The project of cosmic gamma-ray observation by nuclear emulsion

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***Abstract*. A new gamma ray observation project with the balloon borne emulsion chambers is presented. New technique based on the accelerator emulsion experiments was implemented for studying high energy stellar objects with cosmic gamma rays. This paper provides the concept of this project and the current status as well as some results of test experiments.**

***Keywords*: gamma ray astronomy, nuclear emulsion technology, balloon borne experiments**

I. Introduction

One of the important issue of high energy astroparticle physics is to understand the origin and acceleration mechanism of charged primary cosmic rays. To investigate these charged particles below 10^{18} eV energies can not provide directly the answer of stellar objects which produce and accelerate primary particles, because of the complex interstellar magnetic field along their passages from the origin to the Earth. When the charged primary cosmic rays are accelerated and they propagate in the vicinity of high energy stellar objects, they can emit energetic penetrating gamma rays. They are directed in a line toward the high energy objects themselves. The gamma rays can be produced by several electromagnetic processes, nuclear decay processes and more exotic particle annihilations, in the vicinity of their sources [1].

To measure the direction of gamma rays, the inverse production mechanisms can be used in aimed energy ranges of gamma rays. For higher energies of 1 MeV of gamma rays, electron-positron pair production cross section dominates, so that converted e^+e^- pairs are detected in the tracking modules and their energies are obtained by the electromagnetic calorimeter modules. Above 100 GeV energies of gamma rays, their flux becomes quite small to observe them by the satellite and balloon borne instruments. And the electromagnetic cascade shower processes occur in the atmosphere. The Cherenkov technique thus plays an important role above 100 GeV energies [2].

The measurement of gamma ray objects are performed with the different angular resolutions, covering energy ranges and energy resolutions acheived by each detector. For example, cosmic gamma-ray telescopes can provide high energy objects such as Crab nebula, with several mrad angular resolutions. Now FERMI satellite [3] also can do that even with higher resolutions in GeV energies.

Though the nuclear emulsion chamber is sort of old fashioned tracking detectors, it can provide sub-mrad angular resolution with 10% energy resolutions. The recent advancement of automatic analysis of nuclear emulsion film enables to recognize tracks very fast.

In this paper, we report the concepts and advantages of emulsion telescope experiments, as well as some results of test experiments.

II. Concepts and Advantages

At GeV energy regions, gamma ray interaction with matter is dominated by electron-positron pair creation process. By detecting electron/positron pair in a tracking chamber system, the energy and direction of a gamma ray can be measured. The more accurate tracking system can provide a new GeV gamma ray telescope.

The nuclear emulsion film can record charge particle trajectories with sub-micron spatial resolution, 3-dimensionally, even if their energy losses are minimum ionization.

An OPERA film [4] has 44 μm thick emulsion layers coated on both sides of a 205μm thick TAC (cellulose triacetate) base. The uniformity of each layer is quite good due to machine pouring. Thin emulsion layers are optimized to recognize tracks by automatic scan

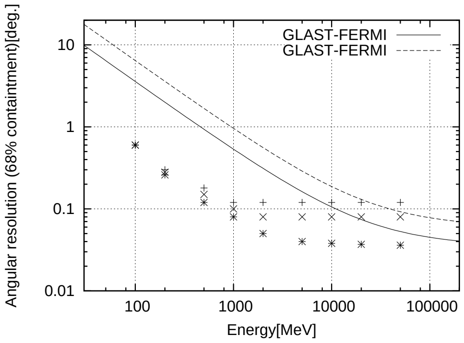

Fig. 1: Simulation results of angular resolution dependencies on gamma ray energies in a few cases of emulsion readout unit. Solid line and dashed one represent the angular resolution reported by GLAST team. Data symbols (plus,cross,asterisk) mean the emulsion digitizing readout accuracy of 0.3μm , 0.2μm and 0.1μm, respectively.

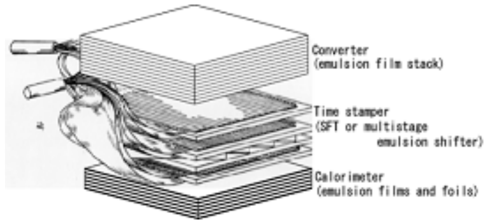

Fig. 2: The conceptual design of emulsion telescope. Though scintillating fiber tracker (SFT) systems would be used to get time stamp information of cosmic gamma ray events originally in this figure, it is going to be replaced by multistage emulsion shifter system, described in the following sections.

system. The background track density in an emulsion layer recorded before the balloon flight is minimized by the emulsion refresh function. Assuming that typical readout accuracy of track position is 0.3 μm, less than 2 mrad angular resolution is to be achieved above GeV energies. The simulation results of angular resolution are presented in Fig. 1 as a function of gamma ray energies.

The conceptual structure of emulsion telescope are shown in Fig. 2 and experimental profiles are summarized in Table I. The structure consists of three modules; (1) the converter part is constructed as emulsion film stacks, (2) the time stamp part part is equipped in order to register accurate time stamps of gamma ray events with their position information by using emulsion shifter or scintillating fiber tracker(SFT), discussing later on, (3)the calorimeter part has sandwich structures of emulsion films and metallic foils to produce electromagnetic shower of electron/positrons to determine each energies. Arrival directions of gamma rays are converted into the celestial coordinates by using the time stamp of each event derived from the emulsion shifter and the star monitoring systems.

The automatic emulsion scanning [5] capability has been improved at Nagoya University emulsion group for the purpose of neutrino oscillation experiments. The recognition of tracks in emulsion films has been carried by the SUTS (Super Ultra Track Selector) in multilayer tomography of CCD images from 44 μm thick emulsion layer.

The most recent and highest scanning power achieved at Nagoya university, is 72 cm^2 per hour, and 4 sets of this scanning system are now working constantly in addition to one scanning system of which power is 33 cm^2 per hour. At this moment, scanning power for 1 m^2 area required in cosmic gamma ray experiments, has been maintained, thus we have a prospect of completing emulsion analysis.

III. Status and New Technology

We have already carried out 4 R&D experiments for cosmic gamma ray detectors since 2004. (1) The balloon experiments of the Micro Segment Chamber (MSC) which were stacked emulsion films and 1mm lead plates into, were carried out at JAXA/ISAS launching site (Sanriku) on May 30, 2004 [6]. Consequently, cosmic gamma ray events above 10 GeV energies were detected by using scanning systems and also the technique of emulsion shifter were implemented to attach time stamp information for each emulsion tracks. (2) In order to confirm the angular resolutions for 1 GeV electron-pairs in emulsion stacks with 50 μm copper target, inverse Compton gamma ray beams were used at SPring-8 synchrotron radiation facilities. We experimentally confirmed $0.1\mathrm{deg}$ angular resolution in the energies of 1 GeV to 2 GeV. We have also studied polarized gamma ray conversion into an electron-positron pair in the emulsion target. (3) In 2007 July and September, the emulsion shifter system were exposed to atmospheric gamma rays at Mt. Norikura (2770m a.s.l) to prove the potential of 100 MeV electron pair detections and to estimate the stability of time stamp system. (4) The emulsion stacks are exposed to several 10 MeV gamma ray beams, of which maximum energy is 47 MeV, at UVSOR in Institute of Molecular Science in order to confirm the feasibility of such a low energy gamma ray detection within reasonable angular resolutions by using emulsion technologies.

A. Emulsion shifter for time stamp system

In the balloon experiments MSC launched in 2004, emulsion shifter system were installed to distinguish tracks recorded in the duration of level flight, among the entire tracks. By shifting emulsion film actively in level flight, tracks recorded show artificial displacements after track reconstruction. Each displacement can indeed be converted into time information, shown in Fig. 3.

TABLE I: Experimental profiles of emulsion telescope.

PSF	1.9 mrad = 6.5 arcmin =0.11 degree	@1 $\sim$ 2 GeV
	10 mrad = 36 arcmin = 0.6 degree	@100 MeV
Aperture area	$>$ 1m ^{2}	
FOV	$>$ 90deg (0.5 π sr, 12.5% of all sky)	
Energy range	10 MeV $\sim$ 100 GeV	

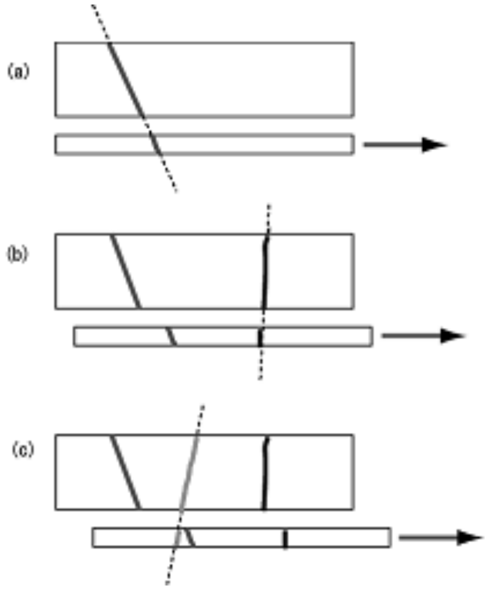

Fig. 3: The schematic view of emulsion shifter. In the upper panel (a), emulsion chamber and emulsion shifter are aligned each other, and then the shifter part are moved to the right direction like (b) and (c). The registered track positions between them show proper displacements.

In the experiment carried out at Mt. Norikura [7], we have tested emulsion shifter system as well as atmospheric gamma ray detections. The prototypes of emulsion shifter were exposed for 20 hours, of which aperture area was 12 cm $\times$ 10 cm. The arrangement of emulsion chamber and shifter looks like Fig. 3. The emulsion films stacked in the shifter part were shifted 9 times every 2 minutes and 15 times every 10 minutes, shown in Fig. 4. After reconstruction of tracks in both emulsion chambers and emulsion shifters, obtained track displacements at shifter part are shown in Fig. 4(a), which made aligned cluster in xy-coordinate and the size of clusters are proportional to the durations of exposure, shown in the histogram of Fig. 4(b). Therefore, time stamp information can be derived from emulsion shifter successfully.

B. Development of multistage emulsion shifters

To improve the resolution of event time stamp with emulsion shifter technologies, multistage emulsion shifter system was developed. The concept of this system comes from the analog clock with the long, short and second hand, of which periodical motions are different.

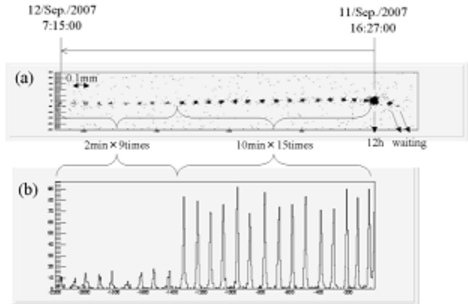

Fig. 4: (a) Observed track displacement at shifter part and (b) the track density at each displacement. The number of tracks at each displacement are proportional to the time duration.

We examined the capabilities of this concept by using the 1/10 scale prototype systems, illustrated in Fig. 5. The experimental conditions were as follows: the exposed area of each emulsion film and SFT is 12 $\times$ 10 cm^2. The exposure time to atmospheric muons at ground level was 28.7 hours, and the duration of shifter operations was 12.1 hours. The shifter#2 moved by 100 μm step every 5 second. After 93 steps of the shifter#2 movement, the shifter#1 moved by 100 μm step and the shifter#2 returned the first position simultaneously. Those series of motions were repeated 93 times. The SFT registered timing and positions of each muon incidence. The separation distance of each emulsion shifter were 4 mm. The main module of emulsion films were used for identifying muon tracks in the SFT data. The tracks registered in every emulsion films were automatically selected by using SUTS, and track pattern matching analyses were carried out to recognize track partners in both main-module and shifter#1 and in shifter#1 and shifter#2. Then muon tracks were reconstructed in both shifter emulsions films and SFT.

The offset position (displacement) of each track we have reconstructed were clearly grouped according to the amount of emulsion film shifts integrated up to muon arrival time, which was the same as described in Fig. 3 and Fig. 4. The obtained displacement distributions in the prototype system were shown in Fig. 6. The quantities of each displacement were able to be converted into event timing information. To estimate the time stamp resolution of shifter system, we compare time stamps obtained by shifter system with ones by SFT. The time stamps converted from displacement quantities at shifter emulsion film were represented as a function of SFT

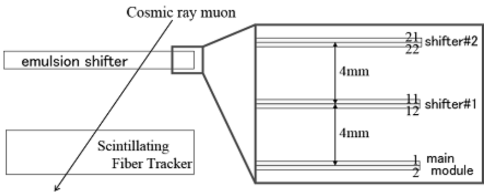

Fig. 5: Schematic views of experimental setting of multi-stage emulsion shifter applications. Emulsion shifter part consists of 6 emulsion films including 2 fixed layers. The scintillating fiber tracker provided the event time stamp for each atmospheric muons.

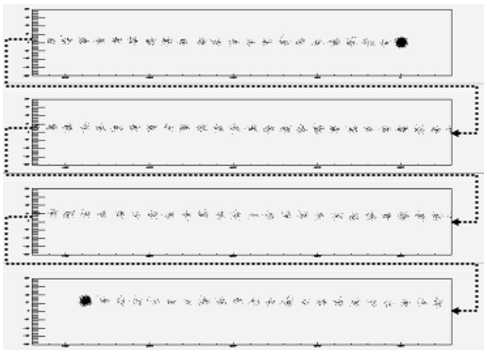

Fig. 6: Track displacement distributions for identified in both shifter emulsion films and SFT. Each cluster of dots represents 93 step movements of shifters

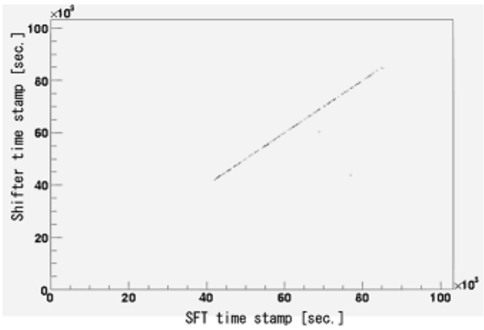

Fig. 7: Shifter time stamps versus SFT time stamp. These are reconstructed events in both shifter emulsions and SFT.

time stamps, shown in Fig. 7. The shifter time stamp system well reproduced SFT's one. The time resolution obtained by the shifter system is 1.5 sec. in r.m.s.

C. Flight model of multistage emulsion shifters

In the previous section, we confirmed the capabilities and performances of multistage emulsion shifters. We have developed 1/10 scaled flight model of the shifters by Mitaka Kohki.Co., Ltd. and Kobe univesity group. The system consists of one-dimensional stage with 2 stepping motors which drive emulsion films in two different velocities, whose 1 μm position accuracy was achieved at ground level test, and the control unit, shown in Fig. 8. This effective emulsion area is 12×10 cm^2 and an assembled size and weight will be $30 \times 45 \times 6$ cm^3 and 5 kg, respectively. The necessary power will be 8 Watts. These system profiles are suitable for balloon borne experiments. Thermal vacuum test and vibration test was carried out in June 2009. Then the system will be ready to test flight experiments.

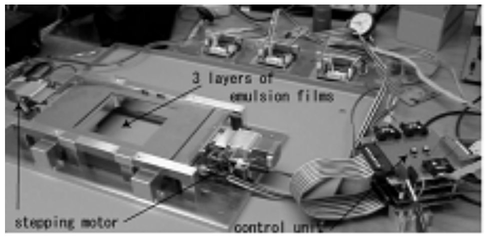

Fig. 8: 1/10 scaled flight model of multistage emulsion shifter.

IV. Summary and Future Plans

The aim of emulsion telescope is to provide mrad and sub-mrad angular resolution images of stellar sources in 10 MeV to 100 GeV energies. And we have already done 4 experiments to develop and confirm emulsion techniques. Consequently, we confirm that the emulsion shifter system can provide time stamp information, as well as the angular resolutions.

Multistage emulsion shifter system [8] for more accurate time stamp was developed instead of SFT readout system, which provided 1.5 second time resolution successfully. The 1/10 scaled prototype shifter system was also constructed and its system profiles are suitable for balloon borne experiments.

Now we are ready to have 12 hour duration balloon flight in order to examine (1)mid-latitude background level of atmospheric gamma rays from 10 MeV to 10 GeV, (2) multistage emulsion shifters and their connection to star monitoring system, and (3) to observe the gamma ray objects such as Crab nebula to estimate overall angular resolutions.

A number of new gamma ray sources will be demonstrated in FERMI satellite experiments from 2009, so that the emulsion telescope can also contribute complementarily to the exploration of the nature of gamma ray sources with higher resolution imaging.

Acknowledgements

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