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Article

Linear Polarimetry with $\gamma \to e^+e^-$ Conversions

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Abstract: γ-rays are emitted by cosmic sources by non-thermal processes that yield either non-polarized photons, such as those from π^0 decay in hadronic interactions, or linearly polarized photons from synchrotron radiation and the inverse-Compton up-shifting of these on high-energy charged particles. Polarimetry in the MeV energy range would provide a powerful tool to discriminate among "leptonic" and "hadronic" emission models of blazars, for example, but no polarimeter sensitive above 1 MeV has ever been flown into space. Low-Z converter telescopes such as silicon detectors are developed to improve the angular resolution and the point-like sensitivity below 100 MeV. We have shown that in the case of a homogeneous, low-density active target such as a gas time-projection chamber (TPC), the single-track angular resolution is even better and is so good that in addition the linear polarimetry of the incoming radiation can be performed. We actually characterized the performance of a prototype of such a telescope on beam. Track momentum measurement in the tracker would enable calorimeter-free, large effective area telescopes on low-mass space missions. An optimal unbiased momentum estimate can be obtained in the tracker alone based on the momentum dependence of multiple scattering, from a Bayesian analysis of the innovations of Kalman filters applied to the tracks.

Keywords: gamma-ray astronomy; gamma-ray polarimetry; pair conversion; time projection chamber; gas detector; optimal methods; Kalman filter; Bayesian method

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1. MeV γ-ray Astronomy

γ-ray astronomy is suffering from a huge sensitivity gap between the sub-MeV energy range for which Compton telescopes are very efficient and the energy range above 100 MeV for which pair telescopes are very efficient [1]. From pair creation threshold (1 MeV) to 100 MeV, the main issue is the difficulty of rejecting true-photon backgrounds due to the bad single-photon angular resolution: the Fermi-Large Area Telescope (LAT), for example, has published results mainly above 100 MeV [2].

Efforts are in progress to improve on the contribution to the angular resolution due to the multiple scattering of the electron and of the positron in the detector. With tungsten-converter-free silicon wafer stacks [3,4] or emulsion detectors [5], an improvement by a factor of three can be expected, at 100 MeV, with respect to the angular resolution of the Fermi-LAT [6]. With gas detectors, up to a factor of ten can be obtained (Figure 1 Left and [7]). For energies lower than 100 MeV, the point-like source sensitivity of gas detectors is dominated by true-photon background rejection and is excellent thanks to the improved angular resolution (Figure 1 Right). At higher energies, it is dominated by photon statistics and therefore a gas detector (10 kg for Figure 1) cannot compete with the multi-ton Fermi-LAT.

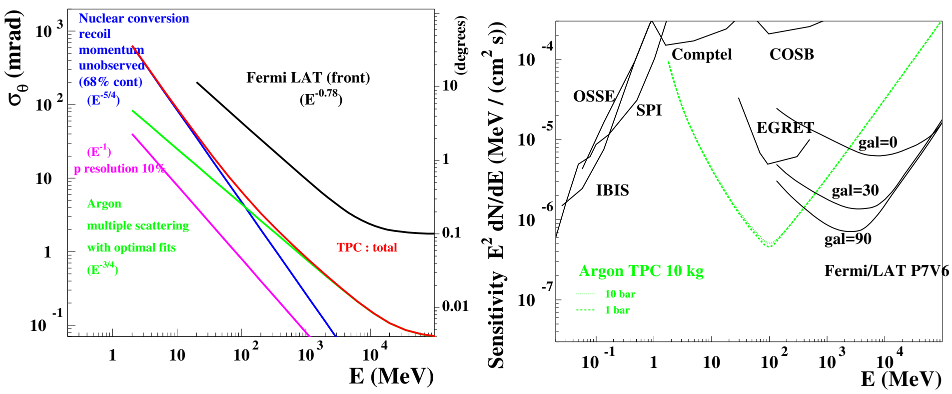

Figure 1. (**Left**) the three contributions to the single-photon angular resolution, namely the lack of recoil ion momentum measurement (blue), the single-track angular resolution (green), the single-track momentum resolution (cyan, assumed here to be of 10 %) and their total (red), as a function of the incoming photon energy, compared to that of the Fermi-Large Area Telescope (LAT); (**Right**) the point-like source sensitivity of a 10 kg gas time-projection chamber (TPC) telescope, computed à la Fermi-LAT, as a function of the incoming photon energy, compared to that of past and present telescopes. Both adapted from [7].

2. Polarimetry with Pairs

In contrast to low-energy (radio waves, optics) polarimetry that formed the core of this conference, and for which polarimetry is performed with detectors that measure electric fields or light intensities, at high energies photons are observed individually: a photon conversion in the detector is named an "event". Whatever the process at work (photo-electric effect, Compton scattering, pair conversion), due to the $J^{PC} = 1^{--}$ quantum numbers of the photon, the one-dimensional (1D) differential cross-section takes the form:

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

The modulation factor of the cosine, $A \times P$, is the product of the polarization asymmetry of the conversion process, A, and of the linear polarization fraction of the incoming radiation, P. φ is the azimuthal angle of the event (i.e., an angle that measures the orientation of the event in a plane orthogonal to the direction of propagation of the incoming photon), and φ_0 is the polarization angle of the incoming radiation.

In the case of pair conversion, $\gamma \to e^+e^-$, the final state is described by five variables that can be chosen to be the azimuthal angles and the polar angles of the electron and of the positron, respectively, and the fraction of the energy of the incident photon that is carried away by the position (ϕ_-, θ_-, ϕ_+, θ_+ and x_+). The full (5D) unpolarized differential cross-section has been obtained by Bethe and Heitler [8,9] based on the two dominant Feynman diagrams, and similarly the differential cross-section for fully polarized photons by [10,11](Misprint corrected in [12]). Please note that:

- Only the linear polarization of the incoming radiation takes part in these first-order Born approximation expressions;
- The circular polarization, which was extensively discussed during the conference, does not.
- The value of the polarization asymmetry, A, is close to 0.2 over most of the energy range, with low- and high-energy asymptotes of $\pi/4$ [13] and $1/7$.
- As the final state is determined by five variables, the definition of "the" azimuthal angle of the event can be done in several ways: examination of the precision of the measurement shows that the optimal choice is the azimuthal angle of the bisectrix of the direction of the electron and of the positron [13].

3. The HARPO Project

A time projection chamber (TPC) is a volume of matter 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 [14]. The anode is segmented so as to provide a 2D image of the electrons raining on it as a function of drift time. The measurement of the drift time provides the third coordinate: An effective way to obtain a fine 3D image of each event. Here the TPC is used as an active target, that is at the same time the converter in which the γ-ray converts and the tracker in which the two lepton trajectories are measured.

In our case, the segmentation consists of two series of orthogonal strips along x and y, which enables a number of electronics channels that scales as $2 \times n$ so as to fit into the limited electrical power available on a space mission (a pad-based system would scale as n^2). This reduction comes at the cost of a track-assignment ambiguity in multi-track events. This issue is easily solved thanks to the wild variation of the energy deposition along each track: track matching is performed by comparing the deposited-charge time profiles of the tracks [15,16]. It is clear from Figure 2 (Left) that shows the (x, t) and (y, t) signal "maps" of a γ-ray pair-conversion event in our detector that the large local "blob" close to $t = 380$ ns—almost a delta-ray—alone enables an unambiguous track matching.

We designed, constructed, and commissioned a gas time projection chamber (TPC) prototype [17], and we exposed it to a γ-ray beam provided by the BL01 line of the NewSUBARU facility (Hyogo, Japan) [18]. Photons are produced by the inverse Compton scattering of a laser beam on the electron beam of the 1 GeV storage ring [19]. By varying the energy of the electron beam and/or the wavelength of the laser, we could vary the energy of the γ rays between 1.7 and 74 MeV [18]. The Compton edge of the laser inverse Compton scattering spectrum (that is, the high part of the γ-ray energy spectrum) was selected by collimation on axis. After collimation, the polarization of the laser beam is almost entirely transferred to the γ-ray beam [20]. Triggering was performed by a dedicated system [21].

We developed a Geant4 simulation of the experiment, with TPC parameters that we have carefully calibrated by comparison with the properties of the experimental data [22]. As we found no appropriate γ-conversion event generator available on the market, we wrote our own, exact, free from any high-energy approximation, energy-momentum-conserving, valid down to threshold, fully 5D and polarized, that we carefully validated "against" all 1D analytical expressions that we could find in the literature [23,24]. We have demonstrated for the first time in the sub-GeV energy range (in which most of the statistics lie for cosmic sources) a high-performance polarimetry with an excellent dilution factor (Figure 2 and [25]).

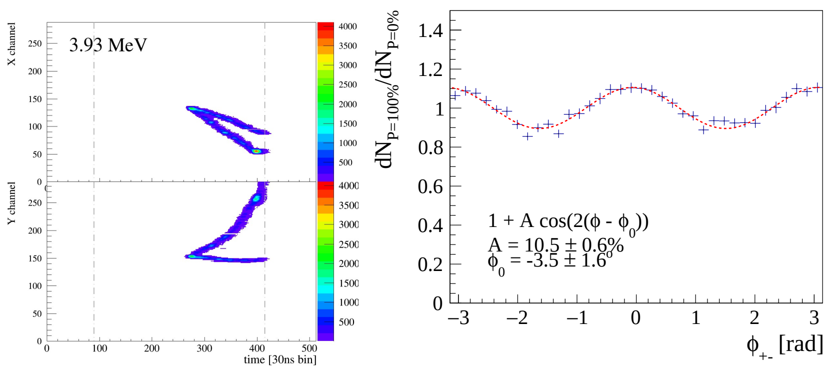

Figure 2. (**Left**) The two "maps" (i.e., the two x, t and y, t projections) of a conversion event of a 3.93 MeV γ-ray converting to an e^+e^- pair in the 2.1 bar argon-isobutane (95–5 %) gas of the HARPO TPC prototype. x and y are the two directions transverse to the drift direction in the TPC; t is the drift time. (**Right**) Distribution of the azimuthal angle of 11.8 MeV γ-rays (ratio of the fully linearly polarized to the linearly non-polarized) converting to an e^+e^- pair in the 2.1 bar argon-isobutane (95–5 %) gas of the HARPO TPC prototype [25].

We also performed a number of hardware developments, such as the assessment of the long-term quality conservation of the TPC gas in a sealed mode [26]. We also designed and characterized a prototype series ASTRE [27], an upgraded version of the readout chip AGET [28] that includes an improvement of the radiation hardness from a threshold linear energy transfer (LET) of $3\,\mathrm{MeV}/(\mathrm{mg}{\cdot}\mathrm{cm}^2)$ to $\approx 20\,\mathrm{MeV}/(\mathrm{mg}{\cdot}\mathrm{cm}^2)$. These chips include a self-trigger facility and provide real-time information of the channels that have seen signal while the drifing electrons from the TPC volume are raining on the collecting strips: a space-grade autonomous TPC trigger system is being studied.

4. Gamma-Ray Astronomy with an Autonoumous Active Target: Optimal Measurement of Charged Particle Momentum from Multiple Scattering with a Bayesian Analysis of Filtering Innovations

The lower-density space telescopes that are currently considered will imply large volume systems so as to maximize the effective area. The measurement of the photon energy in space telescopes can be achieved classically either by calorimetry, by the measurement of the track momenta by magnetic spectrometry, or by transition radiation detection—all systems that would be a challenge to the mass budget on a space mission.

The momentum of a track can also be measured in the tracker itself, making use of the dependence of the RMS multiple scattering angle proportional to the track momentum $\theta_0 \propto 1/p$. Classically, this is performed by segmenting the track into tracklets, and measuring the track angle in each tracklet: in that way, multiple angle deflections can be measured along the track [29]. We had determined what is the tracklet length that optimizes the momentum precision of that segment method, to find that it depends on the track momentum ... which is not known yet [7]. Iteration is to be considered.

Recently we developed a segment-free, optimal, unbiased method based on the Bayesian analysis of the filtering innovations of a series of Kalman filtered (indexed by the putative track momentum) [30]. For a typical silicon wafer stack telescope [4], the method is expected to be usable up to a couple of GeV/c (Figure 3).

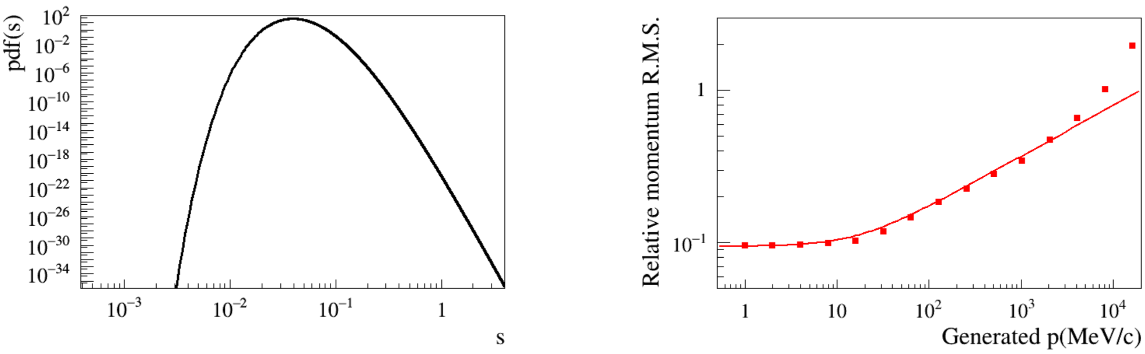

Figure 3. (**Left**) Bayesian probability density function as a function of s, the average multiple-scattering angle variance per unit track length, for a $50\,\mathrm{MeV}/c$ track in a silicon detector [30]. On that track, the momentum is measured to be equal to $49.9\,\mathrm{MeV}/c$. (**Right**) The relative R.M.S of the measured momentum, as a function of the true track momentum, for a silicon detector (the curve is the parametrization of Equation (58) of [30]).

5. Conclusions

We have quantitatively characterized the various contributions to the single-photon angular resolution of pair telescopes and the improvement that can be expected by the use of lower-density active targets. We have shown that with gas-detectors the polarimetry of linearly polarized γ-rays in the range MeV–GeV is possible before multiple scattering ruins the polarimetric information. We have experimentally validated these results by the characterization of a prototype on beam.

We have also developed a number of techniques that will be of interest to make the best use of such telescopes, including an optimal measurement of track momentum in the tracker itself that will make the active target an autonomous low-mass budget space telescope.

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Conflicts of Interest: The authors declare no conflicts of interest.

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