Available online at www.sciencedirect.com

Nuclear Instruments and Methods in Physics Research B 205 (2003) 210–214

NIM B Beam Interactions with Materials & Atoms

www.elsevier.com/locate/nimb

Applications of position sensitive germanium detectors for X-ray spectroscopy of highly charged heavy ions

Th. Stöhlker [a,b,*], D. Banas [a,c], H.F. Beyer [a], A Gumberidze [a,b,d], C. Kozhuharov [a], E. Kanter [e], T. Krings [f], W. Lewoczko [g], X. Ma [h], D. Protic [f], D. Sierpowski [g], U. Spillmann [a,b], S. Tachenov [a,b], A. Warczak [g]

[a] *Gesellschaft für Schwerionenforschung, D-64291 Darmstadt, Germany*
[b] *Institut für Kernphysik, University of Frankfurt, Germany*
[c] *Institute of Physics Swietokrzyska Academy, 25-406 Kielce, Poland*
[d] *Tblisi State University, Tblisi, Georgia*
[e] *Argonne National Laboratory, Argonne, USA*
[f] *Forschungszentrum Jülich, Institut für Kernphysik, 52425 Jülich, Germany*
[g] *Institute of Physics, Jagiellonian University, Cracow, Poland*
[h] *Institute of Modern Physics, Lanzhou, China*

Abstract

The spectroscopy of atomic transitions in the hard X-ray regime above 15 keV utilizing position-sensitive solid state detectors is discussed. Special emphasis is given to the current detector developments for X-ray spectroscopy of heavy ions at the ESR storage ring where applications for precision spectroscopy as well as for polarization studies are of particular interest. For both cases, the advantages and new possibilities which are opened up by position and energy resolving solid state detectors are illustrated by the presentation of first experiments.

PACS: 29.40.Wk; 29.40.Gx; 32.80.Cy; 31.30.Jv; 34.80.Lx

Keywords: Position sensitive detectors; X-ray spectroscopy; Photon polarization; High-*Z* ions; Radiative electron capture

---

1. Introduction

During the last decade, the development of position and energy sensitive solid state detectors has experienced a tremendous progress. This progression is mainly motivated by the demands of nuclear physics experiments for highly efficient γ-ray spectrometers and in particular by the unique advantages of such detection devices which arises for applied research. One also may anticipate that position sensitive germanium detectors (PSG) will play an important role for future X-ray spectroscopy in atomic physics dealing with heavy atomic systems. In the following we will concentrate on the applications of PSG detectors for the X-ray spectroscopy in the field of highly charged heavy ions, such as H-like uranium. The unique properties of such detectors are millimeter to

---

[*] Corresponding author. Fax.: +49-6159-71-3712.
E-mail address: t.stoehlker@gsi.de (Th. Stöhlker).

0168-583X/02/$ - see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0168-583X(03)00557-3

sub-millimeter spatial resolution as well as a good time (e.g. 50 ns at 60 keV) and energy resolution (e.g. 1.6 keV at 60 keV) for the hard X-ray energy regime above 15 keV. As an example, in combination with a focusing crystal spectrometer, a PSG permits the measurement of an energy spectrum wide enough to investigate the whole interesting energy regime simultaneously [1].

Some results of the first test experiments in combination with the new crystal spectrometer [2] will be presented. Along with a new kind of spectrometer this detector may play a key role for a precise test of quantum electrodynamics (QED) in the heaviest one-electron systems. Another important feature of PSG systems is its sensitivity to the photon polarization at energies above 50 keV. By means of such detection devices, the polarization of bound–bound and free-bound transitions in highly charged heavy ions can be measured with high accuracy. First results obtained for bare uranium ions colliding with gaseous matter are discussed.

2. Spectroscopy

The production and cooling of intense beams of fully stripped ions, as introduced by heavy-ion storage rings, constitute an important step for accurate precision spectroscopy of atomic transitions in the realm of high-Z systems. One of the most important goals of these studies is a precise test of QED in the heaviest one-electron systems such as hydrogen-like uranium [3]. Up to now such studies were performed at the storage rings ESR (Darmstadt, Germany) where intense beams of cooled bare uranium ions with well defined velocity and small momentum spread ($\Delta p/p \approx 10^{-5}$) are available for experiments. However, because at the ESR the ions typically move with a high velocity of 30–70% of the speed of light, Doppler shift and Doppler broadening constitute the most serious challenge for accurate spectroscopy. In order to meet the requirements for accurate spectroscopy, the use of segmented germanium detectors appears to be appropriate.

On the one hand the segmentation allows for an event-by-event Doppler correction of the registered X-rays (see e.g. [3]). On the other hand such detectors are essential for the application of high-resolution X-ray spectroscopy methods such as transmission crystal spectroscopy or the absorption edge technique [4,5]. Very recently such a microstrip detector system, developed at the Forschungszentrum Jülich [1], with a position resolution of close to 200 μm has become available and has been tested in combination with the FOCAL spectrometer [2] using an intense radioactive ^{169}Yb source. Even without any strict conditions on the photon energies for the individual strips, the intensity pattern observed with the microstrip detector as function of the position (i.e. strip number) identifies clearly the two X-ray lines of the Kα-doublet from Tm and Yb (Fig. 1) which are separated by approximately 970 and 1030 eV, respectively. This demonstrates that in combination with the FOCAL spectrometer [2], an energy resolution better than 100 eV can be achieved along with high detection efficiency.

3. Polarization studies for hard X-rays

We have to stress the importance of germanium pixel and of two-dimensional strip detectors for the study of the dynamics of heavy ions colliding with electrons or low-density gaseous matter. Such collisions are strongly affected by electron–ion recombination processes, such as radiative electron capture (REC, the time-reversed photoionization process in ion–atom collisions) [6], processes which are of plasma and astrophysical relevance.

Because for high-Z ions and fast collisions, electron–ion recombination in general produces strongly polarized X-rays in the energy regime between 50 and 500 keV [7,8], the polarization sensitivity of two-dimensional germanium detectors via the Compton effect provides an important key to reveal the physics of these processes [9]. Following the Klein–Nishina formula, the differential cross-section for Compton scattering of a photon with initial energy $\hbar\omega$ is given by

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{1}{2} r_0^2 \left(\frac{\hbar\omega'}{\hbar\omega}\right)^2 \left(\frac{\hbar\omega'}{\hbar\omega} + \frac{\hbar\omega}{\hbar\omega'} - 2\sin^2\theta\cos^2\varphi\right), \tag{1}$$

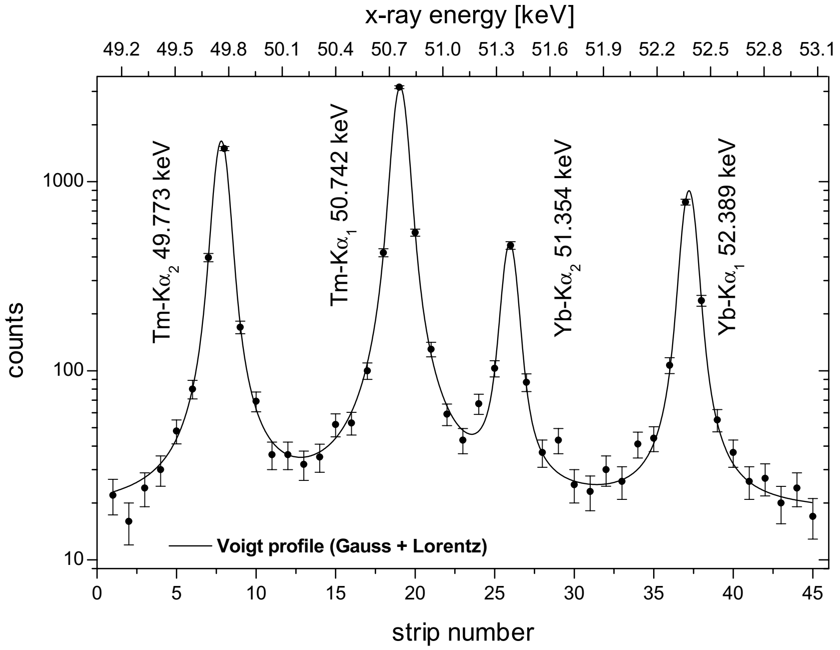

Fig. 1. Result obtained with the germanium microstrip detector mounted at the FOCAL spectrometer. The intensity pattern as a function of the position (energy) shows the two components of the Kα-doublet of Tm and of Yb well resolved [1].

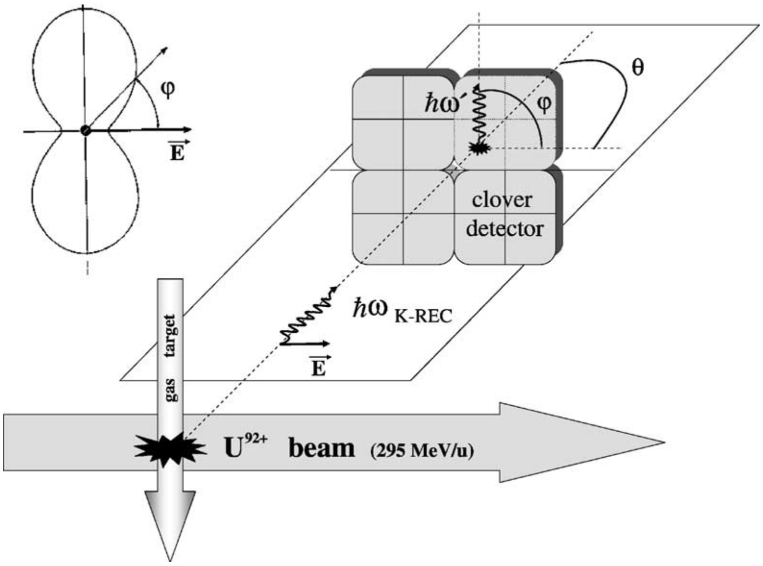

Fig. 2. Experimental arrangement at the ESR jet-target for the polarization measurement of K-REC photons produced in $U^{92+} \rightarrow N_2$ collisions at 295 MeV/u. Following Klein–Nishina formula (see Eq. (1)) the figure illustrates for the Compton process the relation between the initial photon with polarization $\vec{E}$ and the scattered photon.

where $\hbar\omega'$ denotes the energy of the scattered photon, θ the scattering angle between the initial and the scattered photon and φ the angle between the polarization vector of the initial photon and the propagation direction of the scattered one (compare Fig. 2).

For REC occurring in collision of bare uranium ions with low-Z gaseous targets a very first study using a segmented germanium detector has been performed recently at the storage ring ESR. Here a Clover detector [10] has been used, which consists out of four coaxial n-type germanium crystals arranged like a four leaf clover whereby each outer p-type contact of each crystal is segmented longitudinally, splitting each crystal into four quadrants. In the experiment photon polarization was derived by the coincident registration between the segments where Compton scattering occurs and the neighboring one where the Compton scattered photon is detected (for the experimental geometry compare Fig. 2). In addition an energy condition was applied. Note, the energy deposition ΔE (energy of the Compton electron) of the Compton scattering process always fulfills the condition $\Delta E < \hbar\omega'$ which allows us to identify the segment where scattering took place (compare Fig. 3). It is interesting to note that the reconstructed sum energy spectrum of the K-REC line (Fig. 3(d)) is entirely background free whereas the K-REC photon distribution of a single segment (Fig. 3(a)) is strongly asymmetric due to the unresolved contribution of the Compton scattering process.

From the data observed the polarization factor was calculated from the following formula:

$$P = K\frac{I_{\parallel} - I_{\perp}}{I_{\parallel} + I_{\perp}}, \tag{2}$$

where $I_{\perp}$ and $I_{\parallel}$ denote the number of photons scattered in perpendicular and in parallel direction to the plane assigned by the ion beam and the detector, respectively. Here K ($K > 1$) is a normalization factor which depends on the actual detector dimensions and geometry (pixel or strip dimensions including crystal thickness). It must be determined either by Monte Carlo simulations and/or by calibration measurements using γ-transitions with known polarization. As a preliminary result from the discussed experiment, we deduce a linear polarization for the process of REC into the K-shell of larger than 20% whereby the polarization plane coincides with the scattering plane. In order to present a final result, the detector depended constant K must still be determined, a work which is presently in progress.

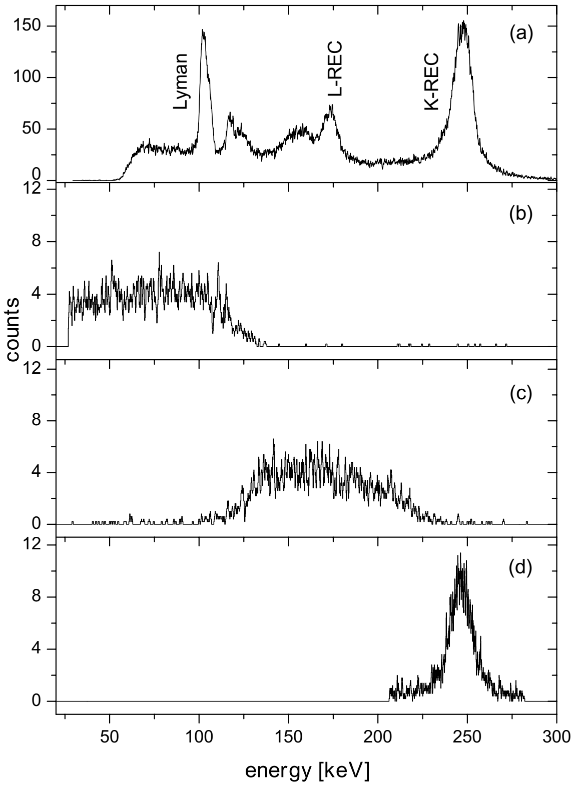

Fig. 3. X-ray spectra measured by one segment of the Clover detector in coincidence with down-charged U^{91+} at an observation angle close to 90°: (a) X-ray spectrum as observed by one segment of the Clover detector; (b,c,d): Compton scattering of K-REC photons as measured in coincidence between two-segments of the Clover detector (see Eq. (1)). (b) Compton electron energy distribution (ΔE) as measured by the first segment; (c) energy distribution of the Compton scattered photons $\hbar\omega'$ as measured by a neighboring, second segment; (d) sum-energy spectrum created from events in both segments ($\Delta E + \hbar\omega' = K_{K\text{-}REC}$).

For future experiments on the polarization of hard X-rays, a 4 × 4 planar germanium pixel detector has been designed at FZ-Jülich with a pixel size of 7 × 7 mm. This detector seems to be most appropriate for polarization measurements in photon energy range of relevance (100–500 keV).

4. Summary and outlook

In summary, an overview over the current development of PSG detectors for X-ray spectroscopy for the heaviest highly charged ions at the ESR storage ring is given. For the case of a microstrip detector, its combination with a focusing transmission crystal spectrometer has shown to improve considerably the overall detection efficiency whereby preserving the resolution properties of the spectrometer. One may also anticipate, that X-ray imaging by two-dimensional (double sided) germanium detectors will be an important feature for future absorption edge spectroscopy which may also provide an highly accurate tool for QED studies in the high-*Z* domain. In addition to the spectroscopy and imaging capabilities of the discussed detectors, their polarization sensitivity via Compton scattering is of particular interest. The already obtained results demonstrate that by means of such detector devices polarization measurements of atomic transitions in the hard X-ray regime as produced e.g. in swift ion–atom collisions have now become accessible. This represents an important break through for a more accurate study of bound–bound and free-bound transitions in the realm of high-*Z* ions. Here, relativistic structure and collision effects are predicted to influence strongly the linear polarization of the emitted X-rays.

Acknowledgements

This research has been supported by a Marie Curie Fellowship of the European Community Programme IHP under contract number HPMT-CT-2000-00197 and by the EU grant EC-HPRI-CT-1999-00001.

References

[1] D. Protic, Th. Stöhlker, H.F. Beyer, et al., IEEE Trans. Nucl. Sci. 48 (4) (2001) 1048.
[2] H.F. Beyer, Nucl. Instr. and Meth. A 400 (1997) 137.
[3] Th. Stöhlker, P.H. Mokler, F. Bosch, R.W. Dunford, O. Klepper, C. Kozhuharov, T. Ludziejewski, B. Franzke, F. Nolden, H. Reich, et al., Phys. Rev. Lett. 85 (2000) 3109.
[4] A. Krämer, Th. Stöhlker, F. Bosch, T. Ludziejewski, H.F. Beyer, C. Kozhuharov, D. Liesen, P.H. Mokler, R.W. Dunford, J. Eichler, et al., Nucl. Instr. and Meth. B 146 (1998) 57.
[5] M. Czanta, Ph.D. Thesis, University Heidelberg, 2001, to be published.
[6] J. Eichler, W. Meyerhof, Relativistic Atomic Collisions, Academic Press, San Diego, CA, 1995.
[7] A. Surzhykov, S. Fritzsche, Th. Stöhlker, Phys. Lett. A 289 (2001) 213.
[8] J. Eichler, A. Ichihara, Phys. Rev. A 65 (2002) 062716.
[9] S.E. Inderhess, B.F. Philips, R.A. Kroeger, W.N. Johnson, R.L. Kinzer, J.D. Kurfess, B. Graham, N. Gehrels, IEEE Trans. Nucl. Sci. 43 (1996) 1467.
[10] J. Gerl, Nucl. Instr. and Meth. A 442 (2000) 238.