# The enhancement effect in K-shell radiative recombination of U⁹²⁺ ions with cooling electrons

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**Abstract.** We report the results of the x-ray radiative recombination (RR) experiment at the electron cooler of the ESR storage ring performed, for the first time, for detuned (off-cooling) electron energies. In this experiment the recombination of stored, decelerated bare uranium ions with electrons in the energy range 0–1000 meV was studied by observing K-RR x-ray photons emitted from direct radiative recombination to the lowest n = 1 state. In this way the RR process was studied in a state selective manner for several off-cooling electron energies. The measured dependency of the recombination rate on the relative electron energies for K-shell RR x-ray photons are compared with the predictions of both nonrelativistic and fully relativistic calculations for the radiative recombination. A role of the relativistic effects, which contribute substantially for higher relative electron energies, are discussed. Strong enhancement of the recombination rate is observed for the the zero relative electron energy (cooling condition) for the K-shell.

## 1 Introduction

The radiative recombination (RR) of high-Z bare ions with cooling electrons in ion storage rings has attracted a wide interest in last years, in particular, due to observation of the recombination "enhancement" effect [1–12]. The recombination experiments performed up to now for bare ions at different cooler/storage rings, in which the recombination events were detected by observing down-charged recombined ions, show that the measured radiative recombination rates agree with the theoretical predictions only for relative electron energies higher than the transverse electron beam temperature $kT_\perp$, while for the lower energies a substantial increase, called the "enhancement", of measured rates with respect to the theoretical predictions for RR process is observed. It was found that for bare ions the observed excess of the recombination rate scales approximately with atomic number as $Z^{2.6}$ [10–12] as well as with transverse and longitudinal electron temperature as $T_\perp^{-1/2}$ and $T_\parallel^{-1/2}$, respectively [8]. Moreover, an influence of the magnetic guiding field in the electron cooler on the recombination rate has been evidenced experimentally [8–12]. In most of the recombination experiments studying the enhancement
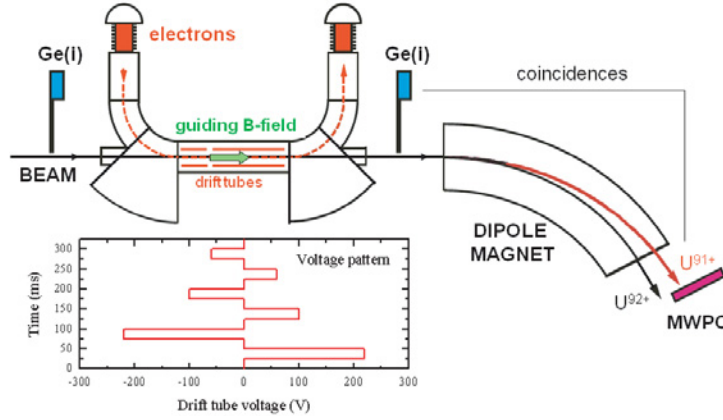
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**Fig. 1.** A scheme of the experimental setup at the ESR storage ring showing the electron cooler, x-ray detectors arrangement, dipole magnet and particle detector position (MWPC).

effect [6–12] for low relative electron energies the down-charged recombined $Z^{q-1}$ ions, which can be separated from stored ion beam ($Z^q$) by a bending dipole magnet in the ring placed next to the electron cooler, were measured by a particle detector. Using this technique only the total recombination rate for a wide range of n-states, namely from n = 1 up to very high Rydberg states limited by the field ionization cut-off limit ($n_{cut}$), can be measured and, consequently, the state-selective information cannot be obtained.

In this paper we describe the first state-selective x-ray radiative recombination experiment performed for low energy electrons in the relative energy range 0–1000 meV. The measured recombination rate dependencies on the relative detuning (off-cooling) electron energy give new access to study the enhancement and relativistic effects in recombination process. It should be noted here, that the first x-ray recombination experiments performed at the ESR storage ring were focused on spectroscopic aspects of K-RR and Lyman x-ray lines in order to measure the Lamb shift in high-Z ions [3–5,13–15]. Consequently, these experiments were performed only at the cooling condition ($E_{rel} = 0$).

## 2 Experiment

The experiment has been performed at the ESR storage ring (Fig. 1) of the heavy ion SIS-ESR facility at the GSI in Darmstadt. Bare uranium ions supplied by UNILAC/SIS accelerators were first decelerated in the ESR storage ring to an energy of 23 MeV/amu and then cooled in the electron cooler down to the transverse temperature of about $kT_\perp = 120$ meV and much smaller longitudinal temperature $kT_{||} \ll kT_\perp$, which characterized the flattened electron beam velocity spread in the moving frame. The electron beam, having electron current of 100 mA corresponding to the electron density $10^6$ cm$^{-3}$, was guided in the electron cooler by a magnetic guiding field of 70 mT. The Doppler shifted x-rays emitted from radiative recombination of U$^{92+}$ ions with electrons in the electron cooler were measured using two germanium detectors placed nearly at 0° and 180° with respect to the ion beam direction. The x-ray photons were measured in coincidence with the recombined U$^{91+}$ ions in order to suppress the background. The recombined U$^{91+}$ ions were separated from circulating beam of U$^{92+}$ ions by a dipole magnet next to the electron cooler and they were detected by a multiwire proportional counter. The measurements were performed both at the cooling condition ($E_{rel} = 0$) as well as for several off-cooling electron energies. These measurements were performed by applying additional voltage to cylindrical drift tubes surrounding the straight ion/electron overlap region in the electron cooler. We used the meandering drift tube voltage-time pattern (Fig. 1) corresponding to six relative detuning electron energies having the absolute values close to $E_{rel} = 70$, 190, 930 meV. After each measurement at off-cooling energy the electron energy was kept at its cooling value for 25 ms in order to "refresh" the ion beam for possible drag force effects.
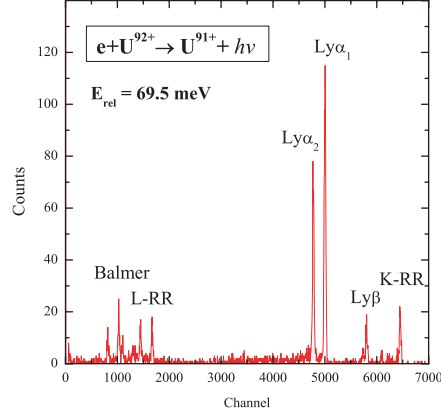
**Fig. 2.** The x-ray spectrum measured at $\theta = 0.5°$ and relative energy $69.5\,\text{meV}$ showing the K-RR (n = 1) and L-RR (n = 2) x-ray lines as well as the x-ray lines of the Lyman and Balmer series.

This experiment allowed us to measure simultaneously the photons emitted from direct radiative recombination to low n-states, namely K-RR (n = 1) and L-RR (n = 2), as well as the Lyman and Balmer x-ray photons from deexcitation cascades following a recombination to high Rydberg states (Fig. 2). From K-RR and L-RR intensities the recombination rates for n = 1, 2 states can be obtained while the intensities of Lyman and Balmer transitions gave information on the recombination into a wide range of high n-states states. In this manner both the recombination to the low lying (n = 1, 2) and high n-states were simultaneously probed experimentally. In the present paper the recombination to the K-shell is discussed in more details as an experimental evidence of the recombination enhancement for the lowest n = 1 state.

## 3 Results

The measured rates for direct radiative recombination to the K-shell (K-RR) are shown in Fig. 3 versus the relative (detuning) electron energy. The experimental rates shown in this figure are compared with the predictions of nonrelativistic dipole approximation [16,17] and fully relativistic calculations for radiative recombination which were calculated for the flattened ($kT_| \ll kT_\perp$) electron beam velocity distribution characterized by transverse electron
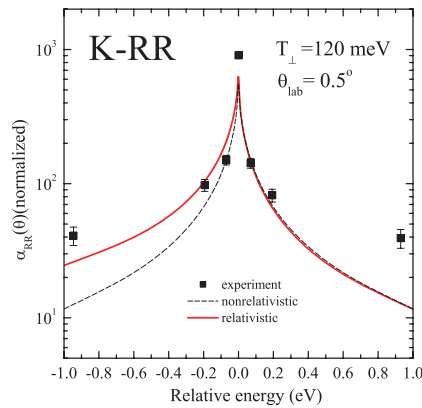


**Fig. 3.** The measured K-shell recombination rate coefficient, derived from intensity of K-RR photons detected at $\theta = 0.5°$, plotted versus the relative electron energy. The data were normalized to the predictions of the relativistic calculations for $kT_\perp = 120\,\text{meV}$ at $E_{rel} = 69.5\,\text{meV}$.

beam temperature $kT_\perp = 120\,\text{meV}$, corresponding to electron gun temperature. The theoretical predictions, normalized to the measured K-RR rates for $E_{rel} = 69.5\,\text{meV}$ expected to be not affected by the enhancement, indicate a presence of the enhancement effect at $E_{rel} \simeq 0$ (cooling condition). The possibly contribution of the two step process, namely the radiative recombination to the high n-states followed by radiative transition to the 1s state, was estimated by considering a range of possible intermediate n-states restricted only by a lifetime of recombined hydrogenic ion for high-n and the acceptable photon energy, within energy resolution of x-ray detector, of the np-1s transition for low-n. The calculated contribution of this process was below 2.5% and, practically, can be neglected. Furthermore, we have estimated that the additional correction playing role for the higher electron energies caused by electric potential drop at the ends of the drift tubes does not influence the results at cooling energy ($E_{rel} = 0$).

In summary, the first results from the x-ray recombination experiment performed at the ESR cooler/storage ring, in which the recombination of bare $U^{92+}$ ions with low energy cooling electrons for relative energies 0–1000 meV, were reported here. In this experiment the radiative recombination into the lowest n-state as well as the enhancement and relativistic effects were studied in a state-selective manner. A comparison of the measured recombination rates for K-RR rates with the theoretical predictions evidences an importance of the relativistic effects, in particular, for higher relative electron energies. The present results show for the first time that the recombination enhancement is observed in the direct radiative recombination to the K-shell, which is important observation to be considered in the theoretical interpretations of the enhancement effect [18–20].

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