Recent experimental developments for the Lamb shift investigation in heavy ions

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Abstract. The latest commissioning experiment of a two arm transmission crystal x-ray spectrometer along with high-performance position-sensitive microstrip germanium detectors is presented. The goal of the experiment was to observe with high resolution the Ly-\(\alpha\)-transitions of H-like Pb\textsuperscript{81+} produced in collisions with Kr atoms. Due to a photon efficiency of only \(10^{-8}\) the position sensitivity as well as the energy and time resolution of segmented solid state Germanium detectors are absolutely essential for experiments using crystal x-ray spectrometers dealing with beams of heavy ions. A detector system with the desired properties has become available through a collaboration with the Forschungszentrum Jülich.

1. Introduction

Aiming at an accurate determination of the effect of quantum-electrodynamics (QED) on the ground state binding energy in high-\(Z\), H-like ions [1], an accurate spectroscopy of atomic K-shell transitions is needed. Despite its success for light systems, the QED theory is less well tested for electrons in the strong fields seen by the inner electrons of atoms having high nuclear charges. For this purpose, novel high resolution spectrometer setups are presently commissioned for x-ray experiments at the Experimental Storage Ring (ESR) at GSI, Darmstadt. Up to now, for the case of H-like uranium, an accuracy of 1\% could be reached in an experiment performed at the electron cooler [2] using the deceleration capability of the ESR. A further improvement by almost one order of magnitude is expected by a transmission x-ray spectrometer setup in the FOcusing Compensated Asymmetric Laue (FOCAL) geometry [3] as well as by the implementation of high-resolution micro-calorimeter devices [4, 5]. Also position-sensitive germanium detectors will play an important role in future x-ray spectroscopy experiments (see also Ref. [6]). The unique properties of such detectors are the sub-millimeter spatial resolution as well as a good time and energy resolution. In combination with the FOCAL-spectrometer these position-sensitive detectors permit the simultaneous measurement of all energies in the regime of interest [7].
2. Experimental setup

2.1. The FOCAL spectrometer

In Fig. 1, a scheme of the experimental setup used is given. The setup consists out of two FOCAL spectrometers, arranged along the same optical axis at the gas-target of the ESR; facing each other at 90° with respect to the beam line. The x-ray optics of the FOCAL spectrometer has been designed for a high systematic wavelength accuracy with an efficiency of close to $10^{-8}$ which is large in comparison with previous crystal-spectrometers in the energy region of 30–120 keV [8]. The crystal component consists of a silicon crystal (220) with a radius of curvature of 2 m. Its thickness and area are optimized for photon transmission and Doppler corrections. The spectrometer may adapt to both stationary as well as fast moving sources. For the calibration a $^{169}$Yb gamma-ray source was used. The source is mounted on a positioner which can put the source into the optical axis or withdraw it inside an efficient radiation-shielding cell while measuring the x-rays from the ion beam. For a more detailed description of the spectrometer setup and performance we refer to [3, 9]. For completeness we like to mentioned that during the same run a low-temperature micro-calorimeter detector system for hard x-ray radiation in the regime between 50 keV and 80 keV was commissioned successfully, a development also devoted to an accurate photon spectroscopy of Ly-α transitions in heavy H-like ions [4].

2.2. The detection system

Since the first test experiment performed in March 2003 with Au$^{78+}$-ions [10] and a one-dimensional microstrip germanium detector [11] a newly developed two-dimensional microstrip detector [12] has become available. Both detectors are providing a position resolution of about 200 μm. The detectors are mounted on movable platforms which enable us to cover a large range in the direction of dispersion of the x-rays. While the 1D Ge-strip detector was mounted on the outer side, the 2D detector was used for the spectrometer setup at the inner side of the storage ring (see Fig. 1).

The 1D Ge-strip detector consists of 200 strips covering an area of 47 mm × 23.4 mm

Figure 1. Scheme of the experimental setup used in the commissioning run at the ESR jet target. See text for details.
separated by 35-\( \mu \)m-wide grooves [11]. In the present experiment only 64 strips were used covering 16 mm along the dispersion direction. The 2D Ge-strip detector has a 128-strip structure on an area of 32 mm \( \times \) 56 mm with a pitch of 250 \( \mu \)m on the implanted p\(^{+}\)-contact (front-side). The position-sensitive strips are separated by about 15 \( \mu \)m deep and 28 \( \mu \)m wide grooves. On the amorphous-Ge-contact (rear-side) only 48 strips with a pitch of 1167 \( \mu \)m were created, separated by 10 \( \mu \)m deep and about 25 \( \mu \)m wide grooves. In addition the detector is mounted in a cryostat which will enable any orientation of the detector with respect to a photon source [12]. For the experiment all 48 strips on the rear-side and 64 strips on the front-side were read out by the DAQ.

3. Experiment

The current experiment was performed in March 2006 at the ESR storage ring at GSI, Darmstadt. A beam of completely stripped Pb\(^{82+}\) ions was stored at an energy of 219 MeV/u corresponding to a velocity \( \beta = 0.5865 \). Ly-\( \alpha \) transitions of hydrogen-like Pb\(^{81+}\) were induced following charge exchange with a krypton gas target. The x-rays were measured in coincidence with the down-charged ions, detected with a particle detector mounted behind the first dipole magnet downstream of the target. Due to the low efficiency of the spectrometer of merely \( \varepsilon = 10^{-8} \) the expected counting rate was close to 3 events per hour.

During the experiment, several calibration runs were performed using a \(^{169}\)Yb gamma-ray source. In figure 2 we show a 2D image as it was recorded with the 2D-detector. As one may see the lines are slightly tilted. Due to the relativistic energy of the ion beam the photons observed in the experiment are influenced by the Doppler effect. In order to prevent the experimental spectra to be tilted, the detector was turned in a way that compensates for this effect. Therefore, the calibration data which are not Doppler shifted appear tilted. Looking at the most intense calibration line (63 keV) there are strips where the intensity seems to be lower. This effect is caused by charge-splitting. If an emitted photon hits the detector in the groove between two neighboring strips the energy of this photon is shared. This feature could be used as a clue to interpolate the position readout to a fraction of a strip width.

Figure 3 depicts the intensity pattern as a function of the position (energy) of both detectors. While the spectrum of the 1D detector (left) contains a narrow 63 keV line, the lines in the 2D spectrum (right) appear rather broad. This broadening of the lines is due to the above mentioned Doppler effect. Projecting the 2D spectrum of figure 2 on the y-axis broad lines are expected due to the slope of the line. Having a straight line (like in the experimental data) the projection would provide as again with narrow lines. On the opposite side the experimental data of the

![Figure 2](image-url)
1D detector will be broadened. This demonstrates also the advantage of a 2D position-sensitive detector compared to the 1D position-sensitive detector. For the 1D detector it is not possible to determine the cause of possible broadenings. Nevertheless, already the 1D detector enables us to perform experiments with a resolution better than 100 eV [7].

4. Conclusions
The spectral resolution of the FOCAL-spectrometer in combination with the energy resolution of position-sensitive micro-strip Ge-detectors promises to be an excellent tool on the way towards a 1 eV precision in Lamb-shift experiments. Especially two dimensional micro-strip detectors constitute an important step towards this aim because the read out of the second dimension enables us to determine the position of the reflection not only along the direction of dispersion but also its alignment on the detector. Furthermore, utilizing the effect of charge-splitting between neighboring strips an accuracy better then the strip width may be achievable. With this respect a collaboration with the University of Cracow has been formed aiming for a DSP-based data acquisition that is able to reconstruct the point of interaction inside the detector crystal better than the intrinsic strip size [13].

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