Nuclear Inst. and Methods in Physics Research, A 880 (2018) 188–193

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

An optimized photoelectron track reconstruction method for photoelectric X-ray polarimeters

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ARTICLE INFO

Keywords:
X-ray
Polarimetry
Photoelectric polarimeter
Time projection chamber
Tracking algorithm

ABSTRACT

We present a data processing algorithm for angular reconstruction and event selection applied to 2-D photoelectron track images from X-ray polarimeters. The method reconstructs the initial emission angle of a photoelectron from the initial portion of the track, which is obtained by continuously cutting a track until the image moments or number of pixels fall below tunable thresholds. In addition, event selection which rejects round tracks quantified with eccentricity and circularity is performed so that polarimetry sensitivity considering a trade-off between the modulation factor and signal acceptance is maximized. The modulation factors with applying track selection are 26.6 ± 0.4, 46.1 ± 0.4, 62.3 ± 0.4, and 61.8 ± 0.3% at 2.7, 4.5, 6.4, and 8.0 keV, respectively, using the same data previously analyzed by Iwakiri et al. (2016), where the corresponding numbers are 26.9 ± 0.4, 43.4 ± 0.4, 54.4 ± 0.3, and 59.1 ± 0.3%. The method improves polarimeter sensitivity by 5%–10% at the high energy end of the band previously presented (Iwakiri et al. 2016).

1. Introduction

Recent progress in micropattern gas detectors enables us to sensitively track charged particles with energies down to 1 keV. The angular distribution of photoelectrons is sensitive to the electric field vector (or polarization direction) of incident photons. Since the photoelectric effect is the dominant interaction of X-rays, the micropattern gas polarimeter is expected to open up a new window in cosmic X-ray polarimetry.

The angular distribution, $d\sigma/d\Omega$, of the K-shell photoelectron emission in the non-relativistic region is theoretically given by:

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

where β is the ratio of the photoelectron velocity to the speed of light, ϕ is the azimuth angle of the X-ray electric vector, and θ is the polar angle with respect to the incident X-ray direction (e.g. Ref. [1]). Since the angular distribution is represented by the product of independent functions of θ and ϕ, a 2-D photoelectron track projected onto a plane perpendicular to the incident X-ray direction is sufficient to measure the X-ray polarization direction. The projected distribution is given by $\cos^2\phi$, meaning that the modulation factor, defined as the ratio of sinusoidal amplitude to unmodulated offset, is intrinsically 100% for all θ in the photoelectric effect.[1]

Two major types of micropattern gas polarimeters have been developed to image the photoelectron track with sufficient resolution to

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[1] This is a simpler case than for a Compton scattering polarimeter where the intrinsic modulation factor approaches zero for forward and backward scattering; this situation requires 3-D tracking of the scattered X-rays to achieve the maximum polarization sensitivity (e.g. Refs. [2,3]).

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https://doi.org/10.1016/j.nima.2017.10.070
Received 26 May 2017; Received in revised form 2 October 2017; Accepted 24 October 2017

determine the emission angle: a position-sensitive detector with a 2-D readout system called the gas pixel detector (GPD) [4,5] and a position-insensitive but more efficient polarimeter with 1-D strip electrodes using the time projection chamber (TPC) technique [6,7]. In the GPD, the photoelectron track drifts parallel to the original direction of the photon, while in the TPC the drift is perpendicular. This difference enables imaging of astronomical sources in the GPD and higher efficiency in the TPC. Despite this fundamental difference, both the GPD and TPC produce 2-D tracks. In both polarimeters, an algorithm to reconstruct the initial angle of photoelectrons derived from a 2-D track image is essential to maximize polarimetry sensitivity (e.g. Ref. [6] for the TPC and Refs. [8,9] for the GPD). The new algorithm described here extends and improves our previous method in Ref. [6]. In addition, it adopts measured data-driven approach, while the method in Ref. [8] needs helps with a Monte Carlo simulation to know the real interaction position and bring a reconstructed position close to it.

This paper describes the angular reconstruction and track selection for 2-D images with image moments and its verification using experimental data from the TPC polarimeter we have developed [7]. The method is applicable to the other photoelectric polarimeters, such as the GPD polarimeter with hexagonal pixels. Section 2 briefly reviews the polarimeter and the experimental setup. We describe the angular reconstruction in Section 3 and the track selection in Section 4, and lastly, conclude the study in Section 5. Throughout this paper, all errors are given at the 1σ confidence level unless otherwise stated.

2. Experimental setup and track images

The TPC polarimeter we have developed for measuring linear polarization of cosmic X-rays is capable of taking a 3.6-mm square image divided into 30-by-30 pixels to track a photoelectron induced by an incident X-ray. Pure dimethyl ether (DME) is sealed as target gas at a pressure of 190 Torr in the polarimeter chamber. The polarimeter was tested with linearly polarized X-rays at the X-19A beamline at the National Synchrotron Light Source facility in Brookhaven National Laboratory. The details of the measurement setup and data processing are available in Ref. [10]. Data sets at 10 monochromatic energies (2.7–8.0 keV) were used in this work, each having approximately 50,000 events. In addition, the polarimeter was irradiated with the X-ray beam at three different positions, which correspond to the electron drift length from the interaction point to the nearest readout electrode of 0.6, 0.8, and 1.0 cm, where the position of the 0.8 cm drift length is designed to be at the optical axis of the X-ray mirror. The three data sets at each energy are combined into a single data set and analyzed in the same manner because the drift length would be unknown in a measurement of cosmic X-rays. The beam polarization direction was aligned diagonally with the square image. The beam polarization was separately measured with a scattering polarimeter and was determined to be 94% [11].

Typical track images taken with 2.7, 4.5, 6.4, and 8.0 keV X-rays are shown in Fig. 1. Pixels in which the measured signal is less than three times the noise are set to zero. The electron continuous-slowing-down approximation ranges at 2.2, 4.0, 5.9, and 7.5 keV, which are the photoelectron energies calculated by subtracting the K-shell binding energy of oxygen in DME from the incident X-ray energies, are estimated to be 0.31, 0.90, 1.8, and 2.7 mm, (or 2.6, 7.4, 15, and 22 pixel), respectively. They were calculated according to the analytic formula given in Ref. [12], although it was validated for electrons in condensed materials. For the lowest energies, and shortest tracks, the images are dominated by electron diffusion. The standard deviation is estimated to be 0.15 mm or 1.3 pixel for 0.8 cm drift distance with Magboltz [13]. Above 4.5 keV, tracks are clearly elongated. The high charge density region corresponds to the Bragg peak at the end of the track. This is because the electron ionization loss per unit length depends on the inverse of its energy according to an approximation of the Bethe formula in the low-energy limit: $-dE/dx \propto E^{-1}$, and therefore the charge distribution tends to be biased along its trajectory. In addition, in the higher energy range, some of the tracks are curved due to large-angle scattering of the photoelectron with a gas molecule.

3. Angular reconstruction

An accurate and robust method to reconstruct the initial ejection angle of a photoelectron from the various track images (see Fig. 1) is vital to achieve high polarization sensitivity. In digital image processing, image orientation, Φ, having the centroid as its pivot is given by:

$$\Phi = \frac{1}{2}\arctan\left(\frac{2\mu_{11}}{\mu_{20}-\mu_{02}}\right) \tag{2}$$

in general (e.g. Ref. [14]). In the above equation, μ_{ij} is a centralized (i,j)-moment of a 2-D image in which the pixel at (x,y) has a charge amount of Q_{xy}:

$$\mu_{ij} = \sum_x \sum_y (x-\bar{x})^i (y-\bar{y})^j Q_{xy}, \tag{3}$$

where $(\bar{x},\ \bar{y})$ is the charge centroid position. The Φ direction is the same as the major principal axis of the charge distribution. Although Φ calculated with the atan2 function ranges from $-\pi/2$ to $\pi/2$, it is expandable to all angles $[-\pi,\pi]$ by using the sign of the third moment or skewness, which is sensitive to bias of the charge distribution, along the major principal axis with respect to the centroid. Fig. 2(a) illustrates an example of the above track reconstruction hereafter called "the single-stage reconstruction". It is clear that the single-stage method fails to accurately reconstruct the initial photoelectron angle for curved tracks which often appear in the higher energy range.

Since the track direction is randomized by Coulomb scattering with gas molecules, the charge distribution near the beginning of the track carries the most information about the initial direction and thus the photon electric field. In order to improve the estimated track direction for curved tracks, the image region with the track end should be disregarded. In the previous works [6,11], we divided the track image by the minor principal axis, which is perpendicular to the major axis with respect to the centroid, ignore the half with the track end determined with the sign of the third moment along the major axis, and calculate the angle with the remaining half (which includes the interaction point) from Eq. (2). In the cutting of pixels with their position, a charge amount in each pixel is assumed to be located at its center. This revised method, hereafter called "the two-stage reconstruction" and illustrated in Fig. 2(b), is applied to elongated tracks (eccentricity $e > 0.8$), while the single-stage method is applied to tracks with $e \le 0.8$. (Eccentricity is defined in Section 4.) Further improvement is possible for some tracks; the improved angle in Fig. 2(b) is closer to the initial direction, but does not yet account for all of the visible curvature in the first half of the track.

In order to adaptively remove the curved part of a track image and keep the beginning without overcutting, we use image moments up to the second order for not only a grayscale image with Q_{xy} but also its binary image created by image thresholding with the same value (three times the noise) as that described in Section 2. We hereafter distinguish the two moments by defining μ_{ij} and μ'_{ij} for grayscale and binary images, respectively. For example, the zeroth moment for a binary track image is μ'_{00} which represents the number of hit pixels. We can calculate the maximum and minimum of second moments, $M_2^{\max}$ and $M_2^{\min}$, which corresponds to the standard deviations along the major and minor axes, respectively, as follows:

$$M_2^{\max} = \frac{1}{2}\left[\mu_{20}+\mu_{02}+\sqrt{(\mu_{20}-\mu_{02})^2+4\mu_{11}^2}\right], \tag{4}$$

$$M_2^{\min} = \frac{1}{2}\left[\mu_{20}+\mu_{02}-\sqrt{(\mu_{20}-\mu_{02})^2+4\mu_{11}^2}\right]. \tag{5}$$

The track image is repeatedly cut off in half pixel steps along the major axis of the entire image until the remaining number of pixels or the maximum second moment falls below set thresholds. The modulation factor derived from all the data is the highest when the threshold condition is set to be

$$(\mu'_{00} \le 23) \text{ or } (M_2^{\max} \le 3.0), \tag{6}$$