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POLAR: a space borne GRB polarimeter

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The direction and the level of polarization of high energy photons emitted by astrophysics sources are valuable observables for the understanding of the corresponding emission mechanisms, source geometry and strength of magnetic fields at work. POLAR is a novel compact space-borne detector conceived for a precise measurement of hard X-ray polarization and optimized for the detection of Gamma-Ray Burst (GRB) photons in the energy range 50-500 keV. In POLAR, the GRB photons undergo Compton scattering in a target made out of 1600 plastic scintillator bars. The azimuthal distribution of the scattered photons inside the target provides the information on the GRB polarization. The target is divided into 5×5 units, each one consisting of 8×8 scintillator bars optically coupled with a multi-anode photomultiplier. POLAR, thanks to its large modulation factor (μ_{100}=40%), its large effective area (Aeff = 250 cm^2), and its large field of view (1/3 of the sky) will be able to determine the degree and angle of polarization of a strong GRB with a minimum detectable polarization of less than 10% (3 σ). In this communication the present design and status of the POLAR project is presented. Expected results through deep Monte Carlo simulation studies as well as the recent results of laboratory measurements are detailed.

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1. Introduction

The observation of astrophysical objects through the detection of their electromagnetic emission reveals information regarding time, direction, and energy and enable construction of light curves, images, and spectra for the understanding of their nature. Some among the most energetic astrophysical objects of the universe, e.g. Gamma Ray Bursts (GRBs), produce emission via processes that take place in environments with strongly structured magnetic fields and are sites of non-spherical accretion and jetted outflows. Such complex geometries are not readily available with the more traditional lightcurves and spectra, while polarimetry is the frontier experimental approach providing essential information for their identification. Recent advances in instrument capabilities finally enable the exploration of polarization of X-ray and gamma-ray emissions from GRBs. Two polarization quantities to be determined, namely polarization degree and polarization angle, can greatly increase our understanding of the observed phenomena and help to distinguish between competing physical mechanisms. GRBs are the most violent, transient cataclysmic explosions in the universe taking place randomly across the sky and ranging in duration from a fraction of a second up to a few hundred seconds. They are produced at cosmological distances, being considered the brightest events in the universe after the Big Bang. In spite of extensive studies conducted by numerous instruments, almost forty years after their discovery the creation mechanism of GRBs and their progenitors is still uncertain. Several theories differing in the physical processes involved in the γ-ray generation have been elaborated to explain the origin of GRBs, predicting different levels of polarization. Basically the GRB process would result in the formation of a black hole. Regardless of the progenitor and the central engine, a generic fireball model [1] suggests that a relativistic jet is launched from the center of the explosion, with a bulk Lorentz factor, Γ, greater than 100, which beams toward the Earth. The internal dissipation due to internal shocks leads to emission in the X-ray and gamma-ray band, which corresponds to the observed GRB prompt emission. Theoretical models can be grouped into two main types [2]: 1) The physical model which invokes a globally ordered magnetic field in the emission region, so that electron synchrotron emission in this ordered field gives a net linear polarization. Such a model applies for most observer viewing-angle geometries, and the maximum polarization degree can be as high as $\sim$(60-70)%. 2) The geometric model which requires an optimistic geometric configuration to achieve a high degree of polarization. In this model, both the magnetic field configuration and electron energy distribution is random in the emission region so that no net polarization is detected if the viewing angle is along the jet beam (regardless of the radiation mechanism). If however the viewing direction is near the edge of the jet, in particular about $1/\Gamma$ outside the jet cone (Γ is the bulk Lorentz factor of the GRB jet), a high polarization degree would result due to breaking of emission symmetry. Within this model, although synchrotron models can produce polarization level Π as high as $\sim$(60-70)%, in a scenario where a fraction of photons undergo inverse Compton scattering on relativistic electrons from the ejected plasma, Π can in principle achieve $\sim$100%, under the most optimistic geometric configurations. In general, given a random distribution of viewing angle, the fraction of bursts that can achieve a high Π in the geometric models is significantly smaller than that in the physical models. A statistical study of polarization properties of a large sample of GRBs can therefore differentiate between the models, and provide a direct diagnostic of the magnetic composition, radiation mechanism and geometric configuration of GRB jets.

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2. Detector overview and working principle

The POLAR detector [3] is a space-borne Compton polarimeter of an overall volume of about 30 × 30 ×30 cm^3, a mass around 30 kg, and a mean power consumption below 30 W. The active target consists of 40×40 low-Z plastic scintillator bars (BC400) (i.e. doped polystyrene, chemically and mechanically stable and supporting high total radiation doses with little degradation)(Fig. 1). The bars, optically insulated from each other, have dimensions 6 × 6 × 200 mm^3, with their long axis facing the preferred photon entry direction. They are grouped in sub-elements of 8 × 8, each of which is optically coupled to a multi-anode photomultiplier (MAPMT, H8500 from Hamamatsu) that collects the scintillating light of each bar separately. The whole target is read with 25 MAPMTs in total, whose electrical output signals are then analyzed by front-end ASICs and FPGAs. In general the working principle of any Compton polarimeter [4] is based on the Compton scattering, for which photons tend to be scattered at a right angle to the incident electric field vector. In the case of an unpolarized beam of incident photons, there will be no net positive electric field vector and therefore no preferred azimuthal scattering angle; the azimuthal distribution of the scattered photons will be uniform. However, in the polarized case, the incident photons will exhibit a net positive electric field vector and the azimuthal distribution will be asymmetric. Therefore the level of linear polarization can be determined by measuring the azimuthal distribution that they present after Compton scattering. The modulation curve can be fitted with the following function: $C(\xi) = Acos2(\xi - C) + B$ where ξ is the azimuthal scattering angle measured with respect to the detector X-axis, and A, B, and C are the fitting parameters (amplitude, offset and phase shift of the curve, respectively). The position of the minimum in the modulation curve corresponds to the angle of polarization of the incoming photons. A/B is the so-called modulation factor (μ) that serves to calculate the degree of linear polarization of the incoming photons: $\Pi = \frac{\mu}{\mu_{100}} = \frac{A/B}{\mu_{100}} = \frac{1}{\mu_{100}} \frac{C_{max}-C_{min}}{C_{max}+C_{min}}$, where Π is the polarization degree, C_{min} and C_{max} are the minimum and the maximum of the curve as marked in Fig. 1, and μ_{100} is the response of the instrument to a fully polarized photon flux. This last value is a characteristic of the instrument and can be determined experimentally or via simulations. The polarization direction can be reconstructed by observing the recoil electron from the Compton scattering and then observing the scattered photon by a subsequent process depositing sufficient energy (second Compton scattering or photoelectric effect) (see Fig. 1). In addition, the cross section is symmetric with period π such that it is not necessary to know the order in time of the two observations. The observation consists of recording all pairs of bars that show a coincident energy deposition $>$ 5 keV. Applying an upper cut of about 300-500 keV total energy deposition would efficiently remove all cosmic ray induced events. A histogram of the angle defined by the line joining the two bars and an arbitrary chosen reference direction is accumulated for all photons during a GRB. Information about GRB polarization degree and direction of the polarization is extracted from this histogram by simulating effect of a 100% polarized signal coming from the same direction. Prediction of the background contribution in the histogram can be achieved with data collected before and after the GRB or by simulation.

3. Performance and simulation study

POLAR [3] [5] is designed as simple as possible, exclusively devoted to polarimetry and opti-

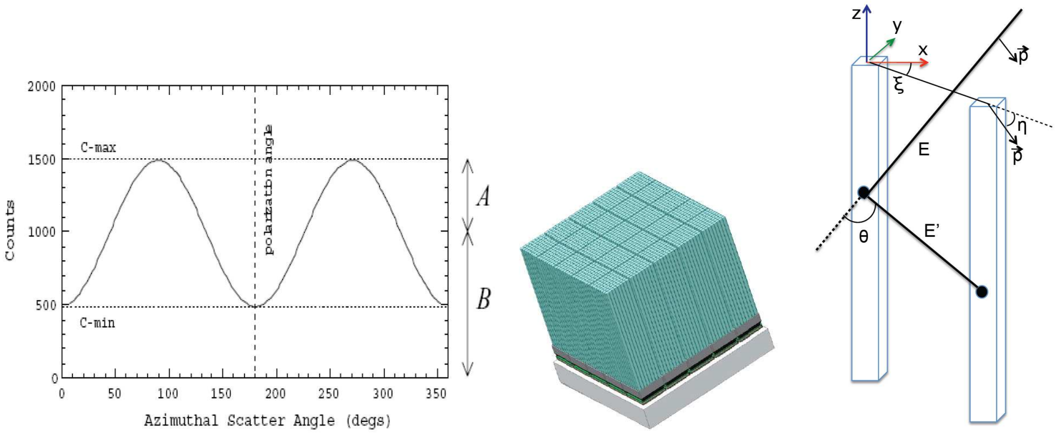

Figure 1: From left to right: 1) Theoretical modulation curve of polarized photons as expected from a 100% polarized photons. 2) POLAR design: a uniform array of 40×40 plastic scintillator bars on top of 25 MAPMT. 3) Geometry of the large angle Compton scattering between two scintillator bars of POLAR.

mized to precisely measure the level of polarization of the hard X-ray photons (50keV to 500keV) produced during the GRBs prompt emission. POLAR's design fulfill the requirements needed for the study of GRBs polarization: a large field of view (about 1/3 of the sky), a large effective area (Aeff $\simeq$ 250 cm^2), and a large modulation factor ($\mu_{100} \simeq 40\%$). POLAR will be able to determine the degree and level of polarization of a strong GRB[1] with a minimum detectable polarization of less than 10% (3σ). According to the BATSE catalog [6], around 12 such GRBs will be observed by POLAR in a year of flight operation. With less precision, the polarization of a statistically significant sample of less intense GRBs of all kinds will be also measured serving as an important input for systematic studies. Validation of requirements and optimization of the instrument performance have been achieved through a mass model detailed simulation using GEANT4 [7]. In the actual mass model the 1600 scintillator bars that constitute POLAR target have been implemented, each one of them wrapped in a foil of aluminum with thickness 50 μm. The size, material (organic scintillator), and the spatial distribution of the bars were precisely taken into account. The whole target was then placed into a box of aluminum with 1mm thick walls to shield the instrument from low energy cosmic rays. The simulation of physical processes includes the polarization dependence of Compton scattering, and takes into account all electromagnetic processes. As expected, the photon interactions are dominated in number by low energy Compton scattering with small energy transfer to the electron. The two important parameters are: The effective area A_{eff} = 400 cm^2 at its maximum (and almost constant in the energy range 50 to 500 keV) which slightly depends on the photon impinging direction (see Fig. 2); The 100% modulation factor (μ_{100}) that says how much each photon brings information about the real polarization, and which is a purely instrumental quantity. Its value varies in function of the energy and incoming angle of the photon flux. The maximum μ_{100} is reached for a flux of about 200 keV perpendicularly illuminating the top of POLAR detector. In such a case μ_{100} reached values slightly below 0.4 (see Fig. 2).

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[1] *Strong GRB* stands for a GRB with an energy flux 10^{-5} erg cm^{-1}, and a Band-function spectrum with E_{peak}=200 keV, α=-1, β=-2.5, located at POLAR's zenith.

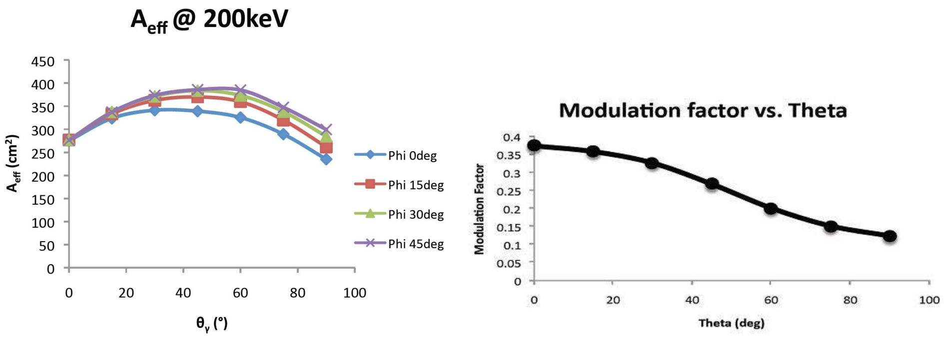

Figure 2: Left-panel) Monte Carlo simulated effective area (A_{eff}) at fixed energy and as a function of zenith θ_γ and azimuth ϕ_γ angles of the impinging photon. Right-panel) The μ_{100} dependency on the incoming zenith angle θ_γ for the case of a strong GRB.

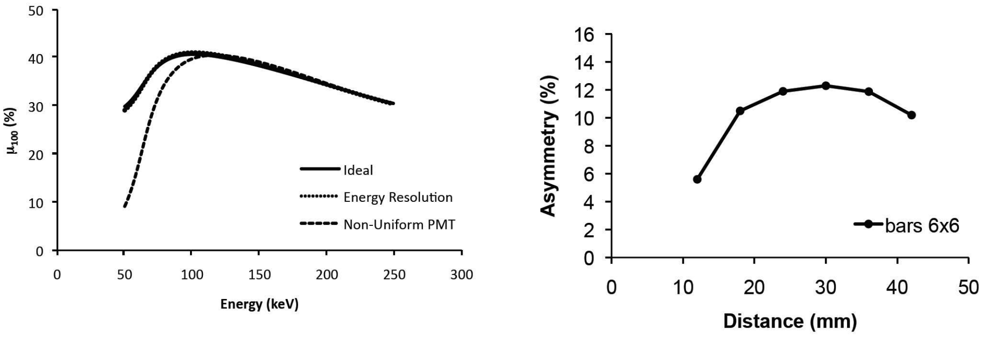

Figure 3: Left-panel) The μ_{100} dependency on the photon energy and the effect of limited scintillators energy resolution and on the non-uniformity of the 64 channels of the MAMPT. Right-panel) Measured level of asymmetry up to 12%, as a function of distance between bars triggering coincident hits.

For a strong GRB the modulation factor for a fully polarized signal was found to be μ_{100} = 0.37 $\pm$0.02. The response to a 0% polarized GRB has also been simulated. In this case the modulation curve shows a $\pi/2$ periodicity due to the square geometry of the detector, and limited amplitude, therefore easily handled.

4. Project development, tests and perspectives

The developments aim to address several critical issues for the definition of the POLAR detector design. $-1-$ Light collection: Dedicated light collection tests were conducted to examine variations in the light output intensity for plastic scintillators irradiated at different distances from the photo-cathode. Guided by Monte Carlo, the two most promising wrapping solutions were investigated: Aluminum foil, Vikuiti (3M) foil and Teflon foil, plus air gap. Two radioactive sources: ^{241}Am (E$_\gamma$=59 keV) and ^{57}Co (E$_\gamma$=122 keV, 86% emission probability) were used. The sources were located 5 mm from either the top or the bottom and also at the middle of the plastic bar. The best result was obtained when using the Vikuiti (3M) tape as wrapping material. The reason for it to be better than the usual aluminum foil is its higher reflective index (higher than 0.98 with respect to 0.90 from the aluminum). −2− A full proof of concept of the detector requires a measurement of a modulation to be compared to the simulation. An 8×8 scintillator bars detector was tested for modulation measurements in a dedicated simplified facility of polarized gamma rays as been described in [5]. It provides a collimated beam of 290 keV photons with an average 40% polarization level. The facility provides also for each photon a synchronous tag in form of an electronic signal. The rate of coincidences between the bar where the beam enters (A), a second bar (B) and the tag signal was measured. Then the detector is turned by 90 degree and the rate is measured again using the same bars A and B. The asymmetry $Asy=(N_{90}-N_0)/(N_{90}+N_0)$, with N_0 and N_{90} are respectively the counts along the two complementary axes respectively, is computed from those two rates and compared with Monte Carlo. Figure 3 summarizes the resulting asymmetry as a function of the distance between bars A and B. An excess of counts was observed in the orthogonal (90) direction of about 12%. Estimating a μ_{100} for this setup of about 30% would correspond to a measured polarization level of $\Pi = Asy/\mu_{100}$ = 40%, which is about the average of the expected value. −3− The simulation studies have demonstrated the critical effects of any non-uniformity of the instrument on the μ_{100}. The most critical issue is the expected non-uniformity in the gain (up to a factor 2-3) among the 64 MAPMT channels as described in the Hamamatsu data-sheet (Fig. 3). Such an effect demands continuous monitoring and a precise calibration of each of the instrument channels. An R&D project in electronics, finalized to a new ASIC MAPRA - Multi Anode Polar Readout Asic - allowing to treat individually every channel, conceived specifically for POLAR and based on previous prototype experiences [8] is in progress. The POLAR demonstration model made of two sub-elements (two MAPMT with the corresponding 64 scintillator bars each) is under test with partially polarized X-rays from a radioactive source and, in addition, in a dedicated tests with a 100% polarized photon beam. The readout is performed by dedicated designed electronic boards using the commercial ASIC from IDEAS, while the original custom-made MAPRA ASIC will be integrated in the final configuration of the readout of the POLAR-flight model. The construction and testing of the full-scale (25 MAPMT) POLAR engineering-qualification model (EQM) will be finished in 2010. First tests for space qualifying some of the components have already been performed. The flight model will be ready for a launch in space by 2012. The Chinese Space Lab and the International Space Station are candidates for hosting on board the POLAR-flight-model.

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