Electron Production in Collisions between Light Ions and Rare Gases: The Importance of the Charge-Transfer and Direct-Ionization Channels

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Coincidence measurements were performed to separate the charge-transfer and direct-ionization channels for 15–100-keV H^+, He^+ collisions with Ne,Ar,Kr. Absolute cross sections are given for the production of single and multiple ionization of the target by these two ionization mechanisms. It is demonstrated that as the collision system becomes heavier, the multiple ionization components of these two channels become increasingly more important, and the production of free electrons results primarily from higher-order charge-transfer channels—not from direct single target ionization.

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A multitude of experimental and theoretical studies of total and differential electron emission resulting from H^+, He^+ collisions with rare-gas atoms have been made over the past several decades. It has generally been assumed that in these collisions single target ionization dominates and that any multiple ionization occurs via the Auger channels. However, it is now well established that multiple ionization of the target cannot always be ignored.[1] Thus, in order to properly interpret the electron emission studies, it is essential that the relative importance of the various processes contributing to multiple ionization be known.

For higher impact energies, multiple ionization can occur as a result of direct multiple outer-shell ionization or from inner-shell ionization leading to Auger emission. It has recently been shown[2,3] that the direct multiple outer-shell process can dominate the Auger channel. At lower impact energies, the Auger channels become less probable; but an additional process (charge transfer) begins to dominate the collision. Since simple charge transfer from the outer shell of the target to the projectile produces no free electrons, the interpretation of the electron emission data is clear—unless higher-order processes become important, in which case free electrons may be liberated. Two such processes are simultaneous capture plus ionization and direct multiple ionization of the outer shell. For singly charged projectiles, capture plus ionization ($C+I$) has one electron being transferred from the target to the projectile and additional target electrons simultaneously liberated to the continuum, thus producing an n-times ionized target ion and $n-1$ free electrons. The competing direct process also produces an n-times ionized target but now all n electrons are liberated. Coincidence techniques can be used to separate these competing channels.

Although some $C+I$ measurements have been made for proton–rare-gas collisions,[4–7] the only studies[5,6] of the direct multiple-ionization process have been for proton impact at energies less than 50 keV. In addition, none of these studies addressed the question of electron emission, although the data indicated that the $C+I$ channel could become competitive in free-electron production.

This paper presents coincidence measurements of multiple-ionization cross sections resulting from charge transfer and direct ionization for 15–100-keV H^+ and He^+ impact on Ne, Ar, and Kr. This energy range was chosen to encompass the region where the collision is changing from domination by capture to direct ionization. It will be demonstrated that the total electron emission in these collisions can be dominated by the $C+I$ process as opposed to the simpler direct ionization process. Specifically it will be shown that the second-order process $A^+ + B \rightarrow A^0 + B^{+2} + e^-$ can be as much as an order of magnitude larger than the competing first-order process $A^+ + B \rightarrow A^+ + B^+ + e^-$.

Figure 1 shows a schematic diagram of the experimental apparatus. A collimated H^+ or He^+ beam passes through a gas cell of known target density. The exiting neutral and singly charged beams are electrostatically charge analyzed and counted by channel electron multipliers mounted on a precision x-y-z positioner capable of scanning across the beams. Slow target ions created in the collisions exit from the gas cell through an aperture in the biased lid of the cell and are counted by a channel electron multiplier.

The data collection consists of two parts: (1) absolute measurements of the total single-electron-transfer cross section σ_{10} from growth curves of the post-collision neutral-beam component for known target length and density parameters, and (2) mea-

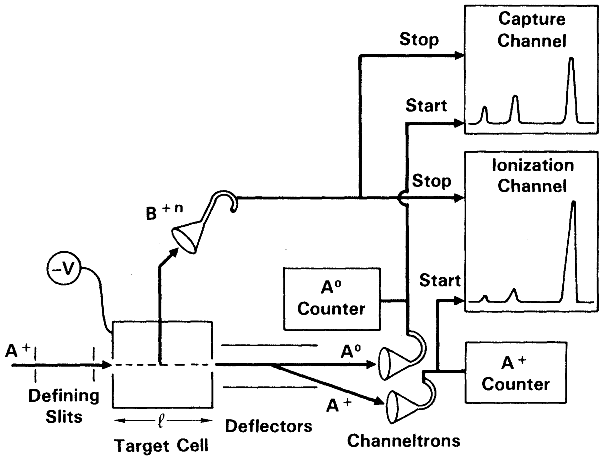


FIG. 1. Schematic of experimental setup showing the coincidence charge-state-spectra electronics for the direct-ionization and capture channels.

surement of relative cross sections for the charge-transfer channels (σ_{10n}) and the direct-ionization channels (σ_{10n}). These relative cross sections are obtained from the slow-ion charge-state spectra produced by coincidences between the slow ions and the electrostatically separated post-collision beams (see Fig. 1). After appropriate background subtractions, the peak areas in the recorded coincidence spectra (N_{10n} and N_{11n}) are proportional to the relative cross sections σ_{10n} and σ_{11n}, respectively. Here the first and second subscripts are the pre-collision and post-collision projectile charge states and the third subscript is the slow-ion charge state. These relative cross sections are then placed on an absolute scale by normalizing to the total charge-transfer cross section by

$$\sigma_{10n} = \sigma_{10} N_{10n} / \sum N_{10n}; \tag{1}$$

and

$$\sigma_{11n} = \sigma_{10} N_{11n} / \sum N_{10n}. \tag{2}$$

This, of course, assumes that all slow-target-ion charge states are detected with equal efficiencies and that the neutral- and charged-beam particles are detected with equal efficiencies. This was confirmed by demonstrating that the cross sections are independent of extraction field strength, target gas pressure, and channeltron preacceleration potentials between 1 and 3 kV. In addition the present data for σ_{10} agree well with values taken from the literature.[8] Thus, the present cross sections are believed to be accurate to approximately 25% except for the higher charge states and lowest impact energies where larger errors are expected.

Cross sections for the various channels contributing to charge transfer and direct ionization are shown in Fig. 2 for three collision systems. Note that the post-collision beam-deflection field will reionize any capture events to n levels above approximately 30 to 50 (lowest to highest impact energies, respectively). Such events are included in the direct ionization channels and not in the capture channels where they belong. The data shown illustrate the trends for the projectile-target systems investigated. In general, for a given projectile, higher-order effects become increasingly more important as the target becomes heavier. For a specific target, the higher-order effects are more important for He^+ than for H^+ impact.

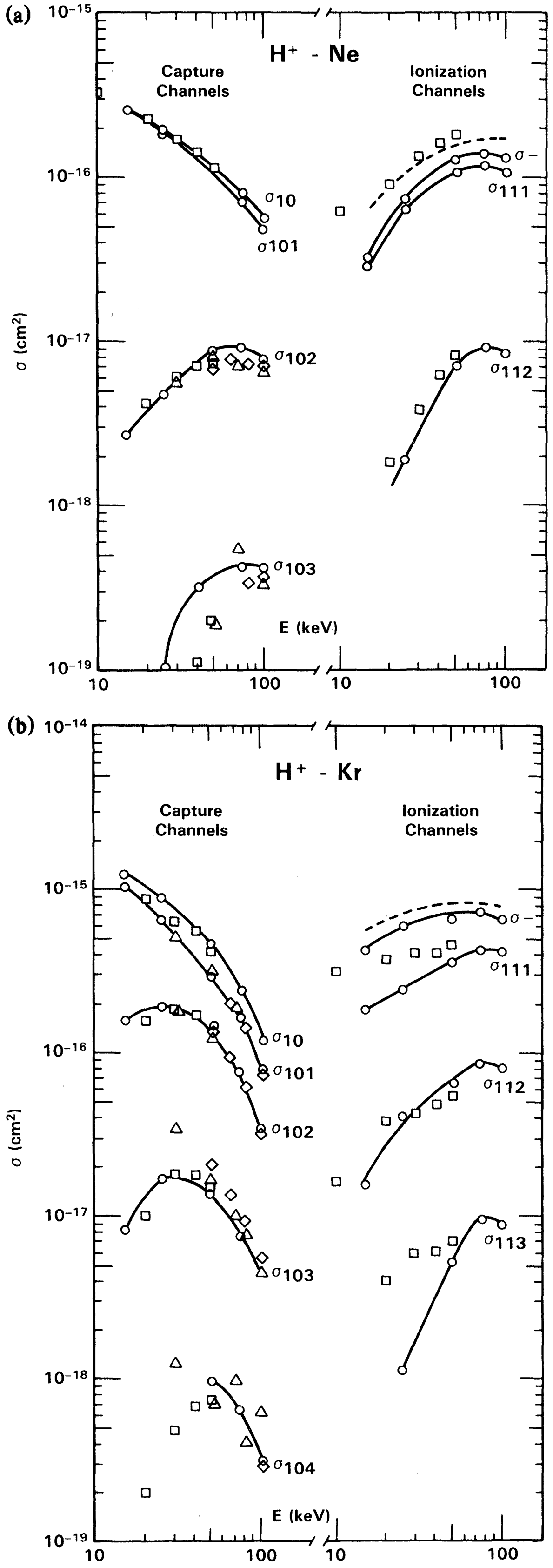
For the case of H^+-Ne the total charge-transfer cross section is almost entirely due to single electron transfer whereas capture plus ionization contributes about 50% of the cross section for neutralization in He^+-Kr collisions. Agreement with previous measurements is quite good. Please note that the relative data taken from the literature (Refs. 4 and 7) were placed on an absolute scale by normalizing to the present total charge-transfer cross sections. Absolute data were presented in Refs. 5 and 6.

The direct ionization channels are also shown in Fig. 2 as well as the total electron-production cross sections obtained by summing the appropriate channels of this measurement (solid curve). The dashed curves are total electron-production cross sections that were measured with a more accurate experimental method.[9] These two sets of total electron production cross sections are in reasonable agreement with each other. The present direct-ionization data are only in fair agreement with that taken from Refs. 5 and 6. This is attributed to the total electron-production cross sections used for normalization in Refs. 5 and 6 that may be in error.[9]

An interesting feature of the direct-ionization data is that for the lighter systems, single direct target ionization is a good approximation for total electron production; but as the collision system becomes heavier, this approximation becomes increasingly poorer. For these heavier collision systems the capture channels contribute significantly to electron production. That is, total electron production is given by

$$\sigma_- = \sum_n \sigma_{11n} + \sum_{n>1} (n-1)\sigma_{10n}, \tag{3}$$

where the first term corresponds to direct channels and the second to capture channels. For the He^+-Kr collisions shown in Fig. 2, the capture channels



are responsible for approximately half of the free-electron production. A comparison of the competing channels for single-electron production shows that the direct process σ_{111} is an order of magnitude larger than the $C+I$ channel σ_{102} for H$^+$-Ne collisions over the entire energy range investigated. But the two channels are comparable for H$^+$-Kr at low energies and the $C+I$ channel is an order of magnitude larger than the direct channel for low-energy He$^+$-Kr collisions. Likewise for He$^+$-Kr collisions the higher-order $C+I$ process σ_{103} is at least as effective as the direct process σ_{112} in liberating two electrons.

The present work has demonstrated that higher-order capture-plus-ionization processes can be considerably more important in free-electron production than lower-order direct ionization processes. For the case of low-energy He$^+$-atom collisions dis-

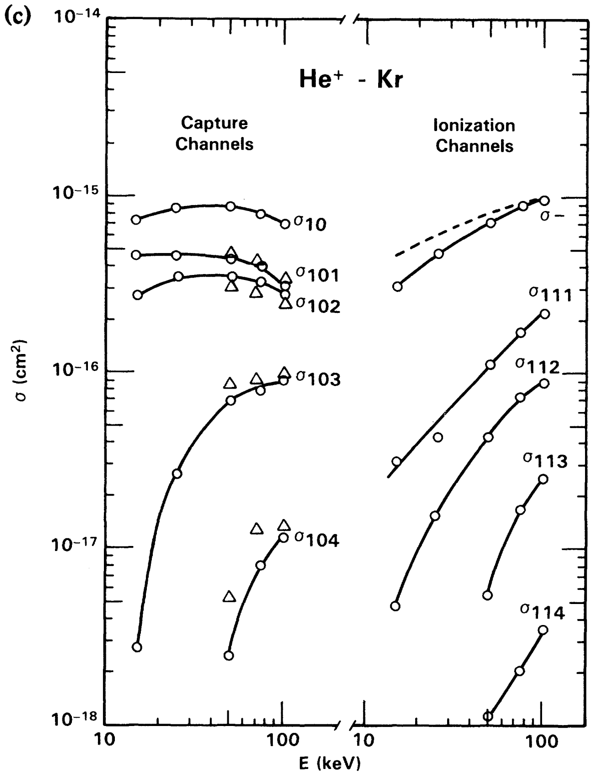


FIG. 2. Cross sections for the direct-ionization and capture channels for H$^+$-Ne, H$^+$-Kr, and He$^+$-Kr collisions. Cross-section subscripts are defined in the text. The capture and direct-ionization channels are on the left-hand and right-hand sides of the figures for each collision system. Circles, present data; squares, Refs. 5 and 6; lozenges, Ref. 4; triangles, Ref. 7; dashed line, total electron-production cross section (σ_-) from Ref. 9 (H$^+$ impact) as well as present measurements using the same device (He$^+$ impact).

cussed here, a complete analysis of the system would require a quasimolecular picture of the collision. Without such a description it is difficult to speculate as to why σ_{102} exceeds σ_{111}. A possible clue may be the amount of autoionization leading to a double ionization observed for slow He^+ impact on Ne, Ar, and Kr.[10] At very low impact energies, charge exchange was shown to produce considerable autoionization in Ar and Kr and much less in Ne. If this process continues to be important for higher impact energies and if direct ionization also produces considerable autoionization, the cross section for σ_{102} would be enhanced while the cross section for σ_{111} would be diminished; thus the higher-order process would become increasingly more important to the total electron-emission cross section. Detailed experimental and theoretical work is needed to provide insight into this phenomenon.

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