Emission characteristics of K cascade photons after radiative electron capture at strong central fields

P H Mokler1, 2, X Ma2, 3, E G Drukarev4, A I Mikhailov4 and I A Mikhailov4

1 Institut für Atom- u. Molekülphysik, Liebig Universität, 35392 Giessen, Germany
2 GSI, 64291 Darmstadt, Germany
3 Institute of Modern Physics, Lanzhou 73000, China
4 Petersburg Nuclear Physics Institute, Gatchina, St. Petersburg 188300, Russia

E-mail: P.Mokler@gsi.de

Abstract. For initially bare and hydrogen-like uranium ions (U92+ and U91+, respectively) a drastic difference in the emission characteristics is observed for the corresponding Ly-į1 and K-į1 cascade photons after radiative electron capture (REC) into the L shell of the projectile. Whereas the Ly-į1 x-rays are emitted preferentially perpendicular to the ion flight direction, the K-į1 photons show practically an isotropic emission pattern in the ion frame. Both, Ly-į2 and K-į2 radiation are emitted isotropically with respect to the ion. Analytical calculations in lowest order for the L-REC—K-x-ray cascade process concur nicely with the experimental findings for the energy region investigated (70 – 300 MeV/u).

1. Introduction

Radiative electron capture (REC) into highly charged heavy ions has extensively been investigated in recent years, both experimentally and theoretically [1-15]. In general, experimental findings and theoretical results concur quite nicely. For very heavy ions, higher multipoles (in particular M1) contribute to REC transitions at the prevailing strong central fields influencing the angular emission characteristics [8, 9]. REC to the various shells of a projectile ion is primarily determined by the total charge of the ion and practically not by the presence of spectator electrons as far as empty states are concerned [4, 13, 15]. Considering the predominance in the strength of the central potential in comparison to the relatively weak electron-electron interaction – for a U-ion (Z=92) it is in the percent region – this fact is quite understandable. REC is driven initially by the central potential, and the captured electron subsequently forms a bound state with the other target electrons, subject to the Pauli principle. For REC to higher shells the subsequent cascade decay to the ground state of the ion is determined by the usual atomic structure properties of the ion. The angular distribution of these cascade photons gives information on the alignment of the intermediate states populated by REC. For L-REC into bare U92+ ions strong alignment for the intermediate p½ state was found by the strong anisotropic emission pattern of the subsequent Ly-ą1 x-rays [5]. In contrast, for the equivalent K-ą1 radiation after L-REC into initially hydrogen-like U91+ ions, practically complete isotropy was reported [16].

The goal of the present paper is to elucidate the REC to the L shell in the strong central potential of highly charged U92+ and U91+ ions and explain the difference in the respective Ly-ą1 and K-ą1 x-ray emission characteristics. The experimental findings will be compared to analytical calculations of the REC—K-cascade process, where the cascade photons are treated in lowest order and Coulomb wave
functions in \((Zn)^2\) expansion are used. In the calculations the interaction between the electrons is totally neglected. For the low relativistic velocity region considered (around 100 MeV/u U ions) good agreement between experiment and theory is found.

2. Experimental results

Highly charged U ions in the region between typically 70 and 300 MeV/u are routinely stored in the experimental heavy ion storage ring ESR at GSI in Darmstadt. The capture of a quasi-free electron from a gas target into the ion is considered. This is a charge changing process and the down-charged ions are detected behind the next down-stream ESR magnet, cf. [1]. For heavy ions and light target atoms the radiative electron capture, REC, is the dominant capture process in this energy region. The emitted x-rays – REC photons as well as possible cascade photons – are detected at the target area by a bunch of solid state x-ray detectors (Ge(i)) at different observation angles \(\theta_{\text{LAB}}\) between 4° and 150°. The emitted x-rays are recorded in coincidence with singly down-charged ions thus excluding other processes possibly contributing to the x-ray emission.

In this communication we concentrate on the emission characteristics of the K x-ray cascade photons after REC to the projectile L shell. In order to avoid large systematic normalization uncertainties we focus here on intensity ratios taken with high accuracy within individual spectra. In particular, we consider the intensity ratios for the K x-ray lines for the two neighboring cases:

i) \(\text{Ly-}\alpha_2/\text{Ly-}\alpha_1\) intensity ratio for REC cascades in 310 MeV/u \(U^{92+}-N_2\) collisions [5], and

ii) \(\text{K}\alpha_2/\text{K}\alpha_1\) intensity ratio for REC cascades in 102 MeV/u \(U^{91+}-H_2\) collisions [16].

In figure 1 the L-REC—K-cascade processes for both the cases are depicted: L-REC populates the different intermediate L states which subsequently decay to the K shell. Two K x-ray lines are found in each spectra, where except for the \(\text{Ly-}\alpha_1\) line two transitions each contribute to the observed lines due to the limited resolving power of the Ge(i) solid state detectors. However, the two K x-ray lines observed are uniquely related with electrons captured to intermediate \(j = 1/2\) and \(j = 3/2\) states, leading to the \(\text{K}\alpha_1\) and \(\text{K}\alpha_2\) lines, respectively.

![Figure 1](image1.png)

**Figure 1.** L-REC—K-cascade process for initially bare and hydrogen-like U ions, left and right side respectively.

![Figure 2](image2.png)

**Figure 2.** Angular dependence of the \(\text{Ly-}\alpha_2/\text{Ly-}\alpha_1\) and \(\text{K}\alpha_1/\text{K}\alpha_2\) intensity ratio for 310 MeV/u \(U^{92+}+N_2\) (top) and 102 MeV/u \(U^{91+}+H_2\) collisions (bottom).

The angular dependences of the \(\text{Ly-}\alpha_2/\text{Ly-}\alpha_1\) and \(\text{K}\alpha_2/\text{K}\alpha_1\) intensity ratios found experimentally for the two cases are depicted in figure 2. Through the data points empirical fits are drawn to elucidate the difference in the emission characteristics. The \(\text{Ly-}\alpha_2/\text{Ly-}\alpha_1\) intensity ratio for the \(U^{92+}+e\) system is clearly peaked in the laboratory frame towards 50°. This transforms to an emission angle of \(\theta_{\text{CM}} = 90°\).
in the emitter frame of the ion at 310 MeV/u. In contrast for the U^{91+} + e system, the K-\(\alpha_1\)/K-\(\alpha_2\) intensity ratio shows no angular dependence within the experimental uncertainties.

It is emphasized that for the intensity ratios only the absolute angles have to be transformed from the laboratory (LAB) into the center of mass (CM) system, but not the solid angles. The solid angle transformation cancels for the intensity ratios and only the absolute angles have to be considered. Hence, from the representation given in figure 2 the emission characteristics in the CM frame can be read already. In this connection we note that both the Ly-\(\alpha_2\) and K-\(\alpha_2\) lines – referring to j = 1/2 intermediate states – show isotropic emission in the emitter frame of the ion [5, 16]. Consequently, the intensity ratios shown in figure 2 represent directly the characteristics of the Ly-\(\alpha_1\) and K-\(\alpha_1\) emission, i.e. the emission characteristics for the j = 3/2 capture states.

In the emitter frame (CM system) the angular distribution can be described by the form

\[ I(0_{\text{CM}}) = 1 + \beta_2 P_2(0_{\text{CM}}) \]

where \(P_2\) is the second-order Legendre polynomial and \(\beta_2\) the anisotropy parameter. We note that this expression can fortunately be applied for both the considered systems (for a detailed explanation see [17]). For the fits to the experimental data shown in figure 2 we used this representation for the distribution in the CM system. From the fits we find an anisotropy parameter of \(\beta_2 = -0.22\pm0.02\) for the U^{92+} + e system and practically of zero for U^{91+} + e system.

3. Comparison with theory

The obvious variance in the emission characteristics for the \(\alpha_1\) cascade x-rays for initially bare (Ly-\(\alpha_1\)) and hydrogen-like (K-\(\alpha_1,2\)) U as a function of ion energy.

**Figure 3.** Anisotropy parameter \(\beta_2\) for cascading K x-rays for initially bare (Ly-\(\alpha_1\)) and hydrogen-like (K-\(\alpha_1,2\)) U as a function of ion energy.

**Figure 4.** Emission characteristics for the two components 2 \(^1P_1\) and 2 \(^3P_2\) contributing to the K-\(\alpha_1\) line (CM system; 102 MeV/u U^{91+} + e).

For the \(K-\alpha_1\) emission two transitions contribute to the K-\(\alpha_1\) line, an E1 transition from the 2 \(^1P_1\) level and a M2 transition from the 2 \(^3P_2\) level. In figure 4 the emission characteristics for both the components of the K-\(\alpha_1\) line are shown separately in the ion frame (102 MeV/u U^{91+} + e). The E1 transition for K-\(\alpha_1\) (U^{91+} + e) behaves like the E1 transition for Ly-\(\alpha_1\) (U^{92+} + e), i.e. in the ion frame (CM system) an emission perpendicular to the ion direction is strongly preferred. Whereas the M2 emission prefers the emission along the ion flight direction, i.e. its characteristics is rotated by 90° to
the E1 emission. Adding up both the components with the proper weights gives an almost isotropic emission for the total K-α1 emission as observed in the experiment.

Finally we like to point to quite recent numerical calculations by Surzykrov and coworkers [18]. They applied a density matrix approach using multi-configuration Dirac-Fock wave functions and yielded closely comparable results, thus confirming nicely also our analytical approach.

4. Conclusions

The L-REC—K-cascade process was considered for the case of strong central fields for initially bare and hydrogen-like U ions at a moderate relativistic velocity regime of typically 100 MeV/u. The cascading Ly-α1 and K-α1 x-rays, respectively, show strong emission anisotropy for the initially bare ion case and almost complete isotropy for the initially hydrogen-like case. Calculations supported completely these experimental findings. However, in contrast to the uniquely defined Ly-α1 line, the K-α1 line is composed of two transitions of the adjacent 2 1P1 and 2 3P2 levels, both referring to captured p3/2 electrons. The respective E1 and M2 transitions show in the calculations both a strong anisotropy, however rotated by 90° to each other, thus mutually canceling for the total K-α1 emission. Experiment and theory for the total emission are in excellent agreement. It is interesting to note that also for the Ly-α1 case the M2 decay mode contributes to some extent also to the total transition amplitude [5, 12]. However, both amplitudes E1 and M2 have to be added coherently in this case. This so-called multipole mixing enhances the anisotropy, whereas the incoherent addition of the E1 and M2 components contributing to the K-α1 line results in an almost perfect cancellation of the anisotropy in the total emission. Moreover, we like to emphasize that L-REC into p3/2 levels yields strongly aligned states, i.e. an angular momentum transfer in flight direction is heavily suppressed. This alignment causes the observed strong anisotropy for the Ly-α1 emission as well as the calculated ones for the E1 and M2 transitions contributing to the isotropic K-α1 line. The E1 and M2 emission anisotropies are rotated by 90° to each other, a fact which has to do with the perpendicular behavior of the E and H components of the photon field. The mutual cancellation of the anisotropies for both contributing transitions was not at all foreseen from the beginning.

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