Nuclear Instruments and Methods in Physics Research A 606 (2009) 552–559

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

Expected performance of a hard X-ray polarimeter (POLAR) by Monte Carlo simulation

Shaolin Xiong [a,*], Nicolas Produit [b], Bobing Wu [a]

[a] Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
[b] ISDC, Université de Genève, Switzerland

ARTICLE INFO

Article history:
Received 22 September 2008
Received in revised form
16 April 2009
Accepted 23 April 2009
Available online 7 May 2009

Keywords:
X-ray
Polarimeter
Polarization
Gamma-ray burst
Simulation

ABSTRACT

Polarization measurements of the prompt emission in gamma-ray bursts (GRBs) can provide diagnostic information for understanding the nature of the central engine. POLAR is a compact polarimeter dedicated to the polarization measurement of GRBs between 50 and 300 keV and is scheduled to be launched aboard the Chinese Space Laboratory around the year 2012. A preliminary Monte Carlo simulation has been accomplished to model the expected performance of POLAR while a prototype of POLAR is being constructed. The modulation factor, efficiency and effective area, background rates and minimum detectable polarization (MDP) were calculated for different detector configurations and trigger strategies. With the optimized detector configuration and trigger strategy and the total weight constraint of less than 30 kg, the primary science goal to determine whether most GRBs are strongly polarized can be achieved, and about 9 GRBs/yr can be detected with an MDP $<$ 10% for the conservative detector configuration.

1. Introduction

Polarization measurements in the X-ray and gamma-ray domain using the photoelectric effect, Compton scattering or pair production is one of the most exciting frontiers in contemporary astrophysics, since it provides a potential diagnostic approach to discriminate very different models that can successfully explain observations, with the exception of polarization. Photons emitted from celestial objects contain four kinds of information: energy, direction, time, and polarization. Although energy, direction and time are measured as spectrum, image and intensity, polarization has rarely been exploited in the X-ray and gamma-ray band.

Almost all non-thermal emission mechanisms that create X-ray and gamma-rays can produce high degrees of linear polarization that also depend on the magnetic field and the geometry of the source emission zone [1]. All magneto-bremsstrahlung radiation, including cyclotron, synchrotron and curvature radiation, are potential sources of linearly polarized photons whose polarization degree depends on the configuration of the magnetic field. For the observed range of power-law indices, from 1.5 to 5.0 for astrophysical synchrotron radiation sources, the maximum observed degree of linear polarization is expected to vary from approximately 65% to 80%, which will be reduced by the inhomogeneity of the magnetic field configuration [1]. Electron–proton bremsstrahlung radiation can produce linear polarization as high as 80%. Compton scattering can create energy-independent polarization [1, Eqs. (2.31), (2.33)], which is opposite to the synchrotron radiation and thus could be used to distinguish one from the other. Magnetic photon splitting can also lead to polarization levels of up to 30% [1]. Furthermore, before the polarized photons reach the Earth, the environment during their journey will also mark its signature in the polarization information, for instance, Compton scattering or Faraday rotation can change the status of polarization. Therefore, polarimetry in the high-energy regime is expected to yield crucial information about the emission mechanism, geometry, magnetic field and environment of the journey for a wide variety of high-energy astrophysical sources such as gamma-ray bursts (GRBs), soft gamma repeaters (SGRs), solar flares, isolated pulsars, jet-dominated AGNs, accreting black holes and neutron stars [2,3].

Although polarimetry is such an important and powerful tool, it has rarely been implemented successfully and accurately in the X-ray or gamma-ray range, especially in the energy band above 30 keV. A sounding rocket launched in the year 1971 was the first to measure X-ray linear polarization in the Crab Nebula, which determined that the X-ray emission in the nebula was due to synchrotron radiation [4]. OSO-8 searched for linear polarization for 15 bright X-ray sources with a Bragg crystal polarimeter. For most sources the polarization was of low significance [5]; however, observations of the Crab Nebula showed a polarization of $19.2\pm1.0\%$ at 2.6 keV and $19.5\pm2.8\%$ at 5.2 keV when contamination from the pulsar was removed [6], for Cygnus X-1

---

[*] Corresponding author.
E-mail addresses: zhenxialin@hotmail.com, xiongsl@ihep.ac.cn (S. Xiong).

0168-9002/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2009.04.033

a polarization of 2.4 ± 1.1% at 2.6 keV and 5.3 ± 2.5% at 5.2 keV [7] and for Scorpius X-1 a polarization of 0.39 ± 0.20% at 2.6 keV and 1.31 ± 0.40% at 5.2 keV [8]. COMPTEL [9] and BATSE [10], both aboard the CGRO, attempted to gain some polarization signature from their data. No successful results have so far been obtained from COMPTEL [9]. Although some analysis of the BATSE Albedo Polarimetry System (BAPS) data shows strong evidence that the lower limits of the polarization degree are 35% and 50% in the prompt flux of GRB 930131 and GRB 960924, respectively. The polarization degree cannot be firmly constrained beyond the systematic error [11]. RHESSI [12], a solar X-ray and gamma-ray spectroscopic imaging detector as well as a possible hard X-ray polarimeter [13] has measured 80 ± 20% linear polarization of the prompt emission in the energy range 15–2000 keV of the GRB 021206 [14], which has not been confirmed by the other two independent studies of the same data [15,16], so that the degree of polarization for GRB 021206 remains uncertain. In principle, both the IBIS and SPI instruments on INTEGRAL were capable of polarimetry in the gamma-ray range [17,18]. But the capabilities of IBIS were limited by the high level of random coincidences between the two detection planes and by the geometry, which was not optimal. Nevertheless, SPI has measured a high level of polarization of the very intense burst GRB 041219a, but the systematic effects which could mimic the weak polarization signal could not be excluded, hence this result cannot significantly constrain GRB models [19,20]. SPI has however been reported to detect gamma-rays of 46 ± 10% polarization from the vicinity of the Crab pulsar recently [21]. The detector plane of the BAT onboard Swift [22,23] may have worked as a good polarimeter, but the design of both detectors and signal processing electronics are not suitable for selecting the Compton scattering events [2].

In order to actualize polarimetry to various cosmic sources in the X-ray and gamma-ray energy range, many polarimeters have been proposed to date: Photoelectric polarimeters based on a micropattern gas chamber (MPGC) for X-ray Evolving Universe Spectroscopy (XEUS) and POLARIX [24–26], Compton polarimeters like the Gamma-Ray Polarimeter (GRAPE) [27], the Polarized Gamma-ray Observer (PoGO) [28] and the smaller version PoGOLite [29], the soft gamma-ray detector (SGD) onboard NeXT [30], the Coded Imager and Polarimeter for High Energy Radiation (CIPHER) [31], the X-ray Polarimeter Experiment (XPE) [32], as well as POLAR [33], and pair production polarimeters [34].

2. Compton scattering polarimetry

For a polarized photon having undergone Compton scattering (see Fig. 1), the differential cross-section is given by the Klein–Nishina formula:

$$\begin{aligned}\frac{d\sigma}{d\Omega} &= \frac{r_0^2\varepsilon^2}{2}\left(\frac{1}{\varepsilon}+\varepsilon-2\sin^2\theta\cos^2\eta\right)\\ &= \frac{r_0^2\varepsilon^2}{2}\left(\frac{1}{\varepsilon}+\varepsilon-\sin^2\theta+\sin^2\theta\cos\left(2\left(\eta+\frac{\pi}{2}\right)\right)\right) \qquad (1)\end{aligned}$$

where r_0 is the classic radius of electron and $\varepsilon = E'/E$. For a fixed scattering angle, the cross-section reaches a maximum at $\eta = \pi/2$ and a minimum at $\eta = 0$, and the azimuthal distribution of the scattered photons follows a $\cos 2\eta$ distribution (see Fig. 2).

In order to use a polarimeter, the response of the polarimeter to the 100% polarized photons must be calibrated. This response is known as the modulation factor, M, which is defined as

$$M = \frac{C_{\max} - C_{\min}}{C_{\max} + C_{\min}} \qquad (2)$$

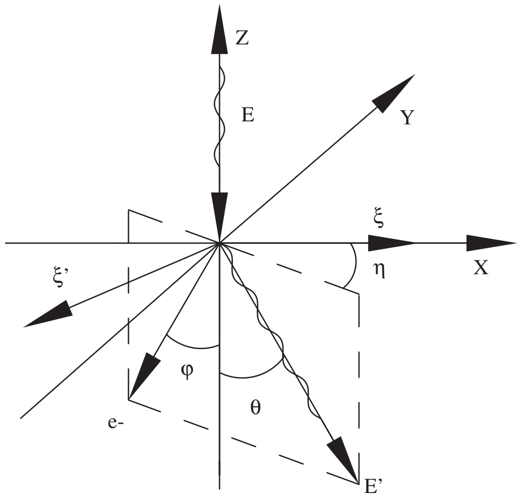

Fig. 1. Compton scattering of polarized photons. E and ξ are the energy and electric vector of the incident photon. E', ξ' and θ are the energy, electric vector and scattering angle of the scattered photon. φ is the recoil angle of the electron. η is the azimuthal angle that represents the angle of the plane of scattered photon and recoiled electron with respect to ξ.

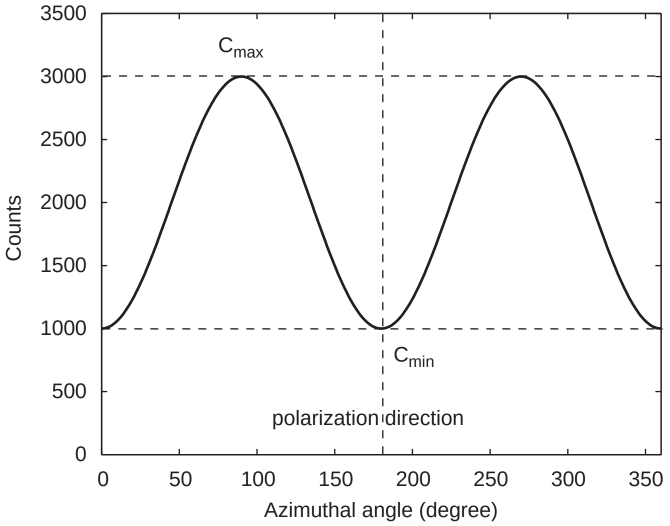

Fig. 2. The azimuthal distribution of scattered photons. The central vertical dashed line represents the polarization direction.

where $C_{\max}$, $C_{\min}$ refer to the maximum and minimum numbers of counts in the azimuthal distribution. Since the azimuthal distribution will be uniform for an unpolarized photon beam, the polarization level of the beam is given by

$$P = \frac{M_p}{M_{100}} \qquad (3)$$

where M_p is the modulation factor for the measured photon beam, M_{100} is the modulation factor for the 100% polarized beam, and P is the polarization level of the beam. The minimum detectable polarization (MDP), which is the minimum level of polarization that is detectable with a significance level, n_σ (number of sigma), due to statistical variations, can be expressed as

$$\mathrm{MDP} = \frac{n_\sigma}{M_{100}S}\sqrt{\frac{2(S+B)}{T}} \qquad (4)$$

where S is the total source counting rate, B is the total background counting rate and T is the observation time.