

## TPCs in high-energy astronomical polarimetry

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**Abstract.** High-energy astrophysics has yet to exploit the unique and important information that polarimetry could provide, largely due to the limited sensitivity of previously available polarimeters. In recent years, numerous efforts have been initiated to develop instruments with the sensitivity required for astronomical polarimetry over the 100 eV to 10 GeV band. Time projection chambers (TPCs), with their high-resolution event imaging capability, are an integral part of some of these efforts. After a brief overview of current astronomical polarimeter development efforts, the role of TPCs will be described in more detail. These include TPCs as photoelectric X-ray polarimeters and TPCs as components of polarization-sensitive Compton and pair-production telescopes.

### 1. Introduction

Polarimetry remains the only largely unexploited observational technique in high-energy astrophysics. While spectroscopy, imaging and photometry have produced a rich and growing database in the 100 eV to 10 GeV band, there has been but a single unambiguous positive detection of X-ray polarization in the Crab nebula [1] about 30 years ago.

Although the importance of polarimetry has always been acknowledged, the sensitivity of available instruments has generally been considered insufficient to warrant the investment and the prospects for a radical advance seemed dim. The best chance for a pathfinder in the 1990s, the Stellar X-ray Polarimeter (SXP) on the Spectrum-X-Gamma mission, was never launched. At the focus of a very large X-ray telescope, even then it would have made sensitive measurements of only about a dozen sources [2], although this still would have been a major advancement.

In recent years there has been burgeoning interest in astronomical polarimetry resulting in many efforts to develop sensitive polarimetry techniques for high-energy astrophysics. As other observational techniques have matured, the void of information that polarimetry could fill has become increasingly apparent. Recent tantalizing polarization measurements of a gamma-ray burst (GRB) [3] and a solar flare [4] from the Ramaty High Energy Solar Spectroscopic Imager (RHESSI) [5] mission have further piqued interest. However, RHESSI was not optimized for sensitive polarimetry and the results remain ambiguous. The RHESSI results do serve to emphasize that astronomical polarimetry requires dedicated instruments or at least instruments designed with polarimetry as a central requirement. In fact, numerous new instrumental techniques and polarimeter designs are bringing within reach the sensitivities required for definitive observations of many classes of astrophysical sources.

## 2. The polarization signature and basic formalism

All photon interaction mechanisms relevant to high-energy astrophysics are sensitive to linear polarization to varying degrees. The common polarization signature is an  $A + B \cos^2 \phi$  distribution in the emission direction of the interaction products, where  $\phi$  is the azimuthal angle with respect to the photon momentum. Measuring this distribution gives a direct estimate of the degree and phase of the polarization of the incident radiation. The analyzing power of a polarimeter is generally described by the modulation,  $\mu$ , a quantity that scales from zero for a polarization-blind instrument to unity for a perfect analyzer and is defined as:

$$\mu = (f_{\max} - f_{\min}) / (f_{\max} + f_{\min}) = B / (2A + B),$$

where  $f_{\max}$  and  $f_{\min}$  are the maximum and minimum, respectively, of the polarization-dependent distribution.

The sensitivity of a polarimeter depends on both its analyzing power and its quantum efficiency and is generally described by the *minimum detectable polarization* (MDP), the apparent polarization arising from statistical fluctuations in unpolarized data:

$$MDP = \frac{1}{\mu \varepsilon} \frac{n_{\sigma}}{S} \left( \frac{2\varepsilon S + B}{t} \right)^{1/2},$$

where  $\varepsilon$  is the quantum efficiency,  $S$  is the signal flux,  $B$  the background flux,  $t$  the observing time and  $n_{\sigma}$  is the detection significance in number of standard deviations [6]. Polarimeters are also subject to systematic errors as any rotational invariance in the instrument can create a false modulation in unpolarized data that may ultimately limit the sensitivity.

In high-energy astrophysics, source polarization levels are often expected to be small and measurements tend to be photon limited, so that polarimeters with simultaneously high modulation, high quantum efficiency, low background and low systematic errors are required. In general, the requirements become increasingly stringent with increasing energy as the inherent modulation of the interaction process decreases along with the source fluxes. Often, techniques sufficient for laboratory use are inadequate for astrophysical investigations in satellite-borne observatories.

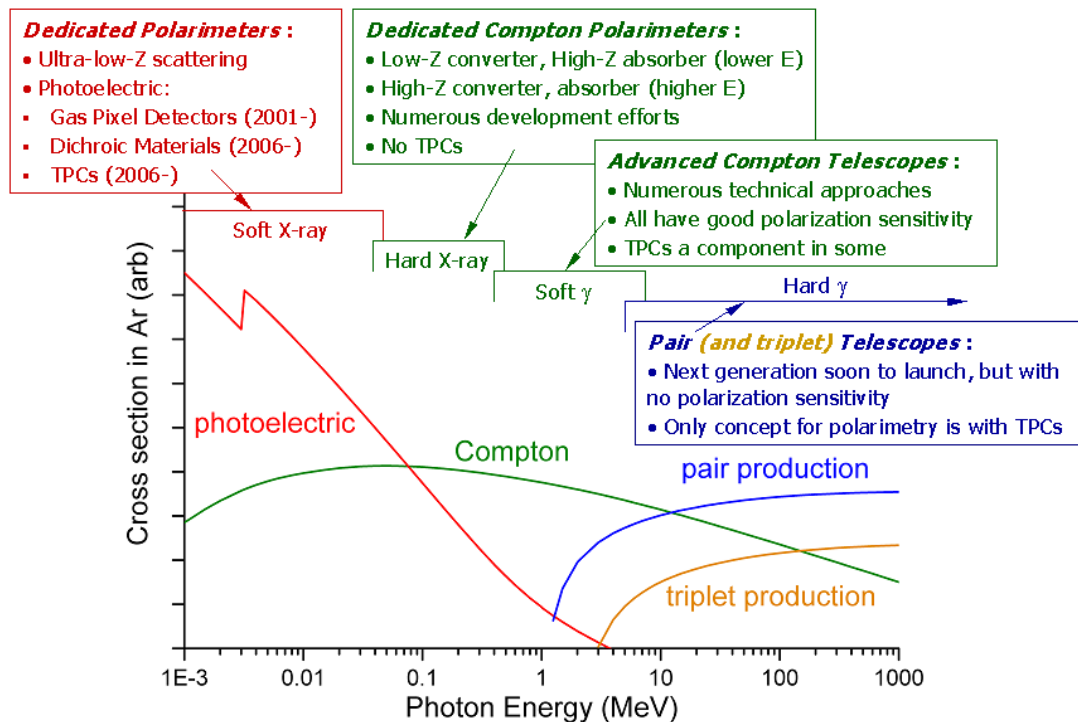
## 3. Overview of current polarimeter development efforts in high-energy astrophysics

In general, polarimeter development efforts in high-energy astrophysics can be categorized in four overlapping energy bands, distinguished by the dominant photon interaction mechanism and by the preferred means of astronomical imaging, as illustrated in figure 1. These energy bands will be referred to as the soft X-ray (1–50 keV), the hard X-ray (30–500 keV), the soft gamma-ray (300 keV–10 MeV) and the hard gamma-ray (10 MeV–10 GeV).

In the X-ray bands, where astronomical imaging can be achieved by collimation or, in the soft X-ray band, with grazing-incidence focusing optics, development efforts are directed toward dedicated polarimeters, or at least instruments whose primary purpose is polarimetry. In the gamma-ray bands, focusing and collimation are not feasible and kinematic reconstruction of the photon interaction is used to determine the source direction. The stopping power required for gamma-ray telescopes tend to make them very large, multi-purpose, facility-class instruments in which the interests of polarimetry may have to compete with other objectives.

In the soft X-ray band, Bragg or Thompson scattering has been the traditional polarimetry technique. Although scattering polarimetry may not be able to attain the sensitivities ultimately achievable with instruments based on the photoelectric effect, its proponents argue that scattering polarimetry is the most inexpensive and reliable means to a pathfinder mission [7]. Development efforts in this band, though, are mainly focused on exploiting the photoelectric effect, whose cross section dominates and which is a nearly perfect polarization analyzer. One recent proposal is to develop dichroic filters as polarization-sensitive X-ray transmission filters [8]. However, most efforts are directed at techniques that determine the emission angle of the photoelectron by imaging its track in a gas medium, either by direct readout of gas pixel detectors [9] or by optical imaging of the light

emitted in a gas avalanche [10]. While these are mostly intended for the focus of an X-ray telescope, gas pixel detector technologies have been demonstrated that would allow fabrication of the large areas required for sensitive collimated polarimeters [11]. Recently, the TPC was introduced as a relatively simple means of photoelectron track imaging with the potential to overcome the quantum efficiency limitations of previous track imagers [12].



**Figure 1.** An overview of current polarimetry development efforts in high-energy astrophysics shown in the context of the relative cross-sections of the polarization sensitive interaction mechanisms in a moderate-Z material. At X-ray energies efforts are toward dedicated polarimeters with focusing telescopes, coded apertures or collimators. At higher energies large multi-purpose telescopes are being developed, many with significant polarization sensitivity. These image by kinematic reconstruction of the incident photon direction.

There are numerous efforts underway to develop dedicated Compton polarimeters in the hard X-ray band [13]. These are designed to maximize their acceptance for photons Compton scattered at large angles, where the modulation is highest. The instruments are based on segmented detector elements that record the position and energy of both the Compton electron and the scattered photon. Instrument designs that emphasize the lower end of the energy band divide the active area between low-Z active scattering elements, such as plastic scintillator, and high-Z photon absorbers [14]. At the higher end of this energy range, homogeneous higher-Z detectors such as silicon, germanium, or CdTe are a viable means to large effective areas [15]. The high spatial resolution of TPCs is not an advantage in this energy band since astronomical imaging is best performed with coded apertures or collimators. At higher energies, collimation becomes infeasible and astronomical imaging is accomplished in Compton telescopes by kinematic reconstruction of the source of each photon.

Past Compton telescopes, such as COMPTEL, have had very poor polarization sensitivity due to the instrument geometry, which limited the effective area for the most polarization-sensitive events, and due to limited spatial resolution [16]. This is a deficiency that gamma-ray astronomers are determined to correct in future telescopes. Numerous technical approaches being pursued for new Compton telescopes that all provide for good polarization sensitivity [17,18]. These all have large

acceptance for the polarization-sensitive large scatter angle events and high spatial resolution. Both gas and liquid TPCs are being developed as major components in some of these instrument designs.

Astronomical polarimetry in the pair production regime remains a daunting experimental challenge. Past and current pair production telescopes have negligible polarization sensitivity. A high resolution TPC is the only concept currently being studied for a polarization-sensitive pair production telescope.

#### 4. TPCs in astronomical polarimeters

TPCs are currently being developed as astronomical polarimeters based on the photoelectric effect and as components of polarization-sensitive Compton telescopes. Some TPC-based techniques being developed for Compton telescopes are extensible to pair production, where some studies are being conducted on the feasibility of TPCs as polarization-sensitive pair production telescopes.

##### 4.1. TPCs as photoelectric X-ray polarimeters

Below about 50 keV, the photoelectric effect would appear to be the most promising basis for polarimetry. It is both the dominant interaction cross-section and a perfect polarization analyser. In the photoionization of an atomic s-orbital electron, the photoelectron is ejected preferentially in the direction of the electric field of the incident photon. In the non-relativistic limit the angular dependence of the cross-section is given by [19]:

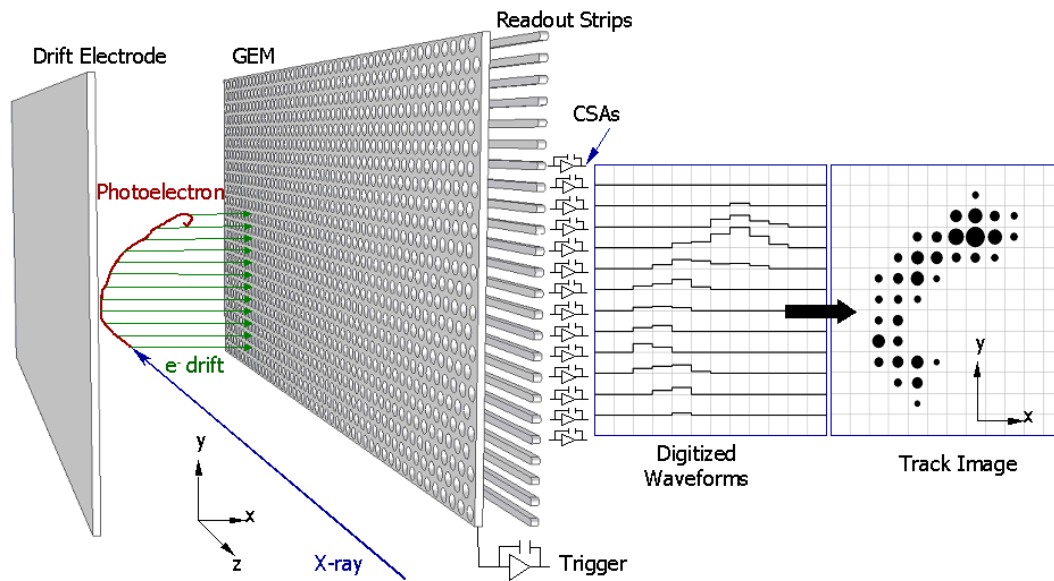
$$\frac{d\sigma}{d\Omega} \propto \frac{\sin^2\theta \cos^2\phi}{(1 - \beta \cos\theta)^4}$$

where  $\phi$  is the polarization-dependent azimuthal angle and  $\theta$  the polar angle with respect to the incident photon momentum. The pure  $\cos^2\phi$  dependence gives an inherent unit modulation.

Realizing the potential with an instrument that has both good modulation and high quantum efficiency remains an unmet experimental challenge. The fundamental difficulty results from the fact that the photoelectron range in any material is at most about one per cent of the X-ray absorption depth. This is further complicated by the fact that the low energy electrons can suffer significant scattering along their trajectory. Accurate kinematic reconstruction of the photoelectron emission angle requires a detector that can image the photoelectron track with resolution that is a fraction of the electron range, while high quantum efficiency requires an active depth of about one absorption depth. The derived detector requirement is, among other things, an electron track imager whose active depth is at least three orders of magnitude larger than its resolution.

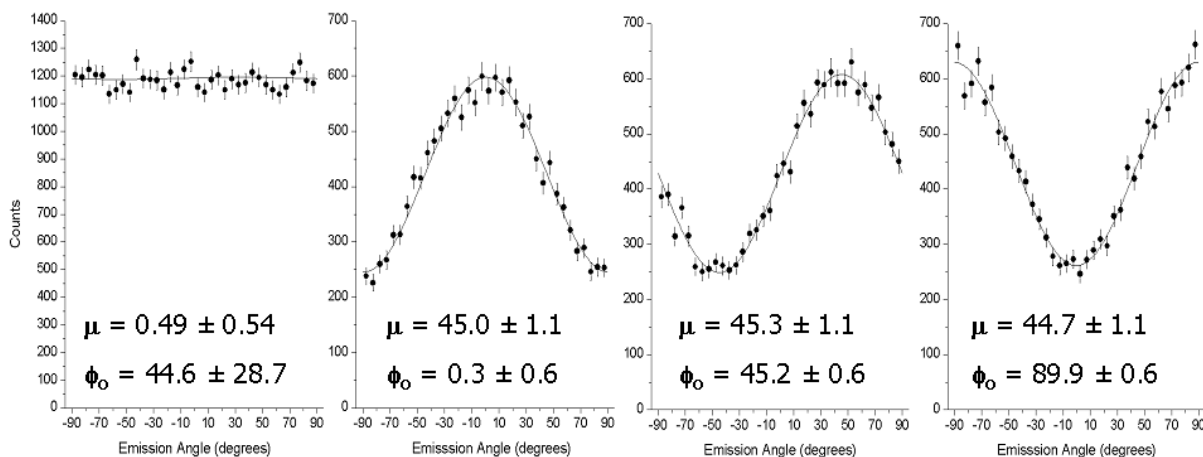
Electron tracking polarimeters demonstrated to date are an order of magnitude from that ideal. In the optical imaging and gas pixel detectors, the readout planes are normal to the incident flux, so that the active depth to image resolution ratio is ultimately limited by diffusion of the primary ionization as it drifts to the readout planes. While quantum efficiency improves with detector depth, the spatial resolution is degraded since the mean drift distance increases. For a given X-ray energy, there is an optimum depth that maximizes the overall sensitivity. For demonstrated gas mixtures, the quantum efficiency associated with peak sensitivity is only about 10% [9].

A recently introduced X-ray polarimeter that tracks photoelectrons with a TPC has a more favorable geometry that gives it the potential for much greater sensitivity [12]. In this geometry, shown in figure 2, the readout elements are parallel to the incident flux, so that the active depth can be increased indefinitely without the resolution being degraded by diffusion. The required mean drift distance is governed by the size and degree of collimation of the incident X-ray beam.



**Figure 2.** Photoelectron track imaging with a micropattern TPC with strip readout. The active depth can be increased indefinitely without affecting the image resolution.

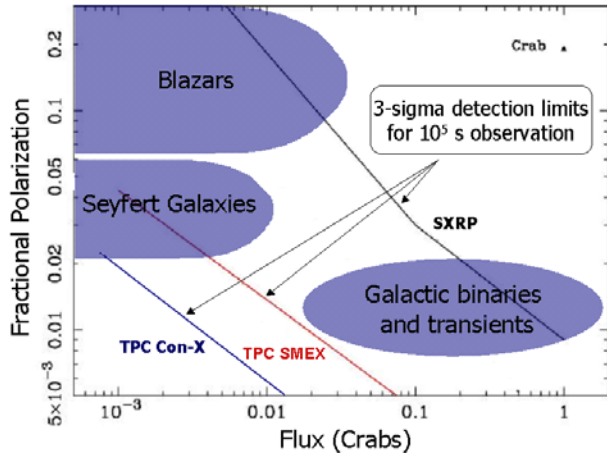
Results from a simple prototype TPC polarimeter at 6.4 keV, shown in figure 3, demonstrate polarization sensitivity comparable to, or perhaps slightly better than, gas pixel detectors with no evidence of systematic errors at the one per cent level. No identified feature of the prototype would prevent improving the statistical sensitivity by a factor of four or five by extending the active depth. However, since the tracks are imaged in fundamentally different ways along the two orthogonal coordinates the TPC polarimeter lacks rotational symmetry, so that care will be required to ensure that the sensitivity is not ultimately limited by systematic errors.



**Figure 3.** X-ray polarization measurements from a simple micropattern TPC [12]. Shown are histograms of reconstructed photoelectron emission angles from unpolarized 5.9 keV X-rays (far left) and polarized 6.4 keV photons at 0, 45, and 90 degrees (far right) with respect to the drift direction. The lines are fits to the data points and on each histogram are the measured values of the percent modulation ( $\mu$ ) and phase angle ( $\phi_0$ ) in degrees.

The relative simplicity and unique geometry of the TPC polarimeter enable new astronomical applications. Efforts are underway to develop TPC polarimeters not only for the focus of X-ray

telescopes (figure 4), but also for investigations that previously could be only be contemplated with Compton polarimeters, such as wide field-of-view, large-volume polarimeters for gamma-ray bursts or for high-resolution imaging polarimetry of solar flares with rotation modulation collimators.



**Figure 4.** Estimated sensitivities for two TPC polarimeter concepts and the SXRP [2], with the expected levels of polarization of astrophysical sources of interest. In red (TPC SMEX) is a small mission concept for dedicated, 24 cm deep TPC polarimeters at the focus of small X-ray telescopes. In blue (TPC Con-X) is a large mission concept that places 15 cm deep TPCs above an X-ray calorimeter at the focus of a large X-ray telescope, for simultaneous polarimetry and spectroscopy. Even in a small mission, the TPC enables sensitive extra-galactic polarimetry.

#### 4.2. TPCs in polarization-sensitive Compton telescopes

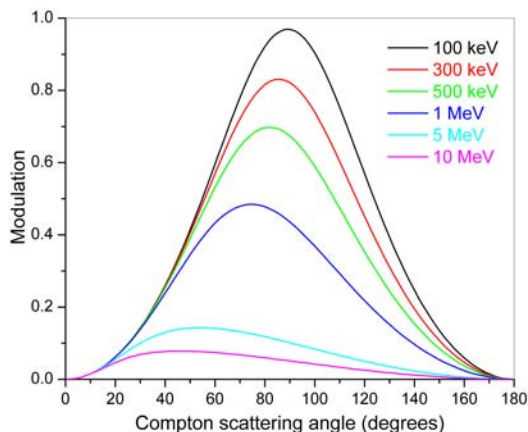
The polarization sensitivity of Compton scattering is somewhat more complicated than in the photoelectric effect. In the Compton effect, the azimuthal scattering angle of the photon and electron is preferentially normal to the electric field of the incident photon. The angular distribution of Compton scattered photons (and electrons) is described by:

$$\frac{d\sigma}{d\Omega} \propto \left( \frac{E_I}{E_S} + \frac{E_S}{E_I} - 2 \sin^2 \theta \cos^2 \phi \right),$$

where  $r_0$  is the classical radius of the electron and  $E_I$  and  $E_S$  are the respective energies of the initial and scattered photons and  $\phi$  is the azimuthal scattering angle with respect to the incident electric field [16]. The polar, Compton scattering angle  $\theta$  is given by:

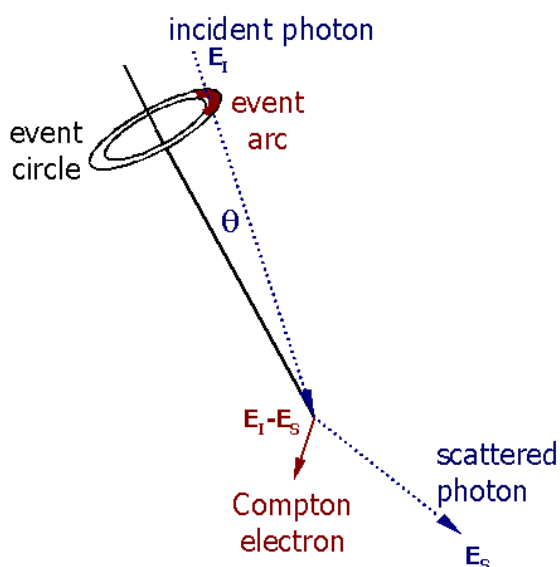
$$\cos \theta = 1 + m_e c^2 \left( \frac{1}{E_I} - \frac{1}{E_S} \right).$$

The inherent modulation of Compton scattering depends on both photon energy and the polar scattering angle as shown in figure 5, so that those quantities must be measured along with the azimuthal angle to estimate the degree of polarization of the incident flux. The modulation is near unity at 100 keV for Compton scattering near 90 degrees. The maximum modulation occurs at shallower angles with increasing energy and asymptotically approaches zero.



**Figure 5.** The inherent modulation of Compton scattering as a function of photon energy and scattering angle.

Compton telescopes image the sky by kinematic reconstruction of the incident photon direction as shown in figure 6. By determining the energy of the incident photon and the direction of the scattered photon, the incident direction is constrained to an annulus on the sky called the “event circle”. The incident photon energy may be determined without fully absorbing the energy in events with three or more Compton scatters [20]. Measuring the direction of the Compton electron further constrains the event circle to an arc. An astrophysical source is identified as the intersection of multiple event circles or arcs. Event circles from the diffuse emission or other sources in the field-of-view that accidentally intersect the source create background. This background can be reduced with electron tracking, while non-tracking telescopes can achieve larger effective areas with higher density detectors. Compton telescopes that image with or without electron tracking are being developed with TPCs and are candidates for NASA’s Advanced Compton Telescope mission [17].



**Figure 6.** Imaging with a Compton telescope. By measuring the energy of the Compton electron and scattered photon ( $E_s$ ) and the direction of the scattered photon, the source of the incident photon is constrained to an “event circle” on the sky. Measuring the recoil direction of the electron constrains the event circle to an arc. TPCs are valued in Compton telescopes for their ability to reconstruct the photon interactions with high resolution, with or without electron tracking.

#### 4.2.1. Non-electron tracking liquid xenon TPC

Liquid xenon TPCs (LXeTPC) have been under development for a number of years as polarization-sensitive, non-electron tracking Compton telescopes [21]. In the LXeTPC, incident photons typically undergo multiple Compton scatters in the liquid and perhaps a final photoelectric absorption. Each Compton electron produces ionization at the scatter site and UV scintillation photons. Photomultiplier tubes measure the UV photons, defining the time of the event. The ionization charge drifts in a uniform electric field to orthogonal sense wires that measure the x and y coordinates of the scatter, while the z coordinate is measured by drift time. The energy of each interaction is measured from the total charge but may also be estimated from the light output.

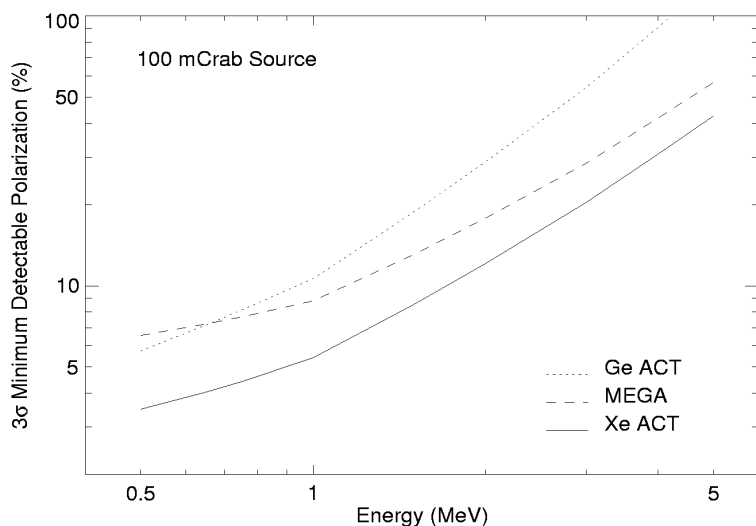
The LXeTPC achieves high efficiency above a few hundred keV with a single homogenous active volume of dense, high-Z liquid xenon that acts as both converter and calorimeter. It has both large acceptance for polarization-sensitive large angle Compton scattered events and the required ability to reconstruct the events in three dimensions with millimeter resolution to measure polarization. Simulations of one configuration of the LXeTPC show large modulations that approach the achievable limit (figure 6) above one MeV [22], where the instrument is optimized. The three-dimensional event imaging also enhances background rejection as multiple Compton scatter events can easily be distinguished from charged particles.

#### 4.2.2. Electron tracking gas TPC Compton telescopes

Gas TPCs are being developed for Compton telescopes as a means to the most accurate electron tracking [23,24]. In these telescopes, a large homogeneous high-pressure xenon volume serves as the

scattering medium and is instrumented at the bottom with micropattern gas detectors with two-dimensional readout. Surrounding the gas volume, on four sides and the bottom, are high-Z, high-density scintillation detectors instrumented with photomultipliers that serve as both photon absorbers and event triggers. These telescopes are based largely on single Compton scatters in the gas. The interaction point is identified by the source of the electron track, the azimuthal angle from the direction of the electron track and the scattering angle from the interaction point to the absorption point. As in the liquid TPC, the scintillator signal defines the interaction time and the z coordinate is determined by the drift time.

Electron tracking significantly reduces the background from the sky, particularly for the polarization-sensitive large Compton scattering angle events [24]. The area of the event circle is  $2\pi\sin\theta d\theta$ , where  $d\theta$  is the error in the Compton scattering angle, so that the area of the sky from which background enters the measurement is a maximum precisely for those events with the greatest polarization sensitivity. Tracking the electron reduces the area to  $\sin\theta d\theta d\phi$ , where  $d\phi$  is the azimuthal angle error determined from the electron track direction. Figure 7 shows the improved polarization sensitivity that results from accurate electron tracking.



**Figure 7.** The improved imaging provided by an electron-tracking Compton telescope translates into improved polarization sensitivity, all other detector parameters being equal [24]. The sensitivities are shown as a function of energy for a non-tracking germanium-based telescope (Ge ACT), a silicon strip tracking telescope (MEGA) and a gas TPC tracking telescope, all of equal effective area. Due to its low multiple scattering, the gas TPC has the higher resolution electron tracking and thus the best polarization sensitivity.

Some of these gas TPC telescope development efforts have reached a high state of maturity, including demonstrations of high-resolution imaging [25] and a recent high-altitude balloon flight of a prototype. These telescopes, with their electron tracking capability, are also extendable into the pair production regime and currently offer the only viable possibility for polarimetry at those energies.

#### 4.3. TPCs as polarization-sensitive pair (and triplet) telescopes

While all approaches to Compton telescopes that track the Compton electron are extendable to the pair production regime, only those using gas TPCs are considered to have any potential for astronomical polarimetry at these energies. The pair production mechanism itself has a poor inherent analysing power and photon fluxes from astronomical sources in the pair production regime are especially low.

The polarization-sensitive distribution in pair production is in the angle between the plane of the electron-positron pair and the electric field vector of the photon. The pair plane lies preferentially along the electric field with a distribution:

$$\sigma(\phi) = \frac{\sigma_0}{2\pi}(1 + \mu \cos 2\phi),$$

where  $\phi$  is the angle between the pair plane and the photon electric field and  $\mu$  is the inherent modulation. The modulation has an average value of 0.14, but varies from 0.1 to 0.3 depending on the energy and the reaction kinematics [26].

The modulation of pair polarimeters is strongly suppressed by multiple scattering of the electron-positron pair, so that accurate measurements of the pair plane must be made within less than  $10^{-2}$  radiation lengths [27]. Past pair telescopes, such as EGRET, had negligible polarization sensitivity due to multiple scattering in the thick foils used to convert photons [28]. Current pair telescopes are based on similar principles and will suffer the same problem. In a situation analogous to photoelectric X-ray polarimeters, the required radiation length to resolution ratio is currently only possible in a gas medium.

One design using a gas TPC similar to the Compton telescopes described above is being studied with the hope of providing useful polarization sensitivity [29]. The design has large gas TPCs based on high-resolution (200 micron) micropattern gas detectors with two-dimensional readout surrounded by thin plastic scintillator for event triggering and anti-coincidence. However, a calorimeter is not used in this design, since the tracking is accurate enough to measure the energies of the electrons from their average multiple scattering along their tracks.

Initial simulations with gases such as Xe/CO<sub>2</sub> show that electron diffusion in the gas obscures the information near the vertex so that polarization information is lost. Simulations are currently being constructed using negative-ion capture agents to suppress diffusion and using argon instead of xenon to enhance pair production in the field of an electron (triplet production). In triplet production, the recoil momentum imparted to the electron is modulated around the polarization vector in the same way as the pair plane, but the azimuthal distribution of the recoil electron will be far easier to determine than that of the pair planes. The simulations have not yet yielded polarization sensitivities for this concept, but many features are still to be implemented [29].

## 5. Summary

High-energy astrophysics has yet to exploit the unique and important information that polarimetry could provide, largely due to the limited sensitivity of previously available polarimeters. In recent years, numerous efforts have been initiated to develop instruments with the sensitivity required for astronomical polarimetry over the 100 eV to 10 GeV band. Time projection chambers (TPCs), with their high-resolution event imaging capability, are an integral part of some of these efforts.

In the X-ray band, TPCs have recently been demonstrated as photoelectric polarimeters that could enable new types of high-sensitivity instruments. In Compton telescopes, TPCs are valued as a means to high-resolution event reconstruction, either with or without electron tracking. Liquid rare-gas TPCs are being pursued as large effective area Compton telescopes, while electron-tracking gas TPCs are a component in Compton telescopes with the lowest background, especially for the most polarization-sensitive events. In the pair-production regime, only TPCs currently offer the hope, albeit faint, of tracking electron-positron pairs or recoil electrons with the accuracy and efficiency required for astronomical polarimetry.

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