Nonresonant Electron Transfer and Projectile *K*-Electron Excitation in Ion-Atom Collisions

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Evidence is presented for nonresonant and resonant electron transfer and projectile K x-ray excitation in 15–94-MeV $\mathrm{Si}^{11+}+\mathrm{He}$ collisions. In the former, the projectile K electron is excited by the Coulomb field of the target nucleus, and a target electron is captured. In the latter, the electron-electron interaction gives rise to the resonant process. The nonresonant process reached its maximum cross section at ~ 20 MeV, while the resonant process peaked at ~ 85 MeV, in agreement with theory.

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Recently a new process called resonant transfer and excitation (RTE) has been shown to occur in certain types of ion-atom collisions by Tanis and co-workers[1,2] and by our group.[3] Here, electron capture by the projectile and projectile *K*-electron excitation occurs in a correlated manner. An uncorrelated capture and excitation process called nonresonant transfer and excitation (NTE), which has the same signature as RTE, is the subject of this report. The term nonresonant transfer and excitation was first introduced by Pepmiller *et al.*[4] in connection with high-resolution x-ray satellite experiments. It is applied to a relatively close ion-atom collision in which both electron capture by the projectile and *K*-electron excitation in the projectile take place in an independent or uncorrelated manner. Since both RTE and NTE lead to the same final state in our experiment, i.e., a projectile K x ray detected in coincidence with a projectile which has captured one electron, they are not distinguishable from each other in a given measurement. They may be distinguished in favorable cases, however, by their projectile energy depedence, as will be demonstrated below. The new feature of the present experiment is a clear demonstration of both processes for the first time.

Figure 1 illustrates the NTE processes in a diagrammatic representation, in which time goes from left to right. Also shown are schematic electron energy-level diagrams for both target and projectile at various times during the collision. The time order of capture and excitation is arbitrary, as both cases result in the same projectile-excited states.

Feagin, Briggs, and Reeves[5] have studied these processes theoretically using the strong-potential Born approximation. Further work with use of the impulse approximation in an impact-parameter formalism is underway by Reeves, Merzbacher, and Feagin.[6] It is hoped that this work will lead to a quantitative comparison with experiment. Meanwhile, we compare the singles and coincidence data with the presently available models, described below.

Si^{q+} ($q=4$–9) ions were produced with the Triangle Universities Nuclear Laboratory (TUNL) FN tandem Van de Graaf and sputter-ion source and were magnetically analyzed to select the desired beam energy. These ions passed through a thin (10 $\mu\mathrm{g/cm^2}$) carbon foil to produce the higher charge states. Li-like Si^{11+} ions were magnetically selected from the emerging charge-state distribution, as is illustrated in Fig. 2. The beam was collimated and then passed through a differentially pumped gas target of He. A solenoid valve and capacitance manometer were used to monitor the pressure in the cell. The target pressure was varied typically between 0 and 100 mTorr in 25-mTorr steps and could be controlled to better than 1%. We observed a linear increase in the coincidence yield with the gas pressure over this region insuring single-collision conditions. The slope of a linear least-squares fit to the yield versus pressure data was used to extract the cross sections.

Separation of the ion beam into various charge states after the target was accomplished by means of electrostatic deflection plates immediately after the gas cell, as illustrated in Fig. 2. The main Si^{11+} beam was deflected into a suppressed Faraday cup, while projectile ions which had undergone single- or double-electron

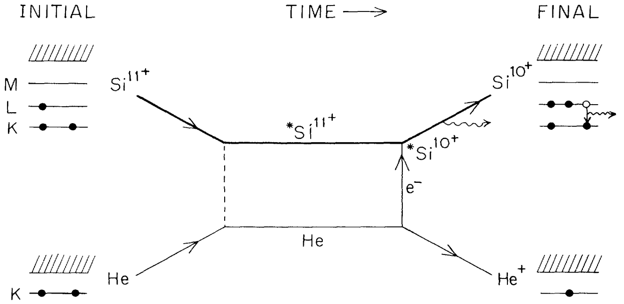

FIG. 1. Schematic representation of the collision. Incoming energy-level diagrams are illustrated on the left. The order of electron capture and excitation is arbitrary.

capture or loss (Si^{9-13+}) were deflected into one of four parallel-plate avalanche detectors[7] located on either side of the Faraday cup. X rays were detected by means of an 80-mm^2 Si(Li) detector (180-eV resolution at 5.9 keV) which viewed the collision region subtending a solid angle of 0.146 sr.

The experimental cross section for single-electron capture in coincidence with projectile *K* x rays, for 15–94-MeV Si^{11+} + He, is shown in Fig. 3. The new feature in this data is the peak at ~ 20 MeV which is attributed to NTE. The high-energy peak at ~ 85 MeV is associated with RTE. The dashed curve is Brandt's[8] calculation of the RTE cross section, using the dielectronic-recombination cross sections of McLaughlin and Hahn[9] and the Compton profiles for He of Biggs, Mendelsohn, and Mann.[10] The dot-dashed curve is a scaled calculation for the NTE cross section, and results from evaluation of the formula

$$\sigma_x^{\mathrm{NTE}} = \bar{\omega}_x 2\pi \int P_{\mathrm{ex}}(b) P_c(b)\, b\, db, \tag{1}$$

where $\bar{\omega}_x$ is an average fluorescence yield for Si^{10+} with configurations $1s2s2pnl$. $P_{\mathrm{ex}}(b)$ is the $1s$-$2p$ excitation probability as a function of impact parameter *b*, calculated by McAbee[11] using hydrogenic wave functions and different screening parameters for $1s$, $2s$, and $2p$ orbitals. $P_c(b)$ is the capture probability calculated by Brandt[12] using a classical, impact-parameter-dependent Bohr-Lindhart model. The NTE calculation has been scaled to the 15-MeV data.

Figure 4 shows the measured single-electron-capture cross section versus energy for Si^{11+} + He. The data are compared with an empirical scaling formula of Schlachter *et al.*[13] and with a semiclassical calculation of Brandt.[12] The present data are consistent with those of Schlachter and indicate that they agree with capture cross-section measurements done in other labora-

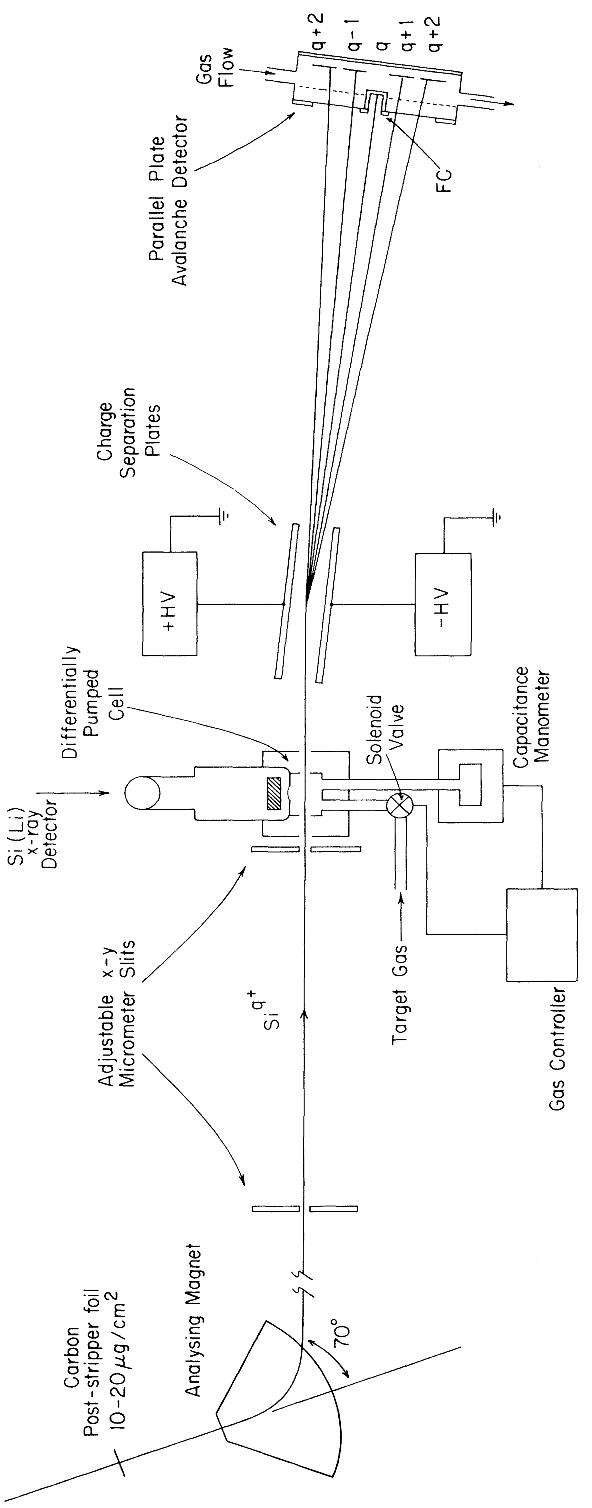

FIG. 2. Experimental arrangement.

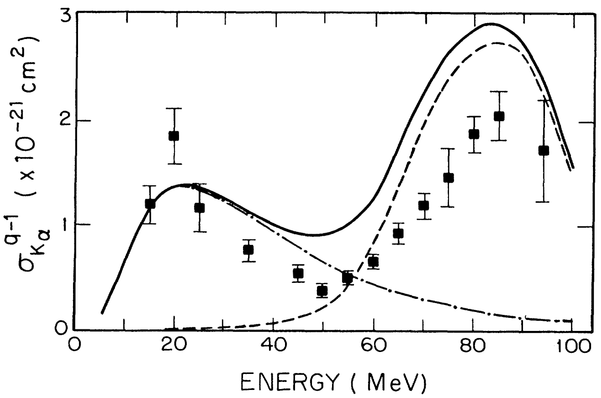

FIG. 3. Cross section for Si *Kα* x rays in coincidence with Si^{10+} vs energy. The dashed curve is the RTE calculation of Brandt (Ref. 8). The dot-dashed curve is a scaled NTE curve of Brandt (Ref. 12) and McAbee (Ref. 11) and is discussed in the text.

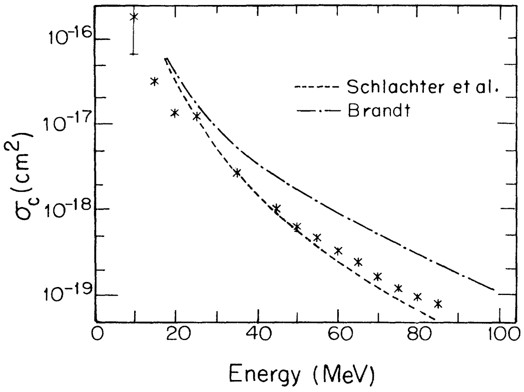

FIG. 4. Electron-capture cross section vs projectile energy for Si^{11+} on He.

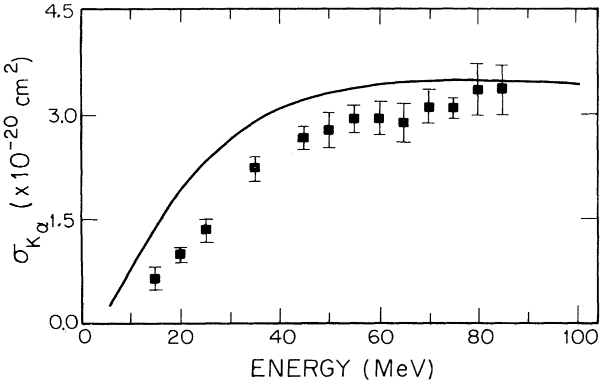

FIG. 5. Si $K\alpha$ cross section vs projectile energy. The solid curve is that of McAbee (Ref. 11) before correction for fluorescence yield.

tories. The agreement with Brandt is, however, not very good either qualitatively or quantitatively, but is best at the lower energies where NTE dominates. In Fig. 5, we present the Si $K\alpha$ x-ray cross sections. The semiclassical impact-parameter-dependent calculations for K-L excitation by McAbee[11] are plotted for comparison. It is evident that the trend with energy is well described by the calculations. Although the curve represents the data quite well, it must be multiplied by a fluorescence yield[14] of the order of 0.3 to be directly compared with experiment. Hence, an intuitive understanding of the NTE peak can be realized from the fact that as the projectile energy increases, the capture cross section rapidly decreases, while at the lowest energies the excitation cross section increases, but then finally levels off at the highest energies. In fact, by use of these calculations for capture and excitation reasonable qualitative agreement with the coincidence data is obtained, i.e., the position of the peak in the calculation is in good agreement with that of the data.

Nonresonant transfer and excitation has been observed for $S^{11+}+\mathrm{He}$ and can be distinguished from resonant transfer and excitation, in this collision system, by the different energy regions where the two processes dominate. The energy dependence of the coincidence measurements shows considerable structure while that of the singles data has very little. A relatively simple model predicts well the shape but not the magnitude. In view of these points, there is a need for better theoretical calculations and more experimental data. The next step in further clarification of these processes would seem to be to study their impact-parameter dependence, since at present no experimental information exists on this aspect of these collision processes.

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