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ABSTRACT: We report on a novel two-dimensional position sensitive Si(Li) detector dedicated to Compton polarimetry of x-ray radiation arising from highly-charged ions. The performance of the detector system was evaluated in ion-atom collision experiments at the ESR storage ringe at GSI, Darmstadt. Based on the data obtained, the polarimeter efficiency is estimated in this work.

KEYWORDS: Solid state detectors; X-ray detectors; Gamma detectors (scintillators, CZT, HPG, HgI etc)

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Contents

1 Introduction

The investigation of x-ray radiation arising from highly-charged ions has proven to be an unique tool for probing the dynamical behavior as well as the structure of atomic systems. This is in particular true for few-electron, high-Z systems which provide detailed information about the interplay of the effects of relativity and quantum electrodynamics [1]. However, due to the lack of efficient polarimeter systems for the energy range above a few 10 keV previous studies were mainly restricted to measurements of the spectral and angular distribution of the emitted radiation.

In recent years novel type x-ray detectors have become available providing good efficiency, energy and time resolution together with submillimeter position resolution and a large detection area. Beside applications in classical x-ray spectroscopy and imaging, such detector systems can be used as highly efficient Compton polarimeters. Thus, linear polarization studies of hard x-rays up to several hundred keV have become feasible [2, 3].

In this work we report on a novel two-dimensional position sensitive Si(Li) detector dedicated to Compton polarimetry in the energy region starting from roughly 70 to a few hundred keV. The detector was recently applied for a series of polarization measurements at the internal gas target of the ESR storage ring at GSI, Darmstadt [4–6].

2 Two-dimensional position sensitive Si(Li) detector

The detector was developed within the SPARC collaboration [7] and consists of a single Li-drifted planar silicon crystal with a total area of $80 \times 80\,\mathrm{mm}^2$ and a thickness of 7 mm. Each side of the crystal is segmented into 32 strips with a pitch of 2 mm giving an active area of $64 \times 64\,\mathrm{mm}^2$ (see figure 1). The segments are isolated against each other by 50 μm wide grooves. The active area is surrounded by a guard ring of approximately 7 mm width to isolate and drain leakage currents. As the strips on the front side and the back side are oriented perpendicular to each other the combination of both sides results in a pseudo-pixel structure of 1024 pixels.

Each individual strip is read out independently with a charge sensitive preamplifier providing a time resolution of about 100 ns and a typical energy resolution of 2.5 keV FWHM at 100 keV photon energy. Moreover, as the positive charge carriers are collected on the front side and the

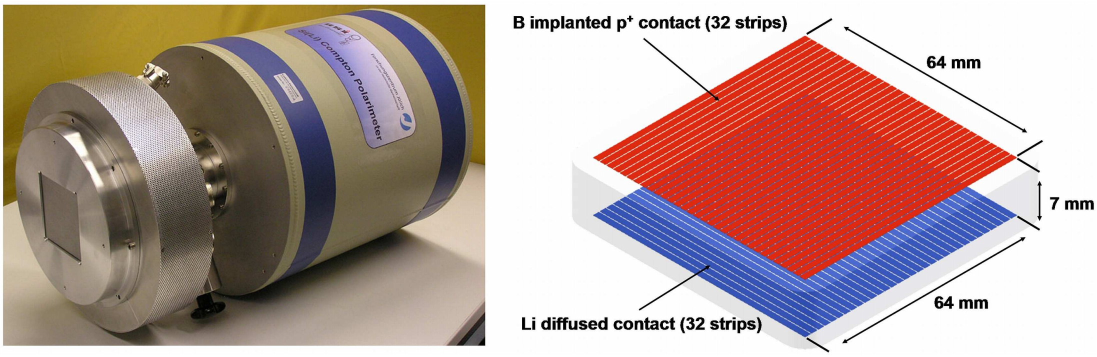

Figure 1. Left: Photograph of the Si(Li) Compton polarimeter developed within the SPARC Collarbotation. The crystal and the preamplifiers are located in the head of the detector which is connected to a LN2 dewar. Right: Sketch of the detector crystal with the front side and the back side each being segmented into 32 strips giving a structure of 1024 pseudo-pixels.

negative charge carriers on the backside, the positional information of ionizing events inside the detector crystal are obtained in two dimensions. By matching the energy and positional information on both sides even multiple hits can be identified unambiguously.

The number of strips on each side detecting an energy signal above the noise level is determined by the number of inelastic interactions, mainly photoionization and Compton scattering, an incoming photon undergoes inside the detector. If exactly one strip on each side was affected by an event, the underlying process can be attributed mainly to photoionization. Compton scattering with the scattered photon having escaped from the detector is also possible, but the typical recoil electron energies affect only the low energy part of the spectrum. If two strips on each side show a signal this is most probably due to Compton scattering where the recoil electron is stopped in the close vicinity of the interaction point and the scattered photon is detected at a different pixel of the detector. Higher hit numbers are related to multiple scattering and absorption processes inside the detector.

Thus, the simultaneous detection of multiple events is a key feature when applying the detector as a Compton polarimeter where the scattering process and the absorption of the scattered photon are detected in the same crystal. This is in contrast to standard Compton polarimeter setups consisting of a dedicated scatterer and one or more seperate detectors as absorbers for the scattered photons.

3 Performance as a Compton polarimeter

The performance of the Si(Li) detector was evaluated in a series of ion-atom collision experiments at the internal gas target of the ESR storage ring at GSI, Darmstadt. The data presented in this work was obtained by colliding 96.6 MeV/u U^{92+} ions and 150 MeV/u Xe^{54+} ions, respectively, with a H_2 target where the detector was located at 90° with respect to the ion beam axis. A coincidence technique between the x-ray detector and particle counters for detecting the down-charged ions was applied in order to discriminate the photons being related to electron capture events. The energy

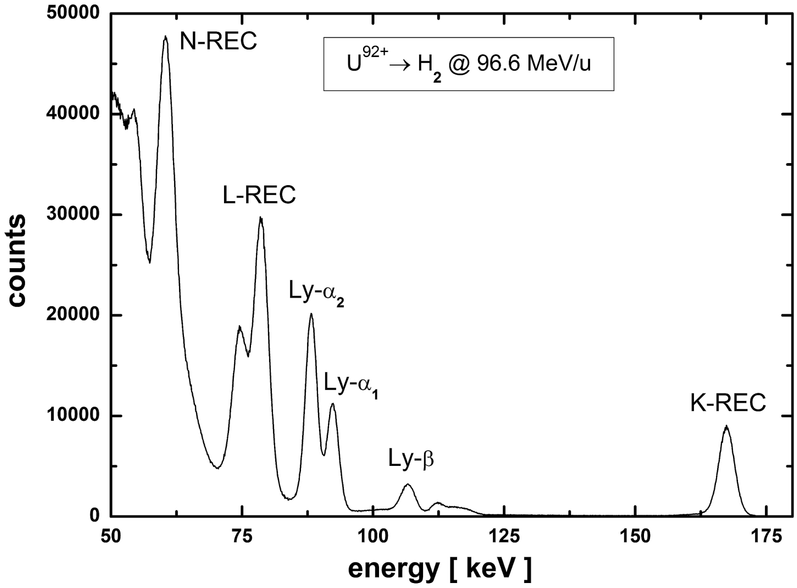

Figure 2. Energy spectrum of x-rays arising in the collision of U^{92+} with H_2, recorded at a beam energy of 96.6 MeV/u. To exclude contributions by Compton scattering and double hits inside the detector, only events with exactly one inelastic interaction were taken into account.

spectrum of all coincident events where only one inelastic interaction was detected is displayed in figure 2. This restriction results in the spectrum being dominated by photoionization events while scattered photons are not displayed. All peaks in the spectrum can be attributed either to the radiative electron capture (REC) process or to subsequent characteristic transitions in U^{91+}, namely the Lyman transitions into the ground state.

Each line with an energy above roughly 70 keV can be subject to polarization measurements by means of Compton polarimetry which is based on the anisotropy of the Compton scattered photon emission. According to the Klein-Nishina equation [8, 9], which depends on the incident photon energy E, the polar scattering angle ϑ and the azimuthal scattering angle φ, the scattered photon is preferably emitted perpendicular to the incident photon electric field vector, whereas emission in the parallel direction is less probable. Thus, the degree of linear polarization as well as the orientation of the polarization plane of the incident photons can be obtained from the distribution of the Compton scattered photons with respect to the azimuthal scattering angle, see [10]. Note that for the photon energies discussed here the Klein-Nishina equation yields the maximum anisotropy and, consequently, the maximum polarization sensitivity at polar scattering angles $\vartheta \approx 90^\circ$. Moreover, for incident photon energies below half of the electron rest mass the energy splitting between the recoil electron and the scattered photon is an unambiguous function of the polar scattering angle ϑ. Thus, in energy dispersive detector systems the so-called kinematic event selection can be used to take into account only the highly polarization sensitive Compton events with scattering angles ϑ near 90°, see [3, 11] for details.

In order to obtain the scatter distribution the Compton events detected inside the crystal must be reconstructed using the energy and position information of the detector. The present analysis

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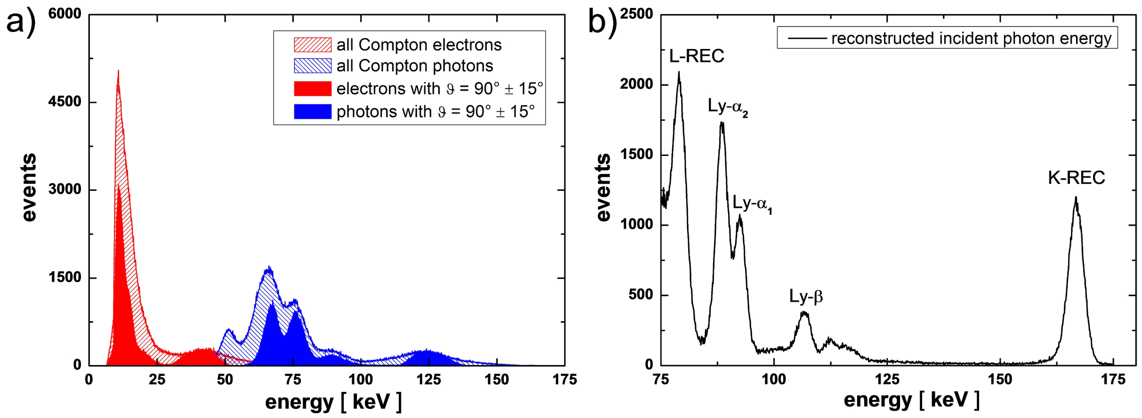

Figure 3. Reconstruction of the Compton events inside the detector: a) By applying several conditions the true Compton events, consisting of the recoil electron and the scattered photon, were identified. A further selection with respect to the polar scattering angle ϑ takes into account only the Compton events with the maximum polarization sensitivity. b) Energy spectrum of the reconstructed Compton events, given by the sum energy of the recoil electron and the scattered photon.

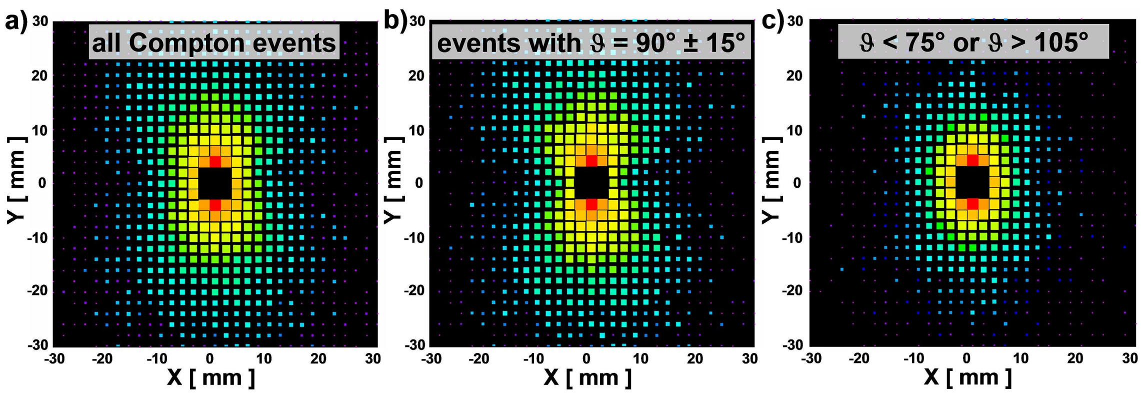

Figure 4. Position distribution of the Compton scattered photons with respect to the pixel where the scattering events took place (0,0). The incident radiation is arising from the K-REC into Xe^{54+} and exhibits a linear polarization of nearly 100 % [6]. a) Compton events with all polar scattering angles ϑ are displayed. b) Taking into account only the Compton events with $\vartheta = 90^\circ \pm 15^\circ$ leads to a higher contrast and thus an improved polarization sensitivity. c) At low and high scattering angles the azimuthal scatter distribution is more isotropic.

algorithm works on an event-by-event basis where all events with exactly two inelastic interactions inside the detector are considered as potential Compton events and several conditions are applied to discriminate the true events from random coincidences. Some results of this procedure are displayed in figure 3 and 4.

Figure 3 a) shows the energy distribution of scattered photons and recoil electrons of the identified Compton events. Note, that energy signals below 7 keV are not taken into account because of electronic noise. Therefore, scattering events with recoil electron energies below that threshold can

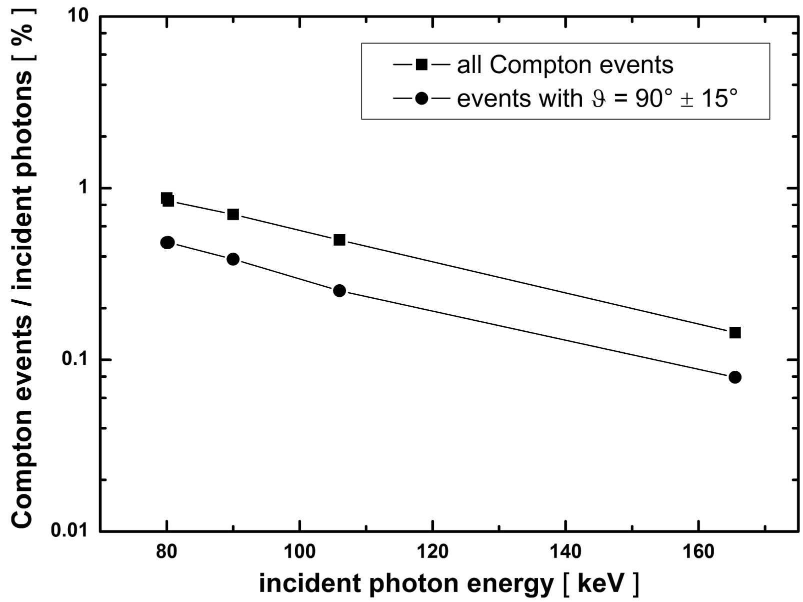

Figure 5. Experimental data for the polarimeter efficiency of the Si(Li) detector. About 50 % of the reconstructed Compton events show polar scattering angles ϑ near 90° providing the maximum polarization sensitivity.

not be reconstructed. Figure 3 b) shows the incident photon energy of the reconstructed Compton events which is given by the sum energy of the recoil electron and the scattered photon. The good agreement between this spectrum and the one in figure 2 indicates the proper functioning of the reconstruction routine.

The polarization properties of the different radiation types are currently subject of detailed analysis. Preliminary results already show a high polarization sensitivity of the Si(Li) detector due to its high granularity. A further improvement is achieved when using the kinematic event selection to restrict the scatter distribution to events with scattering angles ϑ near 90°. The latter is demonstrated in figure 4 where the scatter distribution of highly polarized radiation from REC into the K-shell (K-REC) of Xe^{54+} is shown with and without restrictions on the angle ϑ. Note, that at least one pixel distance between the recoil electron and the scattered photon position is required as Compton scattering in neighboring pixels can not be distinguished from charge splitting.

For the planning of future experiments the efficiency of the polarimeter system is a crucial point. The percentage of reconstructed Compton events with respect to the total number of incident photons can be determined by normalizing the reconstructed Compton peak intensity in figure 3 b) to the corresponding peak intensity in figure 2. The latter is dominated by photoionization where the absolut cross sections are tabulated and, therefore, the absolute detection efficiency can be estimated easily. The polarimeter efficiency yielded by this procedure is displayed in figure 5. As seen, in the low energy region up to 100 keV about 0.5 % of the incident photons can be used for polarization measurements. Taking into account the large active area of the detector, the efficiency of the Si(Li) polarimeter is well suited for polarization studies of x-ray radiation from highly-charged, high-Z ions at electron beam ion traps (EBITs) and storage ring facilities.

4 Summary

Owing to recent progress in the development of highly segmented solid state detectors novel-type energy, time and position sensitive x-ray detectors have become available. First experiments demonstrate that these detector systems, applied as Compton polarimeters, allow efficient and precise polarization studies of x-rays in the energy region from roughly 70 to a few hundred keV. In this work a two-dimensional position sensitive Si(Li) detector dedicated to polarization studies of x-ray radiation arising from highly-charged ions was presented and the polarimeter efficiency was estimated using data obtained in ion-atom collision experiments at the ESR storage ring. The polarization properties of the different radiation types are currently subject of detailed analysis.

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