PROCEEDINGS OF SCIENCE

GeV Gamma-Ray Detection Performance of the Nuclear Emulsion Telescope in the GRAINE2023 Balloon Experiment

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We are advancing precise observations of cosmic gamma rays in the sub-GeV to GeV energy range using a balloon-borne nuclear emulsion telescope with high angular resolution (0.1° at 1 GeV). Balloon experiments were conducted in 2011, 2015, 2018, and 2023. In 2018, we achieved the first detection of an astronomical gamma-ray source and imaged the Vela pulsar with the highest angular resolution in the sub-GeV region. In April 2023, we successfully conducted a 27 hour balloon flight during which the Vela pulsar and the region around the Galactic center were observed (GRAINE 2023).

The nuclear emulsion telescope consists of a converter, a time stamper, and an attitude monitor. The converter, composed of stacked nuclear emulsion films, records electron–positron pairs produced by gamma rays. The excellent spatial resolution of nuclear emulsion enables precise reconstruction of gamma-ray directions and momentum measurements via multiple Coulomb scattering. However, detecting high-energy (>GeV) gamma rays is challenging due to the small opening angles of pair tracks and reduced scattering of high-momentum electrons.

We present a new gamma-ray selection and momentum reconstruction method to improve sensitivity in the GeV energy range. This paper reports the current analysis of the GRAINE 2023 converter data and the status of the newly developed gamma-ray selection technique.

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1. The GRAINE Project and the 2023 Balloon Experiment

Because gamma rays propagate without deflection by magnetic fields, observations of cosmic gamma rays provide crucial clues for understanding cosmic-ray acceleration sources and high-energy astrophysical phenomena in the universe. The Fermi Gamma-ray Space Telescope, launched in 2008, has dramatically advanced gamma-ray astronomy in the sub-GeV to GeV energy range. However, several limitations remain, including relatively poor angular resolution compared to other wavelengths and the lack of polarization-sensitive observations.

The GRAINE project aims to overcome these limitations by deploying an emulsion telescope composed of nuclear emulsion films onboard a balloon platform. By detecting electron–positron pair production with submicron spatial resolution, the experiment seeks to improve angular resolution by approximately one order of magnitude, enabling high-resolution imaging and polarization measurements of gamma-ray sources. The emulsion telescope consists of a converter section made of stacked nuclear emulsion films to record pair-production events, a time stamper (multi-stage shifter) that assigns timing information to tracks by driving multiple emulsion films with different cycles [2], and star cameras that monitor the attitude of the telescope.

In the 2018 balloon experiment, imaging of the Vela pulsar was successfully achieved with a telescope of 0.38 m^2 aperture area, demonstrating that balloon-borne emulsion telescopes can observe gamma-ray sources with the highest angular resolution in the world [1]. Since 2023, scientific observations using repeated balloon flights with a telescope of significantly enlarged aperture area have been initiated.

The 2023 balloon experiment conducted in Australia (GRAINE2023) employed a telescope with an aperture area of 2.5 m^2, corresponding to 6.5 times the scale of the 2018 experiment. Each converter unit consists of 90 nuclear emulsion films of 25 cm $\times$ 50 cm stacked and vacuum-packed, and a total of 20 such units were used. The balloon was launched from the Alice Springs balloon launch station on April 30, 2023, and successfully achieved a long-duration flight with approximately 24 hours of level float, covering observation periods in which both the Vela pulsar and the Galactic center region entered the field of view.

After the flight, the nuclear emulsion films were recovered and transported to Japan, where all films were developed using the large-scale development facility at Gifu University. Subsequently, track data were read out using the automatic track scanning system at Nagoya University. Based on the reconstructed track data, gamma-ray events are being selected, and astrophysical analyses are currently underway by assigning timing and attitude information to these events.

2. Limitations of the Conventional Gamma-Ray Event Selection

The flow of gamma-ray event selection from detected tracks is shown in Figure 1. In the conventional gamma-ray selection procedure, eight consecutive emulsion films are used: three upstream films serve as veto layers for a given search film, and electron–positron tracks extending downstream from the search film are identified as gamma-ray events.

To date, more than 7×10^7 gamma-ray events have been selected from the GRAINE2023 data, and astrophysical analyses, mainly in the sub-GeV energy range, are currently in progress using these data.

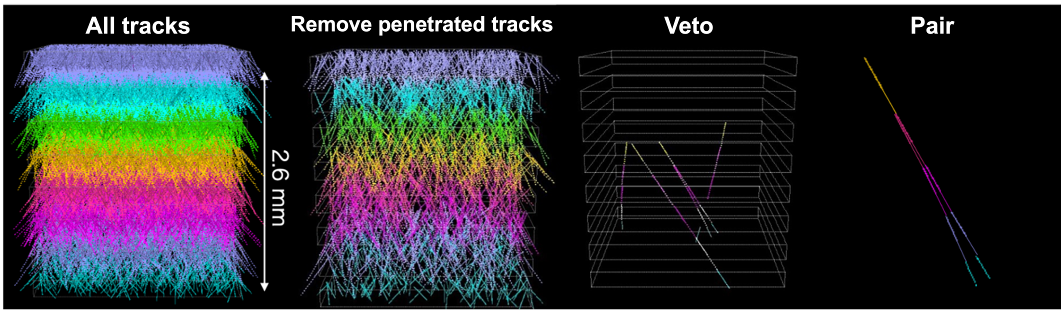

Figure 1: Flow of the gamma-ray event selection. Different colors indicate different emulsion films.

Data recorded in nuclear emulsion films are digitized by an automatic track scanning system, enabling gamma-ray event selection. During the high-speed track reconstruction process, multiple candidate tracks are generated around true tracks. Therefore, tracks with similar positions and angles are merged into a single track. Although the merging criteria depend on track angle, tracks within approximately 5 μm in position and 0.2 in angular difference (in $\tan\theta$) are typically merged.

Because the two tracks produced by electron–positron pair production have small spatial and angular separations, they are likely to be merged into a single track near the conversion point. The two tracks are recognized as a pair only after they propagate downstream and separate beyond the merging criteria. For pair-production events, we define the *Split Layer* as the index of the first emulsion film, counted from the conversion film as zero, in which the two tracks are reconstructed as separate tracks.

In the conventional gamma-ray selection, when searching for a partner track corresponding to a track that remains after the veto process in the search film, the search range is limited to events with Split Layer ≤ 2. Events that do not separate within this range are not identified as gamma-ray events. As the gamma-ray energy increases, the opening angle of the electron–positron pair becomes smaller, and multiple Coulomb scattering of each electron is reduced. As a result, the Split Layer tends to increase, leading to a significant reduction in detection efficiency at higher energies.

To estimate the current gamma-ray detection efficiency, we performed Geant4 simulations in which gamma rays of different energies were injected vertically into the converter. For each event, the Split Layer was determined by examining, film by film, whether the tracks would be merged under the same conditions as the current reconstruction procedure.

Figure 2 shows the Split Layer distributions for gamma rays with energies of 500 MeV, 2 GeV, and 5 GeV. The red line indicates the partner-track search range used in the conventional selection; events with Split Layer values beyond this line cannot be identified as gamma-ray events. While more than 80% of gamma rays with energies of a few hundred MeV separate within the search range, most gamma rays in the multi-GeV range do not. This clearly demonstrates that the conventional search range is insufficient for detecting gamma-ray events at multi-GeV energies.

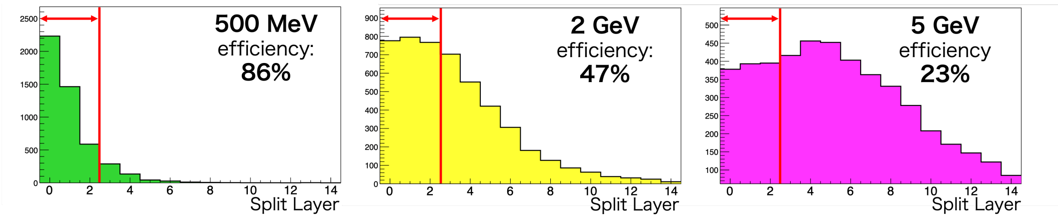

Figure 2: Simulated Split Layer distributions for different gamma-ray energies. Events to the left of the red line are separated into two tracks within the conventional search range.

3. New Gamma-Ray Event Selection

To improve the detection efficiency for gamma rays in the multi-GeV energy range, we developed a new gamma-ray event selection procedure in which the search range for partner tracks was extended from Split Layer = 2 to Split Layer = 23. Although there is still room for further optimization, this search range allows more than 90% of 10 GeV gamma rays incident vertically on the converter to be selected as gamma-ray events.

The new selection procedure is applied only to tracks originating in the search film for which no partner track was found by the conventional procedure. The criteria for identifying a partner track are as follows: the track must be connected across at least three emulsion films, the minimum distance between the two tracks must be less than 15 μm, and the angular difference ($\Delta \tan \theta$) must be smaller than 0.08. Tracks satisfying all of these conditions are identified as an electron–positron pair.

By extending the search range, the probability of accidentally associating nearby unrelated tracks increases, leading to an increased fraction of false pair-production candidates (noise contamination). To estimate the noise contamination rate of the new procedure, the same selection was applied to through-going tracks for which a true pair cannot exist. Using this method, the noise contamination rate was estimated directly from data to be approximately 30% under the above conditions.

To further reduce the noise contamination, we introduced an additional cut using momentum information, in addition to the position and angular criteria. Tracks with low momentum undergo large variations in position and angle due to multiple Coulomb scattering. Therefore, if at least one of the electron–positron pair has low momentum, the two tracks are expected to separate at a small Split Layer. Conversely, events with both large Split Layer and low momentum are likely to be noise. The cut region was determined using Geant4 simulation data by examining the relationship between electron momentum and Split Layer for pair-production events (Figure 3). By applying this cut, the noise contamination rate was reduced to approximately 13%.

To validate the new gamma-ray selection procedure, the expected Split Layer distribution in the observation data was estimated using simulations. To avoid the influence of time-stamp efficiency, data without timing information were used in this study. Since the converter contains not only events recorded during flight but also those accumulated while on the ground, gamma-ray energy distributions incident on the converter were constructed using gamma-ray flux models for both ground and flight conditions together with their respective exposure times. Gamma rays were then

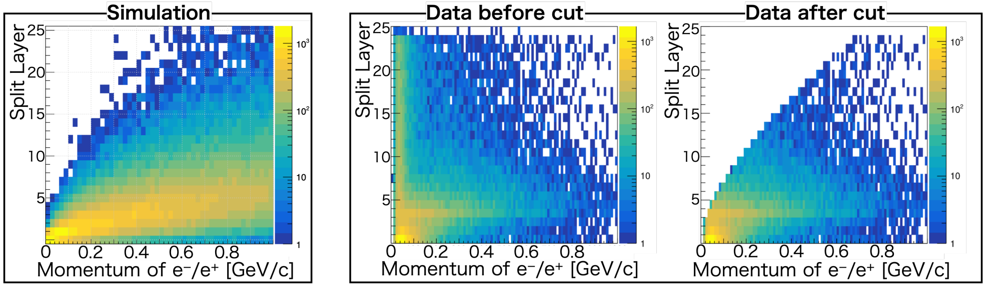

Figure 3: Relationship between the electron momentum and the Split Layer in pair production. (The simulation does not use the same energy distribution as the data.)

injected according to these distributions in GEANT4, and events undergoing pair production were reconstructed to reproduce the Split Layer distribution.

Figure 4 shows a comparison between the simulated and observed Split Layer distributions. The distribution estimated by simulation agrees well with the data obtained by combining the conventional and new selection procedures, indicating that gamma-ray events are selected as expected. Comparing the number of selected events, the total event count increased by a factor of 1.2 over all energies, while the number of events above 1 GeV increased by a factor of 1.6.

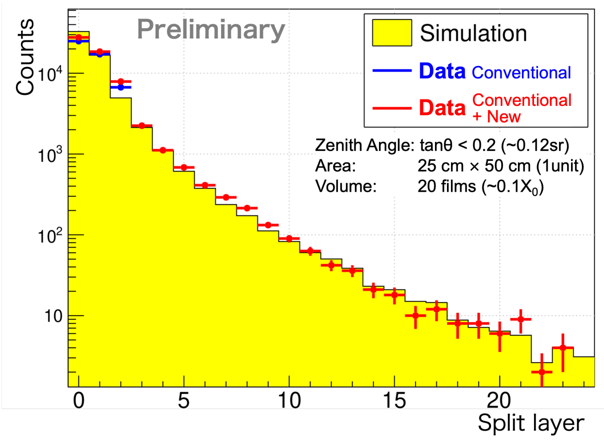

Figure 4: Comparison of the Split Layer distributions for gamma-ray events between simulation and data. The blue line shows events selected by the conventional method only, while the red line shows the combined result of the conventional and the new methods.

Next, we focus on the silver grain density of the selected electron–positron pairs. Tracks reconstructed by the scanning system are assigned a silver grain density parameter called the Volume Pulse Height (VPH). This parameter is approximately equal to the total number of hit pixels in the tomographic images composing a track and is calculated before the track-merging procedure. Figure 5 shows the VPH distributions of the most upstream track in gamma-ray events and of individual electron tracks.

For two nearby tracks to be reconstructed as a single dense track in the VPH calculation, the position difference must be within 2.2 μm and the angular difference (in $\tan\theta$) within 0.01. This condition is significantly stricter than the track-merging criteria (position difference < 5 μm and

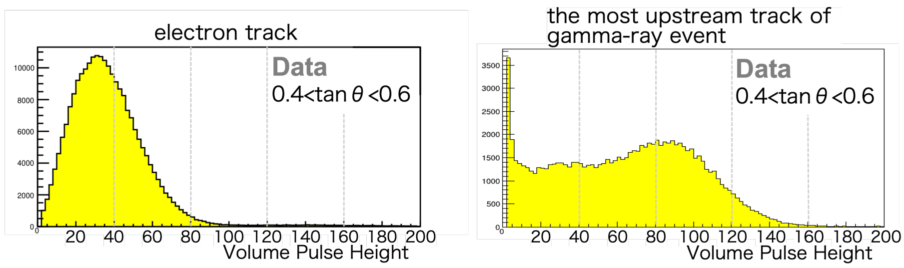

Figure 5: VPH distributions of the most upstream track in gamma-ray events (left) and of individual electron tracks (right).

$\Delta \tan\theta < 0.2$), and the probability of accidental track overlap within this range is sufficiently low. The cluster around VPH $\sim$ 80 corresponds to approximately twice the VPH of a single electron track, which is consistent with the presence of two extremely close tracks from pair production. On the other hand, a population with VPH values comparable to those of single electrons is also observed, which is likely due to relatively low-energy events in which the position and angular separation of the electron–positron pair is larger.

At present, the VPH response for single tracks as a function of angle and momentum is well understood. However, the detector response for VPH distributions produced by two extremely close tracks is still not sufficiently understood. By improving this understanding, we plan to use VPH information as an additional handle for noise rejection and gamma-ray event identification in future analyses.

4. Summary and Outlook

To improve the detection efficiency of gamma rays in the multi-GeV range, we developed a new gamma-ray selection procedure that extends the search range for electron–positron pair tracks. By comparison with simulations and by examining the VPH distributions, we confirmed that high-energy gamma-ray events are successfully selected. In the future, by establishing a momentum measurement method for high-momentum electrons, we aim to accurately determine the energies of GeV gamma rays and advance high-resolution astronomical analyses with the GRAINE experiment.

References

[1] S. Takahashi, et al. *First Emulsion γ -Ray Telescope Imaging of the Vela Pulsar by the GRAINE 2018 Balloon-borne Experiment.* ApJ 2023;960:47.

[2] M. Oda, et al. *First demonstration of a roller-driven timestamp mechanism for long-duration observations with high time resolution using large-area emulsion films.* Prog Theor Exp Phys 2022;2022:113H03.