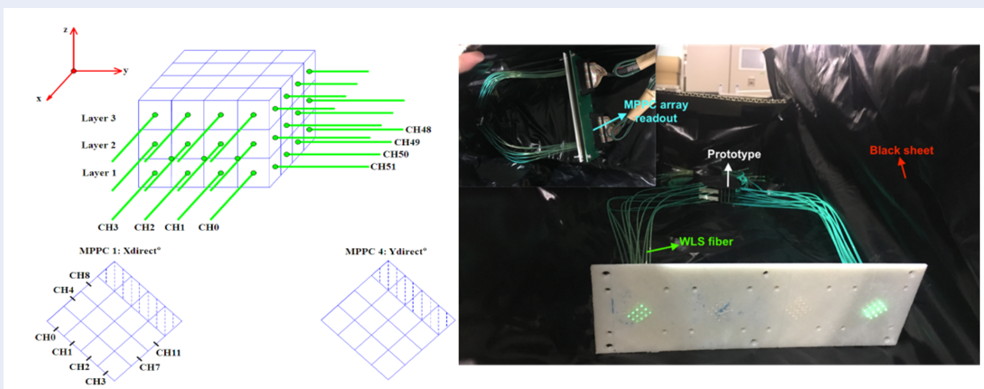

Figure 3: The prototype design setup and detector setup.

Table 1: The information of data recording

	configA	configB	configC	configD
Parameter	$d_{WLS-MPPC}$ = 3 mm		$d_{WLS-MPPC}$ = 1 mm	
Time recording	2h		1h	
DAC	680	650	680	650
Operation Voltage	55.48 V	55.66 V	55.47 V	55.68V
Event numbers	2k	2k	5k	5k

The prototype area is 16 cm^2, thus the flux of cosmic ray around I = 16 particles/detector.min^{-1}. The initial measurement was conducted without a scintillator prototype, to measure the background (dark noise rate). Subsequently, the calibration was performed using a LED with a frequency of 1 kHz, pulse widths of 60 ns and 70 ns. Each measurement was conducted for a duration sufficient to gather a substantial number of counts, aiming to minimize statistical error. Four data sets were recorded with different configurations as listed in Table 1. The experimental process is illustrated in folow chart in Figure 3. The raw experimental data were analyzed and are present in Section 4.

SIMULATION

The left arm of Figure 4 depicts the simulation process, which was implemented using the Geant4[5–7] simulation toolkit in conjunction with CRY[8]. Geant4, initially developed at CERN, is dedicated to simulating of cosmic muons interacting with the sFGD prototype. Meanwhile, CRY generator (the Cosmic-Ray Shower Library)[8] is an open-source software library developed by the Lawrence Livermore National Laboratory. It is utilized to generate correlated cosmic-ray particle showers for various purposes, including transport or detector simulation code . We utilized CRY to generate muon shower information from cosmic rays at sea level. In this developed code, CRY was coupled to Geant4 to generate the initial primary cosmic rays at the beginning of the simulation process.

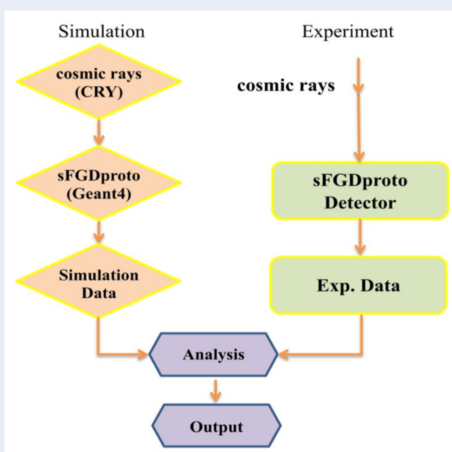

Figure 4: The simulation and experimental processes.

Table 2: The particle percentage in the cosmic ray simulated by CRY

Particle	Contribution (%)
anti_proton	0.000567216
e+	3.46
e-	5.55
gamma	52.3
mu+	19.86
mu-	18.30
neutron	0.097
pi+	0.0035
pi-	0.0028
proton	0.4384

The simulation software of the sFGD prototype used in our work is written and arranged into four major modules. Each part has a distinct task as follow :

- sFGDproGeo: This module is responsible for constructing simulation geometry within the Geant4 framework. In this paper, the geometry consists of several scintillator cubes relevant to the real prototypes, as displayed in Figure 3.
- sFGDproPhysics: This module includes all physics processes that delineate the interaction of cosmic rays with the matter contained within a scintillator cube.
- Output: All interested quantities like energy deposit, interaction location, and angular distribution will be recorded and exported as output.
- Cry-based Primaries: This module is responsible for generating the primary events of cosmic rays based on the output of Cry.

The simulation showed that muon, being the main contribution in the cosmic ray, accounted for 38.15% of the events (Table 2). The simulation results for the energy and angle distributions of the muon showed are shown in Figure 5 a&b. The ratio of the muon distribution going through the sFGD prototype to the initial cosmic muon distribution indicates the acceptance of sFGD prototype. Figure 5c illustrates the acceptance of cosmic muon passing through the sFGD prototype as a function of angle. The simulation of cosmic muon in the sFGD prototype helped to correct the real data.

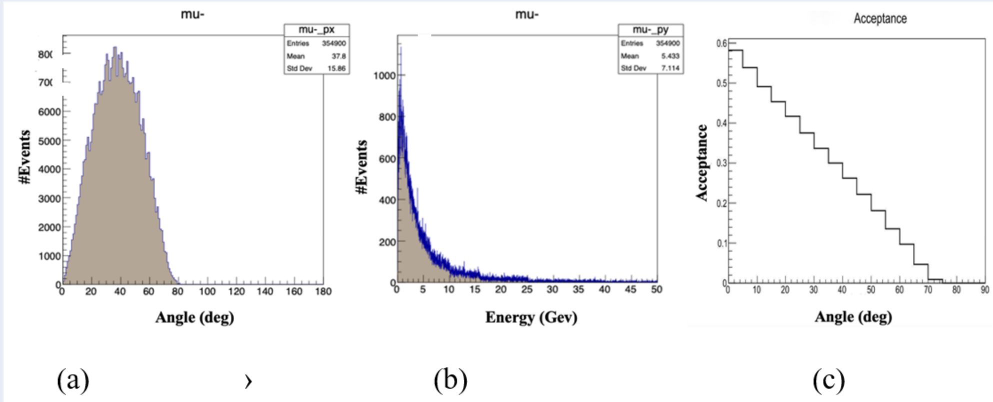

Figure 5: The the angular distribution of mu- (a), energy distribution of mu- (b), and the acceptance of the cosmic muon passing through the sFGD prototype using the developed software.

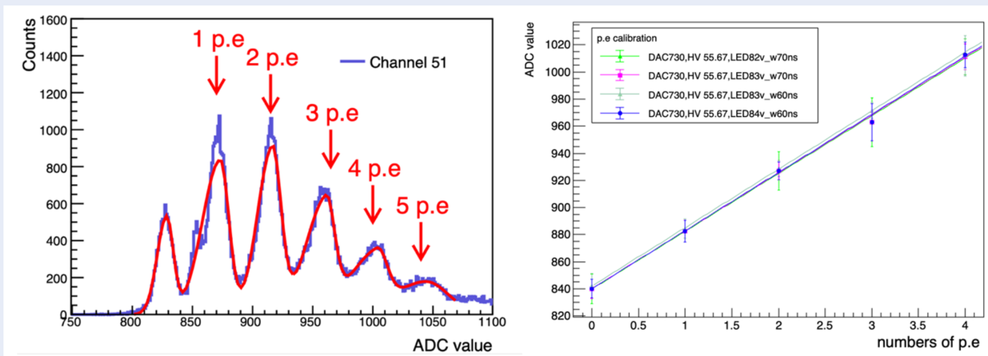

Figure 6: Signal recorded by MPPC array with LED source (a), and calibration curve (b).

EXPERIMENT AND ANALYSIS METHOD

The calibration

The calibration results were obtained using the fourth LED condition, as show bellow. The raw signal was acquired by illuminating the MPPC array with the LED source (Figure 6a). The raw ADC value was plotted in blue, while the red line presents the multi-Gauss function fitted to the experimental data. The first peak on the left corresponds to the pedestal of the measurement system. The subsequent peaks correspond to 1 pe, 2 pe, 3 pe, and so on. The location of the maximum value of each peak was determined from the fitted curves. Consequently, a value of approximately 41 ADC was found for 1 pe in the fourth case of LED condition (Figure 6b).

The analysis strategy

Next, we utilize the prototype to measure the cosmic rays. Figure 7 illustrates the signal of cosmic rays after pedestal subtraction. As shown in Figure 3, each cube contains two WLS fibers along orthogonal directions X, and Y. When a cosmic ray traverses through a cube, the scintillator convert the deposited energy into visible light rays, which are then, partially collected by each WLS fiber. Based on this, we apply the following steps to identify cosmic rays:

- Pedestal subtraction
- On each layer, calculate the summation (SUM_{XY}) of all ADC values obtained for both X and Y directions.
- An event will be considered a cosmic ray if its SUM_{XY} is greater than a given threshold T.

To determine the value of threshold T, we examine the signal of all channels on the layer that contains 16

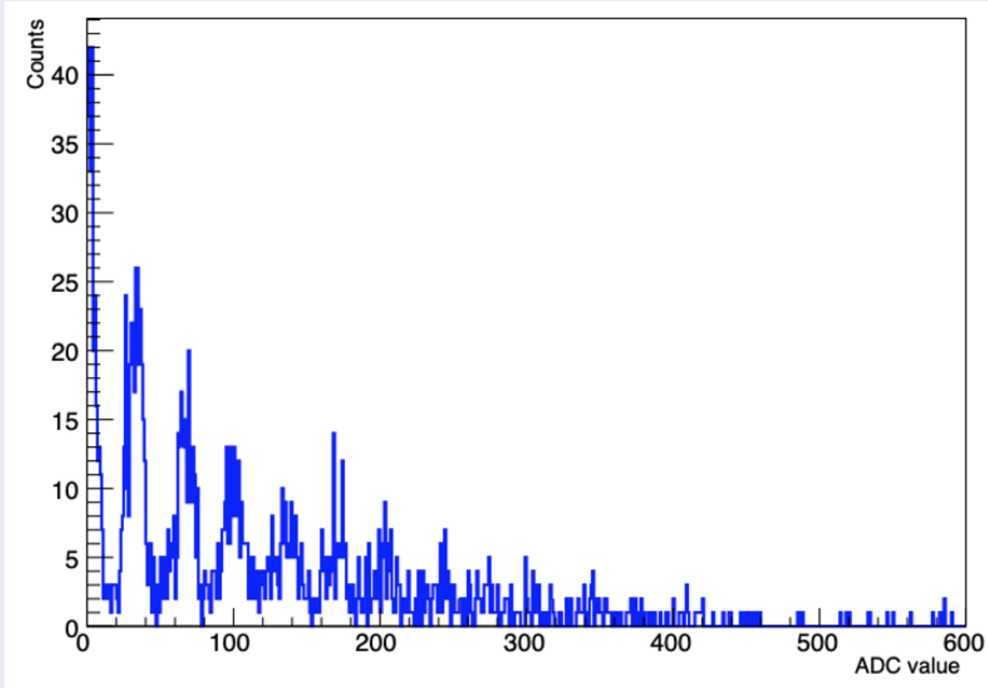

Figure 7: Raw data of cosmic rays measured with DAC 650, HV5566, 3 mm.

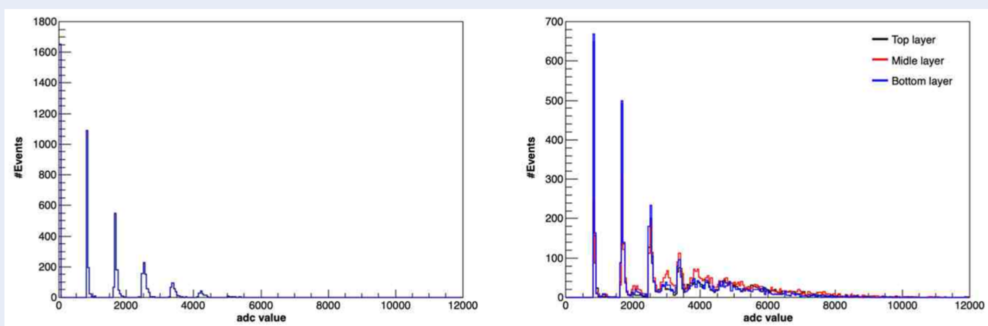

Figure 8: SUMXY of 16 channels without WLS fibers (left) and SUMXY on each layer (right), obtained with configC.

cubes without WLS fiber. These signals, thus, come from the noise signal. Figure 8 displays the SUM_{XY} for this case using a configuration of DAC 680, HV 5547, 1mm. It can be seen that most of the values are below 6000. Therefore, we chose T=5800 as a threshold to identify cosmic rays. Figure 9 presents the SUM_{XY} spectra for signals coming from cosmic rays.

After identifying the cosmic rays, further calculations were performed to estimate the angular distribution and the energy of cosmic rays bombarding the prototype, as shown in the next Section. In particular, the following steps were used:

- Only events that go through 3 layers are considered.
- The Centre of Gravity coordinates (x_{cog}, y_{cog}, z_{cog}) are calculated on each layer to determine the impact position of the cosmic ray.
- In the same event, if the distance between two hit positions is greater than $\sqrt{1^2+1^2+1^2}$, then the two hit positions do not belong to the same track.
- After determining the interaction location in each layer, the track length L_t of a cosmic ray traveling through the prototype is calculated.

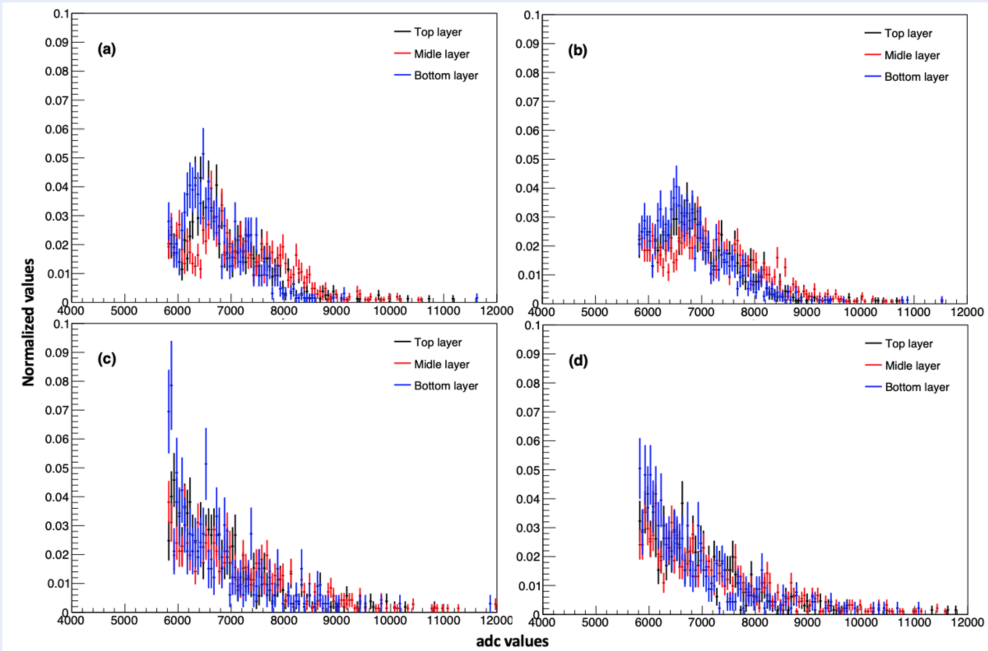

Figure 9: SUMXY spectra obtained by the prototype for different configurations: (a) configA; (b) configB; (c) configC; (d) configD.

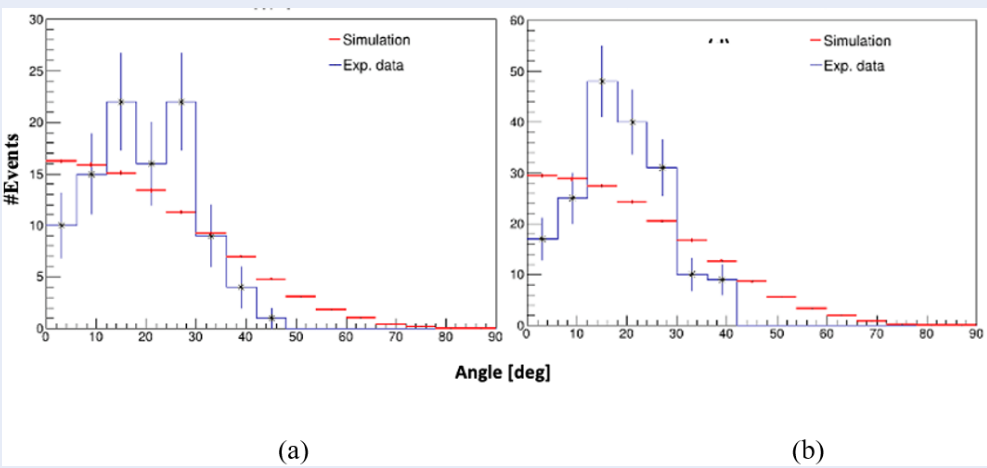

Figure 10: Angular distribution for different configurations: (a) configC; (b) configD.

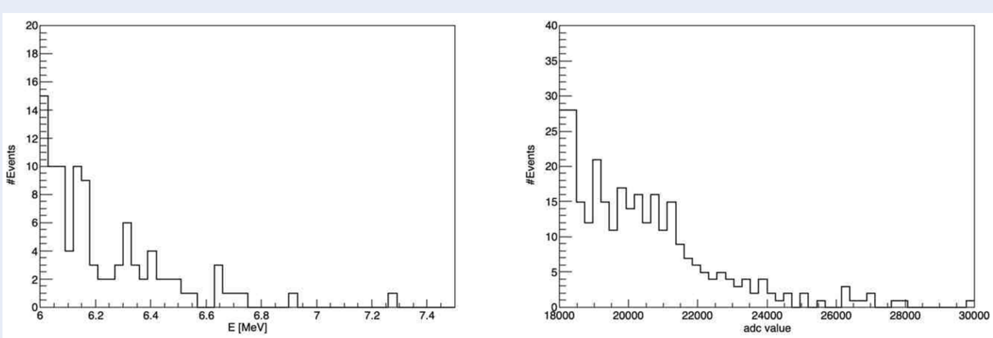

Figure 11: Deposited energy of cosmic rays obtained with different configurations: configC.

- The incident angle of a cosmic ray is calculated as the angle between L_t and the Zenith axis.
- The final angular distribution is obtained after correcting for the acceptance of the prototype, which is determined by the Geant4 simulation.
- The deposited energy is determined as $E = \frac{dE}{dx} * L_t$, where $\frac{dE}{dx} \cong 2$ MeV/cm [2].

RESULTS AND DISCUSSION

The angular distribution

Figure 10 presents the comparison between experimental data and the simulation results for the angular distribution of cosmic rays at Earth's surface. Four measured angular distributions (blue lines) were obtained with different configurations, as listed in Table 1. We utilized the Geant4-based code integrated with CRY (see Figure 4) to determine the acceptance of the prototype and the simulated angular distributions (red lines). There is a difference between experimental data and the simulation curves. The discrepancy may arise from the relatively poor statistics at data points, and the simulation results didn't account for the effect of WLS and electronics. The results of only configurations C exhibited the expected value. To confirm this, we need to collect more data and decrease the distance between WLS and MPPC.

The deposited energy

The deposited energy was determined using the method described in Section 4 as shown in the left figure of Figure 10, while the raw ADC distribution we obtained are displayed in the right figure. Figure 11 shows the initial energy deposited by cosmic rays in the prototype. For all considered configurations, a mean value of deposited energy is determined to be approximately 6.1 MeV

CONCLUSION

This paper reports the findings concerning the angular distribution and energy deposition of cosmic rays observed in the prototype of the new detector designed for the T2K experiment upgrade. While this issue is not novel, experimental investigations are crucial for comprehending the detector's characteristics. Moreover, reconstructing the characterize of cosmic ray enables the development of methods for reconstructing muon particles in the upgraded sFGD detector for the T2K experiment.

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AVAILABILITY OF DATA AND MATERIALS

None.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable.

CONSENT FOR PUBLICATION

Not applicable.

COMPETING INTERESTS

The authors declare that they have no competing interests.

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