Monte Carlo simulations of atomic processes at the gas jet target of the ESR storage ring*

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1 Introduction

In order to analyze x-ray spectra produced in collisions of fast ions with a gas-jet target of a storage ring, at a high level of accuracy, several information on beam and target geometry as well as on parameters of the detectors used (position, size, efficiency) has to be considered, in particular, for precise Doppler-shift assisted spectroscopy in atomic physics experiments [2]. Sophisticated experimental setups [2, 6] force us to test the influence of many parameters on the experimental results where, very often, an analytical description of the experimental conditions by means of these parameters is extremaly difficult. Therefore, in many cases, a detailed response of the detectors upon variation of diverse parameters, can be known only if computer simulated events are modeled and analyzed [5]. It helps to reveal the significance of these parameters and, as a consequence, to optimize experimental setups.

In the following an universal Monte Carlo simulation of atomic collision experiments, conducted at the gas-jet target of a storage ring, is presented. A special emphasis is given to the simulation of x-ray spectra produced in collisions due to radiative processes [6, 7]. The quality of the computer code is tested by comparing the Monte Carlo simulated data with experimental spectra obtained at the ESR storage ring of GSI in Darmstadt. In particular, the x-ray spectra emitted in collisions of bare uranium ions with molecular nitrogen and argon jet-target are analyzed.

*This work was supported by the Polish Committee for Scientific Research (KBN) grant N^o 2P03B10910.

2 Monte Carlo program

The developed Monte Carlo program generates x-ray spectra collected in the laboratory frame due to encounters of heavy ions with atoms or molecules of a jet target at projectile velocities close to the speed of light. The program takes into account most of the parameters which decide how does the spectrum look like. In particular, the overlap of an extended jet target and an extended ion beam is considered. The x-ray emitting target-region can be surrounded by an array of x-ray detectors as shown schematically in Fig. 1 [8].

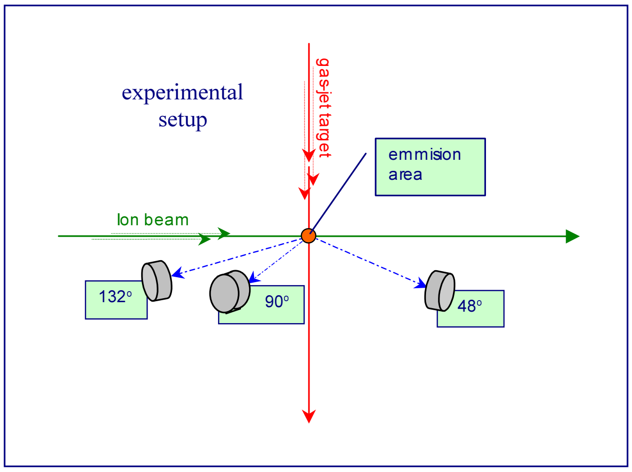

Figure 1: General view of the experimental setup at gas-jet target of a storage ring as discussed in the text.

We assumed that the target and the beam density are given by gaussian distributions with the center of the collision chamber as the center of the reference system. The projectiles and the gas-jet atoms are moving along the z and y axis, respectively.

The program can simulate radiative electron capture processes (REC) [6], the emission of characteristic projectile x-rays, as well as radiative second order capture processes, like a simultaneous capture of two correlated electrons with the emission of two photons (DREC) [9] or with the emission of one photon with twice as large energy (RDEC)[10]. Besides that, background photons can be generated with the presumed energy distribution.

The angular distribution of photons in the emitter frame is described generally by the function $\sim A + B \cdot \sin^2\vartheta$, where the parameters A and B can be set in accordance with the investigated process and ϑ denotes the emission angle of the produced x-ray photon. In special cases, where the angular distribution is a more sophisticated function of the emission angle, an array of numerical values can be used whereby a spline interpolation is applied.

The geometry of the x-ray detector array is described by the observation angles θ of the individual detectors in the laboratory frame (Fig. 1) and by their distances from the center of the collision chamber. Moreover, the size and the shape of the active detector crystals are considered in the program. The spectra are accumulated by taking into account the energy resolution and the efficiency function of the corresponding x-ray detector.

3 Program tests

As a test of the program we performed simulation of two processes. First, the shape of the characteristic $Ly-\alpha$ radiation emitted in collisions of bare 358 MeV/u U-ions with N_2- and Ar-targets was analysed . In particular, the width (FWHM) of $Ly-\alpha_1$ and $Ly-\alpha_2$ components was extracted from the simulated spectra for different widths of the jet-target distribution. For this test the x-ray data collected by one stripe of the sevenfold Ge(i) detector [2], placed at $\theta = 48^o$ with respect to the beam axis, were used. The x-ray energy resolution of 940 eV (FWHM) at about 130 keV was applied in simulations for the considered detector stripe as measured with a standard radioactive source. In this particular experiment [12], the detector dimensions were known very precisely. For comparison, the observed uranium $Ly-\alpha$ components and the calibration line are shown in Fig. 2 together with the simulated spectra. Significant broadening of the $Ly-\alpha_1$ and the $Ly-\alpha_2$ lines of about 1.7 keV, is mainly due to extension of the beam-target interaction region and due to the finite size of the detector.

In Fig. 3 the FWHM of the simulated $Ly-\alpha_2$ line is plotted versus the width (FWHM) of the presumed gaussian distribution of the gas jet. A gaussian ion-beam profile with a typical width of 2mm was used in the calculations. It turns out from Fig. 3 that the observed $Ly-\alpha_2$ width of 1.69 keV (Fig. 2) can be explained by a target width of 3.60 ± 0.45 mm. The corresponding values for both $Ly-\alpha$ components and for the N_2- as well as for the Ar-target are summarized in Tab. 1. These values are in accordance with the generally assumed beam-target interaction length at the ESR storage ring of 5 ± 1 mm as reported in [11].

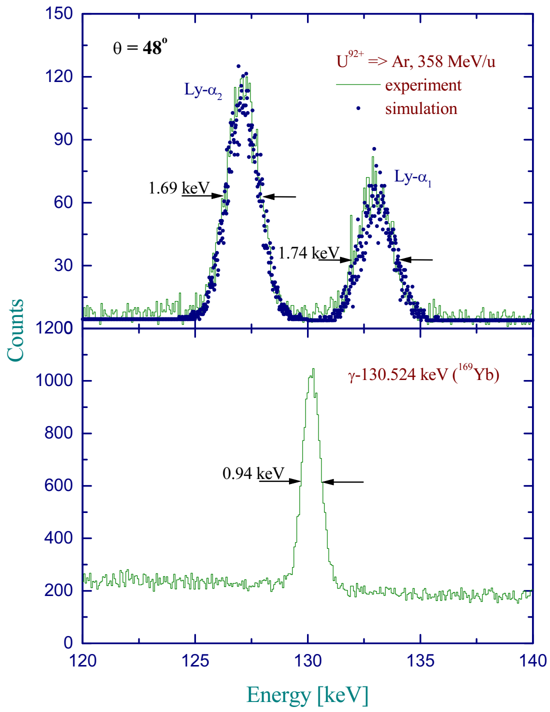

Figure 2: A comparison of experimental and simulated $Ly-\alpha$ spectra obtained in collisions of U^{92+} ions with Ar-gas target at 358 MeV/u. In the lower part of the picture a calibration line is shown as registered by the same x-ray detector close to 130 keV.

Target	$Ly-\alpha_1$	$Ly-\alpha_2$
Nitrogen	3.93 ± 0.61 mm	3.94 ± 0.46 mm
Argon	3.58 ± 0.63 mm	3.60 ± 0.45 mm

Table 1: FWHM of the target for argon and nitrogen obtained for the typical beam diameter of 2 mm.

Second, the K-REC x-ray spectra, observed by means of a planar Ge(i) detector at a backward angle of 132^o, are simulated and compared to the experimental data accumulated for collisions of U^{92+} ions with gaseous targets at an energy of 358 MeV/u. Details of this experiment are reported elsewhere [12]. In the calculations, the corresponding Compton profiles for the

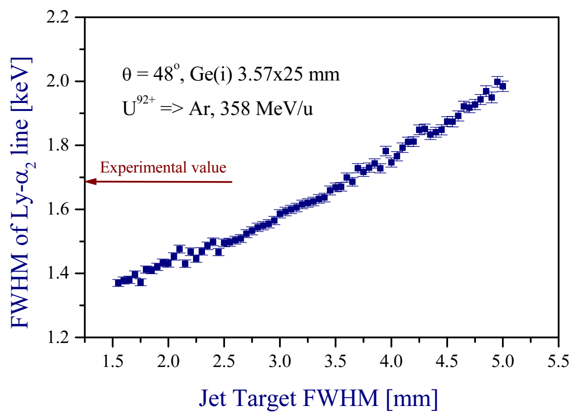

Figure 3: Width of the simulated $Ly - \alpha_2$ line of U^{91+} plotted as function of the jet-target width.

Ar- and the N_2-target are taken from [13]. Note, that for the latter case the molecular character of the target was not considered. In Fig. 4 a comparison of the simulated and measured spectra is displayed. A very good agreement between experiment and Monte Carlo data is to be noted. In particular, due to the stronger binding of the K-shell electrons in Ar, the wings of the REC distribution are considerably broader than for the N_2-target which is nicely reproduced in the simulated spectra.

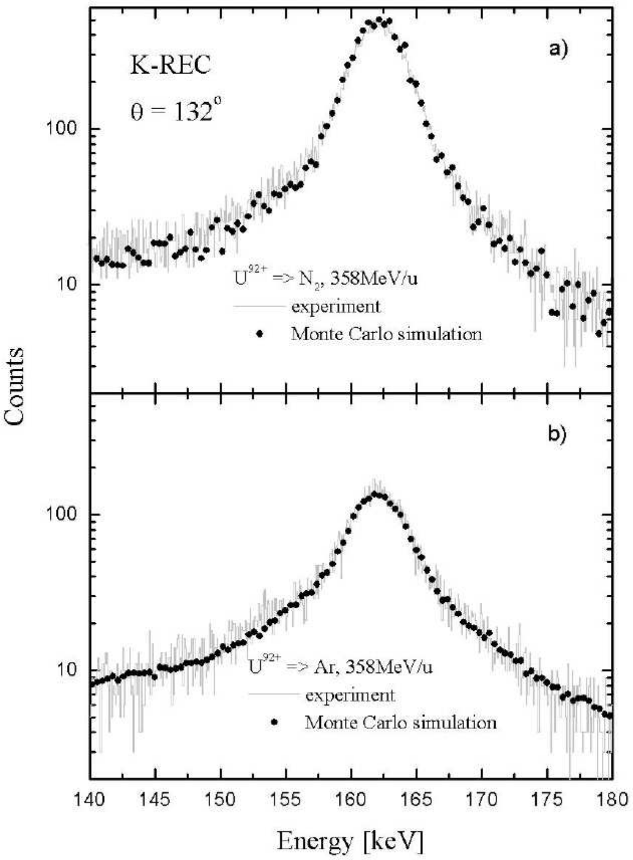

Figure 4: A comparison of experimental and simulated K-REC spectra obtained in collisions of U^{92+}-ions with N_2-target (a) and Ar-target (b) at 358 MeV/u.

4 Summary

The Monte Carlo code discussed provides us with valuable information on the structure of x-ray spectra, which are produced in collisions of fast ions with a gas-jet target. A correct response of the program to the variation of experimental as well as physical parameters has been found. Thus, deviations of this Monte Carlo simulation from simplified models reflect the influence of the higher order effects. Currently, simulations of an already performed experiment on angular distribution of REC photons as well as on a planed experimental identification of higher-order corrections to the radiative electron capture process are in progress.

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