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

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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.

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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
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 combi-
nation 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 spec-
trometer this detector may play a key role for a
precise test of quantum electrodynamics (QED) in
the heaviest one-electron systems. Another impor-
tant 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 transi-
tions 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 ve-
locity 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 ve-
locity 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 spec-
troscopy, the use of segmented germanium detect-
ors appears to be appropriate.

On the one hand the segmentation allows for an
event-by-event Doppler correction of the regis-
tered 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 absorp-
tion 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 FO-
CAL 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 combina-
tion 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 re-
combination 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 detec-
tors via the Compton effect provides an important
key to reveal the physics of these processes [9].
Following the Klein–Nishina formula, the differ-
ential cross-section for Compton scattering of a
photon with initial energy $h\omega$ is given by

$$
\frac{d\sigma}{d\Omega} = \frac{1}{2} \frac{1}{r^2_0} \left( \frac{h\omega'}{h\omega} \right)^2 \left( \frac{h\omega'}{h\omega} + \frac{h\omega}{h\omega'} - 2 \sin^2 \theta \cos^2 \varphi \right),
$$

(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 $^{92}$U + $^1$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 \( h\omega' \) denotes the energy of the scattered photon, \( \theta \) the scattering angle between the initial and the scattered photon and \( \phi \) 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 \( \Delta E \) (energy of the Compton electron) of the Compton scattering process always fulfills the condition \( \Delta E < h\omega' \) 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:

\[
P = K \frac{I_{\parallel} - I_{\perp}}{I_{\parallel} + I_{\perp}}.
\]

(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 \( \gamma \)-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.

For future experiments on the polarization of hard X-rays, a \( 4 \times 4 \) planar germanium pixel detector has been designed at FZ-Jülich with a pixel size of \( 7 \times 7 \) 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.

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