PoS PROCEEDINGS OF SCIENCE

Polarimetry and high angular resolution gamma-ray observations in the MeV regime using a novel detector concept

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We have demonstrated, for the first time, that the polarisation of gamma rays in the MeV regime ($< 74\,\text{MeV}$) can be measured using a novel detection technique, namely tracking the gamma-ray conversion pairs using a gaseous time projection chamber (TPC). HARPO (the Hermetic Argon Polarimeter) is, to date, the only instrument to have successfully carried out this measurement. Having demonstrated that a TPC can be used to detect and measure the polarisation of MeV gamma rays, we have begun a new, larger study with the goal of flying a TPC on a balloon to validate its preformance in a background-dominated environment. We will describe the mission concept for this gamma-ray polarimeter and also the science that can be addressed both with this demonstrator and with an ultimate, satellite-based instrument.

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1. Introduction

We describe here a novel instrument concept to perform gamma-ray observations at high-angular resolution in the pair-production regime (energies above $\approx$ 1 MeV). With the advent of the *Fermi* Large Area Telescope[1] (LAT) in the MeV-GeV energy range and the third-generation of imaging atmospheric Cherenkov telescopes (IACTs) such as H.E.S.S.[2], MAGIC[3] and VERITAS[4]; in the GeV-TeV regime, huge advances have been made in the science of the gamma-ray sky since the era of the Compton Gamma-ray Observatory (CGRO[5]; 1991−2000) and the second generation of IACTs. At MeV energies, however, there remains a sensitivity gap. This is illustrated in Figure 1 using the spectral energy distributions (SEDs) of blazars, a class of source that is particularly prolific in the gamma-ray sky. The blazar sequence of today [2] is plotted alongside the blazar sequence of the CGRO era [3]. The leap in the number of blazars at gamma-ray energies above the MeV regime is evident and speaks to the advances that have been achieved in sensitivity above a few hundred MeV. There is, however, a gap in coverage at low MeV energies that is clearly visible for blazars, which are powerful, broad-band emitters. The implications of this for the science of blazars and many other objects and scientific topics will be discussed in Section 3. The lack of sensitivity in the MeV range can be thought of as an angular-resolution issue. At these energies, (E $\gtrapprox$ 1 MeV), gamma rays interact predominantly by pair producing. To increase the probability of pair production occurring (and therefore the effective area), it is desirable the gamma ray pass through as much matter as possible so, a high-Z material would be the choice for the detector material. High-Z materials, however, introduce multiple scattering of the electron-positron pairs and, thus, information about the geometry of the pair-production interaction is lost when they are employed. This is not as significant of a problem at energies above about 100 MeV (it becomes just about acceptable at 100 MeV where, with the LAT, we are able to determine the direction of the gamma ray to within $\approx 5^\circ$ [4]) but at lower energies, it renders the reconstruction of the gamma-ray direction, necessary to perform effective gamma-ray astronomy, never mind the azimuthal angle of the pair-production event, necessary to deduce the polarisation, infeasible - hence the sensitivity gap.

2. A novel concept: Using a TPC for gamma-ray astronomy

Time projection chambers (TPCs) are simple, robust particle detectors that have been widely used in high-energy physics since the 1970's. They comprise a volume of matter, liquid or gas (or, in some cases, both), immersed in an electric field. When a high-energy charged particle, such as a pair-production electron, passes through the TPC it ionises the matter contained therein producing ionisation electrons and positive ions. An electric field applied across the chamber causes the ionisation electrons to drift and thus enables them to be collected on the anode plate. A segmented anode allows the arrival location of the drift electrons to be specified whilst their arrival times at

[1] https://fermi.gsfc.nasa.gov/
[2] https://www.mpi-hd.mpg.de/hfm/HESS/
[3] https://magic.mpp.mpg.de/
[4] https://veritas.sao.arizona.edu/
[5] https://heasarc.gsfc.nasa.gov/docs/cgro/cgro/

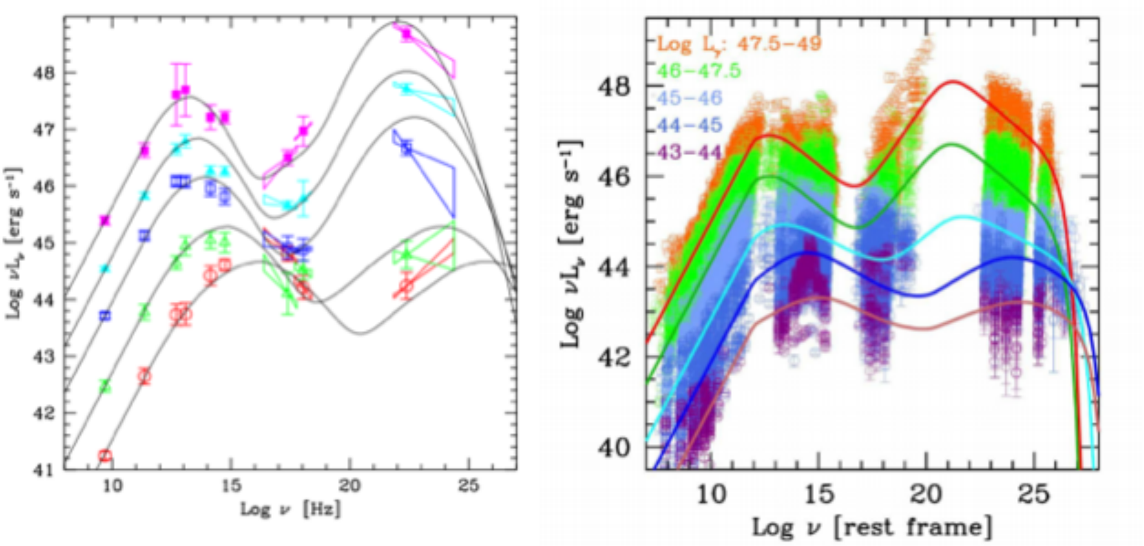


Figure 1: *Left:* The "original" blazar sequence derived by [3] (figure taken from [5]). The average SEDs of 126 blazars are plotted. They are binned according to their radio luminosity. All of the then-available gamma-ray data, from the Energetic Gamma-Ray Experiment Telescope (EGRET[7]) and Whipple [6] are shown. *Right:* The "new" blazar sequence from [2]. The average SEDs of 745 blazars are plotted. The lack of MeV data is evident in both plots.

the anode provides further information on the geometry of the initial, in our case pair-production, interaction.

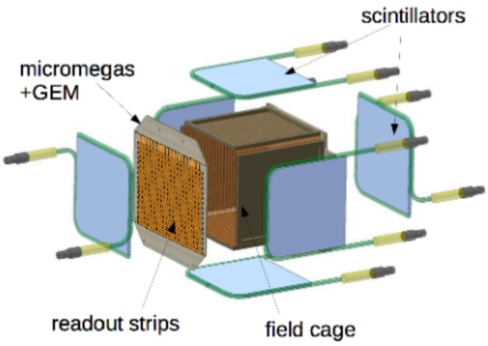
A TPC employs an active target that is, at the same time, the converter in which the gamma ray converts and the tracker in which the two resulting lepton trajectories are measured in the case of a pair conversion. This situation introduces conflicting constraints since, for a given volume it is desirable to increase the matter density (i.e. Z number) to maximise the conversion probability and thus the effective area. In so doing, however, the single-track angular resolution, and therefore the angular resolution of the detector, degrade thus denying us access to the polarisation information (as happens for pair-conversion events in the high-Z Tungsten conversion material of the LAT) [7], [8].

2.1 The Hermetic Argon Polarimeter: HARPO

The Hermetic Argon Polarimeter (HARPO), is an instrument designed and constructed to demonstrate the performance of a TPC for measuring polarised gamma rays. We note that, although it was designed for validation on the ground in a photon beam, the most critical constraints related to space operation (e.g. operating using a reduced number of channels and ensuring gas-quality preservation over time) were respected. The experimental setup, data analysis, full-instrument simulation along with a full description of the results can be found in a dedicated publication [1] whilst a full compilation of references can be found on our webpage[8]. We summarise some of the salient details of the experimental setup and results here. HARPO (Figure 2) comprises a 30 cm^3 cubic TPC with a 95:5 mixture of argon:isobutane at a pressure of 2.1 bar. Surrounding this, a drift cage provides a 220 V/cm drift field. The readout plane consists of two Gas Electron Multipliers (GEMs; [9]) and one Micromesh Gas Structure (Micrgomegas; [10]). The amplified electron signal

[8] http://llr.in2p3.fr/ dbernard/polar/harpo-t-p.html

is collected by two sets of perpendicular strips; in the x-direction these comprise strips with a 1 mm pitch and in the y-direction they comprise pads joined together by underlying strips. The signals are read out and digitised using a set of AFTER chips [11] and associated Front End Cards.



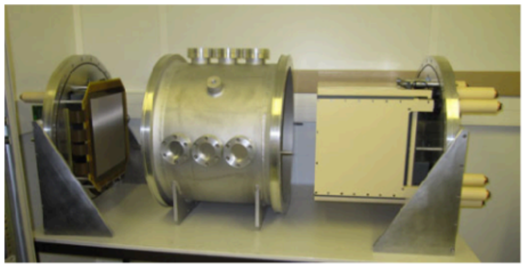


Figure 2: *Left*: Schematic of the HARPO detector. *Right*: Photograph of the HARPO detector system.

HARPO was set up in the NewSUBARU polarised beam line [12] in November 2014 where it was exposed to polarised light at 13 different photon energies from 1.74 MeV to 74.3 MeV. The polarised photon beam was produced by the Laser Compton scattering of an optical laser (different wavelengths were used to attain polarised beams of different energies) on a high-energy electron beam (0.6−1.5 GeV). A selection of reconstructed events is shown in Figure 3 where it can be seen that HARPO allowed us to track the charged particles resulting from each of the gamma-ray interactions (Compton scattering, pair production and triplet conversion) with high precision, including a low-energy pair-conversion event at energy of 3.93 MeV (shown in our presentation at the conference). This enabled us to access the geometry of the gamma-ray conversion, in particular, the azimuthal angle of the conversion plane of the event. It has been shown [13] that the precision of the measurement of the polarisation fraction depends on choosing optimally the angle that is measured and that the highest precision can be achieved if the bisector angle of the electron and of the positron momenta is used. The geometry of the conversion can be seen on the left of Figure 4.

The differential cross section of the photon conversion can be described by Equation 2.1, in which A is the polarisation asymmetry of the conversion process, P is the linear polarisation fraction of the incoming radiation, φ is the azimuthal angle of the event and φ_0 is the polarisation angle of the incoming radiation.

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\varphi} \propto (1 + A \times P\cos(2(\varphi - \varphi_0)))\,. \tag{2.1}$$

Figure 4 (right) shows the ratio of the distribution of the azimuthal angle of fully linearly-polarised 11.8 MeV gamma rays to the distribution for non-linearly-polarised radiation as measured by HARPO [1]. The polarisation asymmetry, A, was measured to be $10.5 \pm 0.6\%$. It reaches a maximum for polarisation angle, φ_0, of -3.5 $\pm$ 1.6°. This is the first time that such a measurement has been performed.

2.2 A self-triggering TPC telescope for gamma rays: ST3G ("stègue")

Now that we have demonstrated that a TPC can be used to perform high-angular resolution tracking of the electron-positron pair thus allowing us to measure the polarisation of MeV gamma

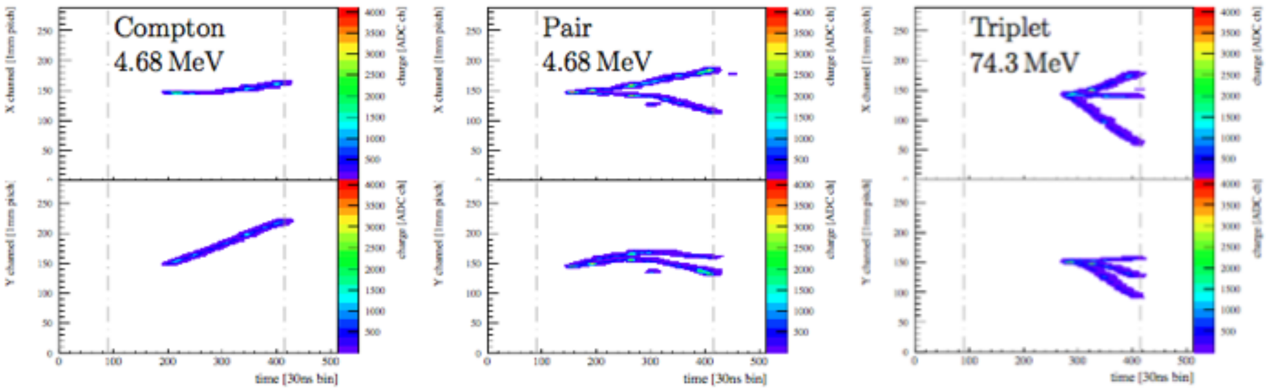


Figure 3: Examples of events recorded in the HARPO detector from [13]. From left to right are plotted events corresponding to a Compton scattering, a pair conversion and a triplet conversion. In the pair-production event, a small, isolated energy deposit is visible. This is from an interaction following the pulse (with a 5 μs delay) on the readout plane.

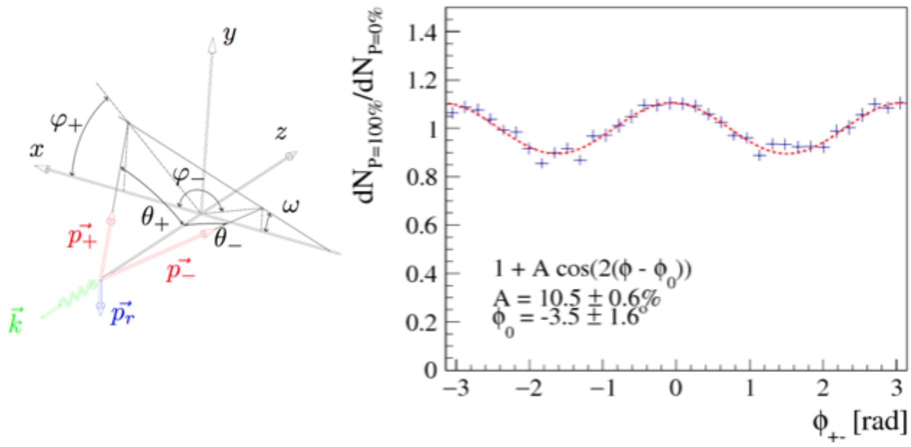


Figure 4: *Left*: Schematic representation of pair-conversion event. *Right*: The ratio of the azimuthal angle distributions of polarised (P = 100%) and unpolarised (P = 0%) 11.8 MeV photons as measured by HARPO.

rays, the next step is to build a prototype instrument to fly on a balloon so that the trigger system can be tested. We are currently performing simulations to develop the trigger system. The main technical hurdle to be overcome is the self-triggering of a TPC in a space (i.e. high-background) environment. This trigger will have to run efficiently and in real time.

ST3G will comprise 60 modules in a $3 \times 4 \times 5$ configuration, optimised to fit within the physical space of the CARMEN platform proposed by CNES (the Centre National d'Études Spatiales). Each module is equivalent to a single HARPO. These modules will be paired such that each pair shares a common cathode thus leaving us with 30 TPCs. We plan to fly ST3G on a balloon, likely from Kirune, Sweden, to calibrate it with actual cosmic data so that we can understand the background and run the trigger in as-close-to its real space environment as possible. In this way, we will be able to characterise the combined sensitivity of the trigger-detector system.

3. Astrophysics in the MeV regime

The astrophysical topics that could be addressed by having a high-angular-resolution instrument capable of measuring polarimetry operating at MeV energies are myriad and were the subject of a workshop that we organised at École Polytechnique in April 2017[9]. They include, but are certainly not limited to, investigations of the formation of super-massive black holes through population studies of high-redshift blazars who have the peak of their SED in the MeV range [14], the study of the afterglow and its emergence as well as the late-time emission of gamma-ray bursts [15], [16], searches for sub-GeV Dark Matter [17] and the connection between supernova remnants and cosmic-ray acceleration [18]. Having an instrument with high angular resolution is important for the study of interstellar diffuse emission [19] whilst the polarisation information of the MeV gamma rays enables us to distinguish between different blazar emission models [20], [21]. In addition to the physics of pulsar winds [22], we can search for postulated new populations of pulsars that have the bulk of their energetic output at MeV energies and investigate acceleration and pair cascades near the pulsar polar cap [23]. Binaries are another class of high-energy emitters whose study would benefit greatly from MeV observations, allowing us to investigate the connection between MeV and $> 100\,\text{MeV}$ emission where it appears that two different emission components are required [22].

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4. Questions after Presentation (1 of 1)

Q: It is not possible for you to operate an anti-coincidence detector to reject the cosmic-ray background since you do not know the drift time, and, by extension, the arrival time at the anode of the drift electrons from the passage of a cosmic ray. How can you operate in space without an anti-coincidence detector?

A: Yes. For a variety of reasons, including the one mentioned in the question, it would be difficult to have an anti-coincidence detector for ST3G. First of all, since we are planning a multi-m^3 detector, surrounding this with a scintillator would be prohibitive in terms of mass. More importantly though, unlike pair-conversion telescopes like the *Fermi* LAT, which have relatively straight electron-positron tracks anchored in the calorimeter, instruments operating at lower MeV energies have much more difficulty discriminating an outgoing track from an incoming one. This is another reason why a veto system would be prohibitive. Hence, we need to use the real-time information of the TPC itself. A series of ASICs have been developed: AFTER [11], AGET [24] and now ASTRE [25]. ASTRE is designed to operate in a space environment, being radiation hard and having both low power consumption and a low number of channels. From [25] "It permits the amplification, filtering, triggering and analog storage of 512 samples at a flexible sampling frequency up to 100 MHz." For information on tracking without a calorimeter, also relevant for this question, see [26], also presented at this conference.