Differential L-shell radiative recombination rate coefficients for bare uranium ions interacting with low-energy electrons

D. Banaś, M. Pajek, A. Gumberidze, A. Surzhykov, and Th. Stöhlker

1 Institute of Physics, Jan Kochanowski University, 25-406 Kielce, Poland
2 ExtreMe Matter Institute EMMI and Research Division, GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany
3 FIAS Frankfurt Institute for Advanced Studies, 60438 Frankfurt am Main, Germany
4 Physics Institute, University of Heidelberg, 69120 Heidelberg, Germany
5 GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany
6 Helmholtz-Institut Jena, 07743 Jena, Germany

Received 8 June 2013 / Received in final form 9 August 2013
Published online 23 October 2013

Abstract. Results of the calculations of differential L–shell radiative recombination (RR) rate coefficients for bare uranium ions colliding with free electrons using the nonrelativistic dipole approximation and fully relativistic calculations are reported. The rate coefficients were obtained for very low, in the range of meV, relative electron-ion energies. We demonstrate that even for such low relative ion-electron energies the relativistic effects significantly modify the differential RR rate coefficients for the L–subshells and, as a result, the measurements of the relative electron energy dependence of the L-RR rates could be used for studying of the relativistic effects. These effects are strongest for the L₃-subshell, which is discussed here in more details.

1 Introduction

Radiative electron-ion recombination is one of the fundamental processes occurring in collisions of highly-charged ions with electrons. In this process, a free electron is captured into a bound state of an ion with emission of a photon, which carries out the energy difference $\hbar \omega = E + E_n$ between the electron energy in continuum $E$ and in bound state $E_n$. For inner shells of heavy ions the energies of photons are in the X-ray energy range and thus the observation of X-rays emitted in RR of heavy ions with electrons allows precise studies of atomic structure of few-electron ions as well as the collision dynamics [1–4] of radiative recombination. In order to interpret the results of RR experiments performed in electron cooler of ion storage rings the calculations of differential RR cross sections and RR rate coefficients, as a function of a fixed relative electron-ion energy, are needed. Such calculations, which were performed recently by our group for the K-shell in context of RR experiments

*e-mail: d.banas@ujk.edu.pl*
in the ESR ion storage ring facility at GSI showed that asymmetry of the \( K \)-shell RR rate coefficient with respect of the zero average electron velocity corresponding to the electron cooling condition observed in experiment [5] could be properly interpreted only within the fully relativistic calculations [6].

Here we report on the calculations of both nonrelativistic [7] and fully relativistic [8] differential RR rate coefficients for the \( L \)-shell which were performed for the experimental conditions of the RR experiment [5] carried out at the electron cooler of the ESR storage ring. In this experiment the x-rays emitted from recombination of 23 MeV/u \( U^{92+} \) ions with cooling electrons, which were characterized by thermal transverse and longitudinal electron temperatures \( T_\perp = 120 \) meV and \( T_\parallel = 0.1 \) meV, respectively, were measured using two germanium detectors placed nearly at \( 0^\circ \) and \( 180^\circ \) (forward and backward directions) with respect to the ion beam direction. In this experiment the average electron-ion relative energy \( E_{\text{rel}} \) could be additionally detuned from its zero value corresponding for the electron cooling condition, which allowed to study the RR process in a wide range \( 0 \)–\( 1000 \) meV of relative energies.

As it was found in this experiment the intensities of measured K-RR X-rays were very sensitive to fine details of the angular distribution of emitted K-RR photons, which were attributed to the relativistic effects. Similarly, the X-rays from RR of electrons to the \( L \)-shell, which were observed in this experiment, are expected to be sensitive on the relativistic effects. However, for the \( L \)-shell only the x-rays emitted in RR to the \( L_3 \)-subshell \( (2p_{3/2}) \) were fully resolved, while for the \( L_1 \)- and \( L_2 \)-subshells \( (2s_{1/2}, 2p_{1/2}) \) the summed RR X-ray intensities were experimentally obtained. Consequently, in the present paper the RR of electrons to the \( L_3 \)-subshell of uranium ions is studied in more details. However, the results of calculations cannot be compared, at the present stage, with the experimental results which are preliminary and need yet to be corrected for different experimental effects. The analysis is currently in progress. Nevertheless the present calculations clearly demonstrate the importance of the relativistic effects, which is the main goal of the paper.

2 RR Cross section and rate coefficient

Radiative recombination cross section to a given \( n \)-state can be conveniently calculated with the Bethe-Salpeter formula [9] which, as a function of electron energy \( E \) in the ion frame, has the following form:

\[
\sigma_{\text{RR}}(E) = \sigma_0 \frac{G_n E_0^2}{nE(E_0 + n^2E)}
\]

where \( \sigma_0 = 2.1 \times 10^{-22} \) cm\(^2\), \( E_0 = Z^2\mathcal{R} \) is the hydrogenic binding energy of electron in the \( K \)-shell of hydrogen-like atom with the atomic number \( Z \) and \( \mathcal{R} = 13.6 \) eV is the Rydberg constant. \( G_n \) is so called Gaunt factor introduced in order to account for deviation of quantal Bethe-Salpeter cross section from the semiclassical result (see Ref. [10]). The Gaunt factor introduces small correction for the low \( n \)-states being for L-shell the value \( G_2 = 0.8762 \). The Bethe-Salpeter formula predicts the \( 1/E \) scaling of of RR cross sections in the low-energy limit \( (E \ll E_0) \), which is well suited approximation for interpretation of RR experiments in cooling storage rings (see Ref. [7]).

In order to calculate the nonrelativistic angle-differential RR cross section we applied the nonrelativistic dipole approximation in the low-energy limit [7,11]. In this approximation the angular dependence of the RR cross section is fully described by the asymmetry parameter \( \beta_{nl} \) as follows [7]:

\[
\frac{d\sigma_{\text{RR}}}{d\Omega} = \frac{\sigma_{\text{RR}}(E)}{4\pi} \left[ 1 - \frac{\beta_{nl}}{2} P_2(\cos \psi) \right]
\]