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Observation of sub-GeV atmospheric gamma rays on GRAINE 2018 balloon experiment and comparison with HKKM calculation

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We report a precise measurement of the sub-GeV atmospheric gamma-ray spectrum at balloon altitude on GRAINE 2018 experiment, and comparisons with the predictions calculated by the latest HKKM, which is widely known as a model for atmospheric neutrino flux calculation. Understanding the interactions between cosmic rays and atmospheric nuclei is important for accurate atmospheric neutrino flux calculations. Observation data of sub-GeV atmospheric gamma rays at balloon altitudes are useful for verifying such hadronic interaction models and pion productions in the low energy region. In April 2018, we conducted a balloon experiment (GRAINE 2018) in Australia with the aim of detecting and imaging the celestial gamma-ray sources with the nuclear emulsion telescope. Following flight data analysis, we derived an atmospheric gamma-ray spectrum in 0.1–1 GeV region at altitudes of ∼36 km (residual depth ∼ 4 g / cm^2). The flux around the 1 GeV region is in good agreement with the HKKM prediction and smoothly connects to the multi-GeV observations of past balloon experiments. On the other hand, the flux around 0.1 GeV shows a discrepancy with the prediction. In this presentation, the balloon experiment, flight data analysis, and observation results are described.

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1. Introduction

Gamma-Ray Astro-Imager with Nuclear Emulsion (GRAINE) project is a balloon-borne experiment to observe cosmic gamma rays in the sub-GeV and GeV energy regions [1–8]. The emulsion gamma-ray telescope mainly consists of nuclear emulsion films. Thanks to precise measurements of the beginning of electron-positron pair creation event using nuclear emulsion, the telescope enables to measure gamma-ray direction with 0.1° resolution in the GeV region (1° at 0.1 GeV) and has the sensitivity of gamma-ray polarization. Nuclear emulsions also have the feature of being able to increase the size of the detector without compromising spatial resolution. GRAINE aims for unique observations that current telescopes on satellites (Fermi Large Area Telescope and AGILE) cannot reach with an order of magnitude higher angular resolution, polarization sensitivity, and the largest aperture area of 10 m^2.

In April 2018, we conducted the balloon experiment (GRAINE 2018) to demonstrate the over-all performance of the emulsion telescope using the prototype model of 0.4-m^2 aperture. As the result, We have succeeded in the first detection of gamma-ray source, Vela pulsar, and the world's highest imaging performance in the 0.1-GeV energy region [9]. According to the results on GRIANE 2018, the next experiment is approved as JAXA balloon experiment program, and the scientific observation will start using enlarged emulsion telescopes.

The main background of GRAINE is atmospheric gamma rays produced via interactions between cosmic ray hadrons (protons, helium nuclei, etc.) and atmospheric nuclei. Towards the next experiment, understanding of the observation performance in the wider energy region (high energy side: multi GeV and low energy side: several tens MeV) is important and the observation data of atmospheric gamma rays is one of the suitable checking sources. In addition, understanding the interactions between cosmic rays and atmospheric nuclei is important for accurate atmospheric neutrino flux calculations. Data of sub-GeV atmospheric gamma rays at balloon altitudes are useful for verifying such hadronic interaction models and pion productions in the low energy region.

In this paper, we report a precise measurement of atmospheric gamma-ray spectrum in 0.1–1 GeV energy region at altitudes of $\sim$ 36 km (residual depth $\sim$ 4 g / cm^2) on GRAINE 2018 experiment. And then we compare it with the prediction calculated by the latest HKKM model, which is widely known as a model for atmospheric neutrino flux calculation [10].

2. GRAINE Balloon Experiment in 2018

2.1 Experimental Apparatus

Figure 1 shows a photograph of the payload of GRAINE 2018 and a cross-sectional view of the emulsion telescope. The main detector, emulsion gamma-ray telescope, was deployed inside a cylindrical shaped pressure vessel gondola [11]. Attitude monitors consisting of star cameras were placed in three different directions on the outside of the gondola. Emulsion telescope consists of the following components from top to bottom of the detector: Flat-alignment films (two or three emulsion films and aluminum honey-comb boards); Converters (a hundred of emulsion films; thickness is 33 mm; 52% of a radiation length unit in the vertical direction); Time stampers (four-stage emulsion shifter[1]). Four units of converter (the size of each emulsion film is 38 cm $\times$ 25 cm) were deployed on GRAINE 2018, and the total aperture area is 0.38 m^2.

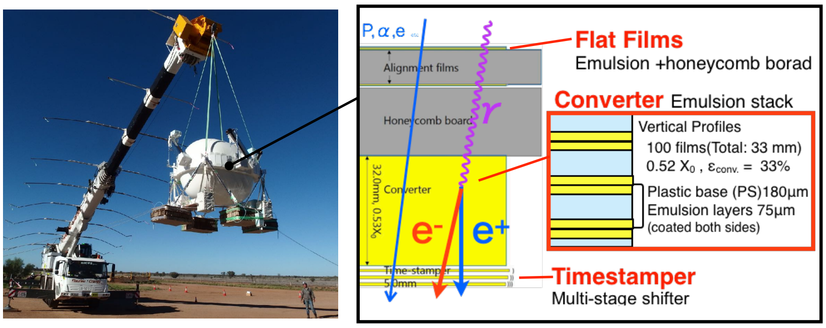

Figure 1: The left and right panes show a photograph of the payload of GRAINE 2018 and a cross-sectional view of the emulsion telescope, respectively.

2.2 Balloon Flight and Data Acquisition

The balloon flight of GRAINE 2018 was performed on April 26th, 2018. The payload was launched from Alice Springs balloon launching station in Australia, floated for 16 hours at an altitude of 36–38 km , and then was parachuted down after observation. The all equipments, including emulsion films, were recovered the next day 250 km southwest of Longreach. Flight films were immediately transported to the University of Sydney and were developed by May 13th.

Track data acquisition of all emulsion films was completed using an emulsion readout system, Hyper Track Selector, at Nagoya University [12] until the end of 2018. Hyper Track Selector read all tracks in the angular range within 0.95 radian toward the normal direction of the film (nearly equal the zenith) . The track density in each flight film was approximately 10^5 tracks/cm^2. Track finding efficiency of high quality emulsion films produced at Nagoya University is more than 95%, which is the enough performance for the large area emulsion data analysis.

3. Flight Data Analysis

Gamma-ray event ($\gamma \rightarrow e^- e^+$) selection was processed in the same way of the GRAINE 2015 converter analysis [7]. Figure 2 shows detected gamma-ray events in a flight film of GRAINE 2018 displayed on the three dimensional viewer. Approximately 2×10^4 events and total 7×10^6 events were detected in each film and all the converter films of GRAINE 2018, respectively.

The gamma-ray energy was determined using measured momenta of electron and positron. The left pane in figure 3 shows an event which was fully reconstructed using 95 converter films. Scattering angles of electron and positron can be measured using segmented angle obtained at each film, and their momenta were reconstructed by the multiple Coulomb scattering method. Since each track has a three-dimensional angle, two projection angles are obtained as two independent measurements. In this momentum reconstruction analysis, we used one of two projection angles, lateral-projection angle, which has small uncertainty of angle measurement by the readout system, and used segmented angles measured on up to 40 films downstream of the conversion position. The right-top and right-bottom panes in figure 3 show the comparison between the reconstructed gamma-ray energy and the Monte Carlo(MC) true energy, and RMS of the reconstructed energy as a function of the true energy, respectively. Here, we simulated using geant4.10.04.p02 package.

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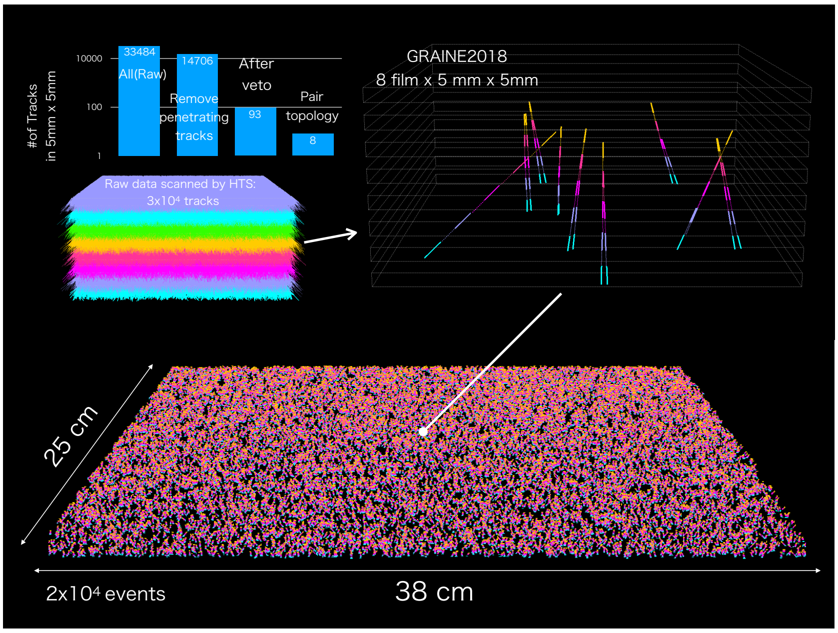

Figure 2: Detected gamma-ray events ($\gamma \rightarrow e^-e^+$) in a flight film of GRAINE 2018 displayed using the three dimensional viewer.

The energy resolution was expected to be ∼ 35% in 0.1–1 GeV region. The calibration of energy determination using flight data has been also performed. In the reference [13], the invariant mass of π^0 meson has been reconstructed using $\pi^0 \rightarrow \gamma\gamma$ decays occurred and detected in the converter, and the energy resolution has been evaluated to be 37.7 ± 6.9%

To simulate the detector response, we checked the consistency between observation data and MC data. Gamma rays with the simple power low spectrum were generated and shot in the simulated converter. Positions and angles of electron and positron tracks were smeared with the accuracy of the readout system, and the simulated track data was processed by the pair-event selection with the same criteria as the flight data analysis. Figure 4 shows distributions of opening angles between electron and positron tracks that were measured at the track-sprit plate. The MC events well reproduce the observed data in each energy bin.

In the reconstruction of the atmospheric gamma ray spectrum, we used the events detected by a converter unit during the Vela observation period (the duration and the averaged residual pressure were ∼ 6 hours and ∼ 4 g/cm^2, respectively). The background events from internal gamma rays were eliminated by the analysis of simultaneous tracks with gamma-ray events[9]. The detector response were estimated by MC data including the event selection and energy determination biases, and fluxes in the 0.1–1 GeV energy range were derived by the unfolding method using RooUnfold package.

4. Result and Discussion

Figure 5 shows spectra of atmospheric gamma rays observed at the balloon altitudes in the sub-GeV energy region. The vertical axis indicates differential fluxes divided by the residual

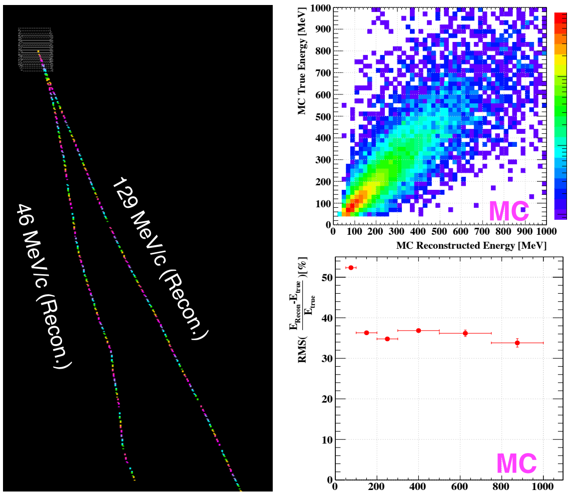

Figure 3: The left pane shows an event which was fully reconstructed using 95 converter films. The right-top and right-bottom panes show the comparison between the reconstructed gamma-ray energy and Monte Carlo true energy, and RMS of the reconstructed energy as a function of the true energy, respectively. (simulated by geant4.10.04.p02)

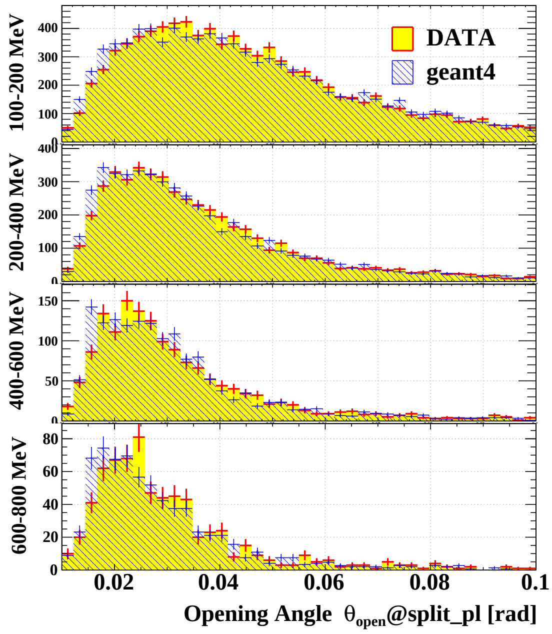

Figure 4: Distributions of opening angles between electron and positron tracks that were measured at the track-sprit plate. The filled and shaded histograms indicate the observation and Monte Carlo data, respectively.

atmospheric pressure in the unit of g/cm^2. Red plots are the result of GRAINE 2018. Black and white plots show past measurements on balloon experiments conducted in the late 60s and the early 70s Blue line indicates the prediction calculated by the HKKM model.

The discrepancy around 1 GeV has been observed between past measurements and the HKKM prediction, but the GRAINE 2018 result shows the favor of the HKKM prediction. Figure 6 shows spectra of atmospheric gamma rays including the Multi-GeV measurements obtained by balloon-borne experiments conducted around the 2000s. The GRAINE 2018 result around 1 GeV shows the smooth connection with the measurements by calorimetric detectors such as bCALET-2, BETS, MSC and ECC [14–17]. Concerning about 0.1 GeV region, GRAINE 2018 measurements and past measurements have fluxes that are about twice as large as the value predicted by the HKKM model. In this energy region, the flux fluctuates due to the influence of the geomagnetic cutoff at observation point, but this discrepancy cannot be explained by the effect. Especially in the low energy region, it may be necessary to readjust the model, such as reviewing the hadron interaction model.

5. Summary

Atmospheric gamma rays are the main background of GRAINE and the observation data are also used as a checking source for the amount of π^0 ($\fallingdotseq \nu$) produced from interactions between

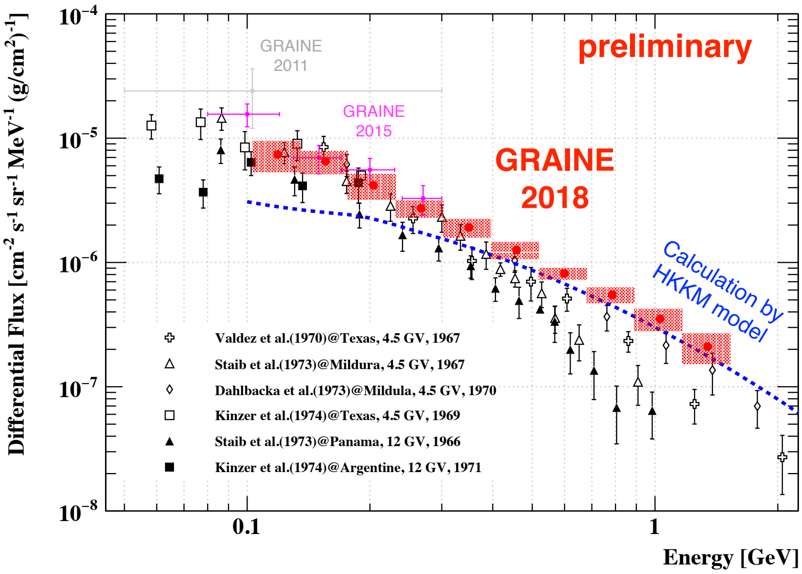

Figure 5: Measured spectrum of atmospheric gamma rays observed at the balloon altitude in the sub-GeV energy region. Red plots are the result of GRAINE 2018. Blue line indicates the prediction calculated by the HKKM model.

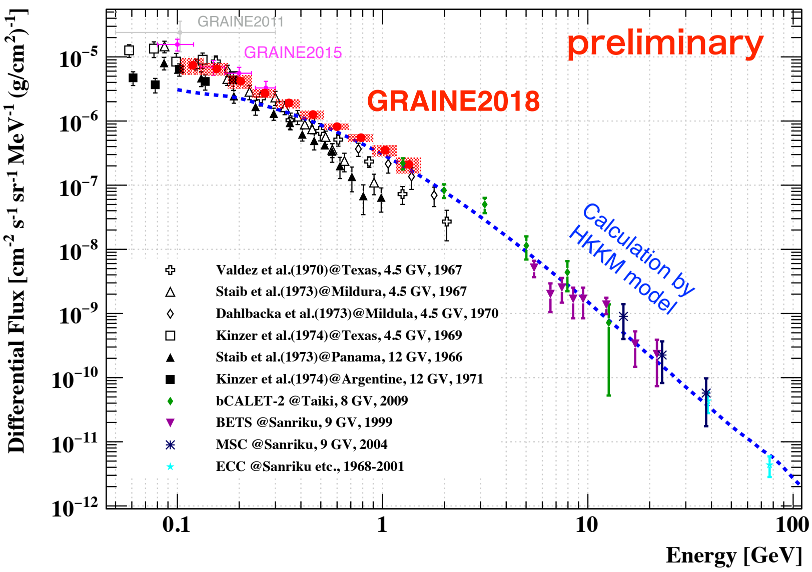

Figure 6: Measured spectra of atmospheric gamma rays including the Multi-GeV measurement obtained by balloon- borne experiments conducted around the 2000s.

cosmic rays and atmospheric nuclei at high altitudes. We have reported a precise measurement of the atmospheric gamma-ray spectrum (0.1–1 GeV) on GRAINE 2018 experiment, and comparisons with past measurements and the prediction calculated by the latest HKKM, which is widely known as a model for atmospheric neutrino flux calculation. Concerning about 1 GeV region, the discrepancy has been observed between past measurements in the 60s–70s and the HKKM prediction, but the GRAINE 2018 result shows the favor of the HKKM prediction. In addition, the result shows the smooth connection with the multi-GeV measurements by calorimetric detectors in the 2000s. Concerning about 0.1 GeV region, GRAINE 2018 measurement and past measurements have a flux that is about twice as large as the value predicted by the HKKM model. It may be necessary to readjust the model, such as reviewing the hadron interaction model.

The next balloon experiment of GRAINE was approved by JAXA. It is scheduled for 2023. Two payloads and two balloon flights using enlarged emulsion telescopes (the aperture area will be 2.5 m^2 and 6.6 times larger than that of GRIANE 2018) will be planned. The scientific observation of GRAINE will start toward initial targets such as precise observation of the galactic center, polarization measurement of pulsars, survey of transient sources, etc.

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