Nuclear Instruments and Methods in Physics Research A 833 (2016) 165–168

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Demonstration of polarization sensitivity of emulsion-based pair conversion telescope for cosmic gamma-ray polarimetry

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ARTICLE INFO

Article history:
Received 28 March 2016
Received in revised form
15 July 2016
Accepted 15 July 2016
Available online 18 July 2016

Keywords:
Gamma-ray
Polarimetry
Emulsion
Balloon-borne experiment

ABSTRACT

Linear polarization of high-energy gamma-rays (10MeV–100 GeV) can be detected by measuring the azimuthal angle of electron–positron pairs and observing the modulation of the azimuthal distribution. To demonstrate the gamma-ray polarization sensitivity of emulsion, we conducted a test using a polarized gamma-ray beam (0.8–2.4 GeV) at SPring-8/LEPS. Emulsion tracks were reconstructed using scanning data, and gamma-ray events were selected automatically. Using an optical microscope, out of the 2381 gamma-ray conversions that were observed, 1372 remained after event selection, on the azimuthal angle distribution of which we measured the modulation. From the distribution of the azimuthal angles of the selected events, a modulation factor of $0.21+0.11-0.09$ was measured, from which the detection of a non-zero modulation was established with a significance of 3.06σ. This attractive polarimeter will be applied to the GRAINE project, a balloon-borne experiment that observes 10–100 GeV cosmic gamma-rays with an emulsion-based pair conversion telescope.

1. Introduction

Cosmic gamma-ray observations can explore high-energy phenomena in space with imaging, timing, energy spectra, and polarization. It is important to observe the polarization because the polarimetry of cosmic gamma-rays can be distinguished in the emission model of an astronomical object (e.g., [1]). However, high-energy gamma-ray polarimetry in space has not yet been investigated because of measurement difficulties [2].

Polarimetry with electron–positron pairs from high-energy gamma-rays was suggested in 1950 [3]. The signature of linearly polarized gamma-rays can be detected by measuring the azimuthal angle of the produced electron–positron pairs. The azimuthal distribution can be presented as $\sigma = \sigma_0\left[1 + P_l \cdot R \cdot \cos(2\psi)\right]$, where P_l is the linear polarization fraction, R is the modulation factor, i.e., the maximum amplitude when P_l is 100%, and ψ is the azimuthal angle between the polarization direction and the detected electron–positron pair. Fig. 1 shows the geometry of the produced electron–positron pair and its associated variables. The angle ω between the polarization plane and the electron–positron plane is a directly observable parameter.

It is important to measure the azimuthal angle of an electron–positron pair using a thin converter before the tracks have traversed $\sim 10^{-3} X_0$ [2], because the azimuthal angle is diffused by multiple Coulomb scattering while the particles traverse a detector. However, it is also important to efficiently produce electron–positron pairs using a thick converter. A pair polarimeter for linearly polarized gamma-rays has already been developed at the ground level [4]; however, this is not optimal for cosmic gamma-ray observations in terms of detection efficiency. Several groups are studying the polarimetry for cosmic gamma-rays (e.g., [5]); however, it is difficult to develop a gas or solid-state detector capable of both suppressing multiple Coulomb scattering and converting gamma-rays efficiently.

Here we choose an other approach to develop an optimum pair polarimeter, keeping the high density of an emulsion, and using a sub-micron resolution.

2. GRAINE project

The GRAINE project is a balloon-borne experiment that observes cosmic gamma-rays using an emulsion-based telescope [6]. The telescope comprises a nuclear photographic emulsion, i.e., a 3D-charged particle tracking detector with sub-micron spatial resolution. Emulsion acts not only as a converter but also a tracker;

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http://dx.doi.org/10.1016/j.nima.2016.07.033
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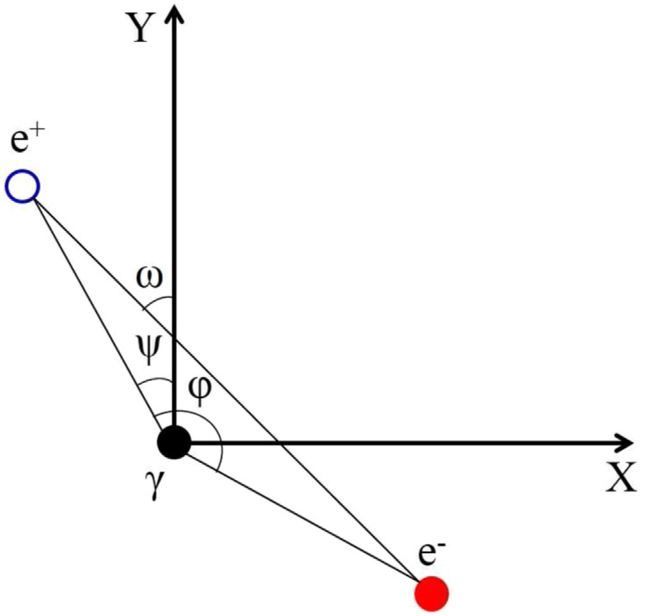

Fig. 1. Geometry of an electron–positron (e^-e^+) pair and the azimuthal angle in the detector plane. The polarization direction is parallel to the *Y*-axis. The angle ϕ is called the coplanarity angle. The angle ψ is the azimuthal angle and ω is the observable azimuthal angle.

therefore, it can detected the beginning of the electron–positron pair and measured its azimuthal angle before multiple Coulomb scattering could exert its deleterious effect. The conversion efficiency of incoming gamma-rays can be enhanced by stacking emulsion films. Therefore, the emulsion-based telescope can be optimum polarimeter for high-energy cosmic gamma-ray observations.

Fig. 2 shows the structure of the emulsion-based telescope. The components (converter, time-stamper, and calorimeter) are aligned along the gamma-ray direction.

The first balloon-borne experiment (GRAINE-2011) was performed at the Taiki Aerospace Research Field in Japan in June 2011 [7,8]. The second balloon-borne experiment (GRAINE-2015) was performed at Alice Springs in Australia in May 2015 [9,10]. As a next step, GRAINE will convey a large-area emulsion-based telescope $(\sim 10\ \mathrm{m}^2)$ in repeated long-duration ($\sim$1 week) scientific balloon flights.

The telescope covers the energy range from 10 MeV to 100 GeV with high angular resolution (1.0° at 100 MeV, 0.08° at 1–2 GeV, obtained from both experimental data and simulation [7]). We aim to observe the polarization of astronomical objects such as pulsars, blazars, GRBs and gamma-ray flares.

In this paper, we report the first demonstration of polarization sensitivity of emulsion-based telescope.

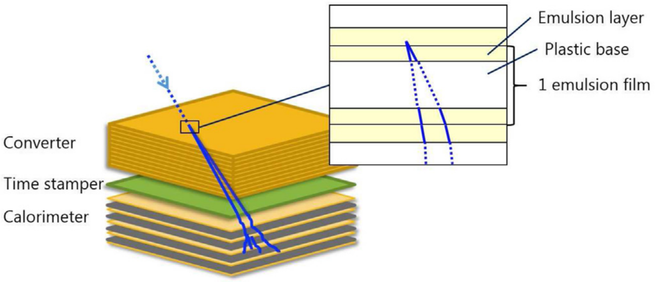

Fig. 2. Schematic of the emulsion-based telescope.

3. Experiment

Polarized gamma-ray beam exposure was performed at the SPring-8 facility in Japan using LEPS (Laser Electron Photon beam line at SPring-8) [11]. The gamma-rays were produced by inverse Compton scattering of an Argon polarized laser (with a wavelength of 351 nm, 95% linear polarization) off the electrons (the energy was 8 GeV) circulating in the storage ring. The maximum energy of the gamma-ray at the Compton edge was 2.4 GeV and the polarization fraction had a maximum value of 93% and 50% at 2.4 GeV and 1.5 GeV, respectively. The produced gamma-rays traveled to the experimental hutch located 69 m from the inverse Compton scattering region. The gamma-ray beam was exposed perpendicular to the emulsion chamber for $\sim$1 s. The beam spot size was collimated to a diameter of 2.3 cm. The layout of the emulsion chamber is shown in Fig. 3. In this experiment, we used OPERA films [12], which were jointly developed by the Nagoya University and the Fuji Photo Film Corporation. Approximately 0.1% of the gamma-rays converted to the electron–positron pairs in one OPERA film.

4. Analysis

4.1. Gamma-ray event selection using scanning data

After the emulsion films development, they were scanned by an automatic emulsion scanning system at the Nagoya University [13] in the $3 \times 3\ \mathrm{cm}^2$ region around the beam center, and all the emulsion tracks were reconstructed [14]. To enhance the polarization fraction of the gamma-ray beam, the connection window (the angle and position difference) of emulsion tracks between films was calculated in accordance with multiple Coulomb scattering, and the reconstruction threshold was set to 500 MeV/c. We searched for unbiased single-tracks, which started at mid-film and connected to #25, as candidates of gamma-ray events. The search simultaneously required that the candidates be located in a 0.63 cm radius from the beam center. This corresponded to the selection of >0.8 GeV for the primary gamma-rays. Subsequently, 4228 gamma-ray event candidates were selected automatically from film #5 to #20.

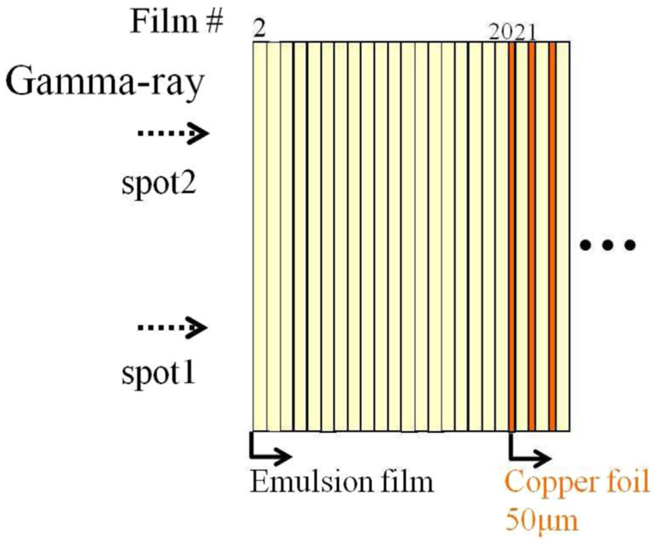

Fig. 3. Layout of the emulsion chamber. The OPERA films (12.5 cm × 10 cm × 293-μm thick) were stacked from film #2 to #20. A sandwich structure of the OPERA films and copper foils (50-μm thick) was stacked after #20.