PROCEEDINGS OF SCIENCE

New high-precision measurement system for emulsion gamma ray telescope in sub-GeV/GeV

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The Gamma-Ray Astro-Imager with Nuclear Emulsion (GRAINE) project is aimed at the precise observation of astronomical gamma-ray sources in the energy range of 10 MeV-100 GeV using a balloon-borne telescope utilizing a nuclear emulsion, which can help realize precise imaging with a high angular resolution (1.0° at 100 MeV), polarization sensitivity and a large aperture area (10 m^2). The third balloon-borne experiment is GRAINE2018, performed in Australia with an aperture area of 0.4 m^2, in which the brightest known gamma-ray source, the Vela pulsar, was clearly detected and the emulsion gamma-ray telescope with the highest angular resolution in this energy region was established. Although a high-speed scanning system, which was used for scanning all tracks recorded in emulsion films in GRAINE2018, was not accurate enough to ensure the optimum performance of the emulsion film. We developed new high-precision scanning system for only the gamma-ray events detected by the high-speed scanning system. We will report a performance demonstration of the new scanning system for GRAINE2018, and will report the next experiment, GRAINE2023, with an aperture area of 2.5 m^2.

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1. Introduction

The observation of cosmic gamma rays is crucial for understanding high-energy astrophysical phenomena. The Large Area Telescope on the Fermi Gamma-ray Space Telescope (Fermi-LAT) launched in 2008 was used to survey the sub-GeV/GeV gamma-ray sky [1]. The high-sensitive observation detected more than 5000 gamma ray sources, and many significant results were reported. Furthermore, a combined analysis using gravitational waves and high-energy neutrinos recently led to new insights [2][3], making the observation of cosmic gamma-rays even more significant. However, the observations of the Galactic center or plane region, which contains many gamma-ray sources and diffuse emissions, are limited by its angular resolution and may suffer from particularly large systematic errors. Thus, observations with higher angular resolution are required to implement the next step of gamma-ray astronomy.

The Gamma-Ray Astro-Imager with Nuclear Emulsion (GRAINE) project pertains to the precise observation of cosmic gamma rays in the 10 MeV–100 GeV region using a balloon-borne telescope with a nuclear emulsion chamber [4]. A nuclear emulsion is a three-dimensional tracking detector with submicron spatial resolution. It can precisely measure the electron and positron tracks produced in pair production (γ (Z or e^-) $\rightarrow e^+e^-$ (Z or e^-) where Z is an nucleus.) immediately below the conversion point. Thus, the angular resolutions obtained using the nuclear emulsion film is excellent for gamma rays (1.0° at 100 MeV and 0.1° at 1 GeV), which are approximately an order of magnitude higher than those obtained using the Fermi-LAT, and it is highly sensitive to gamma-ray polarization. The GRAINE project plans to observe with an aperture area of 10 m^2 repeatedly. Such an observation with a high angular resolution is expected to help address the problem of unexpected GeV gamma-ray excess in the Galactic center region [5], aid in obtaining the first result of polarization observation for the pulsar, blazer in the high-energy region.

So far, in the GRAINE project, the detector has been developed and balloon experiments have been conducted repeatedly. The angular resolution and polarization sensitivity of the nuclear emulsion film was demonstrated through beam experiments [6][7]. Automated emulsion read-out systems were developed while the study of the emulsion gamma-ray telescope. The scanning speed has been improving, and it has realized some experiments with large amount of emulsion films. We also conducted four balloon experiments. The third one is GRAINE2018, performed in Australia, in which the brightest known gamma-ray source, the Vela pulsar, was clearly detected with the latest high-speed scanning system, Hyper Track Selector [8], and the emulsion gamma-ray telescope with the highest angular resolution in this energy region was established [14]. The validity of the obtained angular resolution was confirmed [15]. The latest one is GRAINE2023, performed in Australia, and it is just under analyzing.

The nuclear emulsion records the tracks for all the charged particles, and a high-speed scanning system was necessary to measure enormous number of tracks recorded in the film and to search gamma-ray events. However, only the gamma-ray events detected by the high-speed system could be reanalyzed using another system, which has better measurement accuracy. Thus, we developed an automatic high-precision measurement system combining the high-speed system for the observations with a large aperture area. In this study, we illustrate the method of measurement used the new high-precision system comparing with the high-speed system, and evaluate the measurement accuracy. Furthermore, we demonstrate it for the gamma-ray events in GRAINE2018.

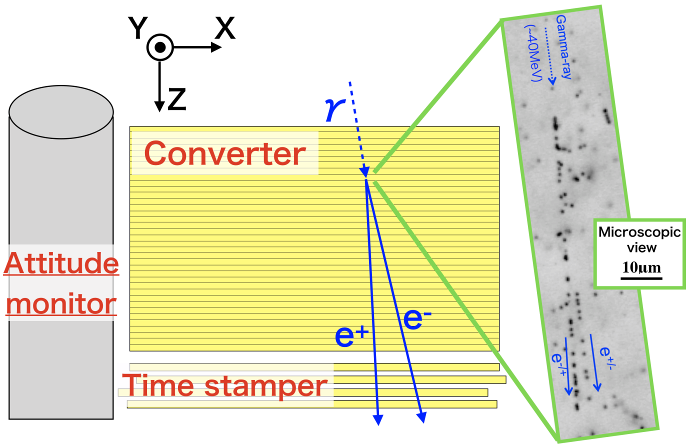

Figure 1: Emulsion gamma-ray telescope, cross sectional view of the emulsion chamber and attitude monitor.

2. GRAINE2018 experiment

An emulsion gamma-ray telescope consists of an emulsion chamber and a star camera for the attitude monitor (Figure 1). Gamma rays enter the emulsion chamber and get converted into electrons and positrons in the converter. For GRAINE2018, the converter consisted of 100 emulsion films, each composed of a 180-μm-thick plastic film and 75-μm-thick emulsion layers (measuring $25 \times 38\,\mathrm{cm}^2$) applied on both sides. All tracks are recorded as the form of a series of silver grains, and the right figure in Figure 1 is microscopic view of a gamma-ry event. Each event could be mapped in terms of celestial coordinates by combining the direction, time, which is obtained by multistage shifter [16], and attitude information, which is obtained by star camera. GRAINE2018 balloon experiment was conducted on April 26, 2018, in Alice Springs Australia. The duration of the flight was approximately 17 h and its altitude was more than 35 km (3–5 $\mathrm{g/cm}^2$ of the residual atmosphere). We used this flight films for developing the new high-precision scanning system.

3. High-precision scanning system

3.1 scanning method

Existing emulsion scanning machine, S-UTS [17], is used as hardware of the high-precision scanning system. We developed new scanning algorithm. Figure 2(a) shows tomographic image of emulsion layer taken by high-speed and high-precision system, and Figure 2(b) shows depth dependence of brightness of one grain taken by high-precision system. In high-speed system, the image with the 0.45 μm of pixel is binarized, and tracks are searched through the 16 binarized tomographic images with the previous track selector algorithm [17]. The method uses simple shift and sum functions, and detects tracks as straight lines. On the other hand, the size of pixel is 0.15 μm in high-precision system, and the XY positions of each silver grain are decided as centroid of brightness in the pixels. Furthermore, imaging interval of each tomographic image is 0.5 μm in high-precision system, 4 μm in high-precision system, and the Z positions of each grain are

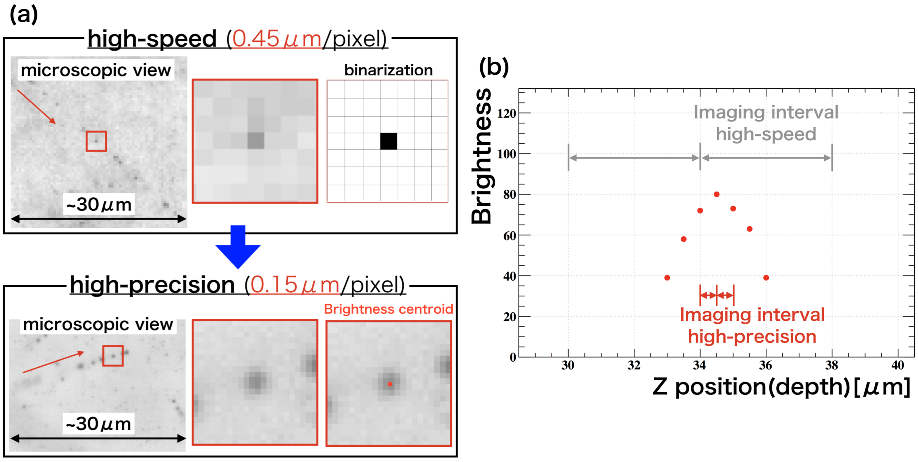

Figure 2: (a): Tomographic image of emulsion layer taken by high-speed and high-precision system. In high-speed system, the image is binarized, and in high-precision system, positions of each grain are decided as centroid of brightness in the pixels. (b): Depth dependence of brightness of one grain taken by high-precision system. Imaging interval is 4 μm and 16 tomographic images are taken for an emulsion layer in high-speed system, and 0.5 μm and 150 images in high-precision system.

decided as centroid of brightness too. Thus, positions of each grain are decided precisely through the described algorithm in high-precision system.

3.2 Evaluation of position determining accuracy

The position determining accuracy of the developed high-precision scanning system was evaluated. The high-energy tracks in the flight films of GRAINE2018 was scanned for the evaluation. These tracks penetrate the converter from top to bottom with a lower differences in angles caused by multiple Coulomb scattering than the angular resolution of the high-speed scanning system, and the selection requirement cut 99.9% of 10 GeV proton tracks. Thus, these tracks consists of straightly aligned silver grains in emulsion layers, so the accuracy can be estimated to evaluate the deviation of each silver grain from the fitted straight line. Figure 3(a) shows the obtained standard deviation for one track and simulated value for 10000 pseudo tracks with assuming the position determining accuracy. Figure 3(b) is the probability, χ, distribution of the accuracy. χ is calculated by $\chi = \sqrt{d^2_{X-XY} + d^2_{Y-XY} + d^2_{Y-YZ} + d^2_{Z-YZ} + d^2_{X-XZ} + d^2_{Z-XZ}}$ where d_{X-XY} is difference between the deviation obtained from the data, red line, and mean value of the simulation, that of the yellow distribution, for the deviation in X direction for XY projection of silver grains (Ref. top left in Figure 3(a)). The others are same in X,Y,Z direction for XY,YZ,XZ projection. Figure 4 presents the distribution of the most probable accuracy obtained from 189 tracks. The mean values indicate the accuracy in the direction of the plane, $\delta_{x,y} = 0.067 \pm 0.001$ μm, and that in direction of the depth, $\delta_z = 0.231 \pm 0.007$ μm. This value was approximately an order of magnitude smaller than that attained by the high-speed scanning systems ($\delta_{x,y} \simeq 0.4$ μm, $\delta_z \simeq 2.0$ μm).

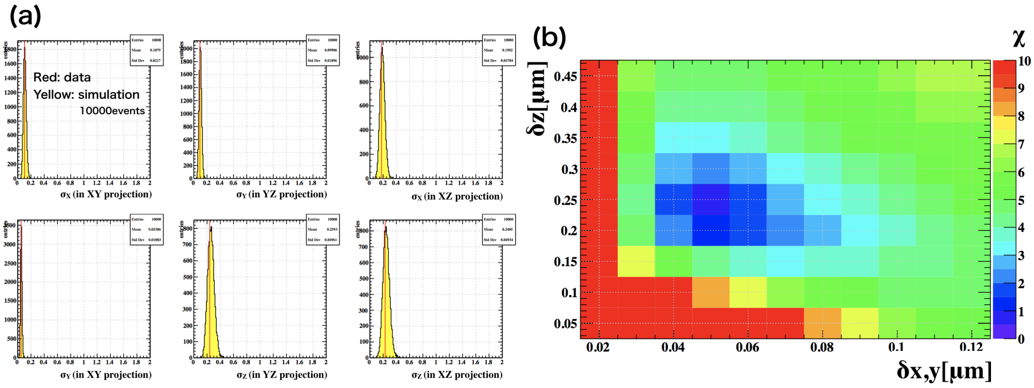

Figure 3: (a) The obtained standard deviation for one track (at red line) and simulated value for 10000 pseudo tracks with assuming the position determining accuracy (yellow distribution), the accuracy in the direction of the plane, $\delta_{x,y} = 0.05\ \mu$m, and that in direction of the depth, $\delta_z = 0.25\ \mu$m. (b) Probability distribution of accuracy in determining the position.

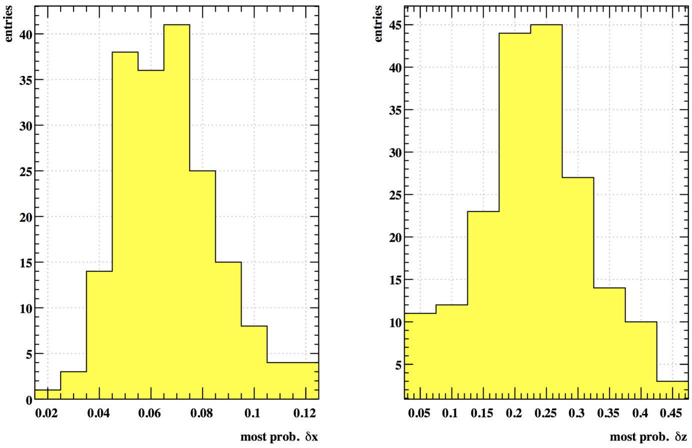

Figure 4: The distribution of the most probable accuracy obtained from 189 tracks. The mean values indicate the accuracy in determining the position in the direction of the plane, $\delta_{x,y} = 0.067 \pm 0.001\ \mu$m, and that in the direction of the depth, $\delta_z = 0.231 \pm 0.007\ \mu$m.

4. Performance for gamma-rays with new system

4.1 evaluating method

The gamma-ray direction and energy were reconstructed using the angles of the electron and positron tracks and their momenta determined using the differences in angles caused by multiple Coulomb scattering. Details of the analysis method is described in [13]. The angles of the electron and positron tracks are determined by High-speed scanning system when tracks are detected in both emulsion layers and virtual track in the base film, called a "base track", is defined by linking the passage positions at both surfaces of the base film. We scanned the emulsion layers around the gamma-ray events detected high-speed system with using the new high-precision system, and redetermined the angles of the electron and positron base tracks and re-reconstructed the gamma-ray

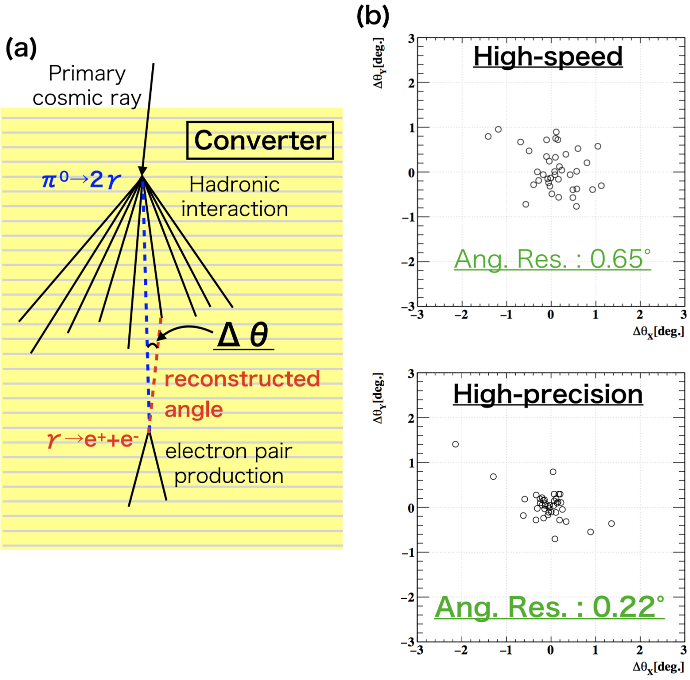

Figure 5: (a) The evaluation method for the observation performance in the flight data. (b) The distribution of angle difference, $\Delta\theta$, obtained by the high-speed system and the developed high-precision system.

direction using them.

For evaluating the performance of high-precision system, concomitant gamma-ray events from hadronic interaction in GRAINE2018 was used. Figure 5(a) presents the evaluation method. Concomitant gamma-rays mean that gamma-rays produced in π^0 decays($\pi^0 \rightarrow 2\gamma$), these π^0 are produced hadronic interactions caused by some cosmic rays (such as proton and helium nucleus) enter the detector during the observation. The arrival direction of these gamma-rays can be determined, and the angular resolution can be evaluated from the distribution of angle difference, $\Delta\theta$. This evaluation method was used for GRAINE2018 and the detail is in [15]. In this study, we rescanned the randomly selected 40 concomitant gamma-rays in 500-700 MeV with the high-precision system, and around 100 high-energy tracks were scanned to correct the difference of the scanning coordinate between the high-speed and the high-precision system for each gamma-ray event because the hadronic interaction events are in the coordinate of high-speed.

4.2 Result

Figure 5(b) shows the distribution of angle difference, $\Delta\theta$, obtained by the high-speed system and the developed high-precision system. The gamma rays reanalyzed by the high-precision system is concentrated more around the origin, which was the expected direction. The angular resolution is defined as the radius which contains 68% of the events after subtracting the uncertainty of the expected direction calculated for each incidence-angle and energy region (detail is in [15]). Thus, the angular resolution obtained by the high-precision system is about three times less than that obtained by high-speed system. Figure 6 shows the summary of this study. Yellow line shows the

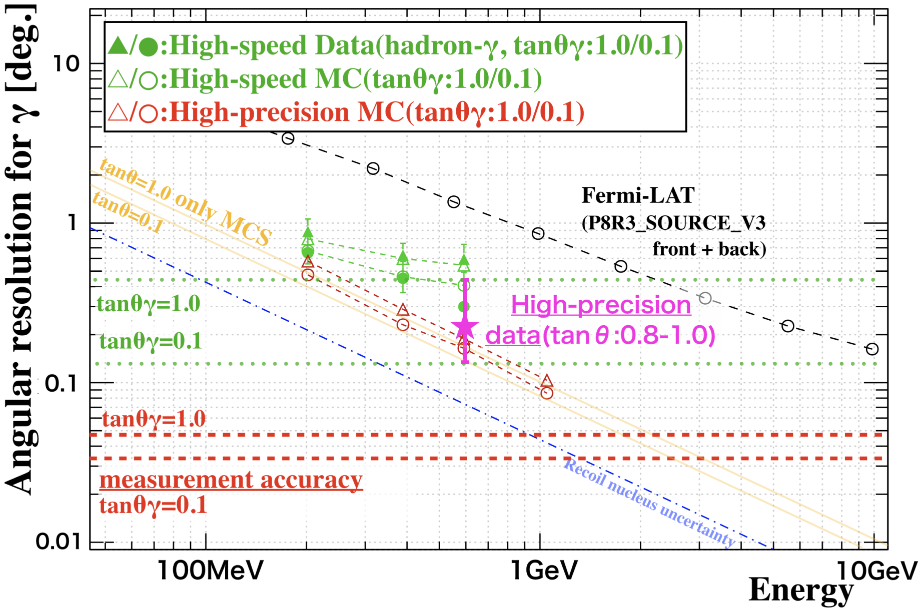

Figure 6: Energy dependence of the angular resolution for gamma ray. Yellow lines are simulated angular resolution with only the multiple Coulomb scattering. Green dotted horizontal lines are measurement accuracy of high-speed system with different two incident angles. Red dashed lines are same as that for high-precision system. Green opened triangle and circles are simulated angular resolution for gamma-ray event and the evaluated value with high-speed system with different two incident angles. Red marks are same as that, and magenta star shows the evaluated value obtained by high-precision system in this study.

expected angular resolution with only the multiple Coulomb scattering. The horizontal lines shows measurement accuracy. The total angular resolution for gamma-rays is affected by both of them, so the angular resolution obtained by the high-speed system is limited by the measurement accuracy especially in high-energy region. On the other hand, developed high-precision system achieved higher measurement accuracy to observe in higher energy region. Furthermore, magenta star shows that the evaluated value obtained by the flight data is consistent with the expected performance, red opened triangle.

5. summary and prospects

We promote the GRAINE project, which is a precise cosmic gamma-ray observation project. Through the third balloon experiment, GRAINE2018, the emulsion gamma-ray telescope was performed with highest angular resolution in >80 MeV. However, the measurement accuracy of emulsion scanning system should be better to observe higher energy region, for example around a few GeV region where has the problem of unexpected GeV gamma-ray excess in the Galactic center region.

The new high-precision scanning system was developed. The concept is that the scanning system with higher accuracy scan precisely only around the gamma-ray events detected in the enormous track data by high-speed system. Thus, We developed the new high-precision system, and the position determining accuracy achieved approximately an order of magnitude smaller than that attained by the high-speed scanning systems, and $\delta_{x,y}$ was almost same as the intrinsic value of the nuclear emulsion. Furthermore, we built the algorithm for combining the existing high-speed system. The angular resolution for the gamma rays was evaluated with using the concomitant gamma-ray events in GRAINE2018, and about three times less resolution was obtained.

The fourth balloon experiment, GRAINE2023, was conducted on April 2023 in Australia with an aperture area of $2.5\,\mathrm{m}^2$, it was 6 times larger than that in GRAINE2018. The total flight duration was 27 hours, and the Galactic center region was observed for the first time with the emulsion gamma-ray telescope, flight duration in GRAINE2018 was not enough to observe there. The flight data is just analyzing, and the developed new high-precision scanning system will realize precisely observation in the Galactic center region with the highest angular resolution, 0.1° at 1 GeV. The gamma-ray profile in immediate vicinity from the galactic center will be obtained, and it may help address the problem of unexpected GeV gamma-ray excess. Furthermore, the precisely measurement of electron and positron tracks with the new system will realize the polarization measurement, and it will be started in GRAINE2023.

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