PROCEEDINGS OF SCIENCE

Development and analysis large emulsion converter for GRAINE2023 balloon-borne experiment

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We are promoting precise observation of cosmic gamma rays in the sub-GeV/GeV energy region using a large-scale nuclear emulsion telescope with high angular resolution mounted on a balloon. We have done balloon experiments in 2011, 2015 and 2018. In 2018, we succeeded in the first detection of an astronomical gamma-ray source and imaging Vela pulsar with the highest angular resolution in the world. We conduct a balloon flight in March 2023 (GRAINE2023) and observe Vela pulsar, Galactic Center region and so on. Nuclear emulsion telescope consists of converter, time stamper and attitude monitor. Converter part is a stacked structure with nuclear emulsion films, capturing electron and positron from gamma rays. Nuclear emulsion film ' s high angular resolution enables precise determination of the direction of gamma rays and measurement of momentum by multiple coulomb scattering. For the next experiments, we added chemicals to nuclear emulsion films to enhance environmental resistance. We introduced facilities for mass production of nuclear emulsion films at Nagoya University and made 20 converters with 25cm times 50cm films. We made 2.5m^2 aperture emulsion telescopes which is 6.5 times larger than the previous experiment. This poster reports the results of film performance evaluation tests and mass production, and the performance of flight films in GRAINE2023.

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1. Introduction

Observation of cosmic gamma rays in the sub-GeV/GeV energy region made great progress by the Large Area Telescope on the Fermi Gamma-ray Space Telescope (Fermi-LAT). Fermi-LAT was launched in 2008 and detected more than 6000 gamma-ray sources[1]. In Galactic center region, excess of gamma ray is reported, but the cause has not been clarified because of the lack of angular resolution. So gamma ray observation with higher resolution is required in the sub-GeV/GeV energy region.

Gamma-Ray Astro-Imager with Nuclear Emulsion (GRAINE) project is an experiment of precise observation of cosmic gamma rays in the sub-GeV/GeV energy region. We make the emulsion telescope that consists of nuclear emulsion films. Nuclear emulsion films is a three-dimensional tracking detector and can precisely measure the angle of electron and positron tracks produced in pair production ($\gamma \rightarrow e^- e^+$). Nuclear emulsion film's excellent three-dimensional resolution enable us to observe gamma rays with high angular resolution (0.1° @1 GeV, 1.0° @100 MeV).

Figure 1 shows the structure of the emulsion telescope. Emulsion telescope consists of emulsion converter, time stamper[2] and attitude monitor. Emulsion converter is a stacked structure with nuclear emulsion films and sealed with aluminum bag and vacuum-packed to fix relative potion of films and shield it from light and keep the humidity. The roll of emulsion converter is detecting electron and positron from gamma rays. Nuclear emulsion film ' s high angular resolution enables precise determination of the direction of gamma rays and measurement of momentum by multiple coulomb scattering. Angular resolution of nuclear emulsion films does not worse as area is increased so we can increase aperture area with high angular resolution.

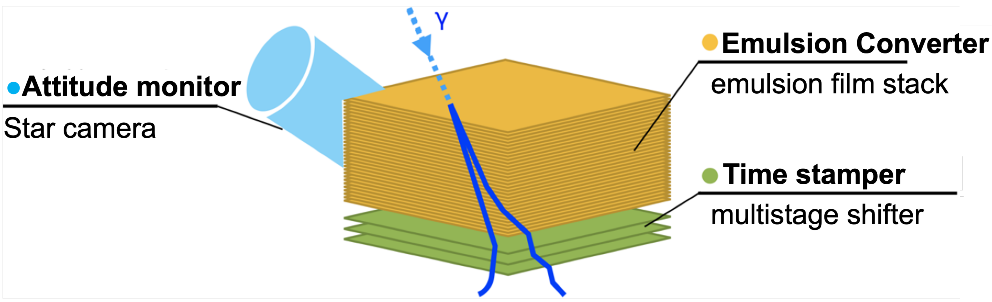


Figure 1: Overview of emulsion telescope.

In 2018, we conducted balloon flight with emulsion telescope with an aperture area of 0.38 m^2 to demonstrate the performance of emulsion telescope (GRAINE2018). we realized the highest resolution imaging of the Vela pulsar (>80MeV).

From the balloon experiment in 2023 (GRAINE2023), we expand the aperture area of nuclear emulsion telescopes and begin scientific observations. The aim of GRAINE2023 is to observe Vela pulsar (>1 GeV) and detect Galactic Center region.

2. Development Nuclear Emulsion Films for GRAINE2023

2.1 New Design Nuclear Emulsion Films for GRAINE2023

We developed new design nuclear emulsion films for GRAINE2023. There are two major differences from previous experiment. First, we made nuclear emulsion films using Roll to Roll mechanical coating machine. Second, we added several chemicals to improve the environmental resistance.

Table 1: Major differences of design of nuclear emulsion films from previous experiment

	GRAINE2018	GRAINE2023
Coating method	handmade	Roll to Roll coating machine
Additive chemicals	-	Benzothiazolium compound PMT Oxim compound

Previously, we made nuclear emulsion films by coating nuclear emulsion gel on the plastic base by hand. For GRAINE2023, we had to make about 600 m^2 nuclear emulsion films. So, we developed Roll to Roll mechanical coating machine at Nagoya University and realized mass production of 100 m^2 of nuclear emulsion films per a month.

In nuclear emulsion films, tracks gradually fade away. This phenomenon is called latent image fading and understood by the following chemical equation.

$$\mathrm{Ag}_n + \mathrm{O}_2 + 2\,\mathrm{H_2O} \longrightarrow \mathrm{Ag}_{n-4} + 4\,\mathrm{Ag}^+ + 4\,\mathrm{OH}^- \tag{1}$$

The higher the temperature, the faster this chemical reaction proceeds. After observation, the emulsion telescope cuts off from balloon and lands in the Australian wilderness where the maximum temperature reaches 40 °C. If the telescope land the place where recovery is difficult, the telescope would be left in place for up to a week. So, Emulsion telescope requires nuclear emulsion films that are resistant to high temperature environment. Recently, several additive chemicals for nuclear emulsion to improve the environmental resistance have been found and used in experiments in severe environments such as muon radiography[4]. We added some chemicals (show Table1) for nuclear emulsion films for GRAINE experiment and evaluated environmental resistance.

2.2 Performance Evaluation of New Design Nuclear Emulsion Films

We made Nuclear emulsion chamber with stacked new design films to evaluate the performance of latent image fading. After exposing cosmic rays for three days, each of the four films was placed in a high-temperature environment for different periods. We readout all tracks recorded in nuclear emulsion films using Hyper Track Selector (HTS)[3] at Nagoya University and evaluated the track finding efficiency of each film. The track finding efficiency is defined as the percentage of tracks detected on the top and bottom films that were also detected on the evaluated film.

Figure 3 shows the track finding efficiency for each angle. (a) shows the results of previous design films for GRAINE2018. We can see a drastic decrease in efficiency as the storage period increases. So we had to recover nuclear emulsion films as fast as possible after balloon experiment

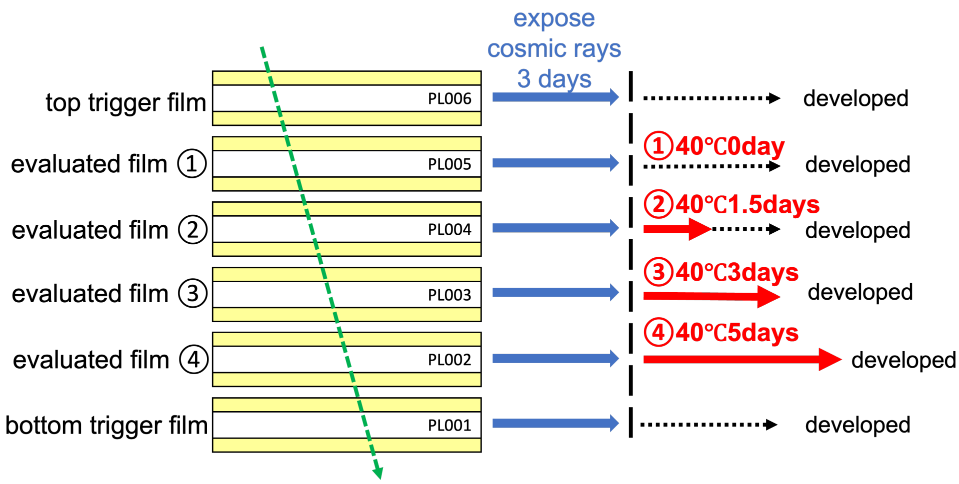
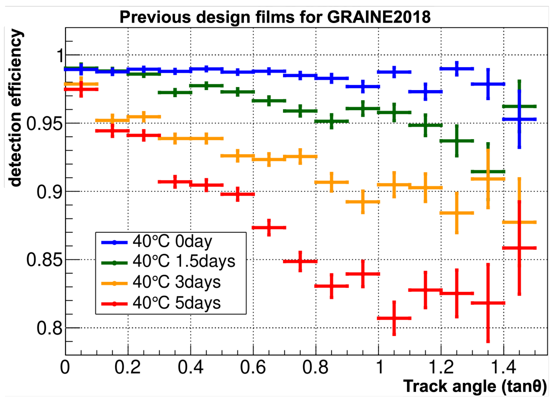


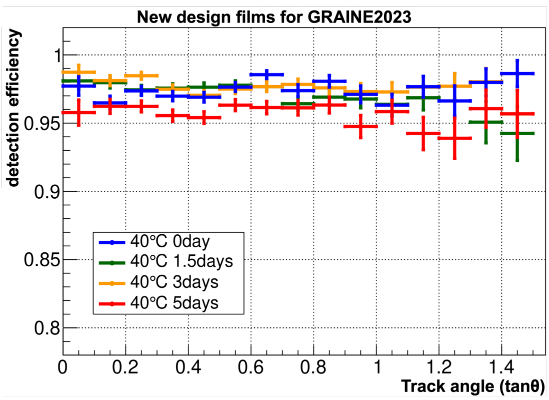
Figure 2: The structure of nuclear emulsion chamber to evaluate the performance of latent image fading

in GRAINE2018. In contrast, New design films have smaller changes in efficiency and smaller angular dependence of efficiency.

Figure 4 shows the shift in average track finding efficiency for $\tan\theta < 1.4$ (θ is zenith angle of track). After 5 days at 40 °C, the average efficiency of previous films (blue) was less than 90 %, while that of new design films (red) maintained more than 95 %. The new design films allow the balloon experiment to be conducted more surely, as it can maintain recorded tracks of charged particles even if it takes about a week to retrieve. New design films allow a longer recovery grace period and increase the success rate of balloon experiments.



(a) Previous design films for GRAINE2018



(b) New design films for GRAINE2023

Figure 3: Track finding efficiency for each angle. Different colors represent different storage periods.

3. Demonstration of Gamma-ray Detection Performance

We demonstrated the detection performance of gamma rays of emulsion converter with new design films at Mt. Norikura. We made half-scale emulsion converter for GRAINE 2023 which

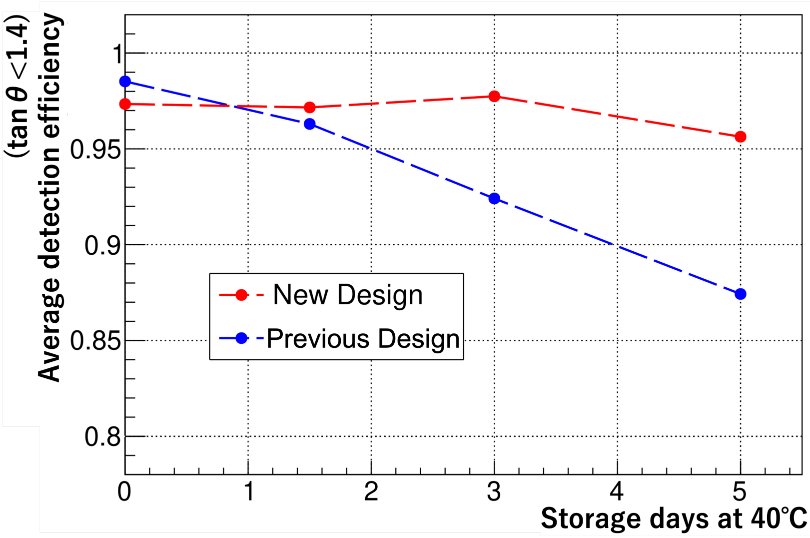


Figure 4: Performance of latent image fading. (Red)New design films for GRAINE2023. (Blue)Previous design films for GRAINE2018.

consists 50 nuclear emulsion films (the size of each film is 25 cm × 50 cm) and observed atmospheric gamma rays at Mt. Norikura where the elevation is about 2700 m for five days. After observation, we developed all films at a large-scale developing facility in Gifu University. we read out the tracks at 10 cm × 12.5 cm area of each film using HTS and searched for gamma ray events with a process similar to GRAINE2018. We select two tracks close to each other that are generated in the converter, and select events that are likely to be electron pair production events based on their shapes and so on. Figure 5 shows detected gamma ray events in a film. Figure 6, 7 show angle and energy of detected gamma rays. We detected about 30000 gamma ray events in 10 cm × 12.5 cm area of emulsion converter. Our nuclear emulsion converter were able to detect various angle and various energy gamma rays.

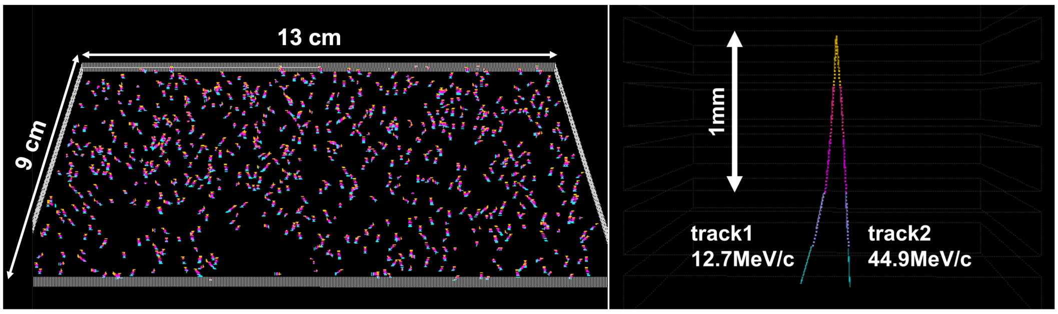


Figure 5: Detected gamma ray events in the converter. We can get three dimensional information of electron or positron tracks. (left)All gamma ray events in a film (10 cm × 12.5 cm). (right) An example of gamma ray event. Different colors represent different films.

We calculated atmospheric gamma ray flux at Mt. Norikura to check the performance of gamma ray detection. Figure 8 shows integral flux of atmospheric gamma rays. Red dots are the data calculated from the number of gamma ray events in the emulsion converter. Blue line is the

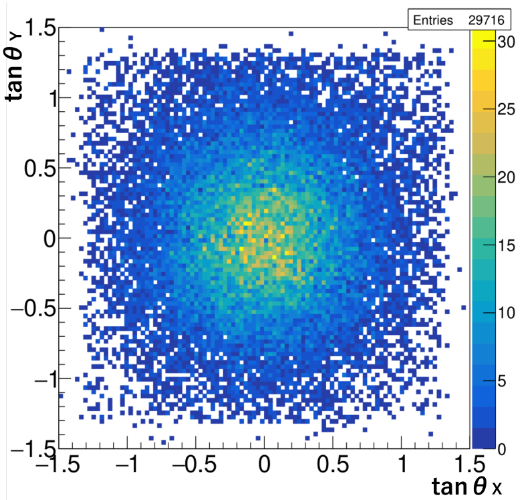


Figure 6: The angle of detected gamma rays

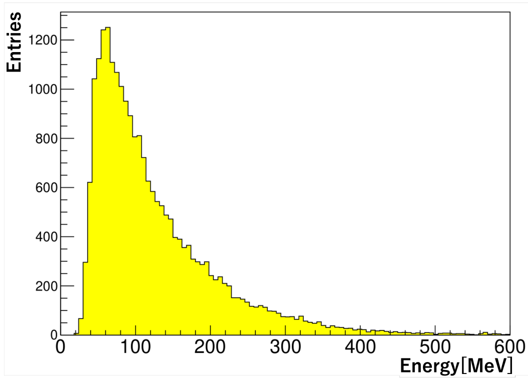


Figure 7: The energy of detected gamma rays

simulation using PARMA/EXPACS. The data and simulations show good agreement, demonstrating that the emulsion converter with new design films has sufficient gamma ray detection performance.

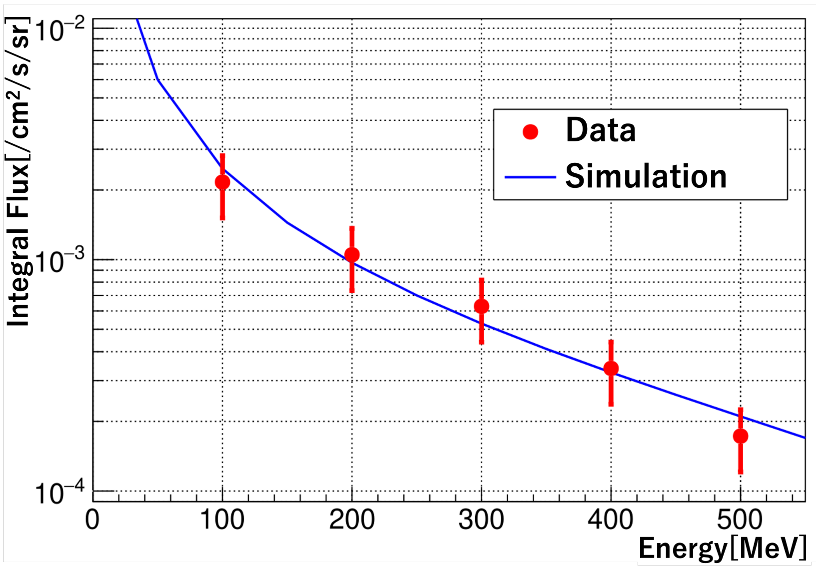


Figure 8: Integral flux of atmospheric gamma rays at Mt.Norikura. (Red)data. (Blue)Simulation (PARMA/EXPACS).

4. GRAINE2023

For 2023 balloon experiment in Australia, we made nuclear emulsion films at Nagoya University. Using nuclear emulsion gel production facility and Roll to Roll coating machine, we made totally 750 m^2 films for emulsion telescope. After refreshing (which is the process of erasing tracks recorded in films before experiments) and humidity control, we made 20 emulsion converters which were made of 90 nuclear emulsion films (the size of each film is 25 cm × 50 cm) and shipped them by air to Australia in January 2023. In Australia, we glued two converters to an aluminum honeycomb plate and 10 aluminum honeycomb plates mounted on two multistage shifters (Figure 9). March 2023, we mounted 20 emulsion converters on the emulsion telescope and completed the emulsion telescope with an aperture area of 2.5 m^2.

The balloon flight was completed from April 30 to May 1. The total duration was 27 hours, including an altitude of 35.4–37.2 km and a level flight of 24 hours and 17 minutes. After observation, the emulsion telescope cuts off from balloon and lands at 220 km south of Longreach. The emulsion telescope was recorded May 3 and the films were shipped by air to Japan. All nuclear emulsion films used for GRAINE2023 balloon flight were developed by July 25 at Gifu University.

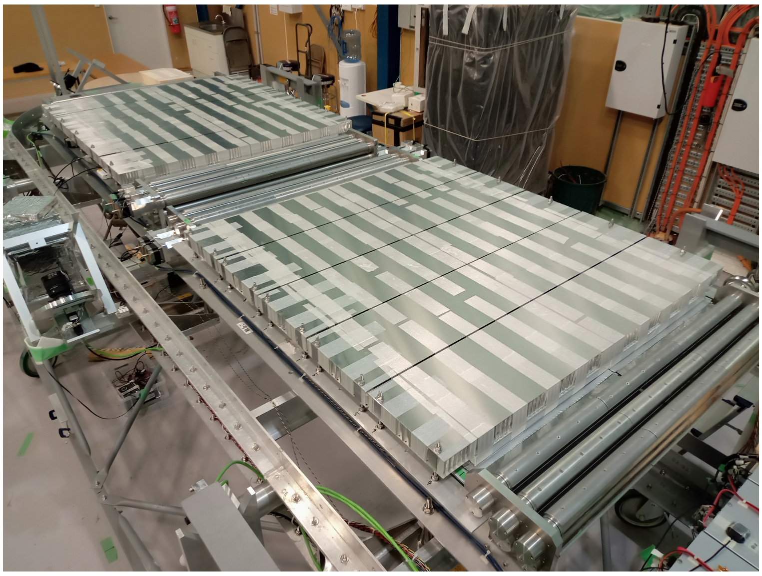


Figure 9: Emulsion telescope for GRAINE2023. 20 emulsion converters mounted on the two multistage shifters.

5. Summary

We developed new design nuclear emulsion films for 2023 balloon experiment in Australia. The new design films have improved environmental resistance compared to the previous films, and can sustain recorded tracks even when exposed to high temperature for longer periods. After checking the performance of gamma ray detection, we made about 20 emulsion converters and the emulsion telescope with an aperture area of 2.5 m^2 for GRAINE2023. We succeeded balloon flight and recovery nuclear emulsion films quickly.

Now, we started to readout tracks recorded in the flight films using next-generation nuclear emulsion readout system (HTS2). Using the track data in flight films, we will try to observe Vela pulsar precisely (0.1° @1 GeV) and detect Galactic Center region.

References

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