The spectroscopic capabilities of imaging GSPCs

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ESLAB 95/132

To be published in Proceedings SPIE v2518 and presented
at the 1995 SPIE International Symposium on Optical
Science, Engineering and Instrumentation 9-14 July 1995

SW 9546

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ABSTRACT

Based on experimental data obtained with a Xenon filled Low Energy Gas Scintillation Proportional Counter (LE-GSPC), the performance and characteristics of such detectors is discussed, in the context of their spectroscopic capabilities. Measurements were made at a synchrotron radiation facility, taking advantage of the tuneability and excellent collimation of the source.

The energy linearity and the associated discontinuities at the Xenon absorption edges are described for the range 0.15 to 6 keV. The results relating to the energy resolution as a function of energy and the L-escape peaks are also presented.

Keywords: X-ray, Xe-absorption edges, imaging, GSPC, detector, non-linearity, astronomy, spectroscopy

1 INTRODUCTION

The spectroscopic capabilities of gas scintillation proportional counters (GSPCs) are given by the physical processes of X-ray photon absorption and charge generation in the absorption gas, typically Xenon, as well as the detector design itself. For a well designed instrument, the energy gain is in principle linear and the energy resolution (FWHM, %) scales as $E_X^{-1/2}$.¹⁻³ At the absorption edges of Xenon the energy gain and resolution show discontinuities, though, caused by the changes in the details of the X-ray absorption processes. Whenever the X-ray energy crosses an absorption edge of Xenon, new relaxation and ionization paths become available and therefore the charge generation efficiency and associated variances change.

In this paper measurements are presented of a high resolution scan through the L, M and N edges of Xenon, using a high performance driftless GSPC detector and a very accurate synchrotron radiation source. With its driftless design and a thin multilayer plastic window the detector is optimized for low energy X-ray detection down to 150 eV.

Also important for the evaluation of the spectroscopic characteristics is the generation of spurious peaks in the energy spectra. While pile-up peaks are instrument specific and dependent on the electronics, escape peaks depend on the X-ray absorption processes.

2 EXPERIMENTAL

2.1 The Detector

A driftless GSPC⁴ was used for the measurements. This design avoids losses of electrons to intermediate grids, since the scintillation region simultaneously acts as the absorption region. In addition the much higher electric field near the entrance window reduces the loss of electrons produced after the initial photoabsorption to this window. This enables the detection of low energy photons, which hardly penetrate into the detector gas. Lateral electron diffusion is also efficiently reduced by the fast drift velocity in the higher field.

After transmission through the entrance window, X-ray photons penetrate into the detector's Xenon gas filling. The penetration depth Z_{pen} is strongly dependent on the X-ray energy E , and shows of course discontinuities near the absorption edges of Xenon. Events that are absorbed deeper in the detector travel a shorter distance in the gas cell, and therefore produce less scintillation light, since in a driftless GSPC the free electrons produced by the absorption of an X-ray photon start emitting scintillation light immediately after their creation. This therefore results in a smaller signal being produced by the detector, compared to the signal of an event of the same energy absorbed near the entrance window.

The selection of events which penetrate only less than a given distance into the detection gas can effectively be performed by using the event pulse duration time, B , which is measured together with the pulse height for each event.

To ensure that the detector is suitable for the detection of low energy X-ray photons, the entrance window must be very thin. At the same time the window must be very gas tight and durable, and must show very little outgassing so as to ensure the high purity of the detection gas required for GSPCs. The detector used has a thin multilayer window, 1.2 μm thick.⁵ Figure 1 shows the transmission function compared to that of a 10 μm thin Beryllium window. Arrows mark astrophysically important lines, and indicate, that the additional decade in energy coverage is important.

The detector uses a multi-anode PMT and resolves the position of the incident X-ray photons to about 1mm at 6keV. The position resolution also provides a significant reduction of background. In addition a veto signal is generated by the instrument, which is effectively an independent measure of the off-axis distance of each event. Both the position and the veto signals can be used to select "good" events originating from the synchrotron source, discriminating them from background events.

2.2 Measurements

In order to cover the energy range bracketing the M, N and L edges of Xenon, two beamlines had to be used at the synchrotron radiation facility Bessy. The range 0.1 to 1.8keV was measured on the SX700 plane grating monochromator beamline⁶ and the adjacent range 1.8 to 6.0keV was covered by the KMC double crystal monochromator beamline.⁷

On the SX700 the energy resolution is $R=E/\Delta E=500$ at 1.8keV, scaling as $E^{1/2}$, and at the KMC beamline $R \geq 500$ is valid in the range used. Flux in higher orders and straylight does not exceed 1% on the SX700. On the KMC ghost images were seen with the detector over a major part of the energy range used, possibly due to spurious reflections in the beamline. These images were however distant enough from the main image, such that they did not have any significant influence on the results. The energy accuracy was calibrated using absorption edges in filters inserted temporarily into the beam, and was found to be better than 0.1% and 0.5% for the SX700 and KMC beamlines, respectively.

Figure 1: Comparison of the X-ray transmission of the multilayer window with a 10 μm Be window. Arrows mark astrophysically important emission lines.

In both set-ups (SX700 and KMC) the detector was mounted at the rear end of the beamline. Slits and pinhole apertures were used to collimate the beam and define the area on the detector window illuminated by the X-ray beam. The spot size on the detector window was $\leq 100\mu\text{m}$ on the SX700 beamline, achieved with a $25\mu\text{m}$ pinhole placed in 35cm distance from the detector. On the KMC beamline a $140\mu\text{m}$ pinhole was used at 30 cm distance from the detector, producing a spot size of $\leq 200\mu\text{m}$. Changes in the solid angle observed by the photomultiplier (PMT) detecting the scintillation light for events at $\pm 100\mu\text{m}$ off-axis is estimated to be $\approx 10^{-5}$, and can therefore be considered as negligible. The detector was mounted on a XY-table, and was positioned such, that the X-ray beam spot was centered in the field of view. The on axis synchrotron source spot flux was adjusted to produce $\approx 500\text{Hz}$ count rate in the detector.

The detector gas cell is enclosed by a protective cover, which was attached to the beamlines via a flexible bellow and an electrically insulating spacer. The protective cover is vacuum tight and was evacuated via the beamline vacuum system. The typical pressure protective cover during the experiments was 10^{-6}mbar . Care was taken to avoid any light leakage into the detector enclosure.

Two ^{55}Fe sources were mounted on the detector, providing a constant calibration reference for the detector gain. They were collimated to $\simeq 1\text{mm}$ and were located symmetrically at the edge of the field of view of the instrument, 23mm from the entrance window center. The calibration source countrate was $\approx 50\text{Hz}$ per source. The detector energy gain drifts, which are mainly caused by temperature changes, were found to be slightly position dependent.

The relative drift observed is limited to $\pm 0.3\%$, but does show occasional excursions of $\approx 1.5\%$. A possible explanation of these relative gain drifts are temperature gradients inside the instrument, which are changing with time. Using a similar cell a controlled thermal cycle was performed. The temperature coefficient of the energy gain was found to be $1.4\%/^{\circ}\text{C}$. The observed relative gain drifts therefore correspond to temperature gradients of $\approx 0.2^{\circ}\text{C}/46\text{mm}$ up to $\approx 1^{\circ}\text{C}/46\text{mm}$. The larger, longer term drift is possibly also due to PMT ageing. The

Figure 2: Energy-burstlength relation for a driftless GSPC illuminated by 4.77 keV photons. The tail (1) is caused by the penetration of X-ray photons into the detector gas. (2) indicates events with lost primary electrons and escape photons and (3) pile-up events.

PMT housing was kept in air during the experiments and there was no major energy dissipating equipment in the next vicinity of the PMT, but air flow or convection may have heated and cooled the PMT non-uniformly.

2.3 Data Analysis

The penetration effect requires a somewhat detailed consideration during data analysis. Both the raw data E and B spectra deviate from gaussian, showing tails towards lower channels. Removal of the tails is possible by event selection, removing those events which penetrated deeper into the detector. Figure 2 shows a sample EB image, a plot of event counts as function of event energy and event burst length. A point-source was measured, located at the center of field of view (FOV) of the instrument, with $E_X = 4.77$ keV, i.e. just below the L_{III} edge of Xenon. Only events near the FOV were selected. Marked in the figure are: events penetrating deep into the gas cell (1), causing a strong tail towards lower energies, events with lost primary electrons and escape events (2), and pile-up double events (3).

By selecting those events, which are near the peak of the B -spectrum, B_{peak} , say within $\pm 1\sigma$, the E -spectrum becomes almost gaussian. Vice-versa, selecting events near E_{peak} results in an almost gaussian B -distribution. B_{peak} is still dependent on the X-ray energy, even if the above selection steps are repeated iteratively a few times, reflecting the energy dependence of the X-ray absorption cross-section of Xenon.

Since the detector electronics is calibrated such, that the B -determination is not E -dependent, a constant B -selection window may be applied for all X-ray energies to select only events absorbed near the entrance window of the detector.

Figure 3: The measured non-linearity of the detector gain around the Xenon L-edges. The sizes of the discontinuities are indicated for each sub-shell.

To select events absorbed near the entrance window of the detector, first the largest B_{peak} was determined from each set of measurements (measurements at one beamline). Then the fixed B-selection window was defined to be: $B_{peak,max} < B < B_{peak,max} + 1\sigma_{B_{peak,max}}$.

3 RESULTS

3.1 Energy Gain Discontinuities

Thermal and other drifts were removed as far as possible by normalization using the built-in calibration source data. Position and veto signals were used to reduce the background.

As expected,⁸⁻¹¹ the largest discontinuities in the measured energy range are around the Xenon L-edge. In figure 3 all three L-subshells are covered, and the discontinuities at the edges are given. Between the edges linear fits were made to the data points. The statistical error bars are too small to be seen, but are estimated to be of the order of $\pm 0.025\%$. Due to a slightly contamination of the detector gas at the time of the measurements, the absolute values of the jumps need not be fully representative for pure Xenon.

In figure 4 the Xenon M-edge discontinuities are shown. Only the $M_{IV/V}$ discontinuity is significant, while the others lay within the measurement uncertainty. The $M_{IV/V}$ discontinuity is the largest one measured here, if taken relatively (28eV at 676/689eV, i.e. $\approx 4\%$).

For the Xenon N-edges, shown in figure 5, no measurable discontinuities were found.

Figure 4: The measured non-linearity of the detector gain around the Xenon M-edges. The sizes of the discontinuities are indicated for each sub-shell.

Figure 5: No jump of the detector gain was measured around the Xenon N-edges (within error).

Figure 6: The measured discontinuities in energy resolution around the Xenon L-edges. A significant jump is seen only at the L_{III} edge.

3.2 Energy Resolution Discontinuities

Due to the changing mean ionization energy w and the fano factor F of Xenon¹² at the absorption edges not only the energy gain, but also the charge generation statistics and therefore the energy resolution changes. Again the measured data was processed for each energy as described above and then plotted against the nominal X-ray energy of the source.

Figure 6 shows the energy resolution, given as FWHM of the energy spectrum line, expressed in % of the line position or energy, in the L-edge region. A very clear discontinuity at the L_{III} edge is detected, but (within the errors) no jumps at L_I and L_{II} . Note that gas was not very clean in the detector during the measurements, therefore the absolute value of the energy resolution is worse than expected for pure Xenon and that achieved in other GSPC measurements.

For the M-edge region the situation is similar, as shown in figure 7. The energy resolution discontinuity at the $M_{IV/V}$ edge is comparable to that at the L_{III} edge, if the relative jump height is considered.

At the N-edges no discontinuities were found with the achieved measurement accuracy, as shown in figure 8.

3.3 Escape Lines

To evaluate the effect of the escape of fluorescent photons created by incident X-ray photons with energies around the Xenon L-edges, the intensity of the escape lines was plotted as function of distance to the mother peak, i.e. the measured source energy peak. Four energy intervals were defined:

Figure 7: The measured discontinuities in energy resolution around the Xenon M-edges. A significant jump is seen at the $M_{IV/V}$ edges.

Figure 8: The measured discontinuities in energy resolution around the Xenon N-edges. No significant jump is measured (within the errors).

Figure 9: The measured escape lines around the Xenon L-edges. The intensity is plotted against the distance from the mother peak for four X-ray energy intervals. Vertical lines are plotted at the characteristic X-ray line energies, corrected for the measured detector gain discontinuity at the Xenon-L edges (85eV, 117eV and 129eV for the energy ranges $L_{III} < E_x < L_{II}$, $L_{II} < E_x < L_I$ and $L_I < E_x$, respectively).

1. $E_x < L_{III}$ (no escape line)
2. $L_{III} < E_x < L_{II}$ ($L_{III} - M_V$ and $L_{III} - N_V$ escape)
3. $L_{II} < E_x < L_I$ ($L_{II} - M_{IV}$ and $L_{II} - N_{IV}$ escape)
4. $L_I < E_x$ ($L_I - M_{III}$ and $L_I - N_{III}$ escape)

In each energy interval several measurements at different X-ray energies were taken and overlayed to improve statistics. The spectra were then shifted such, that the mother peaks coincided. The L-escape lines measured for the four intervals were then plotted as function of distance to the mother peak in a single plot, producing figure 9. Note that the data for the individual intervals was normalized such, that the mother peaks have the same intensity. Therefore the intensities plotted in figure 9 represent the escape probability convoluted with the detector resolution.

Vertical lines are plotted at the characteristic X-ray line energies, corrected for the measured detector gain discontinuity at the Xenon-L edges, as measured above, see figure 3. For the energy ranges $L_{III} < E_x < L_{II}$, $L_{II} < E_x < L_I$ and $L_I < E_x$, the jump heights 85eV, 117eV and 129eV, respectively, were subtracted from the nominal characteristic X-ray line energies.

Figure 10: The measured response of a thin polyimide window as a function of XUV wavelength (diamonds). The theoretical response of a Fano limited Xenon GSPC to photons from Ne, O, C, and Be K- α lines is also shown (solid line), normalized to the same maximum intensity.

4 GSPCs AS SPECTROMETERS

The measured discontinuities in energy gain and resolution at the absorption edges of the detection gas are important to be considered when using GSPCs as spectrometers. Further important characteristics are:

- large dynamic range (over 2 decades)
- operation at room temperature (no cooling)
- medium resolution (see figure 10).
- good background reduction possibilities
- reasonable position resolution

By using multilayer entrance windows very low X-ray energies can be detected, as shown in figure 10. The response of a Fano limited GSPC equipped with a $0.25\mu\text{m}$ thin polyimide based multilayer entrance window¹³ is shown, for the characteristic X-ray emission lines of Neon, Oxygen, Carbon and Beryllium. The line intensities are normalized, to show the energy resolving capability of such instruments. GSPCs can come very close to this Fano limited resolution.

5 ACKNOWLEDGEMENTS

We would like to thank F. Scholze, G. Ulm, D. Fuchs and T. Lederer of the Physikalisch-Technische Bundesanstalt for support during the measurements at Bessy.

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