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The POLCA Experiments

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Abstract– A gamma-ray telescope mission concept (GRI: Gamma Ray Imager) based on Laue focusing techniques has been proposed in reply to the European Space Agency call for mission ideas (Cosmic Vision 2015-2025). In order to aid the design optimization of its main instrument, a series of experiments based on CdZnTe pixelized detector prototypes was carried out at the European Synchrotron Radiation Facility where a ~ 99% polarized high energy beam is available. The main purpose of these experiments, denominated as POLCA (POlarimtery with Cadmium Telluride Arrays), was to assess the performance of a CdZnTe pixel detector as a polarimeter in the gamma-ray band. The spectroscopic, imaging and timing performances were studied and in particular its potential as a polarimeter was evaluated. The prototype detectors tested were CdTe and CdZnTe arrays up to 7 mm thick. They were irradiated with a monochromatic linearly polarized beam with a spot diameter of about 0.5 mm over an energy range up to 750 keV. Polarimetric *Q* factors of 0.35 were obtained. Further measurements were performed with a copper Laue monochromator crystal placed between the beam and the detector prototype. In this configuration we have demonstrated that a polarized beam does not change its polarization level and direction after undergoing a small angle (<1º) Laue diffraction inside a crystal. Upon rotating this crystal by 360º with 22.5º steps no systematic effects were noticed in the detected polarization after the Laue diffraction process.

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1.Introduction

In spite of recent Crab pulsar polarization measurements [1,2], polarimetry in astrophysics is still a quite unexplored domain in the X- and gamma-ray energy band due to the great deal of complexity that this kind of measurement requires. In fact, no dedicated polarimeters have ever been launched either into space or as balloon-borne experiments. To date X- and gamma-ray source emissions have been studied almost exclusively through spectral and timing variability analysis. By measuring the polarization angle and degree of polarization of the source emission, it will be possible to double the number of observational parameters, thereby allowing better discrimination between various models describing the same observations. Polarimetric observations can provide important information about geometries, magnetic fields, composition and emission mechanisms in a wide variety of gamma-ray sources.

A gamma-ray telescope mission concept (GRI: Gamma Ray Imager) based on Laue focusing was proposed in reply to the ESA (European Space Agency) Cosmic Vision call. The GRI was designed as formation flying mission composed of two spacecrafts where the incoming gamma-rays are focused by a Laue lens crystal system in the Optics Spacecraft on to the Detector Spacecraft focal plane that is 100 m distant [3]. The University of Coimbra, the Istituto di Astrofisica Spaziale e Fisica Cosmica (Bologna) and the University of Ferrara are members of the GRI consortium and are collaborating in the development of a CdZnTe focal plane optimized for the Laue lens configuration. In order to aid the optimization of the design of this detector, a series of experiments based on a CdZnTe pixel detector prototypes was carried out at the ESRF (European Synchrotron Radiation Facility) where a ~ 99% polarized gamma-ray beam is available. The main purpose of these experiments, denominated as POLCA (POlarimtery with Cadmium Telluride Arrays), was to assess the performance of a CdZnTe focal plane as a polarimeter up to 750 keV.

2. Compton Scattering Polarimetry

In the gamma-ray domain, a photon undergoing a Compton interaction will change direction in a manner which depends on the orientation of its polarization vector before the interaction. If these polarized photons go through a new interaction inside the detector, the statistical distribution of the relative positions of the two interactions (double events) allows us to infer the degree and polarization direction of the incident radiation. The Klein-Nishina cross-section for linearly polarized photons gives us an azimuthal dependency for the scattered photons:

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

where r_0 is the classical electron radius, E and E' are the energies of the incoming and outgoing photons respectively, θ the angle of the scattered photon 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 vector and the direction of the incoming photon). As can be seen from (1), after fixing all other parameters the probability varies with the azimuthal angle φ. The maximum relative difference between the cross-section values arises for φ = 0° - where the cross-section reaches a minimum - and φ = 90° - where the cross-section reaches a maximum. However this relative difference is maximized for an angle θ_M, dependent on the incident photon energy. For soft gamma and hard X-rays the θ_M value is about 90°.

The polarimetric performance of an instrument can be evaluated by analyzing the distribution of double events through the polarimetric modulation factor, *Q*. This is obtained by integrating the Compton polarimetric differential cross section formula given by (1) over the solid angles defined by the physical geometry of the detection plane:

$$Q = \frac{N_x - N_y}{N_x + N_y} . \qquad (2)$$

Here we obtain *Q* through the orthogonal *x*- and *y*-axis directions defined over the detector plane, to a polarized beam whose electric vector points in the y direction. N_x and N_y are the number of counts in each of the orthogonal directions.

3. POLCA Experiment Series

3.1 POLCA I

The POLCA I experiment was performed at the ESRF ID (Insertion Device) 15 beamline where a ~99% linearly polarized monochromatic gamma-ray photon beam was available. The POLCA experimental system was composed by four functional subsystems: the synchrotron beamline optical system, the detection system, the shaping and coincidence electronic system and the control and data acquisition workstation. The ID 15 beamline optical system allows tuning the energy of monochromatic photon beam up to 1 MeV, with a beam spot of ~500 µm diameter and a polarized component higher than 99 % [4]. The detectors employed in this experiment were CdTe pixelized devices. The signals were processed by a custom multiparametric system consisting of 128 independent channels with filters, coincidence logic with a 2 µs time window and ADC (Analog-to-Digital Converter) units [6]. The data acquisition was performed with a PXI DAQ-6533 board provided by National Instruments.

Three CdTe monolithic matrices of different thicknesses (3.4, 5.0 and 7.5 mm) were tested in this experiment. Each detector consisted of 4×4 pixels (2.5 mm × 2.5 mm each) defined by a segmented platinum chloride electrode. These detectors, the 16 preamplifiers and the bias circuits for the detectors and the preamplifiers were installed on the same board. The 16 charge sensitive preamplifiers (Eurorad PR 304) were individually connected to each detector pixel. Each prototype was tested under a ~99% polarized monochromatic photon beam in the energy range between 100 keV and 400 keV.

3.1.1 Experimetal procedure

As the CdTe detectors available consisted of 4×4 matrix arrays, such a pixelisation level limited considerably the resolution of the double event distributions obtained. However, due to the 90° double event distribution symmetry produced by a polarised photon beam (1) we were able to simply irradiate a corner pixel of our 4×4 matrix and consider the obtained distribution as a 90° quadrant of a virtual 360° distribution of a 7×7 matrix. This method was verified by rotating the detector at 90º steps with the mechanical system in Fig. 1.

The experimental procedure consisted of three steps: 1) The beam was aligned with the centre of one pixel, since a slight deviation from this position could be responsible for an artificial asymmetric distribution; 2) Each of the 16 CdTe pixels was irradiated by the beam moving the detector in 2.5 mm steps; 3) The detector was rotated by 90° with respect to its initial position and the three steps were repeated. The single events obtained for each pixel allowed us to determine the response map of the 4×4 matrix. We were then able to correct the non uniformity of our monolithic CdTe detectors using this response non dependent on the polarisation of the beam by calculating the true double events counts N_{true} for each pixel by:

$$N_{true} = \frac{N_{pol}}{N_{non}} N_{\max} , \qquad (3)$$

where N_{pol} is the number of double events detected (that depend on the beam polarisation), N_{non} are the single events detected when the pixel is directly irradiated and N_{max} is maximum value among all the matrix pixels N_{non} [7]. Furthermore, using a non-polarized 122 keV (^{57}Co) radioactive source we irradiated each pixel in the same conditions, in order to obtain a response matrix to each detector which allow the correction the squared pixel systematic.

TABLE I

POLCA I polarimetric Q factors compared with Monte Carlo simulations data

Matrix number (thickness)	*Experimental Polarimetric Q factor*			*Monte Carlo Polarimetric Q factor*		
	100 keV	*300 keV*	*400 keV*	*100 keV*	*300 keV*	*400 keV*
1167/11 (3.4 mm)	0.15 ± 0.051	0.46 ± 0.036	0.36 ± 0.091	0.49 ± 0.005	0.47 ± 0.003	0.43 ± 0.003
1283/26 (5.0 mm)	–	0.40 ± 0.12	0.33 ± 0.13	–	0.43 ± 0.002	0.39 ± 0.003
1186/49 (7.5 mm)	–	0.39 ± 0.060	0.31 ± 0.065	–	0.40 ± 0.002	0.35 ± 0.002

3.1.2 POLCA I results

Table I shows the polarimetric *Q* factors - after non uniformity correction - calculated for the three CdTe polarimeter prototypes as a function of the polarized photon beam energy. Simultaneously, the POLCA experiment was replicated by a GEANT4 (GEometry ANd Tracking) based simulation code [5]. The *Q* factors obtained from simulations are also shown on Table I. The experimental dependence of the polarimetric *Q* factor on the beam energy and the detector thickness is in good agreement with simulations, except at 100 keV. In order to minimise the preamplifier's noise, a high discrimination level was required that excluded all pulses corresponding to events that deposited energy below 40 keV inside a pixel. For 100 keV the number of double events over this limit was only a small percentage, explaining the low *Q* factor obtained. It was also found that the *Q* factor is higher when thinner detectors are used. This is due to the *Q* factor dependence of the polar scattering angle θ. As mentioned before, in the considered energy range the *Q* factor is maximised for angles near 90°. Inside thinner matrices Compton interactions with angles θ that differ from 90° have a higher probability to escape from the detector and therefore the double events that interact inside the detector are those with θ near 90°, therefore the higher Q was obtained for the thinnest matrix (3.4 mm).

3.2 POLCAII

The detector employed in the POLCA II experiment was a 5 mm thick CdZnTe IMARAD device with 16×16 pixels, each with 2.5×2.5 mm^2 area (Fig. 1) [8]. Due to limitations in our back-end electronics (only 128 channels available) only 11×11 pixels have been connected for a total sensitive area of ~8 cm^2. The CdZnTe unit was installed on a supporting layer that contains the readout ASIC (Application-Specific Integrated Circuit) supplied by eV Products [9], the bias circuit and the connectors for the back-end electronics.

As in the case of POLCA I, a corner pixel of the 11×11 CdZnTe matrix was directly irradiated and the obtained distribution was analysed as a 90° quadrant of a virtual 360° planar distribution around the same pixel, allowing to extrapolate the distribution obtained to an equivalent 21×21 matrix, generating distributions up to the 10th order pixels, instead of 5th.

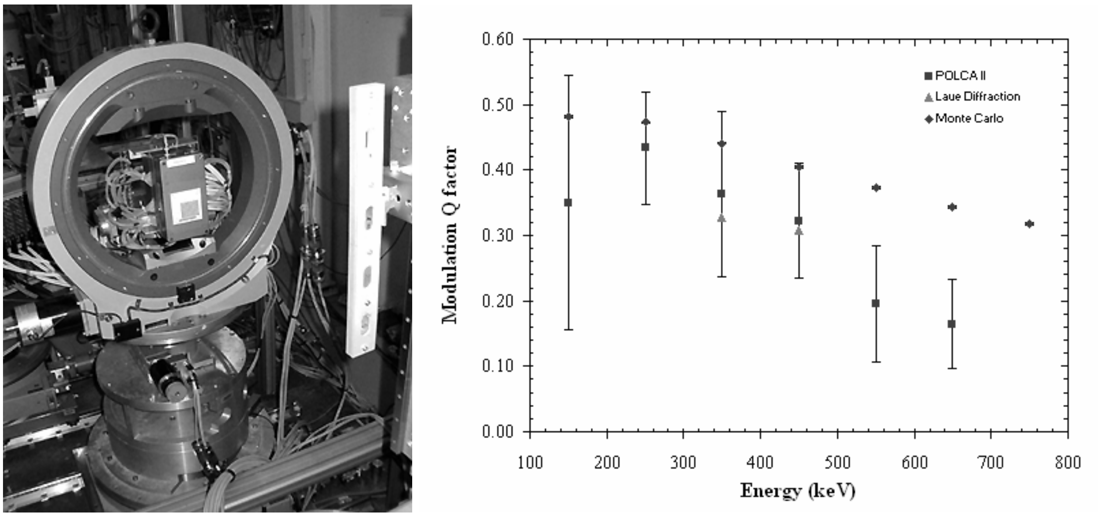

Fig. 1. (left) The detector and the Cu crystals mounted on aligned positioning mechanical system. Three Cu crystals are shown at the right, mounted in the white rack. The CdZnTe is mounted at the centre of the Eulerian cradle. (right) The Q factor as function of the energy for a 5 mm CdZnTe prototype when irradiated by a monochromatic ~99% polarized photon beam. The Q *factor obtained for 350 keV and 450 keV Cu Laue monochromator diffracted beams is also shown. Monte Carlo simulation results obtained in similar conditions are shown for comparison.*

3.2.1 POLCA II detection plane performances

The graph of Fig. 1 shows the polarimetric Q factors obtained for the CdZnTe prototype as a function of the polarized photon beam energy. These Q factors were obtained employing (3) when correcting of the dominant source of errors generated by the non uniformity in the response of the detector volume. For comparison, the POLCA II experimental setup was replicated by our GEANT4 based simulation code. The Q factor values obtained from these simulations are also represented in the graph of Fig.1. The experimental polarimetric Q factor obtained is of about 0.35 or higher up to 350 keV. It decreases to about 0.15 for 650 keV, since for higher energies the probability of Compton interactions occurring with a scattering angle θ lower than 90º is higher than in the 150 keV – 350 keV band. As discussed in chapter 2, Q is maximised for angles of about 90° for gamma-rays. Furthermore, a lower θ also means that an increasing fraction of Compton photons escape the CdZnTe without interacting a second time in the crystal as the beam energy increases. As can be seen in Fig. 1, the CdZnTe prototype performances obtained up to 450 keV are in good agreement with the Monte Carlo simulation results performed with a GEANT4-based code. From 550 keV to higher energies, a secondary synchrotron photon beam was projected onto the CdZnTe active surface area which introduced a substantial error component in the Q factor calculation.

3.2.2 Cu crystal Laue diffraction polarimetric performances

A set of polarimetric measurements were performed by interposing copper crystals (prepared by ILL, Grenoble) between the polarized beam and the prototype CdZnTe detector, 75 cm away from the surface of the detector. The three copper samples employed had a Face Centered Cubic crystalline structure with (111) diffraction planes perpendicular to the surface of the crystal, and are similar to the crystals that we intend to employ in a Laue lens system operating in a future gamma-ray telescope. Both the detector system and crystal were mounted on co-aligned computer-controlled 3-axis and rotation positioning systems (Fig. 2).

Measurements were performed at 350 keV and 450 keV. At both energies the transmitted beam and one or more diffracted beams by the Cu crystal structure were observed in the CdZnTe matrix. Since the Laue lens system is based on the first order diffracted beam detection, we studied the characteristics of this beam, in particular its intensity, its polarization direction and polarization level and its diameter. So far as the precision of our measurements allowed, no changes were observed in the beam diameter, in the polarization level or in the polarization direction of the beam. The projection of the first order diffracted beams in the CdZnTe matrix was about 10mm from the transmitted beam, for 75 cm distance between the lens and the detector. Therefore, small angle (<1º) Laue diffraction of gamma-rays inside a crystal does not change the polarization state of the original beam. It must be stressed that this result is the experimental evidence of the hypothesis that was postulated by Ref. 10 and Ref. 11. In Fig. 1, the Q factor obtained for 350 keV and 450 keV diffracted beams show a good agreement with Q obtained for a synchrotron beam of the same energy when no diffraction crystals are used.

3.3 LaPOLCA

The main objective of LaPOLCA (Laue lens POLarimetry with CZT Arrays) experiment was to assess the reliability and the performance as a scattering polarimeter of a CZT detector in the focal plane of a Laue focusing instrument. In particular to evaluate if Laue diffraction introduces systematic effects on the polarization status of the incoming photons [12]. This experiment was performed in the ID 15 B beam line of the ESRF which generates monochromatic (~99%) linearly polarised radiation at energies of 270 keV and 345 keV with a spot diameter between 0.1-0.2 mm. The detector used was the same detector used in POLCA II, an Imarad CZT detector with 11×11 active pixels.

A Laue lens system is a set of properly oriented crystals [13]. In our experiment it was emulated by using a single crystal that was rotated and placed in the correct positions in front of the beam. The Cu crystal was mounted on a 3 axis linear motion stage coupled with a 2 axis rotation stages to properly align the crystal with respect to the incident beam and to perform the rotation of the crystal itself around the virtual axis of the lens. In this way it was possible to emulate the equivalent of the Laue rings for each available energy line. Furthermore, the advantage of emulating the lens with one crystal is that the mosaic structure is fixed, therefore avoiding additional effects due the intrinsic spread of this structure in a Cu crystal sample. The Cu crystal (4 mm thick and 15×15 mm^2 in surface) was provided by the ILL (Grenoble). The detector unit was mounted on a computer controlled 2- axis and micro positioning system at 200 cm from the crystal (Fig.1). For each beam energy, we have found the Laue diffraction condition for the given Cu crystal. Therefore we rotated the crystal around directions parallel to the axis beam to simulate a Laue ring (Fig. 2) comprising 16 elements (one every 22.5º). For each Cu crystal configuration the detector was moved in order to intercept the diffracted beam always into the same pixel (201) in the central part of the sensitive surface.

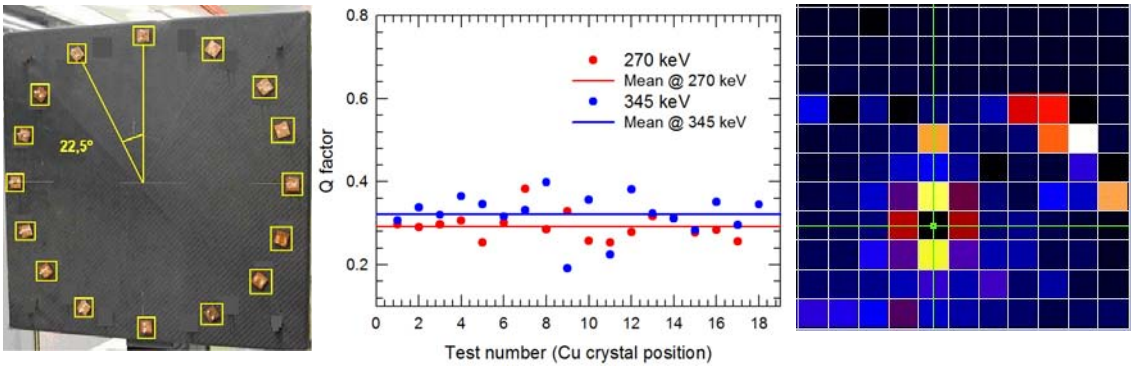

Fig. 2. (left) Demonstration model built at the Ferrara University of the LaPOLCA simulated 16 elements Laue lens ring. (centre) The modulation factor Q obtained for each Cu crystal position in the Laue lens simulation tests. The data errors are of the order of the symbol size. (right) The double event map of the diffracted beam at 270 keV impinging on the detector pixel 201 (target pixel is black with a green spot).

The modulation *Q* factor for each diffracted beam energy and Cu crystal position after applying the non uniformity correction factor (3) is represented in the graph of Fig.2. These results confirmed that the Laue diffraction process does not affect (within few %) the polarisation status of the incoming photons.

4.Conclusions

POLCA series experiments showed that a simple CdZnTe pixelated matrix can potentially perform fine polarimetric measurements up to 650 keV (polarimetric *Q* factors of ~0.35 up to 350 keV and > 0.15 up to 650 keV). These experiments validated our Monte Carlo simulation model up to 750 keV, since the experimental polarimetric *Q* factor was in good agreement with the results obtained by the simulations. The polarimetric measurements performed when interposing a copper crystal between the polarized beam and the prototype detector showed the experimental evidence that small angle (<1º) Laue diffraction of a gamma-ray beam inside the crystal does not change the polarization state of the diffracted beam, as was anticipated by previous theoretical studies. The preliminary results from LaPOLCA experiment data confirm that the Laue diffraction process does not affect (within few %) the polarisation status of the impinging photon. Together, these results are a fine indication of the polarimetric potential of the GRI mission CdZnTe focal plane.

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References

[1] A. J. Dean, D. J. Clark, J. B. Stephen, V. A. McBride, L. Bassani, A. Bazzano, A. J. Bird, A. B. Hill, S. E. Shaw and P. Ubertini, *Polarized Gamma-Ray Emission from the Crab*, *Science*, 321, 1183, 2008.

[2] M. Forot, P. Laurent, I. A. Grenier, C. Gouiff and F. Lebrun, *Polarization of the Crab pulsar and nebula as observed by the Integral/IBIS telescope*, *Astrophys. J.*, 688, 29, 2008.

[3] J. Knödlseder, P. von Ballmos, F. Frontera, A. Bazzano, F. Christensen, M. Hernanz and C. Wunderer, *GRI: focusing on the evolving violent Universe*, *Proceedings of the SPIE*, Vol. 6688, 668806, 2007.

[4] ESRF, *ESRF Highligts 1995/96*, European Synchrotron Radiation Facility, Grenoble, 1996.

[5] R. M. Curado da Silva, E. Caroli, M. Hage-Ali, J. B. Stephen, M. Ayoub, A. Donati, F. Schiavone, G. Ventura and P. Siffert et al., *Experimental polarimetric study of an hard X-ray energy telescope prototype*, *IEEE Trans. Nucl. Sci.*, 50, 1198, 2003.

[6] P. Guazzoni, G. Taiocchi and L. Zetta, *A mixer unit for data acquisition*, *Nucl. Inst. A*, 305**,** 442, 1991.

[7] F. Lei, A. J. Dean and G. L. Hills, *Compton polarimetry in gamma-ray astronomy, Space Sci. R.*, 82, pp. 309-388, 1997.

[8] R.M. Curado da Silva, et al., *Polarimetric performance of a Laue lens gamma-ray*, *J. Appl. Phys.*, 104, 084903, 2008.

[9] G. De Geronimo, et al., *Advanced-readout ASICs for multielement CdZnTe detectors*, *Spie Proceedings*, 4784, 105, 2003.

[10] De Chiara and F. Frontera, *Bragg diffraction technique for the concentration of hard x-ray for space astronomy*, *Appl. Optics*, 31, 1992.

[11] Zachariasen, *Theory of X-ray Diffraction in Crystals*, Dover Publications, 1994.

[12] E. Caroli, et al., *Polarimetry with a Laue Lens and CZT Pixel Detector*, *Proceedings of the IEEE 16th Room-Temperature Semiconductor Workshop*, R03-4, 2008

[13] A. Pisa, F. Frontera, G. Loffredo, D. Pellicciotta, and N. Auricchio, *Optical properties of Laue lenses for hard X-rays (>60 keV)*, *Exp. Astron.*, 20, 219, 2005.