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Electron track reconstruction and improved modulation for photoelectric X-ray polarimetry

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ABSTRACT

The key to photoelectric X-ray polarimetry is the determination of the emission direction of photoelectrons. Because of the low mass of an electron, the ionisation trajectory is not straight and the useful information needed for polarimetry is stored mostly in the initial part of the track where less energy is deposited. We present a new algorithm, based on the shortest path problem in graph theory, to reconstruct the 2D electron track from the measured image that is blurred due to transversal diffusion along drift and multiplication in the gas chamber. Compared with previous methods based on moment analysis, this algorithm allows us to identify the photoelectric interaction point more accurately and precisely for complicated tracks resulting from high energy photons or low pressure chambers. This leads to a better position resolution and a higher degree of modulation toward high energy X-rays. The new algorithm is justified using simulations and measurements with the gas pixel detector (GPD), and it should also work for other polarimetric techniques such as a time projection chamber (TPC). As the improvement is restricted in the high energy band, this new algorithm shows limited improvement for the sensitivity of GPD polarimeters, but it may have a larger potential for low-pressure TPC polarimeters.

1. Introduction

Sensitive X-ray polarimetry in astrophysics based on the photoelectric effect has become possible in recent years with the development of high-resolution micro-pattern gas detectors [1,2]. The azimuthal distribution of the photoelectron direction is dependent on the polarisation of the X-ray. The objective of these gas polarimeters is to measure the 2D photoelectron directions on the plane perpendicular to the incident X-rays. The sensitivity of the polarimeter depends on how accurately and precisely the direction can be measured. Thus, the algorithm to reconstruct the photoelectron emission direction from the measured track image is essential.

Previously, the reconstruction for the electron emission direction was achieved based on the moment analysis of the track image. The principles of the algorithm were introduced in Ref. [3] and the reconstructions of the interaction point and emission direction were later improved [4]. Here we summarise the basic steps of the moment analysis based algorithm, and more details can be found in Section 2.2.1 in Ref. [4]. The second moments of the entire image (charge deposition) in all directions with respect to the barycentre are first calculated. The elongation of the image can be found along the direction Φ where the second moment is maximised. The third moment of the image along the direction Φ is then calculated to determine which part of the image along the elongation axis contains more charges. The end with less charge is regarded as the initial part of the track. Pixels around the photoelectric interaction point are selected from those between a smaller and a larger radius (normalised to the maximum second moment) from the barycentre along the direction with less charge, and the interaction point is estimated as their centre of mass. Once the interaction point is found, the emission angle can be derived as the direction of the new maximum second moment of a distance-weighted charge map around it.

The most important and challenging part of the direction reconstruction is to determine how to locate the interaction point accurately and precisely. However, the algorithm discussed above may fail for complicated tracks, as it simplifies the track image into elliptical distributions of charges. For example, if the photoelectron moves back and forth and does not stop at the very end, the algorithm may misidentify the location of the interaction point. For a gas pixel detector (GPD) filled with 0.8 atm dimethyl ether (DME) [1,5], the current algorithm produces reasonable modulations at energies below ~7 keV, but it is not optimal at energies above due to complications of the

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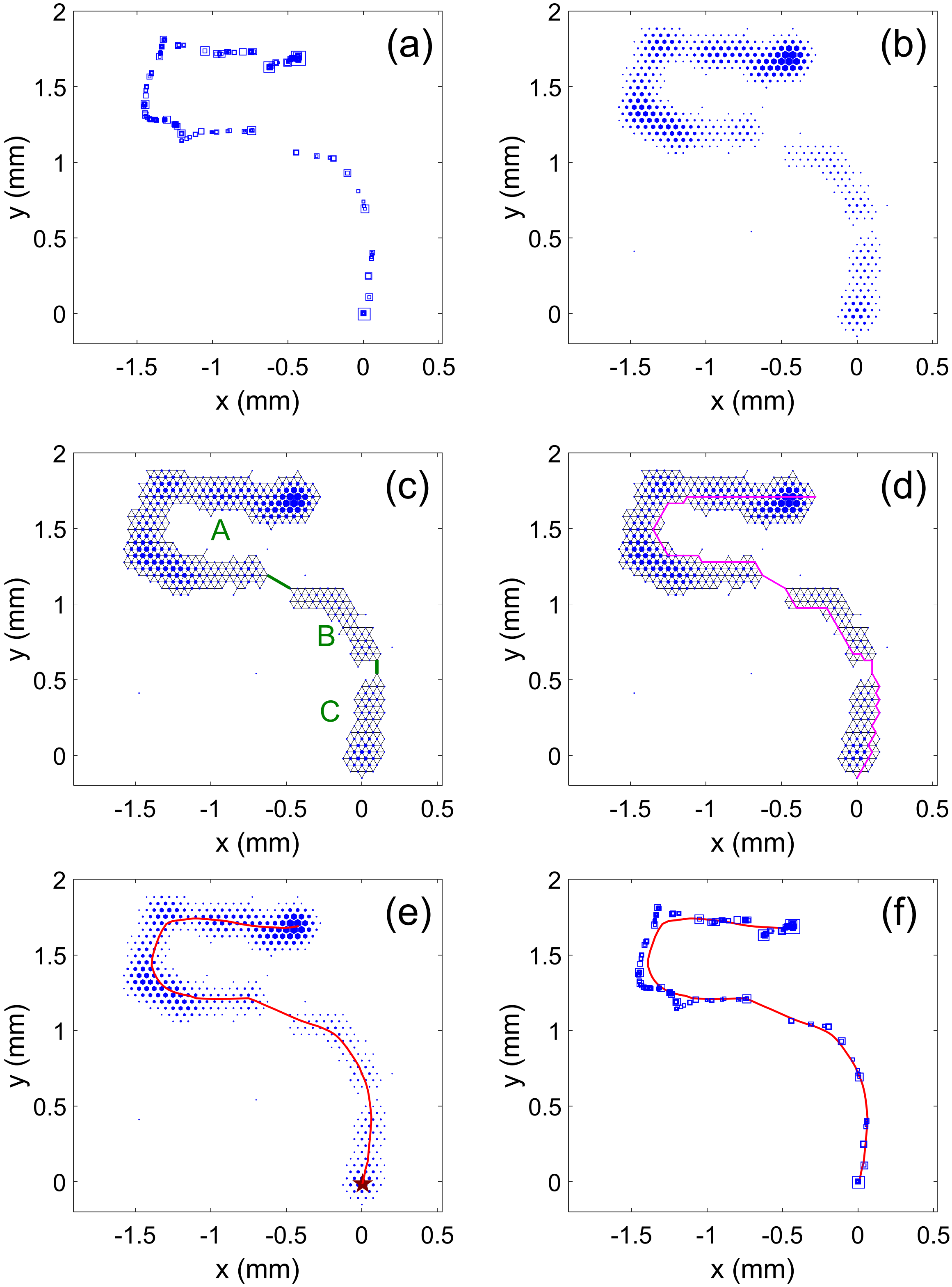

Fig. 1. Illustration of the track reconstruction algorithm. **(a)** Simulated charge distribution produced by a 15 keV X-ray projected onto the plane perpendicular to the X-ray direction. The marker size is proportional to the energy deposition (similarly hereafter). **(b)** Image obtained by the readout ASIC of the GPD detector. **(c)** Neighbouring clusters and neighbouring points are connected with thick and thin lines, respectively. **(d)** For all shortest paths between every two points in the graph, the longest one is defined as the primary path (thick line). **(e)** The reconstructed path (thick line) is derived from the primary path after spatial energy filtering. The end with less charge depositions is determined as the interaction point (star). **(f)** Comparison between the reconstructed path and the initial charge distribution.

electron tracks. The situation may be even worse for the time projection polarimeters, as some of them are filled with low-pressure (0.25 atm) gas [6].

In this paper, we propose a new algorithm to locate the interaction point via a reconstruction of the full electron track. The algorithm is described in Section 2. The results tested with the GPD polarimeter using simulated and measured data are discussed in Section 3. The conclusion is summarised in Section 4.