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**RADIATIVE AND RESONANT ELECTRON CAPTURE
STUDIES FOR HIGH-Z PROJECTILES**

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Radiative and Resonant Electron Capture Studies for High-Z Projectiles

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ABSTRACT

The experimental studies of Radiative (REC) as well as of Resonant Electron Capture (RTE) into highly charged high-Z ions are reviewed. For REC, total and subshell differential cross sections are presented. In particular, the data of an L subshell resolved angular distribution measurement performed for He-like uranium are discussed. The comparison with exact relativistic calculations reveals that such investigations are very sensitive to the final state wave functions and provide unique information on magnetic interactions occurring in relativistic ion-atom collisions. For Resonant Capture the results of a subshell as well as angular differential measurement of KLL-RTE in $U^{90+} \rightarrow C$ collisions are given. The comparison with a full relativistic treatment underlines the importance of the Breit interaction for such high-Z few electron systems. Moreover, the data exhibit a strong anisotropy for $K\alpha_1$ transitions associated with the $KL_{1/2}L_{3/2}$ intermediate states.

INTRODUCTION

In Radiative Electron Capture (REC) the transfer of a loosely bound ‘quasifree’ target electron into a bound state of the projectile is accompanied by the emission of a photon. Within the impulse approximation it can be treated as the time reversed photoionization process [1,2] and constitutes one of the most important projectile charge-exchange channels in fast encounters of high-Z ions and low-Z target atoms. Up to now most of the experimental work has been dedicated to total electron pick-up and K-shell capture cross-sections related to REC into bare and H-like ions [3–9]. By means of the available experimental systematics a universal scaling law for K-REC cross-sections could be established [9] based on the simple non-relativistic dipole-approximation [10]. This scaling law is in addition supported by rigorous relativistic calculations and can be explained in terms of an approximate cancellation among relativistic, retardation, and multipole effects [11]. This phenomenon occurs only for REC transitions into bound projectile s-states and only with respect to absolute cross section values. In particular, this fortuitous agreement between the dipole approximation and the exact relativistic treatment [2] also does not arise for angular-differential cross sections. In general, the angular-differential cross-sections are extremely sensitive to details of the atomic wave functions and give, therefore, detailed insight into the atomic structure of high-Z ions [2]. In the case of REC into projectile s-states such information is of particular interest as it reveals the influence of the electron spin in a unique way [2,12].

Similar to REC, Resonant Transfer and Excitation can be considered as a quasifree electron capture process [13,14]. Here, a loosely bound target electron is captured via resonant excitation of a projectile electron, forming in general a doubly excited state which decays by the emission of characteristic x-rays. This process is closely related to

the time reversed Auger effect (Dielectronic Recombination) which refers to an initially free instead of a quasifree electron. RTE has been studied in great detail for light and medium ions up to Xe [15,16]. However, for high- Z projectiles only one RTE experiment was reported where the resonance profiles were scanned via total charge exchange measurements [14]. In high- Z ions, the large fine structure splitting causes a splitting of the KLL resonance into three well separated resonance groups, where the subshell resonance cross sections are in particular sensitive to the Breit interaction between the electrons. Compared to total charge-exchange measurements, more detailed information is accessible when the resonant capture is measured by a $K\alpha_1/K\alpha_2$ resolved detection of the emitted x-rays. Here, angular distributions are in particular of relevance as they are sensitive to the RTE population amplitudes for the various intermediate states. Such experiments may provide information on possible interferences between the REC and RTE processes. Evidence for such interferences have been found for highly-charged uranium ions in a recent DR experiment performed at the Super-EBIT [17].

In section 2 all available electron pick up cross sections for bare high- Z ions related to REC are presented and compared with the dipole approximation as well as with correct relativistic calculations. In section 3 the L-subshell resolved angular differential data for REC into He-like uranium are shown. By comparing with rigorous relativistic calculations the relevance of the final state wave function is outlined. In section 4 a KLL-RTE experiment is discussed, performed for $U^{90+} \rightarrow C$ collisions. The data obtained are compared with complete relativistic calculations. Here, the importance of angular differential RTE measurements is stressed. Finally, in section 5, a short summary of the presented results is given.

TOTAL CHARGE EXCHANGE CROSS SECTIONS RELATED TO REC

In the case of K-REC the available data cover now almost the entire range of projectile charges. It was shown [9] that the various experimental data fall closely together on one common curve if plotted as a function of the 'adiabaticity parameter' η , where η is defined by

$$\eta = v^2/Z^2 \simeq 40.31 \times \frac{E_{\text{kin}}(\text{MeV/u})}{Z^2}, \quad (1)$$

with v denoting the velocity, E_{kin} the kinetic energy, and Z the atomic charge of the projectile. It is important to note that for the η -definition of Eq. (1) the relation $E_{\text{kin}} = \frac{1}{2}Mv^2$ was applied as if the projectile speed was non-relativistic (M is the mass of the projectile). In Fig. 1 all measured total cross section data for REC into bare projectiles, normalized to the number of available target electrons, are plotted versus the η -parameter (lower x-axis) as defined by Eq. 1. The data cover a projectile Z regime ranging from $Z=54$ up to uranium (for references see [9]). In addition the data are compared with the predictions of the non-relativistic dipole approximation [10] (solid line in Fig. 1). From the figure, a good agreement between the experimental results and the simple theory applied can be deduced. This must be attributed to the fact that for fast bare ions, the main contribution to the total REC cross section arises from REC into projectile s-states ($\eta > 1$) and in particular from K-REC. The exact relativistic cross

sections for various Z values do not follow the simple η -scaling rule. However, it has been shown that for low- η values ($\eta < 1$) these cross sections also fall on one common curve independent of Z whereas for higher η -values the theoretical data diverge slightly. Here, within the overall experimental accuracy, the available data are not sensitive to this slight cross section variation. Therefore only the relativistic exact results for $Z=80$ are plotted in Fig. 1 (dashed line) as it is close to the atomic number of the projectile systems used at the largest η -values. For this particular case of $Z=80$ the upper x-axis gives the cross section values as a function of projectile energy. As can be seen from the figure the relativistic prediction deviates at large η -values from the general scaling of the dipole-approximation. In fact, the results of the latter approach underestimate slightly the experimental cross section data at large η -values ($\eta > 3$ measured for Au and U ions at energies greater than 580 MeV/u).

Figure 1: Total electron-capture cross sections per target electron measured for bare ions ($Z \geq 54$) in collisions with light gaseous and solid targets. The results are plotted as a function of the η -parameter as defined by Eq. (1) (lower x-axis).

ANGULAR DIFFERENTIAL REC INVESTIGATIONS

Until recently only one dedicated angular distribution study of the REC process was available [18]. There it was found that for 197 MeV/u $\text{Xe} \rightarrow \text{Be}$ collisions the K-REC angular pattern closely follows a $\sin^2 \theta_{LAB}$ distribution in accordance with the non-relativistic approach, where θ_{LAB} denotes the laboratory observation angle. In order to elucidate in more detail the REC capture mechanism we conducted a first dedicated angular differential study of the L-REC process in 89 MeV/u $\text{U}^{90+} \rightarrow \text{C}$ collisions

[12]. Here, the large L-subshell splitting between the $j = 1/2$ and $j = 3/2$ levels of about 4 keV and the moderate Doppler broadening in the experiment allowed us to separate REC into the different j -sublevels and to investigate the associated angular distributions.

For the experiment, performed at the Fragment Separator (FRS) at GSI in Darmstadt, the reaction target area was surrounded by five solid state Ge(i) detectors mounted at observation angles of 30° , 45° , 90° , 135° and 150° with respect to the beam axis. At 30° and 150° specially designed, granular detectors were installed which consist of seven equidistant, parallel strips allowing us to cover observation angles θ of $27^\circ \leq \theta \leq 33^\circ$ and of $146^\circ \leq \theta \leq 154^\circ$, respectively. The x-ray emission registered by each detector was recorded event by event in coincidence with one-electron capture into the projectile. For the latter purpose, the ion beam was magnetically analysed behind the target and the different outgoing charge states were detected by scintillator counters.

In Fig. 2 one REC x-ray spectrum is shown, measured at 135° observation angle in coincidence with electron pickup by the He-like uranium projectiles. The REC transition lines appear broadened by the Compton-profile of the carbon target atoms and, in addition, by the Doppler effect. However, the various REC contributions due to capture into the L-, M-, N-... shell of the projectile are well resolved. In particular, the L-REC line is split into the two subshell components – $j = 3/2$ and $j = 1/2$.

Figure 2: Charge-state-coincident REC spectrum measured at an observation angle of 135° for 89 MeV/u $U^{90+} \rightarrow C$ collisions.

In Fig. 3 the obtained cross section ratios for radiative capture into the $j = 3/2$ state and into the $j = 1/2$ levels are normalized to the sum of both distributions and given as a function of the observation angle (solid points in Fig. 3). These ratios $\mathcal{R}$ are essentially not affected by possible systematic uncertainties. The solid and dashed lines in Fig. 3 show the corresponding theoretical predictions, based on the rigorous treatment of the REC process [2]. The main feature of the experimental data is a very strong forward/backward asymmetry as predicted by the exact relativistic theory. Also the results of the non-relativistic dipole approximation for $\mathcal{R}(j=1/2)$ are shown which considers also lowest order retardation effects (dotted line in Fig. 3) [19]. Obviously, this approach fails completely in describing the experimental results.

Figure 3: Measured differential L-REC cross sections for capture into the $j = 1/2$ and $j = 3/2$ sublevels in He-like uranium, normalized to the sum of both contributions.

In Fig. 4 the measured subshell-resolved L-REC angular-distributions are plotted. In order to compare the experimental results with the exact calculations, all measured data points were multiplied by one common factor of 0.65 which is still within the total normalization uncertainty. The predictions of the relativistic theory are given in the figure by the solid lines for the $j = 1/2$ levels and the $j = 3/2$ state. The data for the $j = 1/2$ -levels show a considerable bending of the angular distribution into the forward direction, whereas the distribution for capture into the $j = 3/2$ -state exhibits a slight enhancement at backward angles. This confirms in particular the prediction of the relativistic theory that the Lorentz transformation to the laboratory system is not sufficient to cancel for the $2p_{3/2}$ distribution the bending towards backward angles caused by retardation. Also, the calculated individual angular-distributions for the $2s_{1/2}$ and the $2p_{1/2}$ states are presented in Fig. 4 (the dotted and dashed lines, respectively). The $2s_{1/2}$ distribution deviates markedly from a $\sin^2\theta$ form. This distribution determines essentially the radiation pattern for capture into the $j = 1/2$ states at forward angles and the distribution for the $2p_{1/2}$ level follows closely the form for REC into the $2p_{3/2}$ state. The most remarkable aspect of the calculated distribution for the $2s_{1/2}$ state is that it predicts non-vanishing values at 180° and in particular at 0° observation angle. As has been pointed out in Ref. [2,20], angular momentum conservation requires that cross sections in the forward or backward directions can only be attributed to spin-flip transitions which are not considered in a non-relativistic theory. For K-REC into bare

Figure 4: Experimental angular distribution for REC into the $j_{1/2}$ states (solid points) and the $2p_{3/2}$ level (full circles) in comparison with exact relativistic calculations (solid lines). In addition, the theoretical results for capture into the $2s_{1/2}$ (dotted line) and the $2p_{1/2}$ (dashed line) states are shown separately.

high- Z ions ($Z > 54$) at high energies ($E_{KIN} \approx 300$ MeV/u) this effect is predicted to be much more pronounced [20]. In this case, i.e. capture into the $1s_{1/2}$ ground state, the spin-flip contributions can be measured directly by experiments. There is no other case known either by theory or from experiment, in which spin-flip effects mediated by magnetic interactions can be identified so unambiguously in a relativistic atomic collision. This is depicted in Fig. 5, where the K-REC angular distribution for 295 MeV/u $U^{92+} \rightarrow N$ is plotted (dotted line: $\sin^2 \theta_{LAB}$ form; solid line: relativistic correct calculations; shaded area: spin-flip contribution). In the lower part the ratio of spin-flip to total K-REC is displayed separately. Due to the chosen observation angle the only experiment performed up to now for high- Z ions was not sensitive to this effect (solid point in Fig. 5) [9]. However, it demonstrates that the ESR storage ring provides well defined experimental conditions for such challenging investigations.

Figure 5: K-REC angular distribution for 295 MeV/u $U^{92+} \rightarrow N$ collisions; dotted line: $\sin^2 \theta_{LAB}$ form; solid line: relativistic correct calculations [2]; shaded area: spin-flip contribution. In the lower part the ratio of the spin-flip contribution to the total REC distribution is displayed separately.

RESONANT ELECTRON CAPTURE

Using the same experimental set-up as for the L-REC studies the resonant KLL-RTE process was also investigated for $U^{90+} \rightarrow C$ collisions by scanning the beam energies in 20 steps from 105 to 140 MeV/u [21]. For He-like ions the $K\alpha$ emission along with electron capture into the projectile is an unambiguous signature of the resonant capture mechanism, i.e. $U^{90+}(1s^2) + e^- \rightarrow U^{89+}(1s2l_j 2l'_j) \rightarrow U^{89+}(1s^2 2l'''j'') + K\alpha$. Due to the closed K-shell of incident He-like ions neither the non-radiative nor the radiative capture events into excited projectile states can produce $K\alpha$ transitions.

Figure 6 shows the Doppler corrected, charge state coincident spectra for the three KLL-RTE resonance maxima located at the beam energies of 116 MeV/u for the $KL_{1/2}L_{1/2}$ -RTE, of 124 MeV/u for the $KL_{1/2}L_{3/2}$ -RTE, and of 132 MeV/u for the $KL_{3/2}L_{3/2}$ -RTE, respectively. The spectra were generated by adding up the individual spectra of the seven segments of the 30° detector. At this observation angle the characteristic $K\alpha$ transitions are best resolved. Also at this angle, which is close to the transformed 54.7° center-of-mass angle, the $K\alpha$ lines are almost not affected by angular distributions. The $K\alpha_2$ and $K\alpha_1$ lines (shaded area) are fixed for all collision velocities at the center-of mass energies of 96 and 100 keV in contrast to the REC transitions into the projectile L- and M-shell (hatched areas). The main feature of the presented spectra is the drastic variation of the relative $K\alpha_2$, $K\alpha_1$ intensities as a function of beam energy. It is

Figure 6: Coincident CM KLL-RTE x-ray spectra measured at 30° observation angle close to the three resonance maxima.

important to note that all intra-L subshell transitions are in general slower by two orders of magnitude than the $K\alpha$ transitions. Consequently, the subshell population cross sections for the various subshell resonances can be deduced directly from the $K\alpha_2$, $K\alpha_1$ intensities. For the data analysis, all x-ray intensities were normalized to the M-REC intensity in the spectrum by using theoretical M-REC cross sections [2]. As discussed in the previous section for the case of L-REC, the latter was found to deliver an appropriate description of the REC process. Similarly, the measured M-REC angular distributions are in excellent agreement with the applied rigorous relativistic approach [22].

Resonance	Experiment	Theory	Experiment	Theory
	$K\alpha_1$		$K\alpha_2$	
$KL_{1/2}L_{1/2}$	—	—	19.1 ± 0.4	$16.5(10.4)$
$KL_{1/2}L_{3/2}$	7.3 ± 0.2	$7.0(7.1)$	5.2 ± 0.3	$5.2(4.7)$
$KL_{3/2}L_{3/2}$	3.1 ± 0.2	$3.3(2.9)$	—	—

Table 1: Comparison between theoretical [23] and experimental $K\alpha_1$ and $K\alpha_2$ cross section strengths [21] for the KLL-RTE subshell resonances in He-like uranium (see text). All values given are in $\text{kb}\cdot\text{eV}/\text{sr}$.

The cross section strengths of the subshell resonances obtained from the $K\alpha_1$ and the $K\alpha_2$ intensities are summarized in table 1. In addition the results are compared with theoretical resonance strengths [23]. For theoretical predictions the Breit term of the Auger matrix elements was considered in one case and neglected in the other (see number in parentheses). Good agreement is found for the relativistically correct calculations including the Breit interaction. Moreover, the experimental data reveal that an isotropic $K\alpha_1$ emission can in general not be assumed. This is depicted in Fig. 7 where the measured $K\alpha_1/K\alpha_2$ intensities are given for the $KL_{1/2}L_{3/2}$ resonance as a function of the laboratory observation angle. This ratio varies by up to a factor of two. For comparison, also plotted in the figure is the intensity ratio of 1.36 which was derived from the theoretical RTE cross sections by assuming an isotropic emission

pattern. The observed strong variation of the relative $K\alpha$ intensities can be assumed to be essentially caused by the radiation pattern of the $K\alpha_1$ transitions, since the $K\alpha_2$ line contains only $j = 1/2$ to $j = 1/2$ transitions which are almost isotropic in the CM system. From this it can be deduced that there is a strong alignment of the $j = 3/2$ states produced by RTE.

Figure 7: Measured angular distribution of the $K\alpha_1/K\alpha_2$ intensity ratio for the $KL_{1/2}L_{3/2}$ resonance group [21].

SUMMARY

In conclusion, the limits of applicability of the non-relativistic dipole-approximation have been outlined by comparing this simple theory with total charge exchange cross sections as well as with subshell resolved L-REC angular distributions. The comparison with the differential data reveals a complete breakdown of the dipole-approximation in describing the subtleties of the REC process, and the good agreement found between the non-relativistic approach and the measured total cross sections must be regarded as fortuitous. For the angular differential results the applied rigorous relativistic calculations are shown to be most appropriate. The latter comparison exhibits that such studies are very sensitive to the final state wave function and they provide a novel access for the investigation of the magnetic interaction in relativistic ion-atom collisions. Moreover, the results of a dedicated KLL measurement for He-like uranium are given which were obtained by applying an x-ray/particle coincidence technique. Here, the $K\alpha$ production cross sections are found to be in excellent agreement with complete relativistic calculations including the Breit interaction. Also, a pronounced non-isotropic angular distribution for the $K\alpha_1/K\alpha_2$ intensity ratio has been found at the $KL_{1/2}L_{3/2}$ resonance. This indicates a strong alignment of the $p_{3/2}$ electrons in the intermediate state formed by RTE. With respect to this effect no theoretical information is presently available.

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REFERENCES

- [1] P. Kienle et al., 1099 (1973).
- [2] A. Ichihara, T. Shirai, and J. Eichler, Phys. Rev. A 49, 1975 (1994).
- [3] H.W. Schnopper et al., 898 (1972).
- [4] H. Tawara, P. Richard, K. Kawatsura, Phys. Rev. A 26, 1975 (1982).
- [5] S. Andriamonje et al., Phys. Rev. Lett. 59, 2271 (1987).
- [6] Th. Stöhlker et al., Z. Phys. D 23, 121 (1992).
- [7] L.C. Tribedi et al., Phys. Rev. A 49, 374 (1994).
- [8] C.R. Vane et al., Phys. Rev. A 49, 1847 (1994).
- [9] Th. Stöhlker et al., Phys. Rev. A 51 2098 (1995).
- [10] M. Stobbe, Ann. Phys. 7, 661 (1930).
- [11] A. Ron et al., Phys. Rev. A 50, 1312 (1994).
- [12] Th. Stöhlker et al., Phys. Rev. Lett. 73 3520 (1994).
- [13] P.H. Mokler, S. Reusch, Z. Phys. D 8, 393 (1988).
- [14] W.G. Graham et al., Phys. Rev. Lett. 65, 2773 (1990).
- [15] W.G. Graham, W. Fritsch, Y. Hahn, J.A. Tanis (Eds.), Recombination of Atomic Ions, Plenum Press, New York, 1992.
- [16] S. Andriamonje et al., Phys. Lett. A 154, 194 (1994).
- [17] D. A. Knapp et al., Phys. Rev. Lett. 74, 54 (1990).
- [18] R. Anholt, et al., 53, 234 (1984).
- [19] K.I. Hino and T. Watanabe, Phys. Rev. A. 36, 581 (1987).
- [20] J. Eichler, A. Ichihara, and T. Shirai, Phys. Rev. A 51, 3027 (1995).
- [21] T. Kandler et al., Phys. Lett. A accepted (1995).
- [22] T. Kandler et al., submitted to Z. Phys. D (1995).
- [23] M. Zimmermann, private communication and P. Zimmerer, N. Grün, W. Scheid, Phys. Lett. A 148, 457 (1990).