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L-Shell Alignment Observed after Resonant Transfer and Excitation in $U^{90+} \rightarrow C$ Collisions

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Abstract

With heavy, highly-charged ions the electron-electron correlation is probed in the relativistic domain by Resonant Transfer and Excitation, RTE. For the studied case of initially He-like U^{90+} ions the KLL-RTE splits into three resonance groups according to the j values of the electrons involved in the doubly-excited intermediate states. For a K to L excitation into a $j = 1/2$ state with a simultaneous capture also to a $j' = 1/2$ state, relativistic effects yield a strong cross section enhancement. The doubly excited states with $jj' = 1/2$–$3/2$ show a strong anisotropy for the radiative ground state transition of the $j' = 3/2$ electron manifesting a pronounced non-isotropic population of the magnetic substates.

1. Introduction

Resonant Transfer and Excitation, RTE, which is analogous to dielectronic recombination, can be considered as the time reversal of the Auger effect. Hence, it gives access to the interaction between the electrons involved. In strong central potentials the electron-electron correlation gets strongly influenced by relativistic effects. In particular, the Breit term can contribute considerably to the interaction (see e.g. Refs [1–3]). Correspondingly, strong enhancement factors in the resonance strengths for KLL-RTE are found experimentally for instance for the $jj' = 1/2$–$1/2$ resonance groups in the heaviest possible ions, like initially He-like U^{90+}. This has been observed both in the total charge exchange cross sections (Ref. [4]) as well as in the yield of stabilizing K X-rays (Refs [5] and [6]). Due to the large fine structure splitting in high Z ions, the doubly excited states split into three resonance groups according to the j value of the electron excited from the K to the L shell and to the j' value of the electron captured to the L shell. We have the $jj' = 1/2$–$1/2$, $1/2$–$3/2$ and $3/2$–$3/2$ resonance groups. The total charge exchange measurements integrate over all stabilizing decay channels of the doubly excited states, whereas the observation of the stabilizing X-rays allows to distinguish between the j values of the electron involved in the transition. The $K\alpha_1$ transition refers to an initial $j = 3/2$ electron state, and the $K\alpha_2$ transition to a $j = 1/2$ level. Both X-ray lines are well separated for U ions allowing to distinguish in the 1/2–3/2 resonance group between the various states involved. For the X-ray emission, additionally, the emission characteristics will give information on the population $P|m_j|$ of the magnetic substates for the doubly excited states. For uni-directional electron bombardment, which is the case for RTE, this alignment is predicted to be also influenced strongly by the strength of the central field (Ref. [7]). From experimentally measured emission characteristics the alignment of the intermediate states is deduced in this paper. For the non-relativistic case of lighter projectiles intermediate state alignment was discussed for RTE already earlier (Ref. [8]) and found experimentally in the Auger-decay channel (Ref. [9]).

2. Experiment and results

Highly-charged uranium ions in the energy range 100 to 140 MeV/u from the heavy ion synchrotron, SIS, are directed after stripping and charge state separation as He-like species, U^{90+}, onto a thin C target foil. Projectile X-rays from the target area are measured in coincidence with one electron capture with five Ge(i) X-ray detectors under lab. angles of 30°, 45°, 90°, 135° and 150°. In Fig. 1, below the sketch of the experimental set-up, the differential X-ray emission cross sections for $K\alpha_1$ (circles), $K\alpha_2$ (squares) and $K\alpha_1 + K\alpha_2$ (triangles) are given for two observation angles, 45° and 150°. The three resonance groups at 116, 124 and 132 MeV/u for the jj' values of 1/2–1/2, 1/2–3/2 and 3/2–3/2 are clearly visible. The resonance strength of the first group is found to be 19.1 ± 0.4 kb eV/sr and compares reasonably well with the theoretical value of 16.5 kb eV/sr, see Ref. [5]. In comparison to fully relativistic calculations a non-relativistic treatment gives only a value of 10.4 kb eV/sr. This confirms the importance of the magnetic interaction between both the electrons in high Z systems. For the two other resonance groups the differences between relativistic and non-relativistic resonance strengths are small and the results are in reasonable agreement with the experimental findings at 90° observation.

From the two excitation functions shown in Fig. 1 it is obvious that at least for the second resonance group, 1/2–3/2 resonances at 124 MeV/u, the ratio for $K\alpha_1$ and $K\alpha_2$ emission varies considerably with the observation angle. The difference in absolute scale for the cross sections at forward and backward observation is a result of the relativistic solid angle transformation from the ion system into the lab. frame. Here, we measured in detail the emission characteristics for the stabilizing $K\alpha_1$ and $K\alpha_2$ radiation.

In Fig. 2 the measured angular distribution for $K\alpha_2$ emission from the first resonance group at 116 MeV/u is displayed. The strong forward peaking is just caused by the

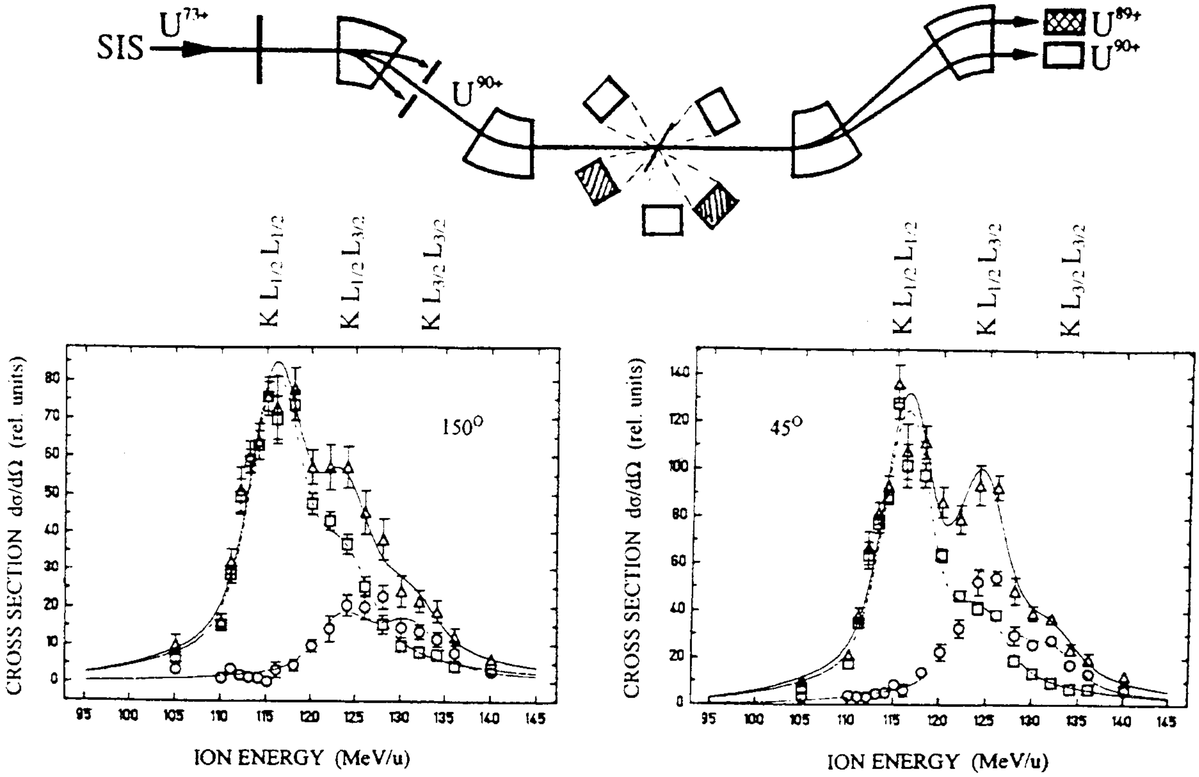

Fig. 1. Experimental set-up and excitation functions for KLL-RTE measured at backwards (150°) and forward (45°) emission angles (open circles: $K\alpha_1$ emission, open squares: $K\alpha_2$ emission, triangles: total X-ray emission).

relativistic solid angle transformation. Transforming an isotropic emission pattern from the emitting ion system into the lab. system gives the line shown in the figure. This isotropic emission distribution in the center of mass system fits exactly the measured emission characteristics observed in the laboratory. As we have solely $j = 1/2$ to $j = 1/2$ transitions for the first resonance group, we can have only isotropic emission in the corresponding reference system.

For the second resonance group, 1/2–3/2, we observe two X-ray lines, $K\alpha_1$ and $K\alpha_2$, referring to transitions from excited $j = 3/2$ and 1/2 states, respectively. Once more, we find isotropy for the $K\alpha_2$ emission as it refers to $1/2 \rightarrow 1/2$ transitions. In contrast, the $K\alpha_1$ emission is strongly anisotropic. Here, we deal with $3/2 \rightarrow 1/2$ transitions. In Fig. 3 the angular differential intensity ratio of the $K\alpha_1/K\alpha_2$ emission is displayed for the lab. system. In the emitting system these data can be characterized by a $\sin^2 \theta_{CM}$ distribution preferring 90° emission. The transformation of this emission characteristics from the CM system into the lab. system yields the curve shown in Fig. 3. This fit can be characterized by

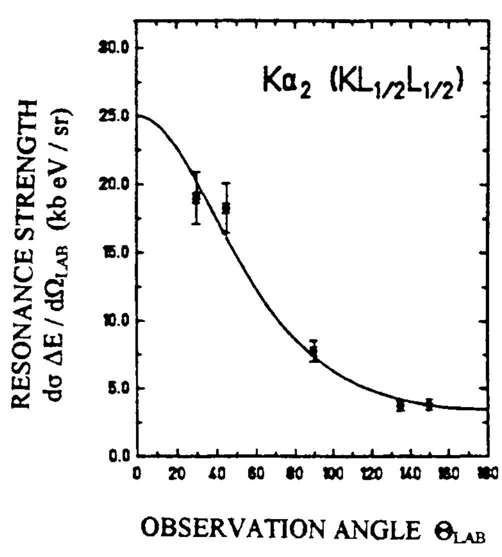

Fig. 2. Emission characteristics observed for the $K\alpha_2$ emission in the lab. frame.

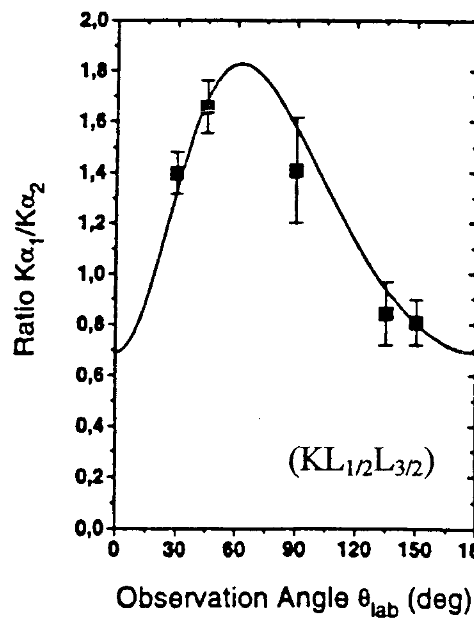

Fig. 3. Angular distribution of the $K\alpha_1/K\alpha_2$ intensity ratio observed in the lab. system.

an anisotropy parameter of $\beta_A = -0.5 \pm 0.04$. As β_A is proportional to the alignment A of the magnetic substate population $(P|m_j|)$ with

$$\beta_A \propto A = (P_{|3/2|} - P_{|1/2|})/(P_{|3/2|} + P_{|1/2|}),$$

a strong alignment of the $j = 3/2$ excited states with respect to the beam axis is found. For a $3/2 \to 1/2$ transition we have $\beta_A = 0.5 \cdot A$. Hence, from the measured large anisotropy value we deduce that only $|m_j| = 1/2$ magnetic substates are populated by RTE. Or, in other words, angular momentum can only be transferred perpendicular to the collision direction which is evident for the electron-electron interaction considered.

3. Conclusions

Strong alignment has been observed for KLL-RTE involving doubly excited states with $j = 3/2$ electrons for initially He-like U^{90+} projectiles. Similar anisotropies have recently been predicted for uni-directional dielectronic recombination processes with initially H-like U^{91+} ions (Ref. [7]): For the dielectronic satellites large anisotropy parameters for the corresponding transitions have been reported: the $2s2p\ ^1P_1$ and $^3P_2$ states lead to anisotropy parameters of -0.68 and -0.33, respectively, and the $2p^2\ ^3P_2$ and $^1D_2$ states to β_A values of -0.50 and -0.46. These transitions correspond in our He-like case to the $1s2s2p_{3/2}$ and $1s2p_{1/2}2p_{3/2}$ intermediate states contributing most pronouncedly to the 1/2–3/2 resonance. From this a clear concordance between the predictions and the experimental finding can be stated. Nevertheless, calculations adjusted to our system are needed for a final comparison. Finally, we like to emphasize that, according to our findings, the $K\alpha_1$ X-ray radiation has a strong linear polarization.

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