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Nuclear Instruments and Methods in Physics Research A

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

Measurement of 1.7–74 MeV polarised γ rays with the HARPO TPC

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ARTICLE INFO

Article history:

Received 22 March 2016

Received in revised form

3 June 2016

Accepted 8 June 2016

Keywords:

TPC

Gamma-ray

Polarimetry

Gaseous detector

ABSTRACT

Current γ -ray telescopes based on photon conversions to electron-positron pairs, such as Fermi, use tungsten converters. They suffer of limited angular resolution at low energies, and their sensitivity drops below 1 GeV. The low multiple scattering in a gaseous detector gives access to higher angular resolution in the MeV–GeV range, and to the linear polarisation of the photons through the azimuthal angle of the electron-positron pair.

HARPO is an R&D programme to characterise the operation of a TPC (Time Projection Chamber) as a high angular-resolution and sensitivity telescope and polarimeter for γ rays from cosmic sources. It represents a first step towards a future space instrument. A 30 cm cubic TPC demonstrator was built, and filled with 2 bar argon-based gas. It was put in a polarised γ -ray beam at the NewsUBARU accelerator in Japan in November 2014. Data were taken at different photon energies from 1.7 MeV to 74 MeV, and with different polarisation configurations. The electronics setup is described, with an emphasis on the trigger system. The event reconstruction algorithm is quickly described, and preliminary measurements of the polarisation of 11 MeV photons are shown.

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1. High angular resolution γ -ray astronomy and polarimetry in the MeV–GeV energy range

γ -ray astronomy provides insight into understanding the non-thermal emission of some of the most violent objects in the Universe, such as pulsars, active galactic nuclei (AGN) and γ -ray bursts (GRBs), and thereby understanding the detailed nature of these objects.

Alas, between the sub-MeV and the above-GeV energy range for which Compton telescopes ($\gamma e^- \rightarrow \gamma e^-$) and pair telescopes ($\gamma Z \rightarrow Ze^+e^-$) are, respectively, highly performant, lies the MeV–GeV range over which the sensitivity of past measurements was very limited, in particular as the degradation of the angular resolution of pair telescopes at low energy ruins the detection sensibility. This hinders the observation and the understanding of GRBs,

whose spectra mostly peak in the MeV region; it could also bias the description of the Blazar sequence. More generally, it limits the detection of crowded regions of the γ -ray sky such as the galactic plane to its brightest sources: to a large extent, the MeV–GeV sensitivity gap [1] is an angular resolution issue.

The angular resolution of pair telescopes can be improved, from the Fermi-LAT's $\approx 5^\circ$ at 100 MeV [2] to $1 - 2^\circ$, by the use of pure silicon trackers, i.e. without any tungsten converter plates [3–5]. An even better resolution of $\approx 0.4^\circ$ can be obtained with a gas detector such as a time-projection chamber (TPC), so that together with the development of high-performance Compton telescope, filling the sensitivity gap for point-like sources at a level of $\approx 10^{-6}$ MeV/(cm² s) is within reach ([6] and Fig. 1).

Furthermore the measurement of the linear polarisation of the emission, which is a powerful tool for understanding the characteristics of cosmic sources at lower energies in the radio-wave to X-ray energy range, is not available for γ -rays above 1 MeV [7]. The use of a low density converter-tracker, such as a gas detector, enables the measurement of the polarisation fraction before multiple scattering ruins the azimuthal information carried by the

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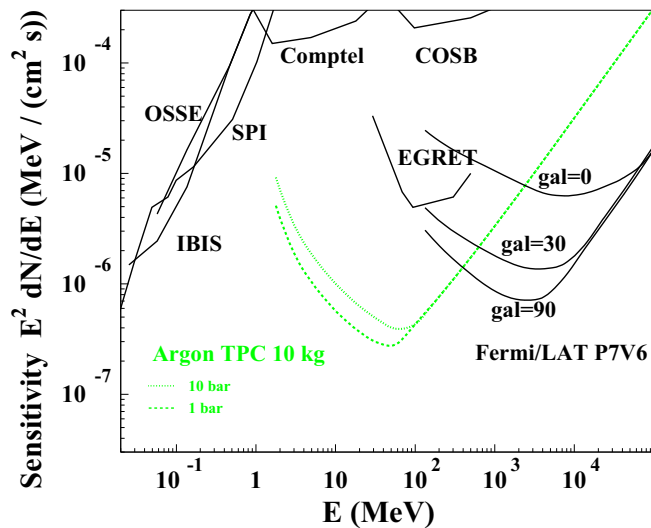


Fig. 1. Differential sensitivity as a function of energy (argon-gas-based HARPO TPC, green) compared to the 90° galactic latitude performance of the Fermi-LAT [2] and of the Compton telescope COMPTEL [1]. Adapted from [6]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

pair [8].

γ -ray polarimetry would provide insight into understanding the value and turbulence of magnetic fields in the γ -ray emitting jet structures of most γ -ray emitting sources. And, for example, could enable us to distinguish between the leptonic and hadronic nature of the emitting particles in blazars [9].

2. The HARPO detector

We have built a TPC which is using argon-based gas mixtures in the range 1-5 bar [10]. The drifted electrons are amplified by a hybrid amplifier whose performance has been characterised in detail [11].

We have exposed the detector to a tunable γ -ray source, using the head-on inverse-Compton scattering of a laser beam on the 0.6 – 1.5 GeV electron beam of the NewSUBARU storage ring (Hyōgo, Japan) [12]. The detector was positioned so that the photon beam would be aligned with the drift direction z of the TPC, coming from the readout side, and exiting through the cathode.

The present detector is aimed at ground-validation tests, but we have designed it taking into account the constraints of space operation.

HARPO produces very fine 3D images of γ -ray conversions to e^+e^- pairs by tracking these events. This is done at a low cost in terms of power consumption and data flow in the presence of a large number of background noise tracks.

The TPC is a 30 cm cubic field cage, enclosed with a copper cathode and a readout plane anode including a hybrid multi-stage amplification system composed of two GEM (Gas Electron Multiplier) + one MICROMEAS (128 μm -gap bulk Micro MESH Gaseous Structure).

As shown in Fig. 3, the signal is collected by two orthogonal series of strips (x and y), which, in our case, reduces the number of channels by a factor 144 compared to the equivalent pixel sensor. This reduction is only possible if the channel occupancy is low enough to avoid unsolvable ambiguities and comes at the cost of the need for off-line association of each x track to a track in the y view. Then, only 576 channels (x and y strips, 1 mm pitch) are read

out and digitised at 33 MHz (up to 100 MHz) by eight AFTER chips mounted on two FEC boards. Channel data are then zero suppressed and sent to a PC via Gigabit Ethernet by two FEMINOS boards synchronised by one TCM board. These versatile boards were originally developed at IRFU for the T2K and MINOS experiments [13]. To mitigate the dead time induced by readout and digitisation (1.6 ms) we developed a sophisticated trigger, with a multi-line system so as to provide real-time efficiency monitoring of each component. A summary of the full trigger and DAQ system is shown in Fig. 2.

To provide presence and timing information on events, six scintillators surround the TPC. Each scintillator is equipped with a pair of photomultiplier tubes (PMTs) which are read out by a PARISROC2 chip [14] mounted on a PMM2 board [15].

The timing of the charge induced on the mesh is used for trigger. The signal, which is long with an unpredictable shape, corresponds to the time distribution of tracks in the TPC. To get a signal from the rising edge, we use a constant fraction discriminator (CFD), which shows the beginning of the signal, and therefore the position of the beginning of the track. We can measure the delay between the start of the event and this signal to build a veto on tracks created upstream from the TPC. This is illustrated in Fig. 4.

The main line of the trigger selects pair-creation events which follow from the interaction of a γ photon with the nucleus of a gas atom in the TPC. It is composed of:

- a veto on upstream scintillator (which reveal an interaction before the active gas region),
- a signal on mesh of MICROMEAS with a veto based on the presence of a very early signal (we reject most of the γ -rays that convert in the material of the readout plane),
- a signal in at least one of the five others scintillators,
- a laser signal, whenever available (for the pulsed laser), in coincidence with the signal in the scintillators.

This trigger suppressed the huge background rate from the accelerator (up to 5 kHz) by a rejection factor of greater than two orders of magnitude [16] during the data-taking campaign.

3. Analysis of data from a polarised photon beam

We took data with the HARPO TPC in a polarised photon beam at the NewSUBARU [17]. The photon is aligned with the drift direction z and arrives from the readout side. The detector was rotated around the z -axis to study the systematic angular effects related to the cubic geometry of the TPC. A total of about 60 million events were taken, with 13 different photon energies from 1.7 to 74 MeV, and 4 the TPC orientations. Both polarised and unpolarised beams were used.

Fig. 5 shows a pair conversion event as observed in the HARPO TPC. The two electron/positron tracks are visible in each of the two projections (X - Z and Y - Z).

The electron tracks were reconstructed on each projection using a closest-neighbour search based on a Kalman filter [18]. Unfortunately, since the two tracks are difficult to disentangle near the vertex, it was impossible to use the Kalman filter to estimate the track direction near the vertex. The identified tracks were therefore fitted with a straight line. Then, the tracks reconstructed on each projection (X - Z and Y - Z) were paired together using their charge profile as a function of the drift time (equivalent to the Z coordinate). In this way we were able to define tracks in 3D.

For each pair of reconstructed 3D tracks, the point and distance of closest approach (POCA and DOCA) were calculated. We selected only the track pairs where the POCA was close enough to

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