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# High resolution gamma-ray astronomy and polarimetry above $e^+e^-$ pair creation threshold

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A case for and a characterization of the use of a thin detector such as a TPC as an active target for an excellent angular resolution  $\gamma$ -ray telescope for cosmic sources in the [MeV - GeV] energy range, with sensitivity to the fraction of linear polarization of the radiation.

Keywords: polarimetry; gamma rays; TPC; pair conversion ; event generator.

#### 1. Non polarized $\gamma$ -ray astronomy

Up to the present,  $\gamma$ -ray astronomy in the [MeV - GeV] energy range has been performed with "thick" telescopes that consist of a tracker followed by a calorimeter. The tracker is made of a series of high-Z slabs in which photons convert to an  $e^+e^-$  pair, interleaved with position detectors (e.g. W slabs and Si detectors for the Fermi/LAT). The strong degradation of the angular resolution at low energy is a major issue, as it hinders the study of highly crowded regions of the  $\gamma$ -ray sky and makes background rejection a challenge: with the exception of gamma-ray bursts (GRB) for which background is not an issue, Fermi has published mostly above 0.1 GeV.

The way out is the use of a "thin" active target, such as a gaseous timeprojection chamber (TPC), in which conversion takes place and tracks are tracked. In contrast to thick detectors that convert photons with a high probability ( $p \approx 1$ ) and that have an effective area commensurate with the geometrical surface, for thin detectors  $p \ll 1$  and the effective area is proportionnal to the detector mass and to the photon attenuation; for argon its high-energy asymptotic value is not that small,  $3.6m^2/ton$ .

I have used the results of optimal track fits in the presence of multiple

scattering (MS) to obtain<sup>1,2</sup> a parametrization of the dominant MS contribution to the single-photon angular resolution as  $\sigma_{\theta} \approx (E/p_1)^{-3/4}$ , where  $p_1$  is a momentum that characterizes the detector,  $p_1 = p_0 \left(4\sigma^2 l/X_0^3\right)^{1/6}$ , where  $\sigma$  is the detector single point space resolution, l is the track sampling,  $X_0$  is radiation length and  $p_0 = 13.6 \,\mathrm{MeV}/c$  is the momentum that parametrizes multiple scattering. These optimal fits can be implemented by Kalman filters<sup>4</sup> and indeed, the RMS of the residues of such fits agrees<sup>2</sup> with the expression of  $\sigma_{\theta}$ . This dominating contribution is plotted for various



Fig. 1. Various contributions to the photon angular resolution, compared to that of the Fermi/LAT, with  $\sigma = 0.1$ mm and l = 1mm.

TPC materials and densities as the color curves in Fig. 1. The  $\sigma_{\theta} \propto E^{-3/4}$  dependence is universal and should apply to W/Si converter/trackers too: it compares well with the heuristic  $\sigma_{\theta} \propto E^{-0.78}$  obtained by Fermi.

The second contribution to the single-photon angular resolution is due to the unmeasured momentum of the recoiling particle in the case of a nuclear conversion as the path length of the ion in the detector is much too small to enable a measurement. It is plotted as the thin line with  $E^{-5/4}$ .

The third and smallest contribution is due to the resolution of the measurement of the magnitude of the electron tracks, the thin line with 1/E (assuming a 10% relative momentum uncertainty).

The excellent angular resolution translates to an excellent differential

sensitivity to a point-like source, estimated as the limit detectable flux (multiplied by  $E^2$ ). I compute the sensitivity a la Fermi, i.e. with 4 bins / energy decade, a  $5\sigma$  detection over T = 3 years, an  $\eta = 0.17$  exposure fraction, and the detection of at least  $10\gamma$ . The background I used is the extragalactic background, and therefore I compare the results to the 90° values for Fermi, i.e. far from the galactic plane. Figure 2 shows the impressive improvement in sensitivity over the [MeV - GeV] energy range, which closes the sensitivity gap between the pair thick telescopes and that of the Compton-based telescopes, such as Comptel.



Fig. 2. The point-like source differential sensitivity of a TPC made with various materials (Ne, Ar, Xe) at various densities (1bar and 10 bar gas, 10kg; liquid/solid 100 kg) and with  $\sigma = 0.1$ mm and l = 1mm, compared to the 90° values for the Fermi/LAT.

The measurement of the electron energy is usually performed by a calorimeter, which takes most of the mass budget. Magnetic spectrometers and transition radiation detectors (TRD) have also been considered. In the low energy part of the photon spectrum, which is of special interest here, the TPC provides its own estimate, by the multiple estimation of multiple scattering. After optimization of the track segmentation on which this is performed, the method can be shown to be practical<sup>2</sup> for E < 100 MeV.

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## 2. $\gamma$ -ray polarimetry

It is generally considered that polarimetry using nuclear conversions to  $e^+e^-$  pairs in a converter/tracker system is impossible in practice because the multiple scattering in the material blurs the azimuthal angle  $\phi$  before it can be measured (see, e.g., Ref.<sup>5</sup>). Neglecting the small logarithmic correction term of the expression for multiple scattering,  $\theta_0 = p_0/(\beta p)\sqrt{x/X_0}$ , and taking the most probable value  $\hat{\theta}_{+-} \approx E_0/E$  of the pair opening angle  $\theta_{+-}$ , with  $E_0 = 1.6$  MeV, the resolution of the azimuthal angle of the pair would be  $\sigma_0 \equiv 2\sqrt{2}p_0/E_0 \approx 24$  rad. The resolution is independent of the photon energy E because the smaller multiple scattering at high track momentum is counter balanced by the smaller pair opening angle. The dilution D of the polarization asymetry  $\mathcal{A}$  induced by the spread in azimuthal angle is  $D = e^{-2\sigma_0^2 \times x/X_0}$ , a factor that reaches 1/2 for a thickness as small as 110 microns of silicon or 4 microns of tungsten.<sup>2</sup>

Again the way out is the use of a thin active target. In that case the single track angular resolution is proportional to  $p^{-3/4}$ , and therefore  $\sigma_{\phi}$ improves at low energy.<sup>2</sup> Still using the most probable value of the opening angle, it can be shown that polarimetry is within reach in the [MeV - GeV] energy range for a gas TPC, see Fig 19 of Ref.<sup>2</sup> For a more quantitative characterization, I have built an event generator of the full (5D) probability density function (pdf) free of any low-energy approximation and which includes the linear polarization of the incoming photon.<sup>2</sup> Building on a work<sup>6</sup> that used the BASES integrator,<sup>8</sup> I used the HELAS amplitude calculator with the SPRING event generator.<sup>9</sup> When using the moments method, the expectation value of the weight  $2\cos 2\phi$  provides an estimate of  $\mathcal{A}P$  with an RMS uncertainty close to that of a fit of the  $\phi$  distribution. I then obtained an optimal "5D" weight that makes use of the full pdf, and which provides a gain on the precision  $\sigma_P$  of the measurement of P by a factor larger than 2. I used this event generator to study the dilution D as a function of E and of the detector parameter  $p_1$ , obtaining a parametrization  $D(E, p_1) = \exp\left[-2(ap_1^b E^c)^2\right]$ , where a, b and c are constants.

Finally I studied the potential of a modest detector, a  $1\text{m}^3$  gas TPC with  $\sigma = l = 1\text{mm}$ , for the polarimetry of the  $\gamma$  radiation from a Crab-like source for one year (but with unit exposure fraction  $\eta$  and efficiency  $\epsilon$ ). The precision improves with TPC density at low density (Fig. 3) as the statistics increase with mass but at higher densities the improvement saturates due to the deleterious effect of the dilution. For 5 bar argon gas, we can reach a precision of  $\sigma_P = 1.0\%$ , and with the application of an event selection including reasonable cuts on the opening angle, the track momentum and

 $\rho/\rho_{1\ bar\ gas}$ 



Fig. 3. Average polarization asymmetry (thin line) and polarization fraction precision (thick line) as a function of detector density normalized to the 1 bar gas density, for a  $1 m^3$  sensitive volume detector exposed for 1 year and a Crab-like source (nuclear conversion,  $\eta = \epsilon = 1, \sigma = l = 1$ mm). 1D (solid line) and 5D (dashed line) weight. The vertical lines show the density of the liquid phase.

the direction of provenance of the photon, of  $\sigma_P = 1.4\%$ .

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