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The Balmer spectrum of H-like uranium produced by radiative recombination at low velocities

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Abstract

For radiative recombination occurring during electron cooling of highly charged ions the associated Balmer spectrum has been observed for the first time. The experiment has been performed for bare uranium ions at the ESR storage ring at GSI, Darmstadt. Also the recombination into the L-shell sublevels $j = 1/2$ and $3/2$ could be observed. The spectrum is compared to a cascade simulation taking into account capture into high-Rydberg states.

Keywords: Radiative recombination, Storage ring, High-Z ions, Electron cooling

1. Introduction

Radiative recombination (RR) is one of the most important interaction processes in collisions of highly charged ions with free electrons. In this process a free electron undergoes a direct transition into a bound state of the stationary ion via the emission of a photon, carrying away the energy difference between the initial and final state. With the advent of heavy ion storage rings equipped with electron cooler devices and electron-beam ion traps (EBITs) this process attracted particular attention (Wolf et al., 2000; Marrs et al., 1995). Whereas in electron cooler devices RR can be investigated for the low velocity regime, RR in an EBIT occurs at high collision energies where the cross-sections follow a $1/n^3$ scaling law (n denotes the principal quantum number) and favor low angular momentum states. In contrast, at low-relative velocities, states with large principal and angular momentum quantum numbers are predominantly populated. Here, we report on an experimental study of the Balmer transitions caused by RR into bare uranium ions. For this purpose the deceleration mode of the ESR was used to reduce tremendously the ion beam energy. As a result, only small cooler voltages and electron currents had to be applied. Consequently, the maximum energy and the intensity of the bremsstrahlung resulting from collisions of the cooler electrons with the walls of the ring could strongly be reduced, allowing for the first time for a state-selective investigation of RR at electron cooling conditions via the observed characteristic Balmer radiation. We like to note, that such studies may help to investigate the issue of the so called rate enhancement for recombination in electron cooler devices which is still an unsolved puzzle. Up to now, the investigations of this topic are restricted to total recombination rate studies only.

2. Experiment

The experiment was performed at the electron cooler device of the ESR storage ring at GSI, Darmstadt

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(Gumberidze et al., 2003, 2004). There the X-rays emitted via RR of the cooler electrons into the bound states of bare and hydrogen-like uranium ions (forming H- and He-like systems, respectively) were detected by a solid state germanium detector which viewed the interaction region at an observation angle close to 0°. Behind the first dipole magnet a multi wire proportional counter (MWPC) was mounted, which allowed us to measure the photons in coincidence with the down-charged ions. Due to the applied deceleration mode and the resulting low ion beam energy of 43.59 MeV/u a comparably small cooler voltage of 27 keV was applied leading to an electron beam current of only 100 mA. In the electron cooler the cooling electrons and the ions are moving with approximately the same velocity resulting in collision energies close to 0 eV. At such low energies the recombination rate scales with $\sim 1/n$ (Kramers, 1923), populating also high-Rydberg states having principal quantum numbers of $n \approx 100$ or even higher. An X-ray spectrum as observed in the experiment is depicted in Fig. 1. The spectrum shows a well-resolved Balmer spectrum and also the direct capture into the L-shell sublevels $j = 1/2$ and 3/2.

3. Simulation of the Balmer spectrum

Observing the Balmer radiation is of special interest as it gives the possibility to gain information about population of high-Rydberg states via the de-excitation cascade process. The characteristic Balmer spectrum does not only result from direct capture into the L-shell but stems in particular from transitions of higher excited states to the $n = 2$ level in the H-like system. In our investigation we had a close look which principal quantum numbers n have to be considered in order to find an agreement between the cascade simulation and the experimental data. Since the present experiment was performed at the electron cooler at collision energies close to 0 eV it is evident that high-Rydberg states are populated. Note, this situation is in contrast to the one in previous experiments at high collision energies where agreement between experimental data and theoretical predictions was already found by consideration of states with $n \approx 20$. These experiments were performed at the internal gas target of the ESR storage ring where the collision energies are higher and due to this the recombination cross sections show a $1/n^3$ dependence (Stöhlker et al., 1998).

For the simulation of the de-excitation cascade several input data had to be created. The electron beam has a velocity distribution $f(v)$. Therefore it is more convenient to introduce so called RR rate coefficients α_{nl} instead of the RR cross sections σ_{nl}) which are defined for a fixed electron velocity. Rate coefficients are an integrated quantity defined by

$$\alpha_{nl} = \langle \mathbf{v}\sigma_{nl}(\mathbf{v})\rangle = \int \mathbf{v}\sigma_{nl}(\mathbf{v}) f(\mathbf{v})\, d^3\mathbf{v}. \tag{1}$$

For the velocity distribution of the electrons, a normalized flattened distribution given by

$$f_{\mathrm{f}}(\mathbf{v}) = \left(\frac{m}{2\pi}\right)^{3/2} \frac{1}{kT_\perp (kT_\parallel)^{1/2}} \mathrm{e}^{-(m_e v_\perp^2/2kT_\perp + m_e v_\parallel^2/2kT_\parallel)}. \tag{2}$$

is used. $T_\perp$ and $T_\parallel$ represent the transversal and longitudinal temperature, respectively, and k is the

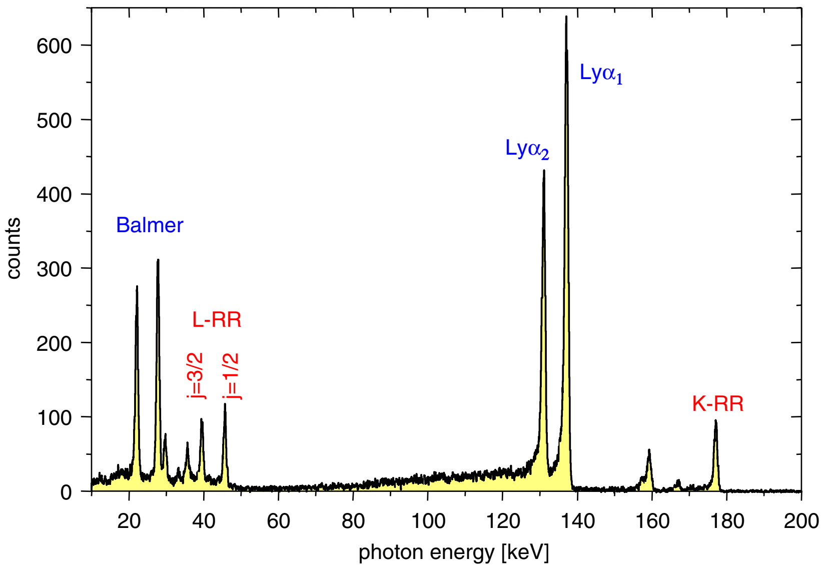

Fig. 1. Coincident X-ray spectrum for initially bare uranium as observed for decelerated ions at the electron cooler of the ESR storage ring.