PROCEEDINGS OF SCIENCE

Nuclear emulsion detector for large-area, high-angular-resolution gamma-ray telescope

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The Fermi Gamma-ray Space Telescope has surveyed the sub-GeV/GeV gamma-ray sky and provided a large amount of data. However, observation remains difficult owing to the lack of angular resolution, and new issues have arisen. We started up a precise gamma-ray observation project, Gamma-Ray Astro-Imager with Nuclear Emulsion (GRAINE), using balloon-borne emulsion gamma-ray telescopes to enable high angular resolution (0.1 degrees at 1 GeV), polarization-sensitive, and large-aperture observations (10 m^2) in the 0.01–100 GeV energy region. In the last balloon experiment, which was performed in 2018, we succeeded in the first detection of a celestial gamma-ray object, Vela pulsar, via the balloon-borne emulsion telescope, and the world's highest angular resolution was demonstrated. We start the scientific observation phase by enlarging the aperture area, extending the flight duration, and repeating balloon flights. The GRAINE 2023 balloon experiment was conducted in April 2023. The experiment aims at the observation of Vela pulsar, the Galactic center, etc. in the GeV energy region, and the survey of transient phenomena by the largest aperture area telescope. In preparation for GRAINE 2023, the new facility constructed at Nagoya University was used to produce nuclear emulsion, completing a 750 m^2 emulsion films, the largest area of all the experiments using Nagoya-made emulsion. In this presentation, we report on the emulsion detector for gamma-ray measurement and its technology, as well as the latest status of GRAINE 2023.

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1. Gamma-Ray Astro-Imager with Nuclear Emulsion (GRAINE) Experiment

The Fermi satellite has continued all-sky observations of gamma rays in the sub-GeV/GeV band, providing high-statistics gamma-ray data, since its launch in 2008 [1]. And the Fermi has achieved various breakthroughs, including the detection of more than 6000 gamma-ray sources. On the other hand, the lack of spatial resolution (angular resolution) has been a stumbling block to observation. In order to understand the complex structure of the Galactic plane/center and extended supernova remnants, precise observation data is needed, and high-resolution observations are the next step in the gamma-ray astronomy.

While several groups around the world have proposed projects focusing on improving angular resolution, we have developed a gamma-ray telescope with both high angular resolution and a large aperture area using nuclear emulsion technology, and have promoted the "GRAINE Project (Gamma-Ray Astro-Imager with Nuclear Emulsion)," an observation experiment using scientific balloons, in advance. Nuclear emulsion, which realizes a small amount of material ($\sim 10^{-3} X_0$) and submicron spatial resolution, becomes a novel detector for gammma-ray direction measurement bu precise measurement of the tracks just below $\gamma \rightarrow e^{+}+e^{-}$ interaction point, and realizes high-resolution precision observations with an order of magnitude improvement compared with the angular resolution of the Fermi-LAT. The GRAINE project aims to obtain an exposure equivalent to the annual satellite observations and to make precise observations of cosmic gamma rays by employing a large-area emulsion telescope of 10 m^2 on a balloon and repeatedly launching it for several days to a week. [2].

Figure 1 shows an overall view of the full-scale GRAINE payload. It consists of two large balloon-style pressure vessel gondolas, three star cameras to be installed in three directions, and eight units of emulsion gamma-ray telescopes. Figure 2 shows an unit of emulsion telescope, which is unitized with an aperture area of 1.25 m^2. The upstream converter section consists of a hundred stacked emulsion films fixed to an aluminum honeycomb board, which detects the electron pair interaction and measures the arrival direction and energy. The time stamper, consisting of a multi-stage shifter mechanism, is composed of movable emulsion films. Multiple layers are driven in independent cycles during observation to control the positional relationship between the films to be unique, and position displacement value is detected from the post-observation track reconstruction analysis to obtain time information with sub-second precision.

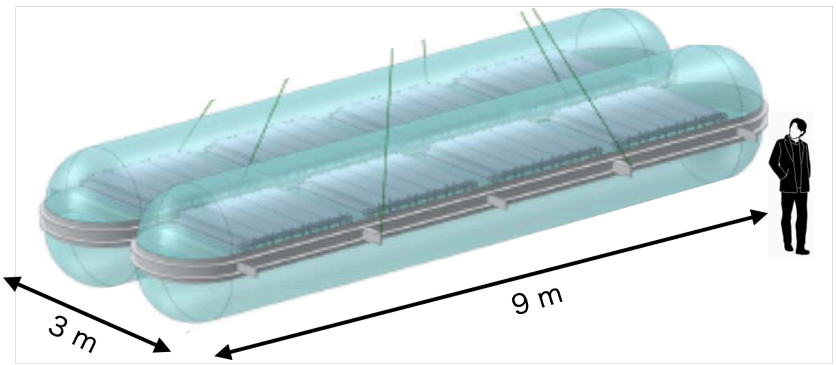

Figure 1: An overall schematic view of the full-scale GRAINE payload with a 10 m^2 aprerture area.

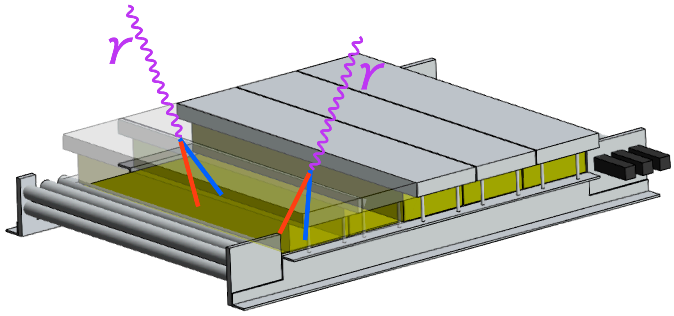

Figure 2: Unitized emulsion gamma-ray telescope with a 1.25 m^2 aperture area.

The 2018 balloon experiment (GRAINE2018) was the first successful detection of a celestial gamma-ray object (Vela pulsar) with a small aperture telescope (0.4 m^2), demonstrating that balloon-borne nuclear emulsion can observe sub-GeV gamma-ray sources with the highest resolution in the world [3]. The GRAINE project aims to shift its phase from the performance demonstration to the scientific observation, and will promote balloon experiments and detector-area expansion .

This paper describes the development of mass production system of nuclear emulsion films to enable the GRAINE experimental science observations, and a balloon experiment which was performed in April 2023.

2. Emulsion Film Production for Large-area Gamma-ray Telescope

2.1 Development of Machine Coating Method for Nuclear Emulsion Film

In recent years, applications of nuclear emulsion have expanded beyond the measurement of particle physics to the field of high-resolution imaging of gamma-rays, muons, neutrons, and so on. In order to realize further scale-up and activation of these researches including GRAINE, Nagoya University has upgraded its infrastructure facilities to scale-up the production capacity of emulsion films by one order of magnitude.

So far, emulsion films produced at Nagoya University have been applied one by one by hand and then dried naturally for about two days, on both sides of a plastic base. We have been developing a mechanical coating that can supply emulsion films at 10 times larger capacity for next-generation experiments and measurements. The GRAINE experiment usually uses emulsion films with 70–75 μm-thick emulsion layers coated on both sides of a 200 μm-thick polystyrene base. On the other hand, the emulsion thickness of a typical photographic film is 20 μm. In the OPERA experiment conducted in the 2000's, a 40-μm-thick machine-applied emulsion film was achieved by coating one side twice.

We employed a coating head, a knife coater, to achieve thick emulsion layer application. Figure 3 shows a cross-sectional view of the knife coater. When the coating liquid is poured into the liquid pan, the liquid is carried over the flowing plastic film, and the knife head scrapes off extra thickness to continuously and uniformly apply the coating liquid equivalent to the mechanically set clearance on the plastic base. The coating liquid, a nuclear emulsion gel, is also manufactured at Nagoya University, and its water content is adjusted in the manufacturing process. Ninety percent of the volume is water, which means that a coating thickness of approximately 700 μm must be achieved.

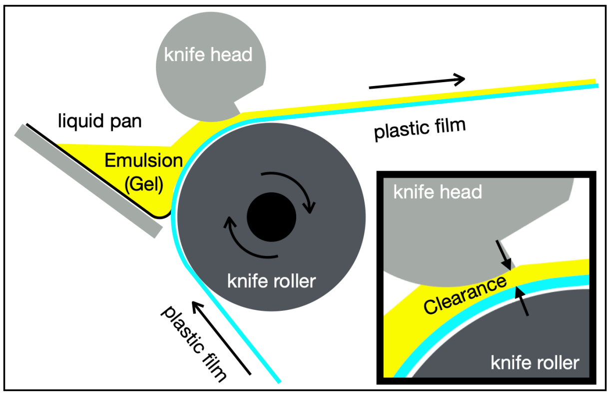

Figure 3: A cross sectional view of knife coater.

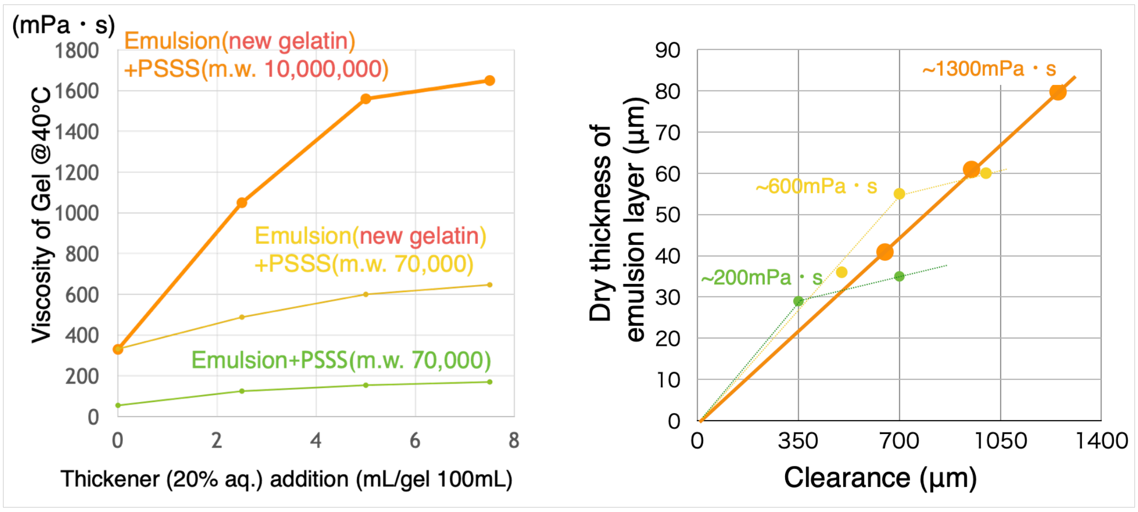

Figure 4: Left: the viscosity of nulear emulsion gel at 40 °C as a function of addition amounts of poly sodium styrenesulfonate (PSSS) solution. Right: the thickness of emulsion layer after drying as a function of values of clearance of knife coater.

The viscosity of the emulsion gel needed to be increased to achieve a thicker coating with a knife coater. The reaction of poly sodium styrenesulfonate (PSSS), which thickens gelatin, with the emulsion gel at 40 °C is shown in the left plot on figure 4. The viscosity of the original gel was very low at about 40 mPa·s, and the viscosity was not increased significantly by adding PSSS. As a result of further investigation, we changed the type of gelatin used in the emulsion and increased the average molecular weight of PSSS, we succeeded in increasing the viscosity to over 1000 mPa·s. The results of the knife coater application test are shown in the right plots on figure 4; the emulsion gel thickened to 1300 mPa·s increased the thickness of the emulsion layer after drying in proportion to the clearance, enabling application of more than 70 μm.

2.2 Roll-to-roll Emulsion Production System

Figure 5 shows photographs of roll-to-roll emulsion coating system newly installed at Nagoya University. It consists of film unwinder/winder machines, web-tension controllers, a corona dis-

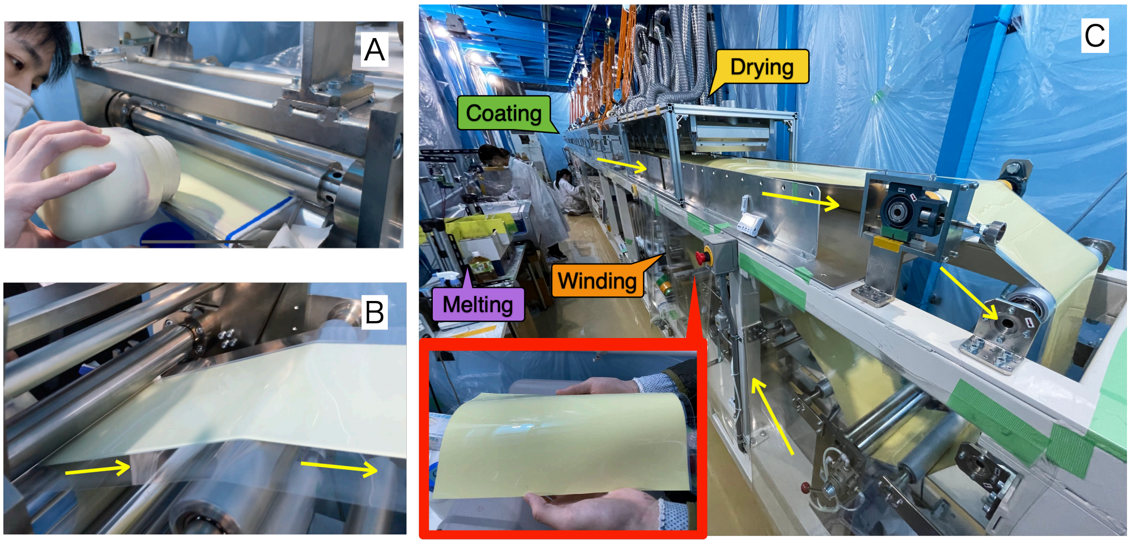

Figure 5: Photographs from the view of upstream(A) and downstream(B) of knife coater. A photograph C shows a whole of roll-to-roll emulsion film coating system. (The actual work is done in the dark.)

charge machine, a roller coater for applying under-coat gelatin layer, a knife coater for applying emulsion layer, and drying units consisting of a slit nozzles and hot air blowers. The system established "roll-to-roll automatic mechanical coating" of nuclear emulsion films, in which a plastic film rolled up is pulled out, emulsion gel is uniformly and continuously coated, water including the gel is evaporated online by passing through a 9 m-long drying zone, and the film is wound up at the end of the roll. It has made it possible to expand the scale and stable supply of all experiments/measurements using nuclear emulsion, such as the GRAINE experiment, accelerator neutrino experiments, muon radiography, and so on.

2.3 Performance of New Emulsion Films and Production Facility

To verify the performance of emulsion films produced at the new facility, a rehearsal experiment was conducted using a prototype converter consisting 50 emulsion films of 25×50 cm^2, which was transported to the Norikura Mountain (the altitude of 2700 m, the pressure of $\sim$ 700 hPa) to observe cosmic rays and atmospheric gamma rays. The left histogram on figure 6 shows the thickness distribution of the 45 films used in the rehearsal experiment. It was observed that an emulsion layer of 70 µm per side was applied to the 200 µm-thick plastic base with a few microns of variation.

The developed emulsion films were used to acquire and evaluate the track data by an automatic track reader, and it was confirmed that the high track-finding efficiency (>95%) satisfying the experimental requirements of GRAINE was obtained over a wide range of angles (the left plot in figure 6).

In addition, we detected about 3,000 electron pair production interactions and determined the interaction positions, incident angles, and energies using the program of the electron pair topology selection employed in the previous balloon experiment. Atmospheric gamma-ray fluxes at Mt. Norikura were derived, and good agreement with simulations was confirmed. Through this rehearsal and analysis, it was demonstrated that the new emulsion films to be used in the 2023

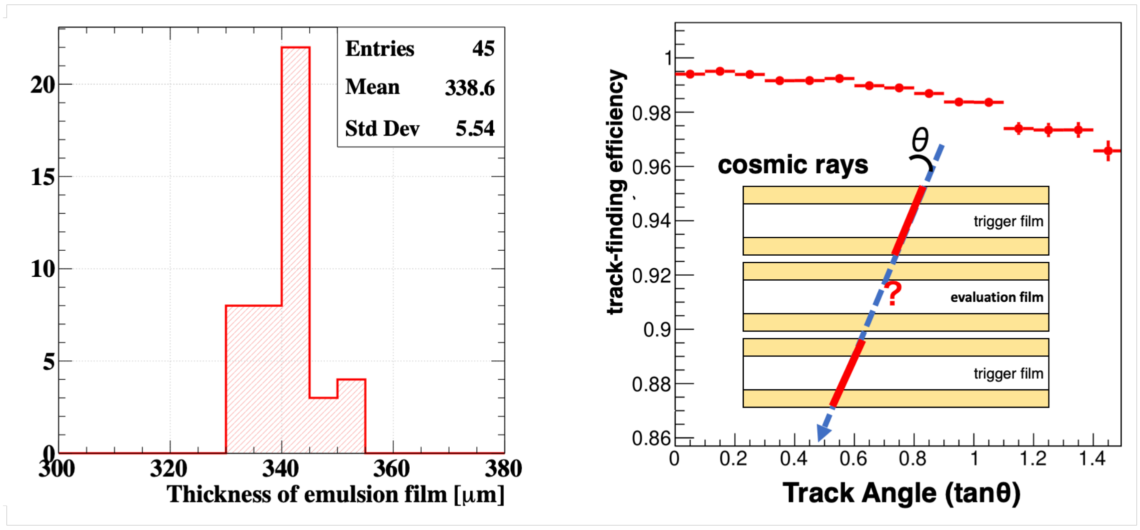

Figure 6: A left histogram shows the thickness distribution of nuclear emulsion films produced at the new facility in Nagoya University. A right plot shows track-finding efficiency evaluated using scan data of films which employed in the cosmic-ray and gamma-ray observation rehearsal at the Mt. Norikura

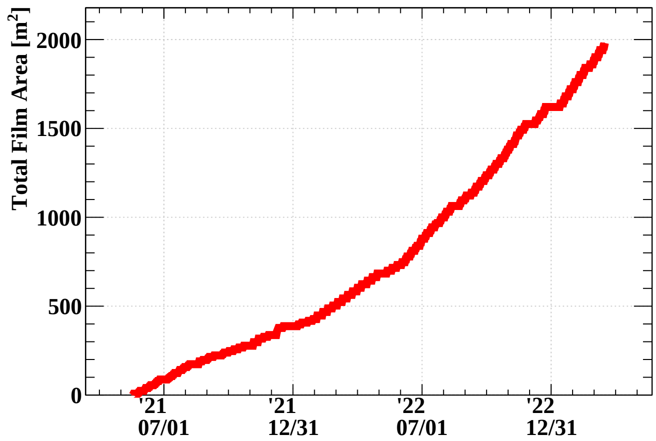

Figure 7: Result of nuclear emulsion film production at the new facilities constructed in Nagoya University.

balloon experiment worked properly as a gamma-ray detector [4].

The newly launched mass-production nuclear emulsion production facility and roll-to-roll film coating facility have been in continuous operation since May 2021, and started supplying emulsions films to various projects. From June 2022, the speed of operation was doubled to complete the production of approximately 750 m^2 (equivalent to 1670 kg of emulsion gel) to be used in the production of the 2023 balloon experiment (figure 7). All batches of mass-produced films were sampled to evaluate sensitivity and noise, and stable performance was confirmed to meet the experimental requirements of grain density over 40 and fog density ~ 2. Pre-treatment and packing of the emulsion films were conducted from October 2022, and the construction of the converter was completed by the end of January 2023.

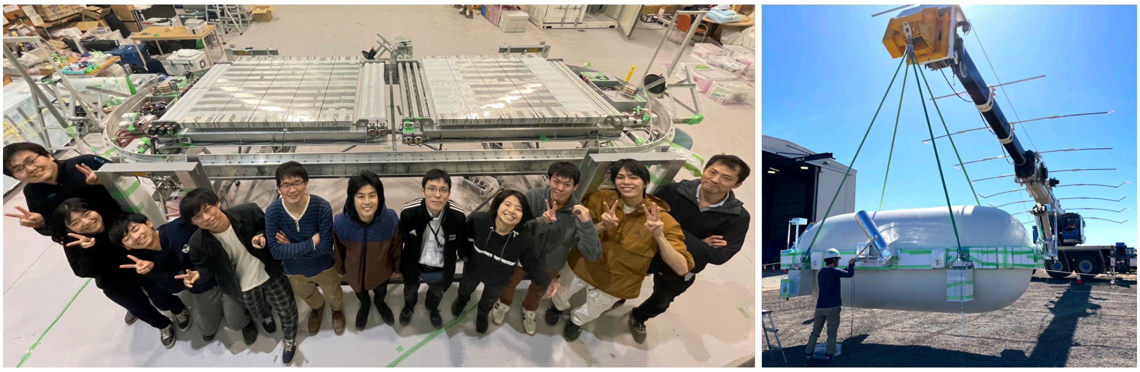

Figure 8: A left photograph shows GRAINE 2023 emulsion gamma-ray telescope system with 2.5 m^2 aperture area. A right photograph shows a payload after closing pressure vessel during a communication test in front of Alice Springs Balloon Launching Station.

3. Balloon Experiment in 2023

The 2023 experiment was conducted in April 2023 [5], two years later than scheduled due to COVID-19. Observations were carried out by a payload (B300 balloon, PI weight about 700 kg) with an emulsion telescope of 2.5 m^2 in the aperture area.

The GRAINE 2023 experiment was originally adopted with a plan to launch two balloons with two payloads, and the GRAINE group completed the production of emulsion films for both of the first and second payloads, in addition to confirming the installation of all onboard equipment and completing preparations for the experiment in Japan. Just before shipping all equipment to the Alice Springs Balloon Launching Station (BLS) in Australia, it became clear that there was a problem with procurement due to the rising price of helium gas, and it was decided that there would be one flight. The emulsion telescope system and emulsion films for one payload were shipped to the site at the end of 2022.

The GRAINE group installed the detector and conducted final operational checks at BLS starting in mid-February 2023 (Figure 8). The balloon was released at 6:32 am (UTC+9.5) on April 29. After ascending to an altitude of 36 km, the level flight continued for 24 hours and the emulsion telescope successfully observed the Vela pulsar and the Galactic center region during the full coverage of the time period when they were within the telescope's field of view. During that time, operation monitoring telemetry of the multi-stage shifter, star camera, and pressurized container monitor showed that all instruments were working properly. Operations ended at 8:00 am on May 1, and balloon detachment was performed at 8:47 am.

On the day the balloon flight was completed, the recovery team arrived at the balloon landing site via Cessna and helicopter. The payload was found without major damage, and the nuclear dry plates and data storage equipment were recovered quickly and in good condition. The nuclear dry plates were quickly brought back to Japan by refrigerated transport, and all development was completed at Gifu University. Data acquisition for some of the films has begun (as of July 2023) [6].

Figure 9: Left photograph shows the moment of the balloon release. Right photograph shows the payload when it was found at the landing point.

4. Conclusion

We have been promoting the GRAINE Project, which aims at precise observations of sub-GeV/GeV gamma-ray sources through repeated long balloon flights with large-area emulsion telescopes. The GRAINE project enables precise measurements of electron pair production events by combining nuclear emulsion films with excellent area scalability and high spatial resolution, automatic reading technology, and time assignment technology to achieve observations with high angular resolution.

It was essential to prepare a large amount of emulsion films, the heart of the telescope, in order to realize the 2023 experiment, which aims to expand the aperture area by a factor of 13 compared to the previous experiment and to start scientific observations. Nagoya University, the only research institute in the world that develops and supplies emulsion film, has developed facilities and technology to increase film production capacity by a factor of 10, making it possible to conduct this experiment. The assembly of the telescope with an aperture area of 2.5 square meters was completed in Australia, and the balloon release was carried out in April 2023. 24 hours of balloon flight achieved observations of the Vela pulsar and the Galactic center region. The recovery of the instruments and development in Japan were completed, and data acquisition and analysis are starting with the aim of revealing a high-resolution cosmic gamma-ray view.

References

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