Journal of Physics: Conference Series

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To cite this article: G Weber *et al* 2015 *J. Phys.: Conf. Ser.* **583** 012041

Journal of Physics: Conference Series **583** (2015) 012041 doi:10.1088/1742-6596/583/1/012041

Compton polarimetry using double-sided segmented x-ray detectors

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Abstract. Hard x-ray polarimetry of radiation emitted in collisions of heavy ions, electrons or photons with matter provides detailed information on the collision dynamics as well as of the atomic structure in the presence of extreme field strengths. Moreover, it also opens a route for polarization diagnosis of spin-polarized ion and electron beams which, for example, might be useful in future parity non-conservation studies. Owing to recent progress in the development of highly segmented solid-state detectors, a novel type of polarimeter for the hard x-ray regime has become available. Applied as Compton polarimeters, two-dimensional position-sensitive x-ray detectors now allow for precise and efficient measurements of x-ray linear polarization properties. In this report recent polarimetry studies using such detector systems are reviewed.

1. Introduction

The study of particle and photon polarization phenomena occurring in the interaction of fast ion and electron beams with matter is of particular relevance for the understanding of cosmic and laboratory plasmas where high temperatures, high atomic charge-states and high field strengths prevail. In addition, polarization-sensitive studies of radiative processes in highly-charged, heavy ions may provide detailed insights in both relativistic particle dynamics as well as QED effects and other atomic structure properties at extreme electromagnetic field strengths [1]. Moreover, x-ray polarimetry was proposed as a tool for diagnosis of spin-polarized ion beams [2]. Owing to the recent progress in x-ray detector technology, accurate measurements of the linear polarization for hard x-ray photons as well as the determination of the polarization orientation have become possible. In this report we briefly present the technique of Compton polarimetry and we review a series of recent polarimetry studies that were mainly performed by the atomic physics division of GSI, Darmstadt.

2. Double-sided segmented x-ray detectors applied as Compton polarimeters

While in the soft x-ray regime up to roughly 10 keV linear polarization studies, addressing for example atomic transitions (see, e.g., [3, 4] and references therein) or betatron radiation [5], are routinely performed using crystal optics, hard x-ray polarization measurements were often hampered by the lack of adequate polarization analyzers. Compton polarimetry is the standard technique for hard x-rays, which is based on the fact that the scattered photon is preferably emitted perpendicularly 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 axis of the incident photons can be obtained from the azimuthal emission pattern of the Compton scattered photons. A detailed discussion of this technique can be found in [6].

Though several hard x-ray polarimeter schemes based on the Compton effect were developed during the last decades, in particular in the field of x-ray astronomy [6, 7], most of those instruments are designed for very specific applications and experimental setups, thus being not well-suited (or not affordable) as general-purpose polarimeters for typical x-ray sources in the laboratory. This situation changed with the recent development of highly-segmented planar x-ray detectors, which provide good detection efficiency, energy and time resolution together with millimeter to submillimeter two-dimensional position resolution and a large detection area [8]. When an incident photon undergoes Compton scattering inside such a detector, the scattered photon may be detected at a different position within the same detector crystal. Thus each part of the detector crystal serves both as a scatterer and as an absorber for the scattered x-rays, resulting in a high efficiency due to a big active area and a good coverage of the azimuthal scattering angle. Combining energy, position and time information of each interaction then allows a reconstruction of the Compton scattering events. As a consequence, such detectors are well-suited for the application as Compton polarimeters, enabling precise and efficient linear polarization studies [9, 10, 11]. Depending on the crystal material and the thickness, which can typically reach up to about 2 cm, polarimeters for x-ray energies ranging from a few dozen of keV up to the MeV regime can be constructed.

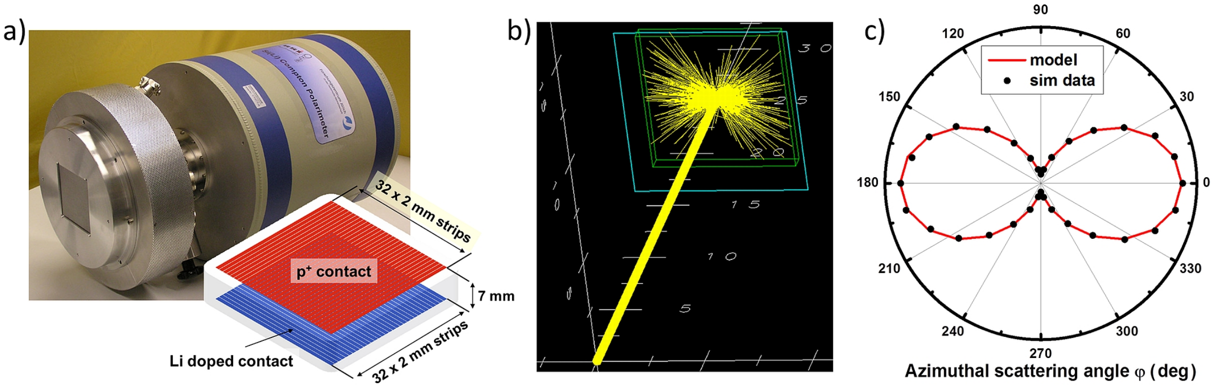

Figure 1. a) Photograph of the 2D Si(Li) polarimeter and a sketch of the crystal segmentation. b) Monte Carlo simulation of 100 % linearly polarized 100 keV photons undergoing Compton scattering inside the detector crystal. c) Azimuthal scattering distribution of the reconstructed Compton events inside the detector. The red line shows an adjustment of the theoretical scattering distribution with the degree of linear polarization as a free parameter.

In recent years several position-sensitive x-ray detectors were developed within a collaboration of the atomic physics division of GSI, the detector laboratory of FZ Jülich and the company Semikon, see [12] for details. The main working horse in terms of polarization measurements is a Si(Li) detector which consists of a 7 mm thick planar crystal with an active area of 64 mm × 64 mm whose electrodes are segmented into 32 horizontal strips on the front and 32 vertical strips on the back side, resulting in a structure of 1024 quadratic pseudo-pixels. Each segment of the detector crystal is connected to a charge sensitive preamplifier acting as an individual detector which provides time ($\Delta t = 50$ to 100 ns) and energy (FWHM = 2 keV at 60 keV) information for the local energy deposition [11]. This detector system was build as a dedicated Compton polarimeter for the SPARC collaboration [13] and is presented in figure 1a, while its measurement principle of x-ray linear polarization is illustrated in figure 1b and 1c. In figure 1b the Compton scattering of a 100 % linearly polarized beam of 100 keV photons is simulated inside the detector crystal using the EGS5 Monte Carlo package [14] while in figure 1c the azimuthal angular distribution of these scattered photons is shown together with an adjustment of the theoretical scattering distribution to the simulated data with the degree of incident photon linear polarization as a free parameter.

In the following we present three significant experimental results in terms of hard x-ray polarimetry in atomic physics that were recently obtained by the GSI atomic physics division.

3. Polarization studies of radiative electron capture

The capture of electrons into bound states of ions is of significant importance for both experiment and theory in the fields of atomic and plasma physics as well as for astrophysics. The capture process is called radiative if it is accompanied by the emission of a photon that carries away the initial electron's kinetic energy and the binding energy of the final state it is captured into. If the initial electron is considered to be free, the capture process is referred to as radiative recombination (RR) [15], being the time-reversal of the photoelectric effect [16], whereas the capture of a bound electron is called radiative electron capture (REC) [17, 18, 19].

The REC process is a prominent charge-changing process for fast, highly-charged ions interacting with dedicated target materials or with residual gas being present in the beamlines of accelerators and storage rings [20]. Moreover, when low- to medium-Z targets and heavy, highly-charged projectile ions are considered, the to-be-captured electrons can be treated as free particles having a momentum distribution equal to the one of the bound target states. This so-called impulse approximation reduces the REC description to the RR cross section convoluted with the incident electron momentum distribution. Consequently, both the REC and the RR process as well as the photoeffect can be treated within the same theoretical framework. Moreover, when compared to the photoeffect, the RR/REC process offers several experimental advantages, such as a more uniform emission pattern due to the partial cancelation of retardation and Lorentz transformation for a moving emitter system and the fact that x-rays, in contrast to electrons, can typically leave the target zone unaffected by secondary-collision effects. These facts motivated various REC measurements aiming for a deeper insight into the photoeffect while exploiting the advantageous experimental conditions present for the study of electron capture into fast, highly charged ions, see [19] and references therein.

A first study of the linear polarization of REC photons was published in 2006 [21] where a 4×4 pixel Ge(i) detector was used for Compton polarimetry of x-rays emitted in collisions of bare uranium ions with a N_2 target at the experimental storage ring (ESR) of GSI. The experimental findings are presented together with theory values in figure 2a. Having only 16 pixels, the relatively low granularity of the detector resulted in a poor angular resolution of the Compton scattering distribution, which limited the experimental accuracy to an uncertainty between ± 5 % and ± 10 % with respect to the degree of linear polarization. The much higher granularity of the newly developed Si(Li) polarimeter (see figure 2b) enables more precise studies and this instrument was already applied in a series of test measurements also addressing the REC radiation [22, 23]. Data analysis is still in progress and we expect an experimental uncertainty for these new polarization studies in the order of ± 1 % of the degree of linear polarization. With regard to future experiments at the new FAIR facility it is worth noting that while the existing ESR is limited to typical ion energies not higher than 400 MeV/u for beams of heavy ions,

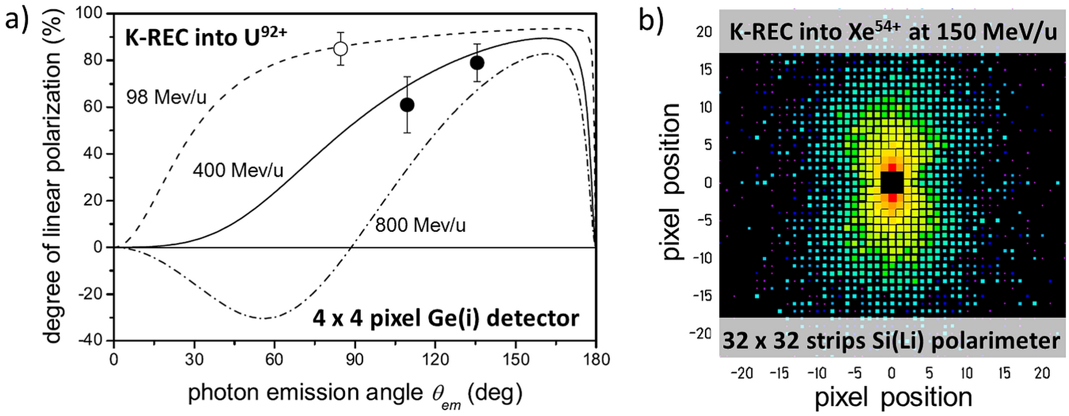

Figure 2. a) Degree of linear polarization of the radiative electron capture (REC) into the K-shell of bare uranium projectiles measured with a 4×4 pixel Ge(i) detector applied as a Compton polarimeter, taken from [21]. b) Position distribution of Compton scattered K-REC photons inside the Si(Li) polarimeter for the capture into bare xenon ions. Data analysis with respect to the degree of linear polarization is ongoing. The much higher granularity of the new detector is expected to enable significantly more precise measurements compared to the 16 pixel detector.

the planned high-energy storage ring (HESR) will reach up to approximately 5 GeV/u for bare uranium [24, 25]. With the extended energy range it will become possible to probe the cross-over effect in the degree of REC photon linear polarization which is predicted to occur at collision energies above 600 MeV/u and for forward emission angles, see the theory data for 800 MeV/u in figure 2a. In terms of the photoeffect this feature indicates that the initially bound electron is no longer preferentially ejected in the direction of the incident photon electric field vector, instead emission along the magnetic field vector is dominant.

4. Determination of atomic multipole-mixing using combined angular distribution and linear polarization measurements

Hydrogen-like ions are the simplest and most fundamental atomic systems whose study along the isoelectronic sequence provides detailed information about the effects of relativity and quantum-electrodynamics on the atomic structure. Since these effects are largest for the 1s ground state, experimental studies of $L \rightarrow K$ transitions are of paramount importance for such investigations. This is in particular true for the domain of high-Z ions, where precision measurements of the Lyman-α_1 (Ly-α_1: $2p_{3/2} \rightarrow 1s_{1/2}$) transition characteristics are a powerful technique to test the theory of strong-field QED [26] and atomic structure [27, 28], as well as to probe relativistic effects on the population processes of the excited state [29, 30]. The latter studies are based on the fact that both the linear polarization and the angular distribution are sensitive to a non-statistical population, i.e. alignment, of the excited states (see figure 3a), which provides subtle details on the dynamics of the respective population processes. However, due to the lack of efficient polarimeter systems for the hard x-ray regime, studies in the high-Z domain were restricted to measurements of the spectral and angular distribution of the emitted radiation.

By applying both the Si(Li) detector described above and a highly segmented two-dimensional position-sensitive Ge(i) detector as Compton polarimeters we recently performed a study of the linear polarization of the Ly-α_1 radiation following radiative electron capture into initially bare uranium ions in collisions with H_2 molecules at the gas target of the ESR. This was the first polarization measurement of a characteristic K-shell transition in a hydrogen-like high-Z system, namely U^{91+}, whose main results were reported in [31]. In accordance with theory [32],

Journal of Physics: Conference Series **583** (2015) 012041 doi:10.1088/1742-6596/583/1/012041

a significant depolarization due to the interference between the dominant E1 and the M2 decay branches of the Ly-α_1 radiation was observed, see figure 3c. It is interesting to note that while the linear polarization is decreased by this so-called multipole mixing, the angular distribution is becoming more anisotropic when compared to the pure E1 case.

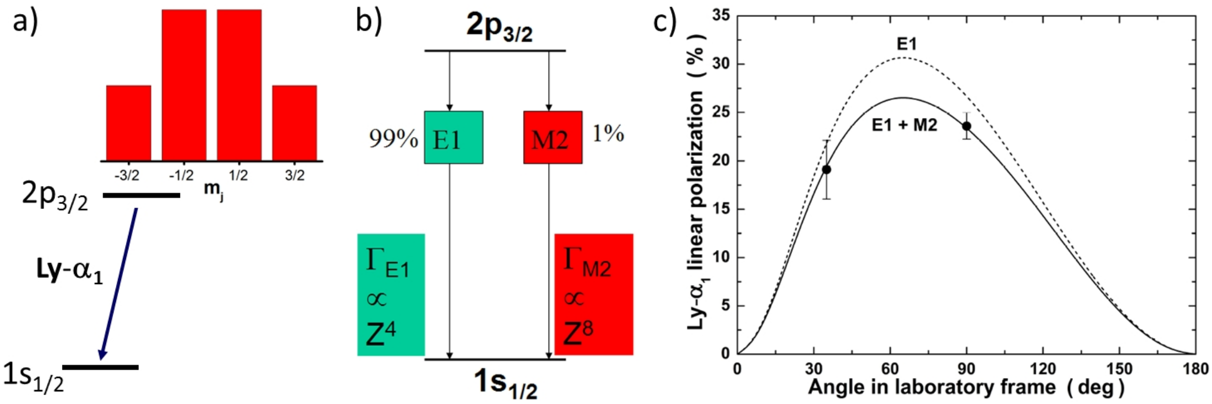

Figure 3. a) Illustration of the non-statistical population of the $2p_{3/2}$ state in a hydrogen-like system. b) Schematic representation of the interference between the dominant E1 and the M2 decay branch. Due to its strong scaling with the atomic number Z, for the heaviest nuclei the M2 branch contributes with about 1 % to the total decay rate. c) Confirmation of the predicted depolarization of the Ly-α_1 radiation as a result of E1-M2 interference in U^{91+}, taken from [31].

Besides the confirmation of the predicted depolarization, it was found that the combination of linear polarization data with a measurement of the Ly-α_1 angular distribution allows to decouple the effects of the collision-induced alignment of the excited $2p_{3/2}$ state and the E1-M2 interference on the transition properties. Thus, a model-independent and precise determination of both the alignment, which is sensitive to the dynamics of the population process, and the ratio of the E1 and M2 transition amplitudes, and consequently the transition rates, is feasible (see [31] for details). Here, in contrast to previous studies based only on the observation of the angular distribution [28], no theoretical assumption about the population mechanism for the excited state or the E1-M2 transition ratio is required. Moreover, with a $\Gamma_{\rm M2}/\Gamma_{\rm E1}$ transition rate ratio of 0.00689 with a relative uncertainty of ±2.8 % a remarkable precision in the determination of the M2 contribution was achieved. This is due to the fact that the experimental observables are sensitive to the ratio of amplitudes rather than transition rates as it is the case for lifetime studies of excited states. This achievement recently motivated a detailed study of the effects of QED on the Ly-α_1 radiation in high-Z systems where they are expected to be roughly of the same order as the experimental uncertainty in the present measurement [33].

5. Polarization transfer in bremsstrahlung emission by spin-polarized electrons

Electron-atom bremsstrahlung, sometimes also referred to as ordinary bremsstrahlung, is one of the basic photon-matter interaction processes. Recent theoretical and experimental studies were focussed on the influence of the incident electron spin-polarization on the bremsstrahlung polarization properties [34, 35, 36]. Due to the spin-orbit interaction a non-zero electron polarization breaks the rotational symmetry of the bremsstrahlung emission with respect to the collision axis, which is defined by the incident electron direction. In terms of bremsstrahlung linear polarization, this gives rise to a rotation of the photon polarization vector with respect to the reaction plane and to an enhanced degree of linear polarization in comparison to the

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unpolarized electron case. While a slight azimuthal anisotropy of the bremsstrahlung emission pattern as a result of incident electron spin-polarization was already observed about 20 years ago [37], the effect on the bremsstrahlung polarization, which was predicted to be more pronounced, could not be studied due the lack of adequate hard x-ray polarimeters.

Recently, two experiments were performed at the polarized electron source SPIN of the TU Darmstadt to study the linear polarization of bremsstrahlung arising from the collision of polarized 100 keV electrons with thin gold targets [38, 39]. The latter one of these measurements was performed by members of the atomic physics division of GSI using the Si(Li) polarimeter described above. The detector was located under 130° with respect to the electron beam axis and recorded the degree and the orientation of bremsstrahlung photon polarization between the short-wavelength limit, i.e. the incident electron kinetic energy, and roughly 70 keV, which is the lower threshold of this polarimeter. In figure 4 the influence of the transverse electron spin-polarization on the azimuthal scattering distribution of the Compton scattered photons is presented. In accordance with theory, a significant rotation of the bremsstrahlung polarization axis due the spin-polarization of the incident electron beam is observed. Also a slight increase of the degree of bremsstrahlung polarization was found.

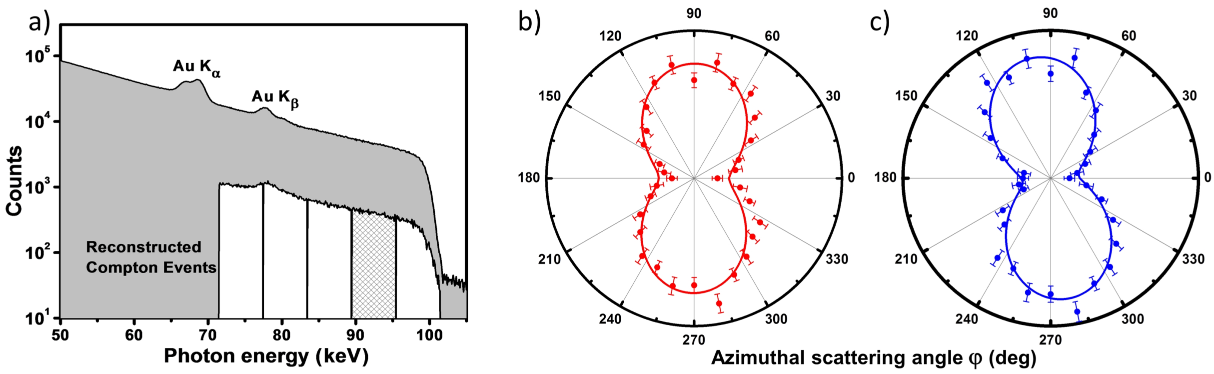

Figure 4. a) Bremsstrahlung spectral distribution arising from 100 keV electrons impinging on a thin gold foil. The data were recorded using a Si(Li) polarimeter located under an observation angle of 130°. For about 1 % of the detected photons a Compton scattering event inside the detector can be reconstructed. For an energy-dependent analysis of the linear polarization features, these events were aggregated into 6 keV broad bins. b) The azimuthal Compton scattering distribution of bremsstrahlung photons with energies of 92.5 ± 3 keV stemming from unpolarized electrons. c) The same distribution for 75 % transversally spin-polarized electrons. A rotation of the polarization axis is visible and the distribution is slightly more anisotropic, indicating a higher degree of linear polarization. All figures were taken from [39].

Such a simultaneous measurement of the degree and the direction of the linear photon polarization as a function of photon energy and electron polarization grants complete insight into the bremsstrahlung polarization correlations, and hence into details of relativistic electron-photon interactions. Beyond the purely scientific interest, there is also a practical application, since similar polarization transfer effects were predicted for the radiative recombination process and are currently discussed as a diagnostic method for spin-polarized heavy ion beams [40]. Using polarized-electron bremsstrahlung as a test case, the present measurements proved the applicability of this technique. Moreover, it was found that bremsstrahlung polarization is surprisingly sensitive to the target thickness, leading to a significant depolarization even for target foils with a thickness of just a few tens of nm [41, 42].

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6. Summary

Owing to recent progress in the development of highly segmented solid-state detectors, novel two-dimensional position-sensitive x-ray detectors with time and energy resolution have become available. When applied as Compton polarimeters, such detector systems enable efficient and precise linear polarization studies of photons in the hard x-ray regime. As a consequence, in recent years a variety of important radiative processes were revisited with respect to the linear polarization of the emitted x-rays, enabling deeper insight into basic photon-matter interactions and the atomic structure of high-Z systems. Moreover, it was demonstrated that x-ray polarimetry can serve as a valuable tool for the control of spin-polarized beams of charged particles.

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