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HARPO, a gas TPC active target for high-performance γ -ray astronomy; demonstration of the polarimetry of MeV γ -rays converting to e^+e^- pair

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Abstract

No γ -ray polarimeter sensitive above 1 MeV has ever flown space. γ -ray polarimetry would be a new window on the radiative processes at work in cosmic sources, processes that produce linearly polarised emission, each of which with different polarisation fractions. The HARPO Collaboration has designed, built and characterised on beam a gas-TPC active target with which we have demonstrated for the first time the polarimetry of a linearly polarised MeV γ -ray beam, from the analysis of the conversions to e^+e^- pairs.

Keywords: γ -rays, polarimeter, TPC, pair production, telescope, gas detector

1. γ -ray polarimetry of cosmic sources: a science case

Today's γ -ray astronomy is polarisation-blind as no significant polarimetry of a cosmic source has been performed. Polarimetry would provide the additional observables needed to solve the pulsar (angle configuration, magnetic field, emission location) parameter degeneracy. In particular in MeV pulsars, it would enable to decipher the high-energy γ -ray emission mechanism (curvature radiation or synchrotron radiation) [1, 2]. Polarimetry would enable to identify the nature of the emitting particles in γ -ray emitting blazar jets (pure leptons or lepton-hadron mixture) [3]. Polarimetry could enable the indirect detection of dark matter [4]; the detection of Lorentz-invariance violation due to "new" physics beyond the standard model, with a potential larger than that of past searches in the X-ray band as the sensitivity varies with the square of the photon energy [5]; the discovery of the axion, i.e. of the pseudo-scalar believed to be the pseudo-Goldstone boson associated to a breaking of the $U(1)$ symmetry devised to solve the QCD CP problem [6].

2. γ -ray polarimetry of cosmic sources: how achieve it ?

For the lowest part of the electromagnetic spectrum, polarimetry is performed by the measurement and the analysis

of light intensities or of electric fields. At high energies, the (photo-electric, Compton scattering or conversion to pair) interaction of each single photon in a detector is recorded, and an estimate of the azimuthal angle, ϕ , of the particles in the final-state is measured. The expression of the cross section, differential with respect to ϕ , is

$$d\sigma/d\phi \propto (1 + A \times P \cos(2(\phi - \phi_0))), \quad (1)$$

where

- A is the polarisation asymmetry of the process at work. Its value depends on the photon energy.
- P is the linear polarisation fraction of the radiation.
- ϕ_0 is the angle between the polarisation direction of the radiation and the reference axis with respect to which the azimuthal angle is measured.

The product $A \times P$ is sometimes named the modulation factor.

The polarimetry of a cosmic source in the MeV-GeV energy range has never been performed. For Compton polarimeters, both the total cross-section and the polarisation asymmetry decrease with energy (Fig. 2 of [7]). For nuclear pair-conversion, $\gamma Z \rightarrow e^+e^-Z$, the multiple scattering undergone by the electron and by the positron in the tracker blur the azimuthal-angle information carried by the pair within $\approx 10^{-3}$ radiation lengths [8, 9, 10].

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45 Hopes have been put in the use of triplet conversions, that is,
 46 of conversions to pair in the field of an electron of the detector,
 47 $\gamma e^- \rightarrow e^+ e^- e^-$, as the target electron often recoils at a large
 48 polar angle with respect to the direction of the incoming photon,
 49 making it easier the measurement of its azimuthal angle.
 50 Alas, the cross section is small and the fraction of it for high-
 51 enough recoil electron momentum is even much smaller (Fig. 6
 52 of [11]), so the potential for a measurement on a cosmic source
 53 ends up to be miserable (Sect. 5.3 of [11]).

54 A way to mitigate the multiple scattering issue is the use of
 55 high-imaging-resolution active targets such as emulsion detec-
 56 tors [12]. Zooming in the first microns of the event just down-
 57 stream the conversion vertex, polarimetry with conversions to
 58 pairs was demonstrated with a prototype detector in a GeV γ -
 59 ray beam [13] but the ability to take data in the MeV energy
 60 range, where most of the statistics lies for cosmic sources (Fig.
 61 2 of [11]), remains an issue.

62 The HARPO project explored an other technique, the use
 63 of a low-density, homogeneous active target such as a high-
 64 pressure gas TPC (time projection chamber) [14]. We first
 65 wrote [11] a Monte-Carlo event generator¹ that samples the
 66 five-dimensional (5D) differential cross section at the first order
 67 of the Born development, i.e., the ‘‘Bethe-Heitler’’ differ-
 68 ential cross section (non polarised [19], polarised [20, 21, 22]).
 69 With that tool we determined the (68 % containment) contribu-
 70 tion to the single-photon angular resolution due to the fact that
 71 the momentum of the recoil nucleus cannot be measured, to be
 72 $\approx 1.5 \text{ rad}[E/1 \text{ MeV}]^{-5/4}$ [23, 24]. We obtained the contribu-
 73 tion to the single-photon angular resolution due to the single-
 74 track angular resolution in the case of an optimal tracking à la
 75 Kalman to be $\propto p^{-3/4}$ [23, 25].

76 At high thicknesses, we found the dilution² of the polarisa-
 77 tion asymmetry due to multiple scattering to worsen less (Fig.
 78 17 of [11]), with this full Monte-Carlo event generation, than
 79 what was predicted by [8, 9, 10] who approximated the pair
 80 opening-angle, θ_{+-} , by its most-probable value. This is due to
 81 the long tail of the θ_{+-} distribution. We demonstrated that the
 82 single-track angular resolution of gas detectors can be so good
 83 that polarimetry can be performed before the azimuthal infor-
 84 mation is lost [11]. Due to the $p^{-3/4}$ variation of the single-track
 85 angular resolution, and given the $1/E$ scaling of the θ_{+-} distri-
 86 bution [26], a better dilution is within reach at lower energies
 87 (Fig. 20 of [11]). The simulation shows that with a 1 m^3 , 5 bar
 88 argon polarimeter observing a cosmic source such as the Crab
 89 nebula for one year, full time, with full efficiency, the expected
 90 precision in the measurement of P is of $\approx 1.4\%$ [11].

91 We implemented the moments’ method to obtain an optimal
 92 measurement of the polarisation modulation factor $A \times P$. In
 93 the case of the simple 1D differential cross section, the method
 94 is equivalent to a maximum likelihood fit of the 1D differential

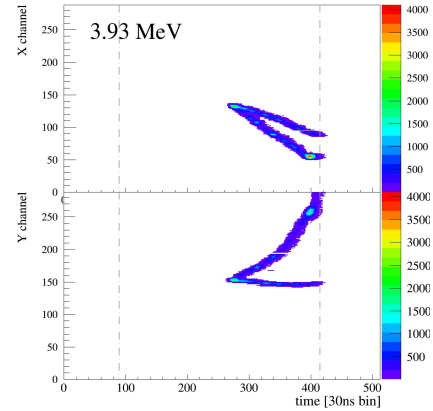


Figure 1: The two ‘‘maps’’, that is, the two x, t and y, t projections of a conversion event of a 3.93 MeV γ -ray provided by the NewSUBARU BL01 beam line converting to an $e^+ e^-$ pair in the 2.1 bar argon-isobutane (95-5 %) gas of the HARPO TPC prototype [34]. The vertical dashed lines denote the physical limits of the detector, i.e. the cathode (left) and the anode (right).

cross section $d\sigma/d\phi \propto (1 + A \times P \cos(2(\phi - \phi_0)))$ [11, 27]. In the case of the full 5D differential cross section, an additional gain in the precision of the measurement of $A \times P$ of a factor of two-to-three is obtained [11, 27].

In the case of interest of a final state consisting of three particles (even when the recoil cannot be measured), the definition of the azimuthal angle, ϕ , is an issue. We determined the bisector $\phi_{+-} = (\phi_+ + \phi_-)/2$ of the azimuthal angles of the direction of the electron, ϕ_- , and of the positron, ϕ_+ , to be the optimal choice [27]. We demonstrated that with that angle definition, our generator is the only one, to our knowledge, to match the known asymptotic expressions for A at low and at high energies [24].

3. HARPO: the experiment

The HARPO Collaboration built a high-pressure (0.5 - 5 bar) gas TPC prototype [14] that uses an hybrid GEM-micromegas amplification system that we characterised precisely [28]. The anode plane is segmented into 2 orthogonal series (x, y) of strips, rather than into pads, so as to limit the number of electronic channels and therefore the power consumption, a key factor for a detector intended to fly a space mission. The ambiguity in the track assignment in the two (x, t and y, t) event projections, where t is the ionisation electron drift time, is easily solved by matching the charge time-distribution for each track (Fig. 6 of [29]).

The detector was exposed to a high-intensity γ -ray beam produced by the head-on inverse Compton scattering of a laser beam on the 0.6 - 1.5 GeV electron beam of the NewSUBARU storage ring [30]. The γ -ray beam was collimated on axis so as to select forward scattering and to obtain a quasi-monochromatic beam with photon energies close to the Compton edge. After collimation, the linear polarisation of the laser beam is transferred almost perfectly to the γ -ray beam. By varying the laser wavelength and the electron beam energy we were able to take data between 1.7 and 74 MeV. We used a dedi-

¹A C++ version of our event generator [15] has been deployed as the G4BetheHeitler5DModel physics model of the 10.5beta release of Geant4 [17, 18] (A fortran demonstrator is documented in [16]).

²The dilution factor D is the factor by which the polarisation asymmetry in an actual detector, A_{eff} , is decreased with respect to the theoretical value, A_{QED} , that is, $A_{\text{eff}} = D \times A_{\text{QED}}$.

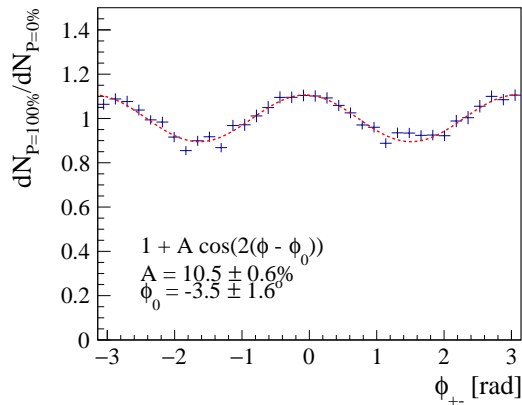


Figure 2: Distribution of the azimuthal angle of 11.8 MeV γ -rays (ratio of the fully linearly polarised to the linearly non-polarised) converting to an e^+e^- pair, in the 2.1 bar argon-isobutane (95-5 %) gas of the HARPO TPC prototype [33].

cated trigger system that enabled the data taking of γ -ray conversions in the TPC gas at rates of several 10 Hz, in the presence of several 10 kHz of background noise, with a negligible dead time [31]. We simulated the experiment with a Geant4-based Monte-Carlo simulation, with a custom implementation of the TPC-specific processes that we calibrated with respect to beam data [32].

The strongly non-cylindrical-symmetric x, y, t structure of the detector induces a bias in the ϕ distribution: the distribution angle of a non-polarised sources is not flat (Fig. 9 of [33]). This was analysed and mitigated by a two-step strategy: (a) chunks of data were taken with the detector rotated around the beam axis by multiples of 45° ; (b) data were taken with either fully polarised ($P = 1$) or non polarised ($P = 0$) beam, so as to form the ratio of the ϕ distributions; On a space mission, a non-polarised beam would not be available, and therefore $P = 0$ simulated samples would be used to apply the bias correction. We demonstrated that this can be done without any additional systematic bias due to a possible difference between simulation and data, within uncertainty (Fig. 11 of [33]). The biases mentioned above would average out for an isotropic exposure anyway, as is the case for a long-duration data taking, so the MC-based correction considered above would be a second-order correction (Fig. 12 of [33]).

The dilution factor is found to be of about 0.4 at 11.8 MeV and to decrease with photon energy, as expected (Fig. 13 of [33]).

4. Results

We have demonstrated for the first time the polarimetry of a MeV γ -ray beam and with an excellent dilution factor [33] (Fig. 2). In contrast to higher-density targets, gas detectors are able to image the conversion to pairs of low-energy γ -rays (Fig. 1). This is of utmost importance as the polarisation asymmetry of conversions to pair does not decrease much on the energy range of a practical polarimeter [11, 27]: the precision of the measurement relies ultimately on the size of the collected statistics and

therefore on the ability to collect data efficiently at low energies.

An attempt to monitor the degradation of the TPC gas in a sealed mode over half a year has shown that after the oxygen contamination (with an oxygen/nitrogen fraction found to be compatible with air) was removed by circulation through a purification cartridge, the nominal TPC fresh-gas parameters are restored [35], enabling a long-duration operation with the same gas on a space mission.

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