Nuclear Instruments and Methods in Physics Research A 620 (2010) 285–293

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

Spectral and polarimetric characterization of the Gas Pixel Detector filled with dimethyl ether

F. Muleri [a,*], P. Soffitta [a], L. Baldini [b], R. Bellazzini [b], A. Brez [b], E. Costa [a], S. Fabiani [a,c], F. Krummenacher [d], L. Latronico [b], F. Lazzarotto [a], M. Minuti [b], M. Pinchera [b], A. Rubini [a], C. Sgró [b], G. Spandre [b]

[a] IASF/INAF, Via del Fosso del Cavaliere 100, I-00133 Roma, Italy
[b] INFN sez. Pisa, Largo B. Pontecorvo 3, I-56127 Pisa, Italy
[c] Università di Roma "Tor Vergata", Dipartimento di Fisica, via della Ricerca Scientifica 1, I-00133 Roma, Italy
[d] EPFL, Route Cantonale CH-1015 Lausanne, Switzerland

ARTICLE INFO

Article history:
Received 27 November 2009
Received in revised form
8 February 2010
Accepted 1 March 2010
Available online 6 March 2010

Keywords:
X-rays
Gas detectors
Polarimetry

ABSTRACT

The Gas Pixel Detector belongs to the very limited class of gas detectors optimized for the measurement of X-ray polarization in the emission of astrophysical sources. The choice of the mixture in which X-ray photons are absorbed and photoelectrons propagate, deeply affects both the energy range of the instrument and its performance in terms of gain, track dimension and ultimately, polarimetric sensitivity. Here we present the characterization of the Gas Pixel Detector with a 1 cm thick cell filled with dimethyl ether (DME) at 0.79 atm, selected among other mixtures for the very low diffusion coefficient. Almost completely polarized and monochromatic photons were produced at the calibration facility built at INAF/IASF-Rome exploiting Bragg diffraction at nearly 45°. For the first time ever, we measured the modulation factor and the spectral capabilities of the instrument at energies as low as 2.0 keV, but also at 2.6, 3.7, 4.0, 5.2 and 7.8 keV. These measurements cover almost completely the energy range of the instrument and allows to compare the sensitivity achieved with that of the standard mixture, composed of helium and DME.

1. Introduction

Detectors able to image charged particle tracks in a gas have been developed over the last few years for different applications. One of the most promising is the possibility to resolve the path of photoelectrons emitted in the gas in consequence of a photoelectric absorption. The reconstruction of the initial direction of photoelectron emission opens the way for measuring the state of polarization of the absorbed photons because the former is modulated with respect to the direction of the photon electric field with a $\cos^2$ dependency. This makes the photoelectric effect a good analyzer of X-ray polarization, and a perfect one for absorption from spherically symmetric shells.

Only a few gas detectors can resolve so finely the photoelectron tracks to accurately reconstruct the initial direction of emission [3,5]. One of the most sensitive is the Gas Pixel Detector (GPD hereafter), developed by INFN-Pisa and INAF/IASF-Rome [7,4] and currently inserted in the focal plane of several future satellite missions [2,6]. The gas cell is 1 or 2 cm thick and a number of mixtures of helium, neon or argon and dimethyl ether (DME hereafter) at 1 or 2 atm have been used, the choice of the gas being of fundamental importance for the polarimetric performance of the detector. A hard limit to the lower energy threshold of the instrument is about twice the binding K-shell energy of the absorbing component because above this threshold the photoelectron track, modulated with polarization, prevails on the isotropic one of the Auger electron. Photoelectron range is determined by density, while the average atomic number fixes the mean free path for scattering with atomic nuclei, which is the length scale on which polarimetric information is smeared. The diffusion coefficient influences the blurring of the photoelectron track during drift in the gas cell and eventually the possibility to resolve the initial part of the photoelectron path and reconstruct correctly the direction of emission. We developed a Monte Carlo software to easily explore the behavior of the instrument to different mixtures and to subsequently test a subset of the most interesting ones.

Recently Muleri et al. [13] measured the modulation factor μ, namely the amplitude of the response of the instrument for completely polarized photons, for the GPD filled with helium 20% and DME 80% at 2.6, 3.7 and 5.2 keV. This data confirmed that measured values are basically consistent with what is expected on the basis of the Monte Carlo software and proved that X-ray polarimetry in Astrophysics with the GPD is feasible. In this paper

* Corresponding author.
E-mail address: fabio.muleri@iasf-roma.inaf.it (F. Muleri).

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doi:10.1016/j.nima.2010.03.006

we characterize the behavior of the GPD with a different gas, i.e. pure DME at 0.79 atm. In particular, we describe the configuration of the GPD and the calibration sources we used in Section 2, while spectral capabilities of the instrument are discussed in Section 3. The measurement of the modulation factor between 2.0 and 7.8 keV is reported in Section 4, together with the comparison with Monte Carlo results and what was reported previously on the He 20% and DME 80% mixture. Note that this is the first time that the modulation factor of a gas polarimeter is presented at energies as low as 2.0 keV.

2. Set-up

2.1. Detector configuration

The Gas Pixel Detector is composed of a sealed 1 cm thick gas cell enclosed by a 50 μm beryllium window, a GEM (Gas Electron Multiplier [17]) which collects and amplifies primary electrons produced by photoelectrons in the gas cell, and a finely subdivided pixelized detector [7,4]. The last component, based on a VLSI ASIC realized in 0.18 μm CMOS technology, is the actual breakthrough of the instrument [3], which otherwise is fundamentally an array of standard yet exceptionally small independent proportional counters. The top metal layer of the CMOS is fully pixellated to collect the charge produced in the common gas volume and allows to obtain a true 2D image of the photoelectron track even at low energy, thanks to the small (50 μm) pixel size. The acquisition is self-triggered and only a small window of about a thousand of pixels enclosing the track is actually read-out in place of the whole matrix. The chip is $15\times15\,\mathrm{mm}^2$ and comprises 105,600 pixels arranged in a hexagonal pattern.

The cell is sealed but can be refilled to test different gases and typically mixtures of helium, neon or argon and DME are used. DME is used to reduce diffusion and also as a quencher, but it acts as the actual absorber in the case of helium mixtures. The first application of the instrument in Astrophysics is expected in the 2–10 keV energy range and within this interval the standard mixture is helium 20% and DME 80% [13]. This was preferred to mixtures of neon because of the longer photoelectron path and lower diffusion for equivalent efficiency, which assure a higher polarimetric sensitivity at low energy where the largest part of photons are concentrated. In this paper we push the use of low-diffusion mixtures to the extreme, exploring the use of a pure DME gas at 0.79 atm (0.8 bar). Since helium is basically transparent to X-rays in the 2–10 keV energy range, we expect a sensitivity comparable to the standard mixture, with a possible enhancement because of the lower diffusion.

An improvement with respect to previous versions of the GPD is the use of a laser-etched GEM made of liquid crystal polymer which shows a better temporal gain stability [18]. A drawback is that the smallest pitch available was only 80 μm (instead of 50 μm of previous detectors), and this has proved to be insufficient to avoid the emergence of systematic effects due to undersampling of short tracks, discussed and removed, as explained in Section 4.1. GEMs with smaller pitch are now in production and will be used for the next GPD prototype. Moreover the thickness is 100 μm instead of 50 μm. The characteristics of the GPD used are summarized in Table 1.

Table 1
Main characteristics of the GPD prototype studied in this paper.

Area	$15\times15\,\mathrm{mm}^2$
Active area fill fraction	92%
Window	50 μm, beryllium
Mixture	DME 100%, 0.79 atm (0.8 bar)
Cell thickness	1 cm
GEM material	Copper-coated liquid crystal polymer
GEM pitch	80 μm
GEM holes diameters	48 μm
GEM thickness	100 μm
GEM voltages	$V_{drift}=3200\,V$, $V_{top}=1145\,V$, $V_{bottom}=500\,V$
Gain	500
Pixels	300×352, hexagonal pattern
Pixel noise	50 electrons ENC
Full-scale linear range	30 000 electrons
Peaking time	3−10 μs, externally adjustable
Trigger mode	Internal, external or self-trigger
Self-trigger threshold	2000 electrons
Pixel trigger mask	Individual

2.2. Calibration facility

The GPD was characterized at the X-ray facility built at INAF/IASF-Rome. Although its detailed description is beyond the scope of this paper, in the following we briefly present what is relevant to measurements presented below.

Polarized and monochromatic X-rays are produced by Bragg diffraction at 45° [8]. Incident radiation on a crystal can be decomposed in two components, polarized parallel (π- component) and perpendicularly (σ- component) to the diffraction plane. The latter is more effectively diffracted because the ratio k between the integrated reflectivity of the π and σ components is always smaller than 1. Hence diffracted radiation is (partially) polarized and the degree of polarization $\mathcal{P}$ is

$$\mathcal{P}=\frac{1-k}{1+k}. \quad (1)$$

If the incident angle θ is 45°, $k=0$ and consequently $\mathcal{P}=1$. For intermediate values, k can be calculated and the value as a function of θ is reported in Fig. 1(a) for graphite crystals. The large dependence of k on the incident angle requires the value of θ to be tightly constrained to prevent the dilution of the average degree of polarization (cf. Fig. 1(b)). The angular constraint also selects the energy of diffracted radiation, related to θ by Bragg's Law:

$$E(\theta)=\frac{nhc}{2d\sin\theta} \quad (2)$$

where h and c are, respectively, Planck's constant and the speed of light, d the crystal lattice spacing and n an integer which specifies the diffraction order.

We already presented a prototype source based on Bragg diffraction, which exploits lead-glass capillary plates to constrain to 45° the incident and diffraction angles and small (2 W) X-ray tubes to produce the radiation to be diffracted [14]. This source was used to generate polarized photons at 2.6, 3.7 and 5.2 keV and calibrate at these energies the GPD filled with a He-DME mixture [13]. An aluminum crystal and an X-ray tube with anode made of calcium were exploited to produce 3.7 keV polarized photons, while 2.6 and 5.2 keV were obtained by first and second order diffraction on graphite of copper X-ray tube radiation. The former configuration is particularly effective in terms of higher flux and control of the output state of polarization because Kα fluorescence emission of calcium is well in accordance with Bragg energy at 45° for aluminum. Then (almost) all incident photons have a well-defined energy, that of Kα line of calcium, and are diffracted exactly at the Bragg angle given by Eq. (2) and the degree of polarization is precisely calculated with Eq. (1). A trade-off between flux (low collimation) and high polarization (high collimation) was instead necessary for diffraction on graphite because X-ray tubes with anodes in accordance with Bragg energy are not available in this case and continuum bremsstrahlung emission is to be used.