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Resonant transfer and excitation: Dependence on projectile charge state and target-electron momentum distribution

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Resonant transfer and excitation (RTE) involving simultaneous electron capture and projectile K-shell excitation has been measured for calcium ions in charge states ranging from neonlike to hydrogenlike incident on molecular hydrogen over an energy range 100–370 MeV. The results establish a projectile charge-state dependence for RTE and provide a detailed test of theoretical calculations. The effect of the target-electron momentum distribution on the RTE process is demonstrated by comparing with previous results for calcium ions incident on helium.

Resonant transfer and excitation[1,2] (RTE) occurs when capture of a bound target electron is accompanied by simultaneous excitation of the projectile followed by deexcitation via photon emission. This process is analogous to dielectronic recombination[3] (DR), in which the captured electron is initially free instead of bound. RTE and DR proceed via an inverse Auger transition and, hence, are resonant for projectile velocities (in the rest frame of the electron) corresponding to allowed Auger electron energies. Many intermediate resonance states are possible for both RTE and DR, each one corresponding to an Auger transition. Experimentally, observation of resonant behavior in the energy dependence of the x-ray yield, resulting from decay of the intermediate excited states, associated with electron capture identifies the RTE mechanism. A formal theoretical treatment of simultaneous charge transfer and excitation in ion-atom collisions has been developed recently by Feagin, Briggs, and Reeves.[4]

DR has been identified as a possible energy-loss mechanism in magnetically confined nuclear fusion plasmas since impurity ions (such as C, O, Fe, etc.) in the plasma can recombine by this mechanism. Hence, DR has been the subject of intense experimental and theoretical investigations. Measurement of cross sections for DR has proven to be a formidable task since either crossed-beam or merged-beam techniques are required, and laboratory data on this important fundamental process have only recently become available.[5]

Recent experimental[1,2] and theoretical studies[6,7] have established the existence of RTE in ion-atom collisions. These studies indicate that RTE closely approximates dielectronic recombination, and it appears likely that RTE can be used as a benchmark in testing theoretical calculations of DR cross sections, particularly for highly ionized ions. Since RTE can be measured in collisions with static targets, merged or cross-beam techniques are not required. DR has been measured to date principally for low-charge-state ions with atomic numbers $Z \lesssim 15$, while RTE has been measured mainly for high-charge-state ions with atomic numbers $Z \gtrsim 15$. It should also be noted that DR has been measured *only* for transitions in which $\Delta n = 0$, while RTE has been measured *only* for $\Delta n = 1$ transitions (n is the principal quantum number).

Having established the existence of RTE and its close relationship to DR, it is of fundamental and applied interest to determine the dependence of RTE on projectile and target atomic number Z, and the dependence on projectile charge state q. We have obtained[8] previously the projectile atomic number dependence of RTE over the range $16 \leq Z \leq 23$. In the present Rapid Communication we report (1) a systematic study of the charge-state dependence of RTE for calcium ions with incident charge states ranging from $q = 10+$ (neonlike) to $q = 19+$ (hydrogenlike) incident on H_2, and (2) the effect of the target electron momentum distribution (i.e., the Compton profile) on RTE, by comparing measurements for lithiumlike calcium ions incident on H_2 and He. The data are compared with calculated RTE cross sections[6] based on theoretical DR cross sections.[7] The charge-state scaling of RTE and DR have not been tested experimentally. The present measurements provide a detailed test of the calculated charge-state dependence of DR cross sections for a wide range of ionic charge states. The comparison with previous measurements for helium targets shows directly the effect of the target Compton profile on the RTE cross sections.

This work was carried out at the Lawrence Berkeley Laboratory using the SuperHILAC facility. The experimental technique consists of measuring projectile K x rays coincident with electron-capture events. Projectiles in a given charge state pass through a differentially pumped gas cell. X rays produced in collisions with the target gas are detected with a Si(Li) detector mounted at 90° to the beam axis. The beam, after emerging from the gas cell, is magnetically analyzed into its charge-state components. Ions which undergo electron capture in the target gas are detected with a solid-state detector. The non-charge-changed component of the emerging beam is collected in a Faraday cup. Coincidences between K x rays and projectile ions which capture an electron are measured using a time-to-amplitude converter. The x-ray and coincidence yields are measured as a function of gas pressure to obtain the desired cross sections and to ensure that single-collision conditions prevail. A capacitance manometer was used to measure the absolute pressure in the target gas cell.

RTE was investigated for 100–370-MeV ${}_{20}\mathrm{Ca}^{10,11,12,16,17,18,19+} + H_2$ collisions. The cross sections for projectile K x rays coincident with single-electron capture $\sigma_{K\alpha\beta}^{q-1}$ are shown in Fig. 1. These results are consistent with previous measurements[2] for Ca^{q+} and V^{q+} + He, in which two maxima were also observed in the energy dependence of $\sigma_{K\alpha\beta}^{q-1}$. These two maxima correspond to groups of intermediate resonance states in the RTE process for which the excited and the captured electrons occupy energy levels with quantum numbers[9] $n = 2,2$ or $n = 2, \geq 3$ [see Fig. 1(b) of Ref. 2]. The present results for Ca^{19+} are the first observation of RTE for a hydrogenlike ion which, of course, has an initial vacancy in the K shell. The large rise in $\sigma_{K\alpha\beta}^{q-1}$ for Ca^{19+} as the beam energy is decreased below 200 MeV is probably due to electron capture, without accompanying excitation, to an excited state ($n \geq 2$) followed by deexcitation via photon emission to the already existing K vacancy in the incident projectile. The strong dependence of $\sigma_{K\alpha\beta}^{q-1}$ on the incident charge state of the projectile is obvious. Since the lower-energy maximum in $\sigma_{K\alpha\beta}^{q-1}$ results from RTE involving $n = 2,2$ transitions, there must be at least two initial vacancies in the L shell of the ion (for calcium ions, charge states $q \geq 12+$) to have a contribution to the first maximum. For the higher-energy maximum, i.e., $n = 2, \geq 3$ transitions, there must be at least one L vacancy (for calcium ions, $q \geq 11+$) for $n = 2,3$ to contribute to the maximum. For calcium ions in charge states $q \leq 10+$ only $n = 3, \geq 3$ transitions can contribute to RTE. However, calculations[10] indicate that the probability of occurrence of these $n = 3, \geq 3$ transitions is very small.

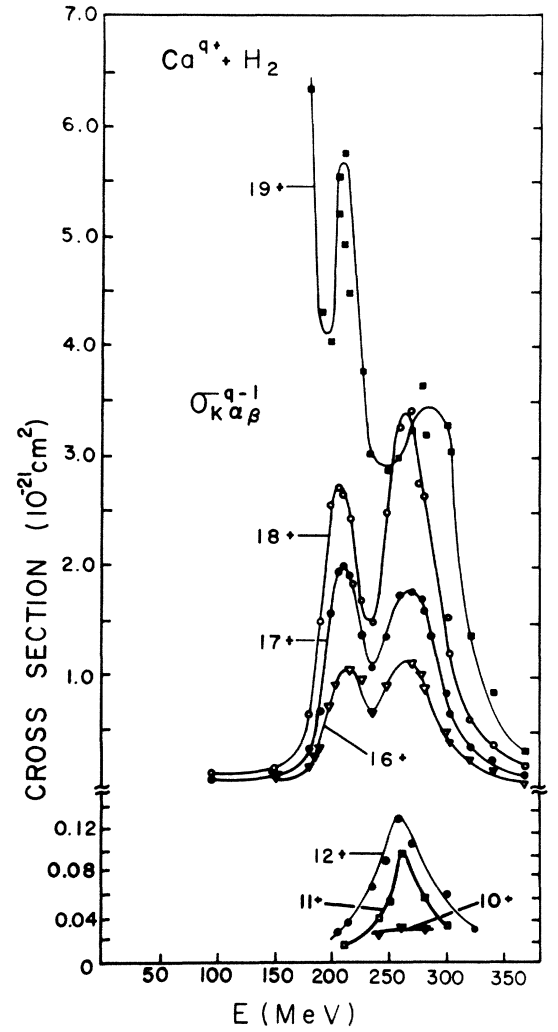

FIG. 1. Cross sections for projectile K x rays coincident with single-electron capture, $\sigma_{K\alpha\beta}^{q-1}$, for collisions of ${}_{20}\mathrm{Ca}^{q+}$ ions with H_2 ($q = 10$, 11, 12, 16, 17, 18, and 19). The solid curves are drawn to guide the eye. Note the scale change for the $\mathrm{Ca}^{10,11,12+}$ data. Relative uncertainties in the data are typically (5–10)%, and the absolute uncertainty is estimated to be ±20%.

The dependence of the $\sigma_{K\alpha\beta}^{q-1}$ cross-section maxima on the charge state of the incident projectile is displayed in

Fig. 2 for both the $n=2,2$ and the $n=2,\geq 3$ transitions. The values for the maxima were obtained by subtracting a linear background from each of the observed $n=2,2$ and $n=2,\geq 3$ peak heights. The background was determined from a linear interpolation of the measured nonzero contribution to $\sigma_{K\alpha\beta}^{q-1}$ near 150 and 370 MeV. The error bars shown in Fig. 2 are relative errors which were determined by combining in quadrature the uncertainties in the peak heights and the background. The absolute uncertainty in the data is estimated to be ± 20%. The lines show the calculated RTE maxima for these same transitions based on the theoretical DR cross sections of Hahn and coworkers.[7] The theoretical DR maxima for Ca^{q+} were determined in some cases by interpolation or extrapolation of the DR cross-section calculations for neighboring ions of the same isoelectronic sequence. Based on calculations[7] to date, which indicate that DR cross sections vary smoothly with the projectile atomic number, these theoretical DR values for Ca^{q+} are expected to be accurate[10] to 10% for charge states $q=16-19+$ and to 50% for charges states $10-12+$. The calculated values for the RTE maxima shown in Fig. 2 were then obtained by multiplying the theoretical DR maxima by a factor[11] to take into account, in an average way, the energy distribution of the DR transitions and the effect of the target electron momentum distribution. It is seen that the predicted charge-state dependence agrees reasonably well with the data.

The measurements for $\mathrm{Ca}^{16,17,18+}+\mathrm{H}_2$ provide a direct comparison with our earlier results for these same ions incident on He. It is expected that the widths of the RTE maxima will be less for H_2, due to the smaller electron momentum distribution of H_2 compared with He. The measurements indicate that this is, in fact, the case, as shown in Fig. 3 for Ca^{17+}. Each of the $\sigma_{K\alpha\beta}^{q-1}$ peaks for the H_2 target are narrower than the corresponding peaks for the He target, and the minimum between the peaks is considerably more pronounced for the H_2 target, in agreement with the theoretical RTE calculations[6,7] shown. In the RTE calculations for H_2, the Compton profile for molecular hydrogen was used.[12] To facilitate comparison between theory and experiment, and between the two data sets, all experimental and theoretical results have been normalized to the same value at the energy position of the lower-energy peak. The calculated positon of the lower-energy maximum agrees reasonably well with the data for both H_2 and He, while the agreement with the calculated high-energy maximum is not as good. This same high-energy discrepancy has been observed in RTE measurements for $_{16}\mathrm{S}^{13+}+\mathrm{He}$ collisions.[8] The origin of the discrepancy is not understood at present, since all possible transitions which occur with appreciable probability have been taken into account in the DR calculations.[10] It should be noted that the relative peak heights of the calculated RTE cross sections in Fig. 3 for the $n=2,2$ and $n=2,\geq 3$ transitions are not the same as those shown in Fig. 2 for $q=17+$. This difference is apparently due to

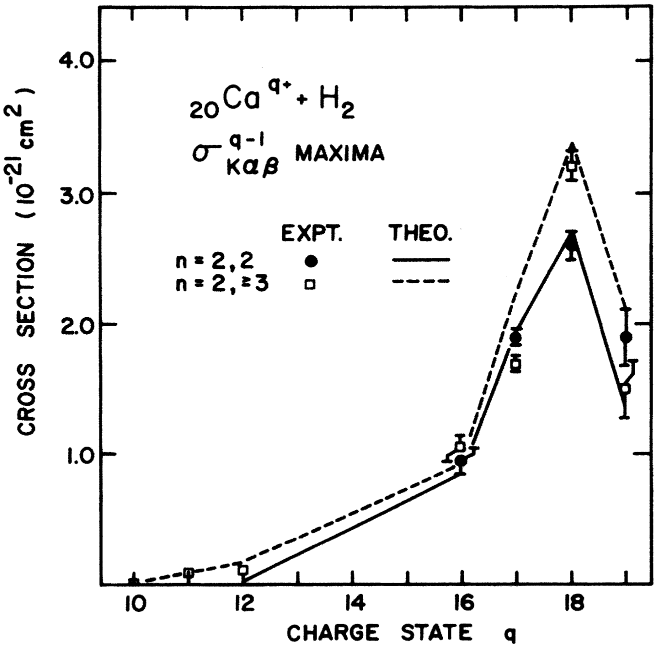

FIG. 2. Maximum values less background (see text) of the $\sigma_{K\alpha\beta}^{q-1}$ cross sections shown in Fig. 1 plotted as a function of the incident charge state of the projectile. The error bars show relative uncertainties in the data. The smooth lines are calculated RTE cross-section maxima obtained from Ref. 7.

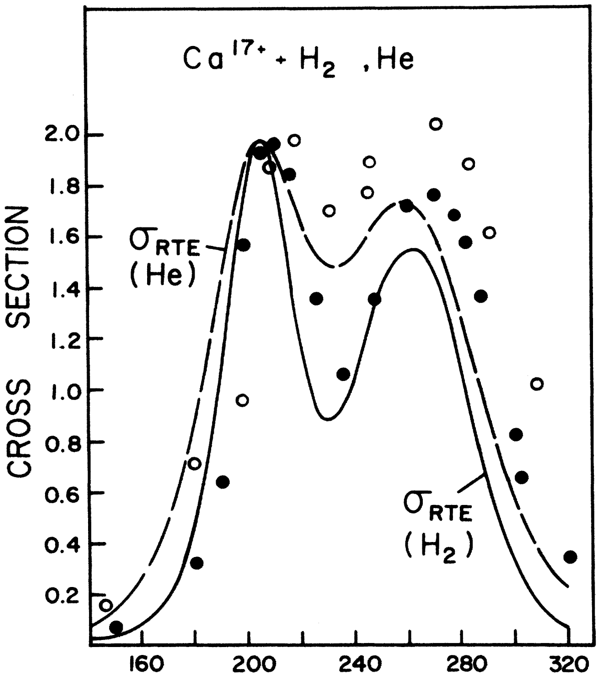

FIG. 3. Comparison of the $\sigma_{K\alpha\beta}^{q-1}$ cross sections for Ca^{17+} ions in H_2 and He. Solid circles are for H_2, and the open circles are for He. Also shown are predicted RTE cross sections for these collision systems. To facilitate comparison, both calculated curves and the data for He have been normalized to the lower-energy maximum of the H_2 measurements. Normalization factors for the He data, H_2 theory, and He theory are 1.51, 0.87, and 1.16, respectively.

the approximate manner[11] in which the calculated RTE maxima were obtained from the theoretical DR maxima for Fig. 2. The RTE calculations shown in Fig. 3, which are based on the method of Brandt,[6] represent a more accurate method of accounting for the energy distribution of the DR transitions and the effect of the target electron momentum distribution.

In summary, the present results (1) establish a projectile charge-state dependence of the RTE process, and (2) demonstrate explicitly the effect of the target electron momentum distribution on the RTE process. In both cases the measurements are found to be in reasonable agrement with RTE calculations based on theoretical cross sections for dielectronic recombination.

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[9] The notation $n=2,2$ and $n=2,\geq 3$ refers to the principal quantum numbers of the intermediate excited states occupied by the two electrons which participate in the RTE process.

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[11] For the theoretical calculations shown in Fig. 2 the DR cross-section maxima were multiplied by a factor of 0.7 [Y. Hahn (private communication)].

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