Astroparticle Physics 97 (2018) 10–18

Contents lists available at ScienceDirect

Astroparticle Physics

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

Performance measurement of HARPO: A time projection chamber as a gamma-ray telescope and polarimeter

P. Gros[a,*], S. Amano[b], D. Attié[c], P. Baron[c], D. Baudin[c], D. Bernard[a], P. Bruel[a], D. Calvet[c], P. Colas[c], S. Daté[d], A. Delbart[c], M. Frotin[a,1], Y. Geerebaert[a], B. Giebels[a], D. Götz[e], S. Hashimoto[b], D. Horan[a], T. Kotaka[b], M. Louzir[a], F. Magniette[a], Y. Minamiyama[b], S. Miyamoto[b], H. Ohkuma[d], P. Poilleux[a], I. Semeniouk[a], P. Sizun[c], A. Takemoto[b], M. Yamaguchi[b], R. Yonamine[c], S. Wang[a,2]

[a] LLR, Ecole Polytechnique, CNRS/IN2P3, Palaiseau, 91128, France
[b] LASTI, University of Hyôgo, Japan
[c] CEA/Irfu Université Paris Saclay, France
[d] JASRI/SPring8, Japan
[e] AIM, CEA/DSM-CNRS-Université Paris Diderot, France

ARTICLE INFO

Article history:
Received 20 June 2017
Revised 6 October 2017
Accepted 20 October 2017
Available online 21 October 2017

Keywords:
Gamma ray
Pair production
Linear polarisation
Polarimetry
TPC
Angular resolution
Gamma-ray astronomy

ABSTRACT

We analyse the performance of a gas time projection chamber (TPC) as a high-performance gamma-ray telescope and polarimeter in the e^+e^- pair-creation regime. We use data collected at a gamma-ray beam of known polarisation. The TPC provides two orthogonal projections (x, z) and (y, z) of the tracks induced by each conversion in the gas volume. We use a simple vertex finder in which vertices and pseudo-tracks exiting from them are identified. We study the various contributions to the single-photon angular resolution using Monte Carlo simulations, compare them with the experimental data and find that they are in excellent agreement. The distribution of the azimuthal angle of pair conversions shows a bias due to the non-cylindrical-symmetric structure of the detector. This bias would average out for a long duration exposure on a space mission, but for this pencil-beam characterisation we have ensured its accurate simulation by a double systematics-control scheme, data taking with the detector rotated at several angles with respect to the beam polarisation direction and systematics control with a non-polarised beam. We measure, for the first time, the polarisation asymmetry of a linearly polarised gamma-ray beam in the low energy pair-creation regime. This sub-GeV energy range is critical for cosmic sources as their spectra are power laws which fall quickly as a function of increasing energy. This work could pave the way to extending polarised gamma-ray astronomy beyond the MeV energy regime.

1. Introduction

A number of groups are developing pair-conversion detector technologies alternative to the tungsten-converter / thin-sensitive-layer stacks of the COS-B / EGRET / AGILE / *Fermi*-LAT series, to improve the single-photon angular resolution. Presently, observers are almost blind in the 1–100 MeV energy range, mainly due to the degradation of the angular resolution of e^+e^- pair telescopes at low energies: to a large extent, the sensitivity-gap problem is an angular-resolution issue [1].

We have shown [2] that gaseous detectors, such as TPCs (time projection chambers), can enable an improvement of up to one order of magnitude in the single-photon angular resolution (0.5° at 100 MeV) with respect to the *Fermi*-LAT (5° at 100 MeV), a factor of three better than what can be expected for silicon detectors (1.0–1.5° @ 100 MeV). With such a good angular resolution, and despite a lower sensitive mass, a TPC can close the sensitivity gap at the level of 10^{-6} MeV/cm^{2}s) between 3 and 300 MeV. In addition, the single-track angular resolution is so good that the linear polarisation fraction can be measured.

* Corresponding author. Now at Department of Physics, Engineering physics and Astronomy, Queen's University, Kingston, Ontario K7L 3N6, Canada.
E-mail addresses: philippe.gros@llr.in2p3.fr, philippe.gros@queensu.ca (P. Gros).
1 Now at GEPI, Observatoire de Paris, CNRS, Univ. Paris Diderot, Place Jules Janssen, 92190 Meudon, France
2 Now at INPAC and Department of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai Laboratory for Particle Physics and Cosmology, Shanghai 200240, China

https://doi.org/10.1016/j.astropartphys.2017.10.008
0927-6505/

We first give a brief overview of the concept of a time projection chamber (TPC) and its physical constraints in the context of gamma-ray astronomy and polarimetry, before describing the current experimental configuration, the simulation of the detector, and the event reconstruction. We then describe the analysis procedure, and in particular the event selection. Finally, we show the measured performance of the detector, in terms of angular resolution and polarimetry. The difficulties encountered and the potential for improvement are discussed.

2. γ-ray astronomy and polarimetry with a TPC

TPCs are simple and robust particle detectors widely used in high-energy physics [3]. A volume of matter is immersed into an electric field, so that the ionisation electrons produced by the passage of high-energy charged particles drift and are collected on an anode plane. The anode is segmented such as to provide 2D images of each track as the corresponding electrons reach the electrode as a function of drift time. The measurement of the drift time provides the third coordinate. In our case, the field is uniform, so that the electron trajectories are straight lines and the electron drift velocity is constant and uniform. Noble gases (mainly helium to xenon) are very convenient as they allow free electrons to drift freely over long distances.

In our case, the TPC is used as an active target, that is, it serves at the same time as converter for an incoming gamma ray and as tracker for the two resulting lepton trajectories. This situation induces conflicting constraints: increasing the matter density and the noble gas atomic number Z increases the telescope effective area on the one side (Fig. 7 of Ref. [2]) but degrades the single-track angular resolution and therefore the single-photon angular resolution on the other side (Fig. 6 of Ref. [2]). For a liquid xenon TPC, for example, the angular resolution would show no improvement with respect to that of the *Fermi*-LAT. When the effective area and the angular resolution are combined, the point-like source sensitivity turns out to be barely affected by the gas choice (Fig. 8 right of Ref. [2], estimated for a given gas mass of 10 kg).

If, in addition, one considers polarimetry, i.e., the measurement of the linear polarisation fraction P and angle ϕ_0 of the incoming radiation, it is essential to measure the azimuthal orientation of the final state leptons before multiple scattering. The use of a liquid or solid TPC would need the tracking of sub-millimeter-long track segments, which is out of reach: we are bound to use a gas TPC (Section 5 of Ref. [4]). Here again we see the same conflicting effects at work. Increasing Z and / or the pressure increases the γ-ray statistics but also degrades the dilution factor due to multiple scattering (Fig. 26 of Ref. [4]). For a 1 m^3 5 bar argon detector exposed for one year, full time with a perfect efficiency, the precision of the measurement of P for a bright source such as the Crab pulsar is expected to be $\approx 1.4\%$ (including experimental cuts), corresponding to a 5σ MDP (minimum detectable polarisation) of $\approx 7\%$.

Since charge amplification is employed in the readout, stable operation requires the addition of a “quencher” gas to absorb all UV photons co-produced in the process. Also electrons accelerated during their drift lose energy by inelastic collisions with the quencher molecules, they cool down, which mitigates the diffusion strongly. A large choice of possible quenchers is available, including the alcanes [3].

In our case of a 2.1 bar argon-based gas mixture, the active-target radiation length X_0 is about 56 m, so the probability of the pair conversion of a given photon crossing the detector is low. The effective area is proportional to the gas mass, while for a thick detector it is proportional to the geometrical surface. The probability of photon “loss” by Compton scattering is small too and the various possible processes are not competing with each other: the pair/Compton cross section ratio is irrelevant here, in contrast to thick detectors.

Astronomers also need to measure the energy of the collected photons, that is, here, the momentum of each track. This can be performed by a number of techniques including calorimetry, magnetic spectrometry, transition radiation detection, all of which would present a challenge to the mass budget on a space mission for the (multi)-cubic-meter detector that would make the desired effective area possible. An other method uses the track-momentum dependence of multiple scattering to obtain a measurement of the momentum from an analysis of the angle deflections in the TPC itself [5]. A pending question was the optimisation of the longitudinal segmentation pitch over which these deflections are computed (Section 6 of Ref. [2]). An optimal treatment has been obtained recently, by a Bayesian analysis of the filtering innovations of a series of Kalman filters applied to the track [6]: meaningful results can be obtained with a gas TPC below 100 MeV/c (Fig. 11 of Ref. [6]).

3. Experimental setup

The HARPO (Hermetic ARgon POlarimeter) detector [7] is a demonstrator of the performance of a TPC for measuring polarised γ rays. It was designed for a validation on the ground in a photon beam. The most critical constraints related to space operation were taken into account, such as the reduced number of electronic channels and long-term gas-quality preservation [8]. It comprises a $(30\text{ cm})^3$ cubic TPC, designed to use a noble gas mixture from 1 to 4 bar. The present work uses an Ar:isobutane (95:5) gas mixture at 2.1 bar. A drift cage provides a 220 V/cm drift field. The electrons produced by the ionisation of the gas drift along the electric field toward the readout plane at a constant velocity $v_{\text{drift}} \approx 3.3\,\text{cm}/\mu\text{s}$. The readout plane is equipped with two Gas Electron Multipliers (GEMs) [9] and one Micromesh Gas Structure (Micromegas) [10] to multiply the electrons. The amplified electrons' signal is collected by two sets of perpendicular strips at a pitch of 1 mm (regular strips in the X-direction, and pads connected together by an underlying strip in the Y-direction, see Fig. 4 of Ref. [11]). The signals are read out and digitised with a set of AFTER chips [12] and the associated Front End Cards (FECs).

Even though a cubic structure cannot be expected to behave as a fully isotropic detector, efforts have been made to have the longitudinal properties of the TPC (along Z) similar to the transverse ones (X, Y). The time sampling was set to 30 ns so that, given the electron drift velocity, the TPC longitudinal sampling was close to the transverse (strip) pitch. The main residual difference are the (longitudinal) shaping of the electronics, of 100 ns RMS, and an unanticipated saturation of the electronics preamplifier that affected one channel (strip) independently from the others.

The transverse diffusion coefficient for that gas at that pressure was of about $380\,\mu\text{m}/\sqrt{\text{cm}}$, which makes the pitch size not far from optimal over most of the drift length range (see Fig. 7 of Ref. [13]); the longitudinal coefficient was of about $220\,\mu\text{m}/\sqrt{\text{cm}}$.

The HARPO TPC was set up in the NewSUBARU polarised photon beam line [14] in November 2014. The photon beam is produced by Laser Compton Scattering (LCS) of an optical laser on a high energy (0.6-1.5 GeV) electron beam. A lay-out of the experiment can be found in Fig. 2 right of Ref. [15]. Using lasers of various wavelengths and different electron beam energies [16], 13 photon energies from 1.74 MeV to 74.3 MeV were obtained. A graphical representation of the γ-ray energies for which we did take data, as a function of laser wavelength and electron beam energy, can be found in Fig. 5 left of Ref. [15].

The Compton edge of the laser inverse Compton scattering, that is, the highest part of the γ-ray energy spectrum, was selected by collimation on axis, a lead brick with a 4 mm-diameter hole located 24 m downstream of the laser-electron interaction point,