## First characterization of a time projection chamber as a high-performance gamma-ray pair-creation telescope and polarimeter

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## Abstract

We have exposed a time projection chamber (TPC) to the polarized gamma-ray beam provided by the BL01 laser Compton scattering (LCS) beam line at NewSUBARU. More than 60 million gamma-to- $e^+e^-$ -pair conversion events were taken in the gamma-energy range 1.7 – 74 MeV. Preliminary results of the on-going analysis of these data show the excellent behavior of the detector despite the high particle flux and for the first time we demonstrate high-performance polarimetry, in the MeV-GeV energy range, with a space-compatible technique such as a TPC.

Several classes of cosmic sources such as active galactic nuclei (AGN), pulsars and gamma-ray bursts (GRB) produce huge flows of gamma rays. These high-energy photons are produced by non-thermal processes such as synchrotron radiation and inverse Compton scattering, and provide insight to enable us to understand the structure of these sources and the emission mechanisms at work.

In the 0.01 - 1 MeV energy range, Compton telescopes are extremely efficient. In the 0.1 - 1000 GeV energy range, past and present pair-creation telescopes are extremely efficient. In between lies a "sensitivity gap", namely the energy range 1 - 100 MeV, in which very few high-sensitivity observations of gamma-ray emitting cosmic sources are available. On the "pair side", performance degrades strongly at low energy because the angular resolution is extremely low because of the multiple scattering of the pair electrons in the converter material (most often tungsten slabs): Even though the pair-creation threshold is at 1 MeV, the Fermi-LAT Collaboration, for example, has barely published any observation below 100 MeV.

Most radiation mechanisms mentioned above produce linearly polarized  $\gamma$ -rays, to some extent, while phenomena such as magnetic field turbulence tend to dilute the polarization of the overall radiation emitted by a given source. In contrast to these radiative emission mechanisms, hadronic interactions of baryonic high-energy cosmic rays (protons or ions) with matter at rest produce non-polarized photons via spin-0  $\pi^0$  decay.

The measurement of the linear polarization (fraction and angle) of the emission, which is such a powerful tool for understanding the mechanisms at work in cosmic sources at low energies (from radio to X-rays) has never been performed above 1 MeV: Compton polarimeters become ineffective at high energies not only because the cross section is decreasing but because the polarization asymmetry falls as 1/E [1]. For pair telescopes, again it's multiple scattering that ruins the azimutal information carried by the pair as soon as a few milli-radiation lengths  $(10^{-3}X_0)$  away from the conversion point [2].



Figure 1: 3D CAD drawing of the HARPO detector.

The aim of the present work is to demonstrate the potential of a low-density (gas), homogeneous detector for high-performance (angular resolution and sensitivity) gamma-ray astronomy [3] and polarimetry [4] in the MeV-GeV energy range, using nuclear<sup>1</sup> conversions to pairs,  $\gamma Z \rightarrow e^+e^-Z$ .

<sup>&</sup>lt;sup>1</sup>In principle the analysis of the recoil electron azimutal angle distribution for triplet conversion events ( $\gamma e^- \rightarrow e^+ e^- e^-$ ) should



Figure 2: Layout of the HARPO detector in the GACKO experimental hutch on the BL01 beam line.

A TPC [6, 7] is a volume filled with matter, here an argon-based gas, immersed in an electric field, here homogeneous. After a high-energy "event" has taken place in the gas, for us  $\gamma \rightarrow e^+e^-$ , the two leptons ionize the gas on their path and exit the detector<sup>2</sup> The ionization electrons drift (opposite to) along the electric field and are collected on the TPC "endplate" anode. We have segmented the endplate into two series of orthogonal strips, the charge collected by each providing two projections on the x and y "transverse" directions, respectively, of the signal that is arriving at the endplate at a given time t. The measurement of the drift duration  $t - t_0$ , where  $t_0$  is the event time, provides the measurement of the third "longitudinal" coordinate, z. During most of the datataking at NewSUB-ARU we used an argon-isobutane 95-5% mixture at a pressure of  $\approx 2.1$  bar. The presence of a small amount of multi-atomic molecules limits the "heating" of the electrons by their multiple collisions during the drift and therefore decreases the value of the diffusion coefficient down to about  $0.03 \,\mathrm{cm}/\sqrt{\mathrm{cm}}$ . Figure 1 shows the layout of the HARPO detector [11].

The data taking took place in November 2014.  $\gamma$ -rays were produced by laser Compton scattering (LCS) of a laser beam on the high-energy (GeV) electrons stored in the NewSUBARU storage ring [12, 13]. Tuning the electron energy in the range 0.6 – 1.5 GeV and using lasers with various wavelenths (Nd:YVO<sub>4</sub> 1 $\omega$  and 2 $\omega$ , CO<sub>2</sub> and Erbium), we were able to vary the Compton-edge  $\gamma$ -energy from 1.7 to 74 MeV.

Monochromaticity was obtained by collimating the  $\gamma$  beam on axis. In that case, the polarization (fraction

and direction) of the laser beam is transferred to the  $\gamma$ -beam. We took most of the data with fully polarized beams ( $P \approx 1$ ). Part of the data was also taken with an unpolarized beam ( $P \approx 0$ , which means here random linear polarization), so as to better control the possible systematic bias induced by the fact that the detector is not cylindrically symmetric: indeed the x, y, z structure of the detector was found to induce such biases. Figure 2 shows the layout of the experimental setup.

The weak point of TPCs is that they generate a huge flow of information that is incident on the digitizing electronics, in our case  $2 \times 288$  charges to be dealt with every 30 ns, with the consequence that, with a storage depth of 511 time bins, the duration of the digitization of an event can be as long as 1.7 ms. Therefore, to cope with the huge rate of background noise mainly due to tracks from  $\gamma$ -ray conversions upstream of the detector or of the detector gas, we have designed and used a sophisticated trigger system that allowed us to reject background by more than two orders of magnitude while the overall trigger efficiency on the signal (ie.  $\gamma$  conversions to pairs in the TPC gas) was kept larger than 50 % [14].

Figure 3 shows a sample of events. The analysis of the data is well advanced [15]. Figure 4, for example, shows the distribution of the azimutal angle,  $\omega$ , of nuclear conversions at a  $\gamma$  energy of 11.8 MeV. The ratio of the  $P \approx 1$  and  $P \approx 0$  distribution enables an almost complete cancellation of the systematic biases. A  $(1 + A\cos[2(\omega - \omega_p)])$  fit of this distribution yields a value of the polarization asymmetry of  $A = 7.4 \pm 0.6\%$ , that is lower than the value of 17% predicted by QED at that energy [4]. Monte Carlo simulations show that this dilution of the asymmetry is compatible with that induced by the single-track resolution at that energy [15].

enable us to perform polarimetry too [5]. In practice though, the cross section for a large enough recoil electron momentum is much too small to perform a measurement on a cosmic source [3, 4].

<sup>&</sup>lt;sup>2</sup>Time projection chambers are considered also for Compton telescopes [8] and photoelectric telescopes [9, 10].



Figure 4: The ratio of the  $P \approx 1$  and  $P \approx 0$  azimutal distributions of 11.8 MeV  $\gamma$  conversion to  $e^+e^-$  pairs in 2.1 bar argon-isobutane 95:5 gas.

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On behalf of the French groups of the project, "the detector team", I would like to express my warmest gratitude to our Japanese colleagues, "the beam team", without the dedication, the effectiveness and the efficiency of whom we couldn't have achieved such a successful data-taking and collected such excellentquality data. I am convinced that the results of this characterization of such a high-performance MeV-GeV  $\gamma$ -ray telescope and polarimeter will set ground to the use of TPCs on board a future space mission.

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Figure 3: Four examples of  $\gamma$  rays provided by the BL01 NewSUBARU beam line, converting to an  $e^+e^-$  pair into the 2.1 bar argon-isobutane gas mixture of the HARPO detector. For each event, the (x,t) and (y,t) signal "maps" are shown. The vertical lines at the  $\approx 90$  and  $\approx 410$  time bins show the event time  $t_0$  and the arrival time of the electrons that were produced very close to the cathode and had to drift over the full 30 cm of gas, respectively. All four events show a conversion point located at > 90 time bin, which means that the conversion indeed took place in the gas, not in the solid material upstream of it. The 18.5 MeV event is a typical "nuclear" conversion, that is  $\gamma Z \rightarrow e^+e^-Z$ . The 33.3 MeV event is a triplet conversion, that is  $\gamma e^- \rightarrow e^+e^-e^-$ , where the large-polar-angle low-energy "recoiling" electron is clearly visible; the two leptons of the pair are seen to overlap in the (y,t) map. The 74 MeV event shows a clear indication of the momentum carried away by the unobserved recoiling nucleus as the two leptons are directed downwards in the (x,t) map, while the incident photon was directed horizontally, coming from the "left". The 11.8 MeV event shows a strong localized energy deposit on the "upper leg", due to a low-energy  $\delta$ -ray.