Calibration and In-Flight Performance of the Compton Telescope prototype LXeGRIT

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Abstract

The Liquid Xenon Gamma-Ray Imaging Telescope (LXeGRIT) is the first balloon-borne instrument developed to validate the concept of a monolithic detector with 3-D imaging capability as a Compton telescope for MeV astrophysics. The geometrical area is about 350 cm^2, an order of magnitude smaller than that of COMPTEL and the thickness of sensitive LXe is 7cm, of equivalent stopping power as COMPTEL D2 detector. The spectroscopic and imaging response of LXeGRIT has been fully characterized in calibration experiments on the ground and during balloon flight experiments. During its most successful flight campaign of 27 hr from Ft Sumner, in Fall 2000, the LXeTPC was operated without any external shield. The γ-ray background, measured at float altitude in the 0.5 - 10 MeV energy band, is well explained by the known atmospheric γ-ray flux. Results on the LXeGRIT in-flight performance, effective area, minimum flux sensitivity and background level are presented in this paper.

Key words: Gamma-ray telescopes, Gamma-ray instruments and techniques
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Introduction

The Liquid Xenon Gamma-Ray Imaging Telescope (LXeGRIT) is the outcome of a systematic program initiated at Columbia University with NASA support to develop the liquid xenon time projection chamber (LXeTPC) technology for MeV astrophysics. Experiments with LXe detectors were carried out to measure charge and light yields, energy and position resolution, electron drift velocity and mobility. Following these basic studies, a LXeTPC, with a sensitive volume of 2800 cm^3, was developed and its performance established with a variety of γ-ray sources. The same TPC is used for the balloon-borne LXeGRIT instrument.

1 Description of the instrument

In the LXeTPC, both ionization and scintillation signals are detected to measure the event spatial coordinates and the energy. The fast UV (175 nm) Xe scintillation light is detected by four PMTs viewing the sensitive volume from below, through quartz windows. The OR of the PMTs' signals provides the trigger signal, marking the time zero of each event. The charge signals induced by free electrons drifting under the applied electric field are detected on two orthogonal planes of 62 parallel wires each, providing X-Y position information with millimeter accuracy. The wires pitch is 3 mm, and the separation between X and Y planes is also 3 mm. Below the wires, at a distance of 3 mm, four anodes collect the total charge and provide the energy measurement. The X and Y wires and the anode are amplified and digitized at 5 MHz, with 8 bit precision for the wires and 10 bit precision for the anodes. The digitized data are stored with 256 samples per event, covering more than the maximum drift time of 35 μs. The absolute drift time measurement gives the event depth of interaction (Z-position), with an accuracy of $\sim$300 μm. This charge readout was designed and tested to image the point-like ionization clouds ($<$ 1mm) produced by low energy electrons from MeV γ-ray interactions in LXe. A key prerequisite for this detector is to minimize the signal loss due to electron trapping by impurities in the liquid. In LXeGRIT free electrons are drifted over the TPC maximum distance of 7 cm with very little attenuation, and the remaining 5-10% charge loss for maximum drift length is corrected for based on the known Z-position. The TPC is enclosed in a cylindrical vessel filled with 7 liters of pure LXe kept at ~ -95°C by a controlled flow of LN_2 through a condenser. The vessel is thermally insulated with a vacuum cryostat. The lower section of the cryostat houses the four PMTs to detect the Xe scintillation light, as well as the HV distribution circuitry for the wires and the cathode. The total mass, including 21 kg of Xe, is about 190 kg.

2 In-flight performance

LXeGRIT had its first engineering flights from Palestine, TX, in the Summer of 1997; after several improvements it has been flown again twice from Ft.Sumner, NM, in May 1999 and in October 2000. To test the LXeTPC at balloon altitude without enclosing the entire structure in a pressurized vessel, all detector subsystems had to be capable of sustaining the near vacuum conditions and the temperature extremes encountered during a balloon flight. In addition, two major new developments were required to make a balloon experiment with the LXeTPC: a new readout electronics and data acquisition (DAQ) flight system, and an instrumentation and control system. These systems, together with the front-end electronics, are described in Aprile et al. (1998, 2001). A parallel effort involved extensive modifications of an existing gondola and veto-shield provided by the University of New Hampshire. The instrument's zenith direction and azimuth orientation is provided by a sensor combining 3-axis magnetometer and 3-axis accelerometer. This information, together with the knowledge of the payload geographical coordinates, is needed for imaging celestial sources. The flight data are stored in two 36-G-byte disk drives and also sent via telemetry at 2×500 kbps to the ground station. Table 1 summarizes some characteristics of the instrument. A recent review of the LXeGRIT instrument is in Aprile et al. (2002); a more detailed description is in preparation.

2.1 The balloon flight in Fall 2000

The flight took place on Oct 4-5, 2000, from Ft. Sumner, NM and lasted 27 hours, including ascent. After ascent the balloon payload was at an atmospheric depth ranging between 5.7 and 3.2 g cm^{-2}. Three "snapshots" of particle interactions in the LXeTPC during the 2000 balloon flight are shown in Fig. 1. LXeGRIT performed flawlessly during the entire flight and collected $\sim$5 10^6 events.

The trigger rate from the PMT-OR vs. time is shown in Fig. 2 for a period of 5 hours, during which LXeGRIT was at a stable altitude of $\sim$39 km or $\sim$3.2 g cm^{-2} atmospheric depth. The rate of events selected and rejected online is shown in Fig. 3. The "gaps" visible in the rate vs. time plots correspond to the TPC cooling periods during which the DAQ is turned off due to the increased noise level on the anodes, while the PMTs remain operational.

3 Background measurement and sensitivity

The 2000 experiment allowed a detailed measurement of the background in LXeGRIT at balloon altitude. A large fraction (∼70%) of the PMT-OR rate shown in Fig. 2 is due to charged particles, both primary and secondary cosmic rays. After the off-line analysis, which selects a very clean sample of γ-ray events, the rate was reduced to about 3 Hz in the 0.15-10 MeV energy band. To compare data and expectation we define an expected input flux and unfold the detector response function from the experimental data; the procedure is described in detail in Curioni et al. (2002). We base our expectation on the measured atmospheric γ-ray flux, as parameterized in Costa et al. (1984), both for its energy and angular dependence. The fluxes, in units of $cm^{-2}sec^{-1}MeV^{-1}$, are extrapolated in the energy range 100 keV - 15 MeV with four angular bins for the following zenith angles:

- 0.03 $E^{-1.61}$ (0° - 45°)
- 0.20 $E^{-1.48}$ (45° - 90°)
- 0.43 $E^{-1.34}$ (90° - 135°)
- 0.23 $E^{-1.51}$ (135° - 180°)

The expected count rate in LXeGRIT, as obtained through Monte Carlo simulation, is shown in Fig. 4, together with the experimental data corrected for the instrumental response function. The agreement is fairly good. The discrepancy at energies lower than 1.5 MeV is mainly due to the fact that, at these energies, the intrinsic internal background, which is not included in the Monte Carlo simulation, plays some role. The discrepancy is well within uncertainties in our model of the instrument and in the input fluxes. We conclude that the measured background level is promisingly *low*, close to the minimum level expected for the known - and irreducible - atmospheric γ-ray flux [1] .

3.1 Sensitivity

The Crab Nebula/Pulsar was in the instrument's field-of-view for about 6 hr and multi-site events recorded during this exposure have been reconstructed and sequenced with the same algorithm tested on calibration data. The effective area, calculated through a Monte Carlo simulation fully accounting for the inefficiencies specific to the flight conditions, is ∼2 cm^2, integrated over the energy band 1-10 MeV for a flux with the Crab spectral index, with a 30% uncertainty. The Crab flux in this energy band is ∼1.7 10^{-3} $\gamma\,cm^{-2}\,s^{-1}$ (van der Meulen et al. , 1998), i.e. ∼50 events in our data would be useful for

[1] A work presenting a more detailed analysis is in preparation; the main results presented here remain unchanged.

imaging the Crab.
The minimal detectable flux $F_{min}(E, \theta, \phi)$, which depends on the energy spectrum (E) and the location (θ, ϕ) of the source, is given as

$$F_{min}(E, \theta, \phi) = \frac{n \sqrt{B(E)}}{A_{eff}(E, \theta, \phi) T_{obs}}$$

where n is the number of standard deviations of the background fluctuations, $B(E)$ the background counts, A_{eff} the effective area and T_{obs} the exposure.
Preliminary studies based on the standard COMPTEL Processing and Analysis Software System (COMPASS), where the background is derived from the observational data themselves (Bloemen et al. , 1994), show that a $\sim 2\sigma$ detection is at reach, which translates into a 3 σ sensitivity of 2.4 10^{-3} $\gamma\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, given an exposure of 2 10^4 s and an effective area of $\sim$2 cm^2.
A detailed Monte Carlo study of the efficiency of LXeGRIT shows that an effective area larger than 10 cm^2 between 0.5-5 MeV would be achieved within the same detector after improving on DAQ speed and/or rejection capability of the fast light trigger. Given the measured background level a detection significance of more than 10 σ for the Crab would be obtained with a 6 hr exposure. At this level, we could start to search for polarization in the Crab Nebula and pulsed spectra at MeV energies, and should be able to easily observe other sources such as Cyg X-1, 3C273 and GRS1915+105.

Conclusions

In this paper we have briefly presented the in-flight performance of the LXeGRIT Compton telescope, together with a measurement of the γ-ray background rate from a sample of data acquired at 3.2 g cm^{-2} atmospheric depth during the 2000 balloon flight from Ft. Sumner, NM. The measured trigger rate at float altitude was about 600 Hz at the first level trigger. Of this about 70% were charged particles, most of which rejected online. We find a good agreement between data and expectation based on the known atmospheric γ-ray flux. A realistic estimate of the LXeGRIT sensitivity to celestial γ-ray sources has also been derived.

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Energy Range	0.15 - 10 MeV
Energy Resolution ($FWHM$)	$8\% \times (1\,\mathrm{MeV}/E)^{1/2}$
Position Resolution (1σ)	1 mm (X and Y) ; 0.3 mm (Z)
Angular Resolution (1σ)	3° at 1.8 MeV
Field of View (FWHM)	1 sr
Detector Active Volume	18.6 cm $\times$ 18.6 cm $\times$ 7 cm
Instrument Mass, Power	2000 lbs, 450 W
Telemetry, On-board Data Storage	2×500 kbps, 2×36 GB

Table 1
LXeGRIT characteristics in the balloon flight 2000 configuration.

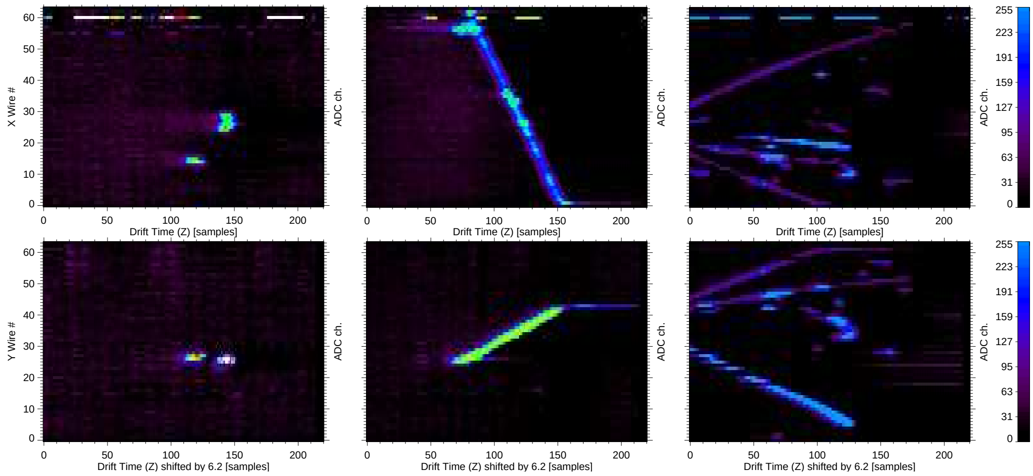

Fig. 1. “Snapshots” of three different events in the LXeTPC recorded during the balloon flight in year 2000; for each of them the X-Z view and the Y-Z view are shown. *Left:* a 2-site γ-ray interaction. *Center:* a relativistic particle passing through the fiducial volume. Several δ-rays are visible in the X-Z view. *Right:* a more complex interaction with several particles detected in the fiducial volume. The vertex happens below the fiducial volume, i.e. at $Z < 0$.

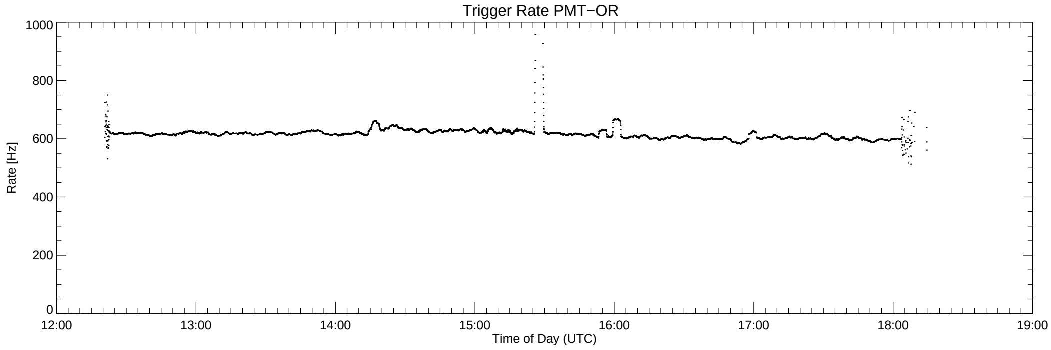

Fig. 2. PMT-OR rate

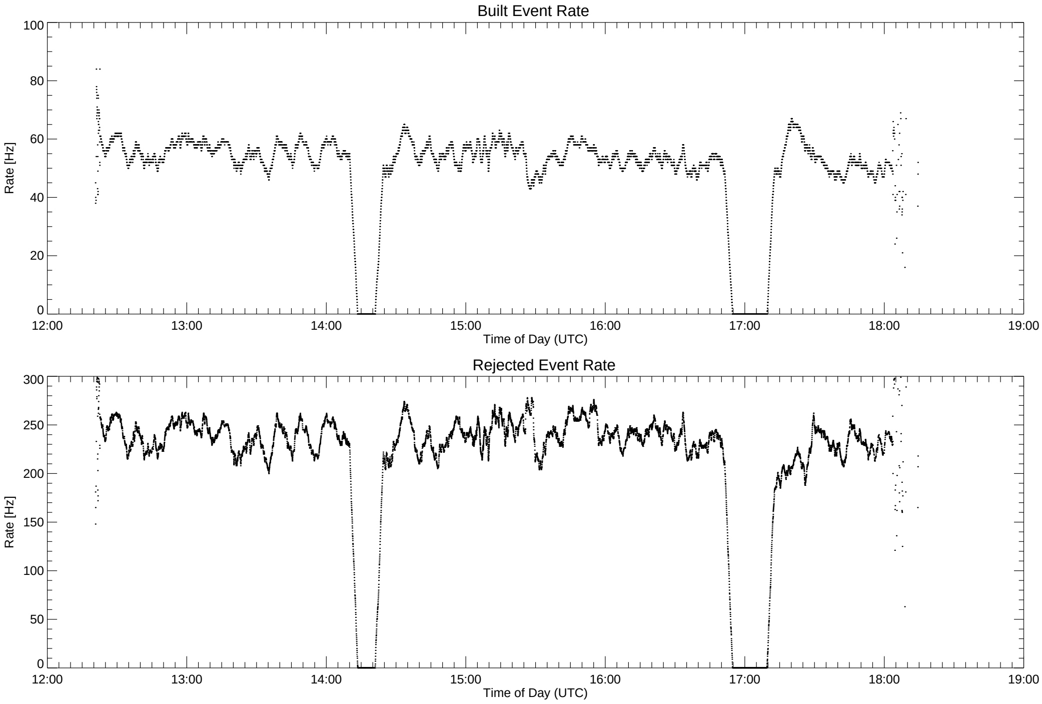

Fig. 3. *Top:* selected event rate, *bottom:* rejected event rate.

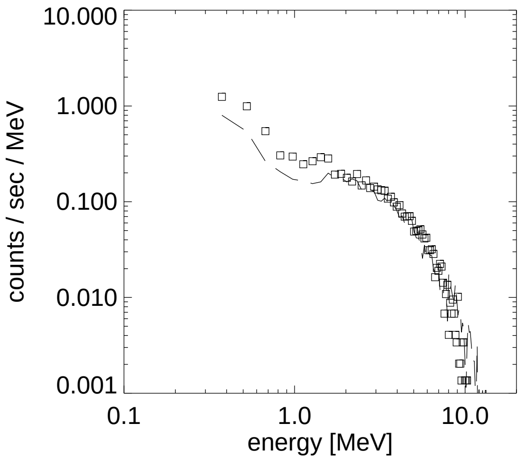

Fig. 4. *Open squares* - Experimental data. *Dashed line* - Monte Carlo prediction. See text for explanation.