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NEW EVIDENCE FOR RESONANT-TRANSFER-AND-EXCITATION FOR $_{16}S$, $_{20}Ca$, and $_{23}V$ IONS COLLIDING WITH HELIUM

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Abstract

Significant new evidence is presented for resonant-transfer-and-excitation (RTE) in ion-atom collisions. This process occurs when a target electron is captured simultaneously with excitation of the projectile followed by de-excitation via photon emission. RTE, which is analogous to dielectronic recombination (DR), proceeds via an inverse Auger transition, and is expected to be resonant for projectile velocities corresponding to the energy of the ejected electron in the Auger process. Cross sections for projectile K x-ray emission coincident with single electron capture have been measured for 70-160 MeV $_{16}S^{13+}$, 100-360 MeV $_{20}Ca^{16+,17+,18+}$ and 180-460 MeV $_{23}V^{19+,20+,21+}$ ions colliding with helium. Strong resonant behavior, in agreement with theoretical calculations of RTE, is observed as a function of beam energy in the measured cross sections. For Ca and V ions two maxima are observed in the energy dependence of the measured coincidence cross sections. Theoretical calculations show that these maxima are correlated to two groups of intermediate resonant states in the RTE process for which the excited and captured electrons occupy levels with principal quantum numbers $n = 2,2$ and $n = 2,\geq 3$.

Introduction

The overall goal of this work is to investigate correlations between charge-changing interactions and K x-ray emission for highly charged ions incident on gas targets under single collision conditions. Experimentally, coincidences are measured between x-rays (emitted from the projectile or the target) and the outgoing projectile charge state of interest. This technique allows the individual inner-shell processes of of excitation, ionization, and charge transfer to be isolated and identified. Cross sections for total electron capture and loss (single and double) and total x-ray production are obtained at the same time. To date the primary emphasis has been the study of x rays associated with single electron capture.

In an ion-atom collision, resonant-transfer-and-excitation[1,2](RTE) takes place when capture of a bound target electron is accompanied by simultaneous excitation of the ion, followed by de-excitation via photon emission. RTE is qualitatively analogous to dielectronic recombination (DR), except that, in the case of DR, the captured electron is initially free. Simultaneous capture-and-excitation involving a free electron is the inverse of an Auger transition and hence is resonant for incident electron energies (in the rest frame of the ion) equal to the outgoing electron energy in the Auger process. In the case of RTE, simultaneous capture-and-excitation is also expected to be resonant for incident ion energies (in the rest frame of the target) which correspond to the ejected Auger electron energies. For both RTE and DR many intermediate resonance states are possible, each one corresponding to an allowed Auger transition. A formal theoretical treatment of simultaneous charge transfer and excitation in ion-atom collisions has recently been developed by Feagin, Briggs and Reeves.[3]

Experimentally, observation of a resonant behavior in the cross section for x rays (resulting from the decay of the intermediate excited state) coincident with electron capture identifies the RTE mechanism and distinguishes it from competing channels such as nonresonant-transfer-and-excitation (NTE).[4] Since the velocity component of the target electrons (due to their orbital motion) along the beam axis contributes to the relative velocity, the widths of the resonance states reflect the distribution of target electron momenta i.e., their Compton profile. This distribution is sufficiently large to result in the overlapping of the separate intermediate resonant states. Hence, only a broad maximum due to the sum of the unresolved contributions of the individual states is expected.[5]

Recent experimental studies[2,6] have provided strong evidence for RTE and indicate that RTE cross sections are closely related to dielectronic recombination cross sections. It appears likely that RTE measurements will be useful in testing theoretical DR cross section calculations, particularly for highly ionized ions. Investigation of RTE is important from a fundamental point of view as well as for its relationship to DR for possible applications to astrophysical investigations and the development of magnetically confined nuclear fusion plasmas.[7]

The first experimental evidence for the existence of RTE was obtained in measurements of 70-160 MeV S^{13+} + Ar collisions.[2] As expected for RTE resonant behavior was observed in the cross section for K x-ray emission associated with capture. The position of the maximum and the width of the peak are in good agreement with theoretical calculations[5] of the RTE process. However, the theoretical interpretation of the results is complicated by the complexity of the argon target with its 3 electronic shells including the tightly bound 1s electrons. In addition, a relatively large nonresonant contribution to the x-ray yield coincident with capture was present for these S^{13+} + Ar measurements.

Investigation of RTE in collisions of ions with a helium target promises a simpler interpretation since there are only 2 target electrons, both weakly bound compared to the relative kinetic energy between the projectile and the target. Furthermore, the 2 electron system of helium should give a narrower "resonant" width due to the smaller electron momentum distribution for the target electrons compared to argon[2].

In the following we present significant new evidence[6,8] for the resonant-transfer-and-excitation process for sulfur, calcium and vanadium ions incident on helium. Strong resonant behavior was observed for all three ions in the energy dependence of the cross section for projectile K x rays coincident with single electron capture.

Experimental Procedure

This work was performed at the University of California, Lawrence Berkeley Laboratory using the SuperHILAC and at the Brookhaven National Laboratory using the MP Tandem Van de Graaff. In each case the apparatus has been described elsewhere[2,9].

Briefly, the experimental technique for measuring x-rays associated with electron capture is as follows: Ions in a given charge state pass through a differentially pumped gas cell. After emerging from the cell, the beam is magnetically or electrostatically analyzed into its charge state components. Ions which undergo capture in the target gas are detected in a solid state particle detector while the x rays are detected with a Si(Li) detector mounted at 90° to the beam. Coincidences between ions and x rays are measured with a time-to-amplitude converter (TAC). The non-charge-changed-component of the emerging beam is collected in a Faraday cup. A capacitance manometer is used to measure the absolute pressure in the target gas cell. Data were obtained for 3-5 pressures in the range 0-80 microns for each beam energy and charge state studied. The total x-ray yields and the coincidence yields were found to be linear with gas pressure in the range studied indicating that single collisions conditions prevailed.

Results

RTE was investigated for 70-160 MeV S^{13+} + He collisions[8] (Brookhaven) and for 100-360 MeV $_{20}Ca^{16+,\ 17+,\ 18+}$ and 180-460 MeV $_{23}V^{19+,\ 20+,\ 21+}$ + He collisions[6] (Berkeley). Figures 1, 2a, and 3a show the cross sections for total projectile K x-ray emission, $\sigma_{K\alpha\beta}$ and the cross sections for projectile K x rays coincident with single electron capture, $\sigma^{q-1}_{K\alpha\beta}$. Figs. 2b and 3b show the measured $\sigma^{q-1}_{K\alpha\beta}$ for $_{20}Ca^{17+}$ and $_{23}V^{20+}$ ions (lithiumlike in each case) along with the calculated[10] RTE cross sections based on the method of Brandt.[5] Also shown are the energy positions and relative contributions of the intermediate resonant states based on the dielectronic recombination cross section calculations of Hahn [11] and coworkers. Relative uncertainties are generally less than ±5% for $\sigma_{K\alpha\beta}$ and less than ±10% for $\sigma^{q-1}_{K\alpha\beta}$. Systematic uncertainties due to x-ray detection efficiency and solid angle lead to an overall uncertainty in the absolute cross sections of about ±20%.

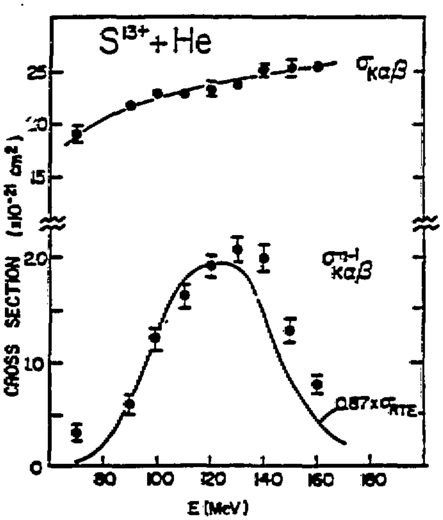
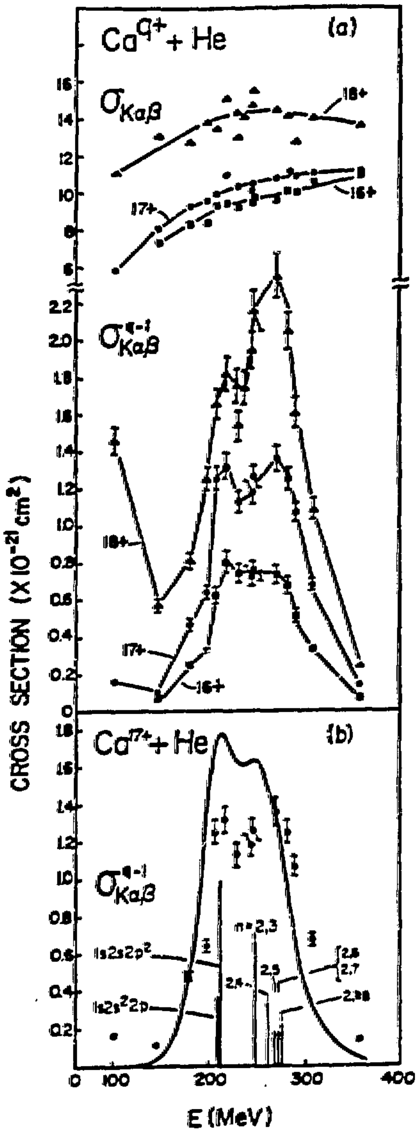


FIG. 1. Projectile cross sections for 70-160 MeV S^{13+} + He. $\sigma_{K\alpha\beta}$ is the cross section for total sulfur K x-ray production and $\sigma^{q-1}_{K\alpha\beta}$ is the cross section for sulfur K x rays coincident with single-electron capture. The solid line through $\sigma_{K\alpha\beta}$ is drawn to guide the eye. The line through $\sigma^{q-1}_{K\alpha\beta}$ is the calculated (Ref. 5) RTE cross section.

FIG. 2 (a) Projectile cross sections for 100–360 MeV Ca^{q+} + He for q = 16+, 17+ and 18+. $\sigma_{K\alpha\beta}$ is the cross section for the total calcium K x-ray production. $\sigma^{q-1}_{K\alpha\beta}$ is the cross section for calcium K x rays coincident with single-electron capture. The solid lines are drawn to guide the eye. (b) $\sigma^{q-1}_{K\alpha\beta}$ for Ca^{17+} + He. The solid curve is the calculated (Ref. 10) RTE cross section. The vertical bars give the theoretical positions and relative intensities of the intermediate states for dielectronic recombination (Ref. 11). The notation n = 2,3 etc. refers to the principal quantum numbers of the two electrons in these intermediate states. The two states near 210 MeV are the n = 2,2 transitions.



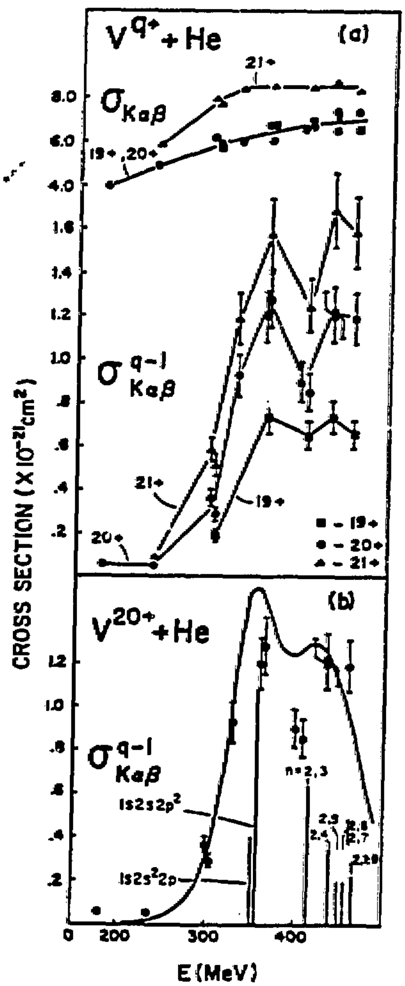


FIG. 3 (a) Projectile cross sections for 180–460 MeV V^{q+} + He for q = 19+, 20+, and 21+. See caption for Fig. 2. (b) $\sigma^{q-1}_{K\alpha\beta}$ for V^{20+} + He. See caption for Fig. 2.

From these figures it is seen that $\sigma_{K\alpha\beta}$ varies slowly with energy in all cases. On the other hand, strong resonant behavior is observed in the energy dependence of $\sigma^{q-1}_{K\alpha\beta}$ for each ion and charge state investigated. Furthermore, from Figs. 2a and 3a it is seen that $\sigma^{q-1}_{K\alpha\beta}$ exhibits two maxima for $_{20}Ca$ and $_{23}V$ ions for each incident charge state. For vanadium the measurements extend to 460 MeV which is the highest beam energy obtainable for ^{51}V at the SuperHILAC. Contributions to the measured $\sigma^{q-1}_{K\alpha\beta}$ for $_{20}Ca^{18+}$ and $_{23}V^{21+}$ (heliumlike) from 1s2s metastable states are expected to be small.[12]

In Figs. 1-3, the data at the highest and lowest beam energies indicate that the nonresonant contribution to $\sigma^{q-1}_{K\alpha\beta}$ is small in contrast to the previous results[2] obtained for S^{13+} + Ar. This nonresonant part may be due to uncorrelated capture and excitation in a single collision with one target atom. For helium the smaller nonresonant yield is probably related to the lower electron capture and K-shell excitation probabilities for helium compared to heavier targets. Recent calculations by Feagin and Reeves[13] show that for the collision systems studied here the nonresonant part of $\sigma^{q-1}_{K\alpha\beta}$ should be a factor of about 10 lower than the resonant part in the "resonance" region.

Discussion

The maxima in $\sigma^{q-1}_{K\alpha\beta}$ are attributed to RTE, which occurs as a result of the formation of intermediate resonant states (for lithiumlike ions) such as $1s^22s \rightarrow 1s2s^22p$, $1s2s2p^2$, $1s2s^23p$, 1s2s2p3p, etc. followed by K x-ray emission. The solid curves in Figs. 1,2b, and 3b are the calculated [5,10] RTE cross sections σ_{RTE} for S^{13+}, Ca^{17+} and V^{20+} using the method of Ref. 5 based on dielectronic recombination cross sections[11]. The shape, magnitude, and energy position of the calculated RTE cross sections are observed to give reasonable overall agreement with the measured $\sigma^{q-1}_{K\alpha\beta}$ in each case.

For Ca^{17+} and V^{20+}, based on the theoretical dielectronic recombination energies[11] (see Figs. 2b and 3b), the lower energy maximum corresponds to intermediate resonant states for which the excited and the captured electrons occupy levels with principal quantum numbers n = 2,2, i.e., $1s2s^22p$ and $1s2s2p^2$. The higher energy maximum corresponds to intermediate states $1s2s^23p$, 1s2s2p3p, 1s2s2p4p, etc., for which $n = 2,\geq 3$. This means that those intermediate states populated in the collision which give rise to the low energy peak decay by $K\alpha$ transitions only, while the higher energy peak contains contributions due to both $K\alpha$ and $K\beta$.

Fig. 4 shows the ratio of $K\alpha$ coincidences with single electron capture to all K x-ray (i.e. $K\alpha$ + $K\beta$) coincidences with single capture for V^{20+} ions. In the region of 360 MeV, this ratio is essentially unity, indicating that all

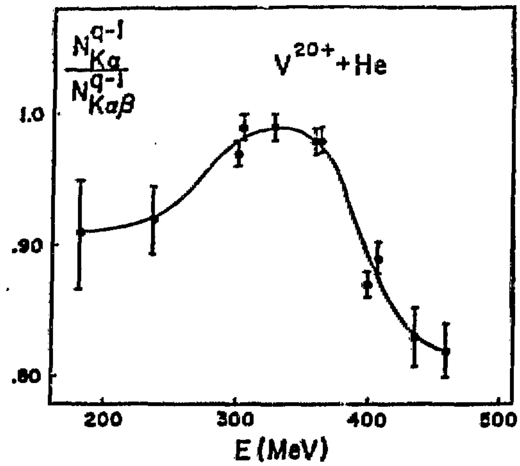


FIG. 4. Fraction of total K x-ray production coincident with single electron capture which results in Kα emission for V^{20+} ions. This plot shows that essentially all coincidence events in the vicinity of 360 MeV arise from Kα transitions. The line is drawn to guide the eye.

the coincidences are associated with Kα, while in the region of 435 MeV about 85% of the coincidences are with Kα. A similar result is found for Ca^{17+} ions. This correlation of certain energy regions within the resonant structure with specific n states as predicted by the RTE calculations,[5,10] provides very strong evidence that the observed maxima in $\sigma_{K\alpha\beta}^{q-1}$ are, in fact, due to RTE. For energies $\lesssim$ 300 MeV, the plotted ratio indicates the fraction of coincidences resulting from Kα emission for uncorrelated capture and excitation events.

For $_{16}S^{13+}$ + He collisions (Fig.1) two maxima are not observed in $\sigma_{K\alpha\beta}^{q-1}$. In this case the energy separation (∿ 20 MeV) of the n = 2,2 and the n = 2, ≥ 3 intermediate resonant states is less than the energy spread in σ_{RTE} due to the bound target electron momenta.

In Fig. 5 we show the calculated[10] RTE cross section for lithiumlike ions from silicon to iron incident on helium. This figure shows that the separation

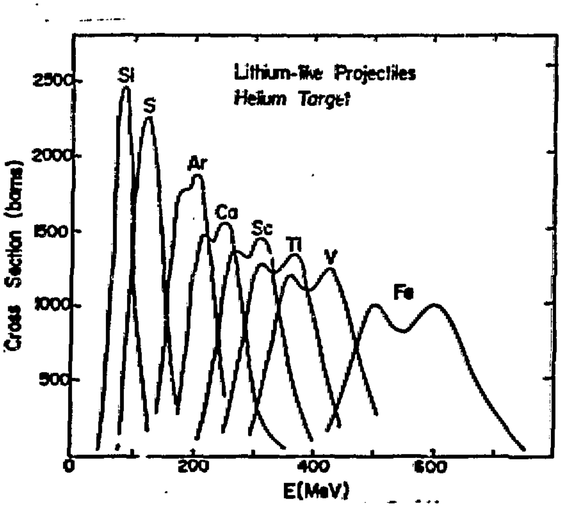


FIG. 5. RTE cross sections, σ_{RTE}, for ions in the range 14 ≤ Z ≤ 26 incident on helium. The magnitudes of the DR cross sections used in these calculations were taken to be constant and equal those given for S^{13+} by McLaughlin and Hahn in Ref. 11. The DR cross sections, obtained from the information in Ref. 11 do not vary greatly over this range of Z. These calculations show the qualitative features of σ_{RTE} and the onset of structure for Z $\gtrsim$ 18.

of the n = 2,2 states and n = 2,≥ 3 states is sufficient to expect partial resolution of these groups for incident ions with Z ≳ 18.

This partial resolution of the intermediate states into the groups n = 2,2 and n = 2, ≥ 3 is significant since it allows a more direct and detailed comparison with theory than earlier measurements[2] without such structure. For example, the lower energy peak, corresponding to transitions with principal quantum numbers n = 2,2 for the two electrons involved, (see Figs. 2b and 3b) arises from only two intermediate resonant states, and so the sum of these two transitions namely, $1s^22s \rightarrow 1s2s^22p$ and $1s^22s \rightarrow 1s2s2p^2$, can be compared directly with theory.

In Fig. 6 the experimental peak heights for $\sigma^{q-1}_{K\alpha\beta}$ are compared with the theoretical[5,10] peak heights for σ_{RTE} for the three ions investigated. For calcium and vanadium the heights of $\sigma^{q-1}_{K\alpha\beta}$ corresponding to the n = 2,2 states were used in this comparison. It is seen that the absolute magnitudes of the experimental cross sections are about 15-25% lower than predicted by the calculations. These results are to be contrasted with those for S^{13+} + Ar collisions [2] (also shown) in which the experimental yield of S Kα x rays coincident with single capture was factor of 2 larger than predicted.

The reasonable agreement of the positions of the maxima and the relative heights of the peaks in $\sigma^{q-1}_{K\alpha\beta}$ with the calculations (Figs. 2b and 3b) suggests that the relative probabilities for the population of groups of intermediate

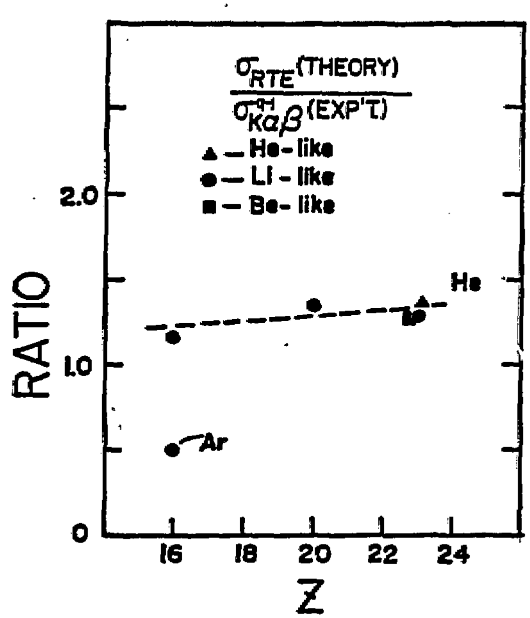


FIG. 6. Ratio of the theoretical RTE cross sections σ_{RTE} and the experimental cross sections for K x rays coincident with single electron capture $\sigma^{q-1}_{K\alpha\beta}$ for $_{16}S^{13+}$, $_{20}Ca^{17+}$, and $_{23}V^{19+,20+,21+}$ ions incident on He. Also shown is this same ratio for S^{13} + Ar from Ref. 2. The RTE calculations for calcium and vanadium are from Ref. 10. The DR cross sections used to obtain σ_{RTE} are from Ref. 11.

states with specific n values in the RTE process are nearly the same as those calculated for dielectronic recombination. Thus it would appear likely that RTE measurements will be useful in testing DR calculations, particularly for highly ionized ions. It should be noted, however, that the experimental minimum in $\sigma^{g-1}_{K\alpha\beta}$ in both Figs. 2b and 3b is lower than that calculated, and also that the relative experimental peak heights are not reproduced exactly by the calculations. For S^{13+} and for Ca^{17+} there is also an obvious deviation between σ_{RTE} and $\sigma^{g-1}_{K\alpha\beta}$ at the higher projectile energies. These differences may be due to one or more of the following reasons: (1) the electron momentum distribution used in the RTE calculation may overestimate the width of the actual distribution, (2) the relative amplitudes for formation of the various intermediate states may be slightly different for dielectronic recombination and RTE, (3) the assumed Z^2 scaling used to obtain the intermediate resonant state transition energies may not be exactly correct, and (4) the DR cross sections for $n = 3, \geq 3$ have not been calculated and hence contributions due to these states are not included in the RTE calculations.

Conclusion

In summary, important new evidence for the existence of resonant-transfer-and-excitation has been presented. The use of a helium target, with only 2 weakly bound electrons, simplifies the theoretical interpretation of the experimental results compared to previous measurements with many-electron targets. The observation of two maxima in the cross section for K x-ray production associated with electron capture for calcium and vanadium provides a more detailed and critical test of the RTE theory and the calculated dielectronic recombination cross sections which go into the theory. The experimental results are in substantial agreement with the predictions of this theory.

Apart from any connection to dielectronic recombination the large resonant contribution to the coincidence yield due to RTE demonstrates the fundamental significance of this process and indicates the necessity of including RTE in theoretical formulations of ion-atom collision interactions.

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