Nuclear Instruments and Methods in Physics Research A 840 (2016) 69–76

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

Polarimetric analysis of a CdZnTe spectro-imager under multi-pixel irradiation conditions

M. Pinto[a,b], R.M. Curado da Silva[a,b,*], J.M. Maia[a,c], N. Simões[a,b], J. Marques[a,d], L. Pereira[a], A.M.F. Trindade[a], E. Caroli[e], N. Auricchio[e], J.B. Stephen[e], P. Gonçalves[a]

[a] LIP-Laboratório de Instrumentação e Física Experimental de Partículas, Portugal
[b] Physics Department, University of Coimbra, Coimbra, Portugal
[c] Physics Department, University of Beira-Interior, Covilhã, Portugal
[d] Centro de Astrofísica, Universidade do Porto, Porto, Portugal
[e] INAF-IASF-Bologna, Bologna, Italy

ARTICLE INFO

Keywords:
Polarimetry
X-rays
Gamma-rays
CdZnTe
Astrophysics
Detectors

ABSTRACT

So far, polarimetry in high-energy astrophysics has been insufficiently explored due to the complexity of the required detection, electronic and signal processing systems. However, its importance is today largely recognized by the astrophysical community, therefore the next generation of high-energy space instruments will certainly provide polarimetric observations, contemporaneously with spectroscopy and imaging. We have been participating in high-energy observatory proposals submitted to ESA Cosmic Vision calls, such as GRI (Gamma-Ray Imager), DUAL and ASTROGAM, where the main instrument was a spectro-imager with polarimetric capabilities. More recently, the H2020 AHEAD project was launched with the objective to promote more coherent and mature future high-energy space mission proposals. In this context of high-energy proposal development, we have tested a CdZnTe detection plane prototype polarimeter under a partially polarized gamma-ray beam generated from an aluminum target irradiated by a ^{22}Na (511 keV) radioactive source. The polarized beam cross section was 1 cm^2, allowing the irradiation of a wide multi-pixelated area where all the pixels operate simultaneously as a scatterer and as an absorber. The methods implemented to analyze such multi-pixel irradiation are similar to those required to analyze a spectro-imager polarimeter operating in space, since celestial source photons should irradiate its full pixilated area. Correction methods to mitigate systematic errors inherent to CdZnTe and to the experimental conditions were also implemented. The polarization level (~40%) and the polarization angle (precision of $\pm 5°$ up to $\pm 9°$) obtained under multi-pixel irradiation conditions are presented and compared with simulated data.

1. Introduction

Polarimetry in high-energy astrophysics has been insufficiently explored due to the complexity of the required detection, electronic and signal processing systems, since celestial gamma-ray sources are only observable by high-altitude balloon or satellite missions in space. To date, no dedicated gamma-ray polarimeters have been launched into space. X- and gamma-ray source emissions have been studied almost exclusively through spectral and timing analysis of the measured fluxes and by using imaging techniques based on coded-mask cameras or telescopes equipped with high efficiency focal plane detectors. Polarization measurements will increase the number of observational parameters of a gamma-ray source by two: the polarization angle and the level of linear polarization. These additional parameters should allow a better discrimination between different emission models characterizing the same object. Polarimetric observations can provide important information about the geometry, the magnetic field, the composition and the emission mechanisms. Polarized emissions are expected in a wide variety of gamma-ray sources such as pulsars, solar flares, active galactic nuclei, galactic black-holes and gamma-ray bursts [1–3]. In the soft X-ray domain (< 10 keV) two observations performed in the 1970's by a rocket flight and by the OSO-8 (Orbiting Solar Observatory) polarimeter measured the Crab Nebula polarization [4,5]. In the soft gamma-ray domain (100 keV to 1 MeV), although some dedicated polarimeters have been proposed [6–14], only a few polarimetric measurements were performed by the SPI (Spectrometer On INTEGRAL) and IBIS (Imager on Board the INTEGRAL Satellite) instruments onboard the INTEGRAL

* Corresponding author at: LIP-Laboratório de Instrumentação e Física Experimental de Partículas, Universidade de Coimbra, P-3004-516 Coimbra, Portugal.
E-mail address: rui.silva@coimbra.lip.pt (R.M.C. da Silva).

http://dx.doi.org/10.1016/j.nima.2016.09.054
Received 29 June 2016; Received in revised form 6 August 2016; Accepted 26 September 2016
Available online 28 September 2016

(INTErnational Gamma-Ray Astrophysics Laboratory) mission [15,16], on the Crab Pulsar, on the galactic black-hole Cygnus X-1 and on the gamma-ray burst GRB 041219A [17–20].

The importance of polarimetry is today largely recognized by the high-energy astrophysical community. Therefore, the next generation of telescopes should certainly provide polarimetric observations, contemporaneously with spectroscopy and imaging. These multipurpose instrument types were proposed in recent high-energy (100 keV to 1 GeV) space mission concepts submitted to ESA Cosmic Vision calls where our groups were proposal partners, such as: the GRI (Gamma-Ray Imager), DUAL and ASTROGAM [21–23]. In the framework of these space mission proposals, we have been studying, developing and proposing different configuration detection plane prototypes for high-energy polarimetry. These prototypes were semiconductor based (mostly CdTe family) detection planes designed for coded mask or for Laue lens instrument solutions. These solutions require a trade-off between the imaging, spectroscopy and polarimetry components [24,25] that depends on the mission scientific objectives and which results in a substantially different configuration than those required for dedicated polarimeters [7,14,25]. So far there has been insufficient interest from the space agencies (including ESA) of our countries to accept a dedicated Compton polarimeter. The broader scientific return of a multipurpose mission (imaging, spectrometry and polarimetry) is often regarded as a better choice, in spite of its additional cost when compared with a simple dedicated polarimeter mission.

LIP (Laboratório de Instrumentação e Física Experimental de Partículas), Coimbra, Portugal is a partner in the Horizon 2020 AHEAD (Activities in the High Energy Astrophysics Domain) project (H2020 EU ref.: 654215) started in September 2015. The main objective of AHEAD is to promote synergies between the distinct national efforts in high-energy astrophysics in order to provide more coherent and mature future space observatory joint proposals to future ESA calls for missions. Therefore our main objective in polarimeter development is mostly associated with multipurpose innovative instruments that can provide a sensitivity increase in the high-energy domain. Although the experiment described herein was performed before the AHEAD project approval, the main purpose of this work is to contribute to optimize the polarimetric performances of future high-energy space proposals. Within this scope, a CdZnTe (CZT) polarimeter prototype was tested under a partially polarized gamma-rays beam generated by Compton scattering on a low-Z target irradiated by a ^{22}Na (511 keV) radioactive source. These measurements were performed in a polarimetry dedicated workbench at LIP laboratory, following a series of experiments carried out at the ESRF (European Synchrotron Radiation Facility) under a polarized synchrotron gamma-rays beam in the 100–750 keV range [27–32]. In these previous synchrotron beam experiments, the beam was collimated to impinge within a single pixel detector area (2×2 mm^2) due to beam diameter technical limitations. Another limitation of the ESRF polarized gamma-rays beam was the exponentially decreasing beam flux as the level of polarization was reduced. Since the number of beam slots available at the ESRF is limited for an experiment session period, generally it was not envisaged to perform measurements for beam polarization levels lower than 80%. In the LIP laboratory we are not subject to this restriction, therefore we were able to reproduce an irradiation configuration closer to in-flight observational conditions. Since celestial source emissions are partially polarized and since the flux irradiates the instrument's full detection plane surface, we tested the CZT prototype under a partially polarized beam (from ~65% down to ~40%) that irradiated multiple detector pixels simultaneously with a total area of ~1 cm^2. Therefore, instead of previously tested irradiation conditions such as central matrix pixel scatterer or scatterer-calorimeter configurations [26–38], we irradiated a large active detection surface where all the detection units (pixels) operated simultaneously as a scatterer and as an absorber. The results obtained are discussed and compared with previous single pixel irradiation polarimetric experiments. In particular, we describe multiple pixel irradiation analysis as well as correction methods to mitigate the CZT matrix inherent systematic errors affecting the polarimetric response.

2. Compton polarimetry

The polarimetric performance of a high-energy detection plane is determined by the fundamental concepts associated with polarized Compton interactions and by its design. The Compton scattering of a polarized photon beam generates non-uniformity in the azimuthal angular distribution of the scattered photons. The scattered photon's angular direction depends on its initial polarization angle. If the scattered photon goes through a new interaction inside the detector, the statistical distribution of photons's angular directions defined by the two interactions (double-event) provides a modulation curve from which the degree and polarization direction of the incident beam can be derived. The azimuthal angular distribution of the scattered photons is given by the Klein-Nishina differential cross-section for linearly polarized photons:

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}\left(\frac{E'}{E}\right)^2\left[\frac{E'}{E} + \frac{E}{E'} - 2\sin^2\theta\cos^2\varphi\right], \quad (1)$$

where r_0 is the classical electron radius, E and E' are, respectively, the energies of the incoming and outgoing photons, θ the angle of the scattered photons and ϕ is the angle between the scattering plane (defined by the incoming and outgoing photon directions) and incident polarization plane (defined by the polarization direction and the direction of the incoming photon). As can be seen from (1), after fixing all other parameters the scattering probability varies with the azimuthal angle ϕ and its maximum and minimum arises for orthogonal directions. For ϕ=0° the cross-section reaches a minimum and for ϕ=90° the cross-section reaches a maximum. However, this relative difference is maximized for a scattering angle θ_M, dependent on the incident photon energy. For soft γ- and hard X-rays (0.1–1 MeV) the θ_M value is about 90°. Note that E and E' are related by:

$$\frac{E'}{E} = \frac{1}{1 + \frac{E}{m_0c^2}(1 - \cos\theta)}, \quad (2)$$

where c is the speed of light in free space and m_o is the electron rest mass.

The polarimetric performance of an instrument can be evaluated by calculating the polarimetric modulation factor, Q_{100}, of double-event distribution generated by a 100% polarized beam. For the case of a planar pixelated detector, Q_{100} can be calculated from the modulation curve resulting from a double-event angular distribution around a central irradiated pixel:

$$Q_{100} = \frac{N_{//} - N_{\perp}}{N_{//} + N_{\perp}}, \quad (3)$$

where $N_{//}$ and $N_{\perp}$, are the double-events integrated over two orthogonal directions defined over the detector plane along the maxima and minima of the modulation curve [39].

3. Experimental setup and methods

This experimental study was performed with a polarimeter prototype based on a 5.0 mm thick IMARAD CZT ($Cd_{0.9}Zn_{0.1}Te$) detector. The detector matrix was divided into 16×16 pixels with an area of 2.0 mm×2.0 mm each and with a 0.5 mm gap between consecutive pixels. Due to electronic constraints only 16 pixels (in 4×4 configuration) could be read in coincidence. Therefore the total sensitive area available for the polarimetric measurements – that require coincidence electronics – was 1.0 cm×1.0 cm. The detector was operated at room temperature with a bias voltage of 600 V (Fig. 1).

The signals generated by the 16 pixels were read by the front-end