# POLAR: THE SPACE EXPERIMENT TO STUDY THE ORIGIN OF GAMMA RAY BURSTS* **

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Measurements of polarisation of $\gamma$-rays emitted in Gamma-Ray Burst (GRB) will provide a new parameter in collected data. This parameter is sensitive to predictions of different models of poorly known $\gamma$-ray emission processes. Here, we present the POLAR experiment — a compact space detector dedicated to the measurement of polarisation of GRB $\gamma$-rays prompt emission. The flight model of POLAR will be ready in 2014, for launch in space by 2015 on the Chinese Spacelab TG-2. Expected lifetime of experiment is 3 years.

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## 1. Introduction

Gamma-ray polarisation measurements using Compton scattering are becoming an important method in high energy astrophysics. They were developed in nuclear physics research (*e.g.* Fagg and Hanna [1], Droste *et al.* [2]).

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POLAR is a novel compact space-borne Compton polarimeter designed for measurement of $\gamma$-ray polarisation and optimized for the detection of prompt emission of GRB (Gamma-Ray Burst) in the energy range of 50–500 keV [3–5]. The POLAR detector will be mounted onto the future Chinese Tian Gong 2 Space Station.

GRBs remain one of the greatest mysteries of modern astrophysics. They are probably the most energetic events observed in the Universe, most of them are at the cosmological distances. They are observed as $\gamma$-ray flashes lasting from milliseconds to several minutes with a typical observation rate about one per day. They are usually brighter than a typical supernova. GRBs are considered as candidates for the sources of ultra high energy cosmic rays (UHECR), with energies above $10^{19}$ eV. The intensity of flash and the short time of duration make it difficult to find answers to any question, in particular, to the origin and structure of magnetic fields in GRBs. The emission mechanism of prompt gamma signal might require strong and energetic particle beam and, therefore, these studies address the nature of the central engine of GRB. In spite of extensive observational efforts, these questions are difficult or even impossible to answer using only the spectral and light-curve information currently collected. Polarimetry measurements of GRBs can help to solve these problems.

## 2. The POLAR detector

The POLAR detector is made of 1600 ($25 \times 64$) scintillation bars which are "the target" for gammas. The target is divided into 25 modular units, each consisting of 64 plastic scintillator bars (dimensions $5.9\,\mathrm{mm} \times 5.9\,\mathrm{mm} \times 176\,\mathrm{mm}$, made of BC404 scintillator). Each module is viewed by one multianode photomultiplier (MAPMT, 64 anodes; H8500, Hamamatsu), which is mechanically coupled to the bottom of the scintillator bars. The module together with Front End Electronics (FEE) is enclosed in a thin carbon fiber socket (see Fig. 1 (left)). The POLAR detector has a field of view about 1/3 of the full sky. The detector is dedicated to polarimetry measurements. The precise location of GRB would be provided by other active instruments. The quality of polarisation measurements would depend on the number of photons detected. For strong GRB with more than 1000 gammas in POLAR, we expect a clear polarisation measurement. We expect to measure polarisation of $\sim 10$ strong GRB/year and many weaker.

The High Voltage Power Supply (HVPS) system for POLAR multianode photomultipliers has been designed and engineering model has been made by the NCBJ Cosmic Ray Physics group in Łódź.

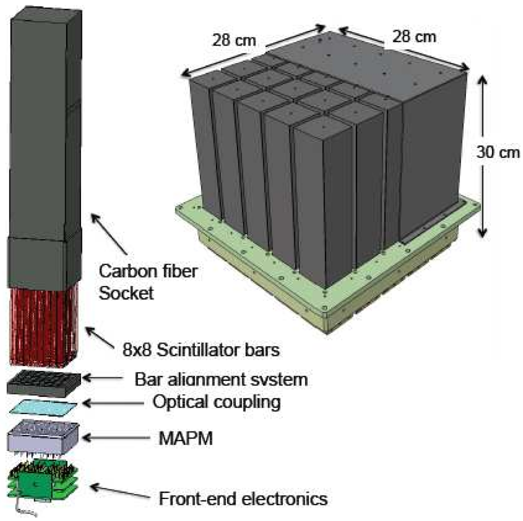


Fig. 1. POLAR schematic. Left: One module segmented view; Right: Complete assembly of 25 modules.

### *2.1. Polarisation measurements*

The POLAR detector will measure the degree of linear polarisation of $\gamma$-rays coming from GRB. The method is based on Compton scattering of polarised photons [6]. In Fig. 2 the incoming photon with energy $E_{\gamma 0}$ and polarisation $\vec{e}_1$ is scattered to a photon with energy $E'_\gamma$ and polarisation $\vec{e}_2$. Polarisation vectors $\vec{e}_1$ $\vec{e}_2$ are perpendicular to the gamma directions. Events with large $(\vec{e}_1 \cdot \vec{e}_2)^2$ are preferred. Thus the differential cross section depends

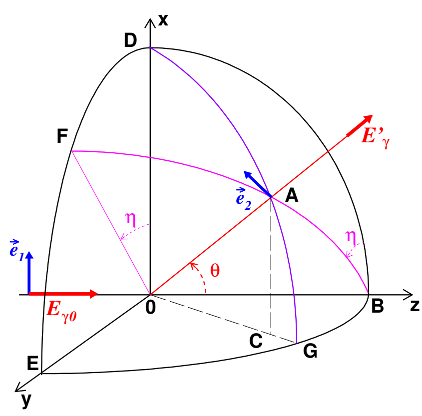


Fig. 2. Geometry of Compton scattering.

on the angle $\eta$, *i.e.* directions with the azimuthal component perpendicular to the direction of polarisation will be preferred, parallel — suppressed. The cross section of polarised $\gamma$-ray scattering on a free electron is described by the Klein–Nishina formula

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}\left(\frac{E'}{E_0}\right)^2\left(\frac{E_0}{E'} + \frac{E'}{E_0} - 2\sin^2\theta\cos^2\eta\right) , \tag{1}$$

where $\theta$ is the scattering angle, $\eta$ — the azimuthal angle with respect to initial polarisation, $r_0$ — the classical electron radius, $E_0$, $E'$ denote respectively energy of incident and scattered photon ($E'$ is a function of $E_0$ and $\theta$, only). Dependence on $\cos^2\eta$ is used in polarisation measurements.

The POLAR detector records all pairs of bars that show a coincident energy deposition within a 50 ns window (as shown in Fig. 3). Energy deposits are due to ionisation losses of the scattered electron. In the first scintillation bar the incoming photon interacts via Compton scattering, in the second bar the scattered photon interaction is registered (another Compton scattering or photoelectric effect).

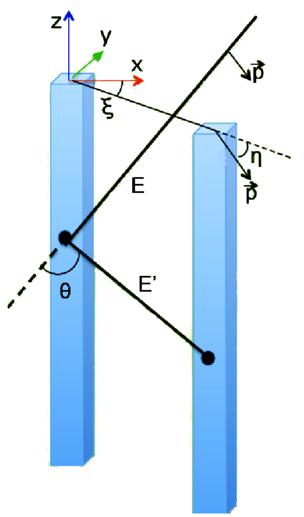


Fig. 3. POLAR geometry of Compton scattering.

## 3. Tests of the POLAR detector performance

Various qualification measurements were performed on the POLAR detector or its parts. These include two measurement sessions with polarized synchrotron beams (ESRF Grenoble, France). Tests confirmed theoretical prediction of the instrument parameters. Electronics and mechanical structure of the POLAR detector are being extensively tested including vibration, vacuum and thermal tests as well as dedicated calibration.

### *3.1. Polarised gamma beam tests — ESRF Grenoble 2012*

The performance test of POLAR were carried out at the European Synchrotron Radiation Facility (ESRF) in Grenoble. ESRF provided X-ray source, with polarised beam and available photon energies in the range of 30–700 keV (for the POLAR detector tests energies of 50, 88, 122, 200, 288, 356, 511 keV were used).

The ESRF photon beam is horizontal. The POLAR telescope was mounted in a way which allowed detector rotation and sliding up–down and left–right to place the beam at the required position and relative angle (see the photo in Fig. 4). The beam cross section was smaller than the scintillation bar cross section.

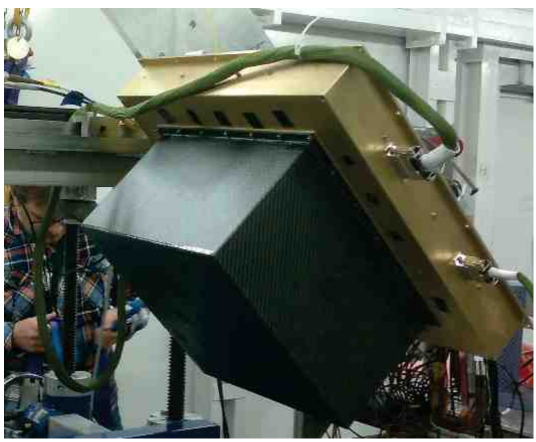

Fig. 4. The POLAR telescope at test facilities.

Below, we present some results from the run No. 0584. Only 6 modules were used during that run. Figure 5 shows the schematic layout. The beam was along the scintillation bars, *i.e.* in the POLAR detector vertical direction. In the run No. 0584 the photons in polarised beam have energy 511 keV.

The main goal for the POLAR detector is to measure the degree of linear polarisation. The distribution of the azimuth angle $\eta$ (with respect to the initial photons direction) of scattered photons (see Fig. 2 and equation (1)) needs to be examined to measure the degree of linear polarisation. The distribution is called modulation curve (Fig. 6). In practice, the modulation

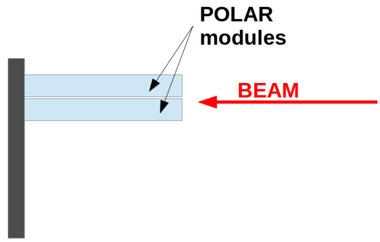


Fig. 5. The schematic layout for run No. 0584.

curve is the distribution of the $\xi$ angles between the two hit bars (see Fig. 3 for reference). Following [7], it can be fitted by

$$f(\xi) = A\cos\left(2\left(\xi - C + \frac{\pi}{2}\right)\right) + B\,. \tag{2}$$

The modulation factor $\mu$ is evaluated from the fitted parameters $A$ (peak amplitude) and $B$ (mean value)

$$\text{modulation factor } \mu = \frac{A}{B}\,. \tag{3}$$

The polarisation degree of GRB photons would be evaluated as a ratio of measured $\mu$ to $\mu_{100}$. The modulation factor $\mu_{100}$ is obtained from laboratory calibration for 100% polarisation photon beam sent from the same direction with respect to the POLAR detector as GRB is.

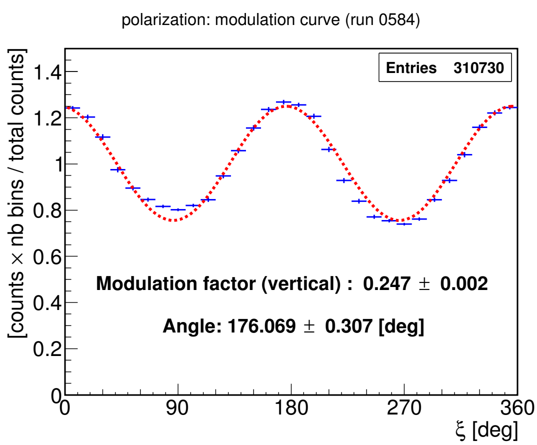


Fig. 6. The measured modulation curve for the run No. 0584 when photon beam was 100% polarised. This result provides $\mu_{100}$ (see the text).

### *3.2. Analysis of muon tracks in POLAR*

During the flight cosmic ray particles would cross the scintillation target, and they would produce unwanted ionisation, but they can be used to check the detector performance. In most cases, the energy deposit is much larger than measured for Compton scattering. During the laboratory tests at ESRF, secondary cosmic ray muons were ionising particles which penetrated the telescope's target (Fig. 7).

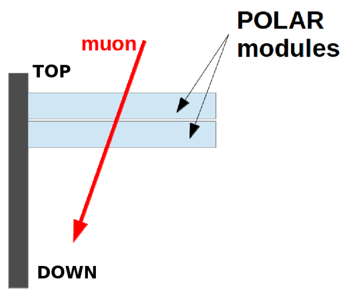


Fig. 7. Schematic view of muon detection.

We have examined the part of run No. 0584 lasting 337 s (about 5.6 minutes), and muons penetrating POLAR were identified.

Events with at least 20 pixels hit were selected. Muons show patterns similar to presented in Fig. 8. The distribution of projection angle (on the $x$, $y$ plane of multianode PMTs) was compared with simulations for expected distribution. In the simulation, the flux of muons is described by the formula

$$I(\theta)d\cos\theta = I_0 \cos^2\theta d\cos\theta\,, \tag{4}$$

where angle $\theta$ is the (geographic) zenith angle of the muon.

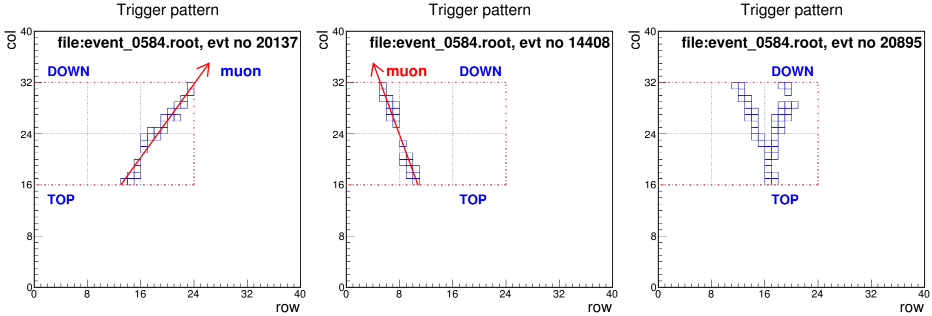


Fig. 8. Two examples of muon tracks (straight lines) in 6 active modules, during the test run No. 0584 (left and middle). In event number 20895, we can see probably effect of muon interaction (right).

The muon angular distribution is shown in Fig. 9. 596 tracks measured contribute to the figure. The observed number of muons was nearly twice smaller than expected for unshielded muon flux at the ground level. The simulated distribution was normalised to measurements. Monitoring of such penetrating events provide some information about the detector condition.

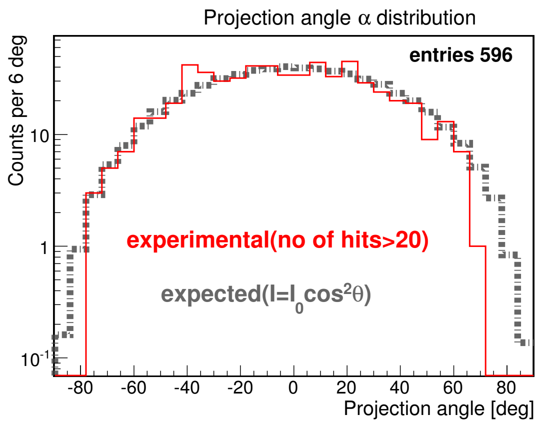


Fig. 9. Distribution of the projection angle for muon tracks. Solid/red line — data, grey/dashed line — simulations.

## 4. Summary

Measurements of X-ray and $\gamma$-ray polarisation are now seen as an important tool to learn more about GRB. The POLAR detector is a pathfinder in these directions. Laboratory tests show that it is functional and capable to measure linear polarisation of GRBs.

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