Electron capture and stripping cross sections for Tl and K ions and atoms in H_2

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Electron capture cross sections (σ_{10}) and stripping or loss cross sections (σ_{01}, σ_{12}, σ_{02}) have been measured for 50- to 600-keV $Tl^{0(+)}$ and $K^{0(+)}$ passing through H_2 gas. Equilibrium fractions were measured by increasing the H_2 target gas density until the fraction was independent of the initial charge state. All capture and loss cross sections increased in this energy range. The equilibrium fractions were dependent only on the particle velocity and were independent of the incident-particle electronic structure.

I. INTRODUCTION

Diagnostics of high-temperature plasmas depend strongly on atomic phenomena. These atomic processes used in measuring plasma parameters can be divided into two classes, passive and active. In passive investigations, use is made of optical or particle emission from the plasma. Examples of passive methods include optical line radiation, bremsstrahlung, and neutral particles emitted by the plasma. In active diagnostics an external beam of particles or photons is used to probe the plasma properties.

An ingenious active method to probe the plasma is the heavy-ion beam probe proposed and developed by Jobes and Hickok.[1] A singly charged ion beam with sufficient momentum to cross the magnetic field containing the plasma is projected through the plasma. At some point in the plasma the doubly charged ions are formed by collisions with electrons and positively charged particles. If the beam dynamics is chosen correctly, a detector line can be found such that as the ion beam is deflected in a transverse direction across the plasma, the doubly charged ions formed on this line will intersect at a position external to the plasma. By placing an electrostatic analyzer at this crossover point, the change in the final and initial ion energy is determined, which gives the plasma potential at the point of formation of the doubly charged ion. The doubly charged ion beam intensity gives the plasma density, which can be made absolute if the pertinent cross sections are known. It is believed that the electron ionization cross section of the incident ion is the predominate cross section. Of equal importance may be charge-exchange or stripping cross section of the heavy ion.

A summary of experimental results of charge-transfer processes involving heavy ions at energies less than 1 MeV has been published by Allison[2] and at higher energies by Betz.[3] A summary of the various experimental techniques has been made by Barnett and Gilbody.[4] Theoretical computations of charge changing processes for heavy particles are very difficult; a limited number of cases have been reviewed by Mapleton.[5] No theory exists which predicts accurately the capture and loss cross sections where the particle velocity is less than the orbital electron velocity. Two approximate theories have been developed by Firsov[6] and Fleischmann.[7]

According to Firsov's original ideas the processes of energy transfer in two-atom collisions are due mainly to an electron flux crossing a hypothetical plane located midway along and perpendicular to the line joining their centers. Hence a momentum transfer is observed. Firsov calculated the electron flux by assuming a spherical distribution of electron velocities at every point in space and integrating over the Firsov plane, using statistical theory. He assumed that this energy was distributed among all electrons of the system and was used up in the ionization process. If the excitation energy is greater than the ionization energy, ionization occurs with a high probability.

In this manner, Firsov obtained a formulation which gives a universal dependence of the cross section for the removal of electrons for any colliding pair as a function of their relative velocity. He developed the following expressions:

$$\sigma_i = \sigma_0[(u/u_0)^{1/5} - 1]^2 ,$$

$$u_0 = \frac{23\times 10^6 E_i}{(Z_I + Z_A)^{5/3}}\ \frac{\text{cm}}{\text{sec}} , \quad \sigma_0 = \frac{3.7\times 10^{-16}}{(Z_I + Z_A)^{2/3}}\ \text{cm}^2 ,$$

where σ_i is the total electron production cross section in a heavy-particle collision, u is the relative projectile velocity, E_i in eV is the smallest of the ionization energies at the two colliding atoms, and Z_I and Z_A are the atomic numbers of the projectile and target atom, respectively. This formula was derived for total electron production in neutral-neutral collisions and also gives a reasonable estimate for stripping cross sections at energies of several keV.

Fleischmann[7] assumed a model of a single-step transition of the ionized electron from the bound state to the continuum. A semiempirical scaling law was developed which in some cases fits experimental data more accurately than does the Firsov model.

In this work the following cross sections are reported: σ_{10}, σ_{01}, σ_{02}, and σ_{12}, where the first index indicates the initial charge state and the second indicates the final charge state after passing through an H_2 target gas cell. Also reported are the equilibrium fractions obtained with a high-density target.

Experimentally, Kikiani *et al.*[8] has measured the total cross section for the production of free electrons, the ionization cross section, and the stripping cross section between alkaline-earth atoms and gas molecules at energies from 3 to 30 keV. In this paper the results of our work are compared with the experimental results of Kikiani *et al.*[8] and with the two theoretical models.[6,7]

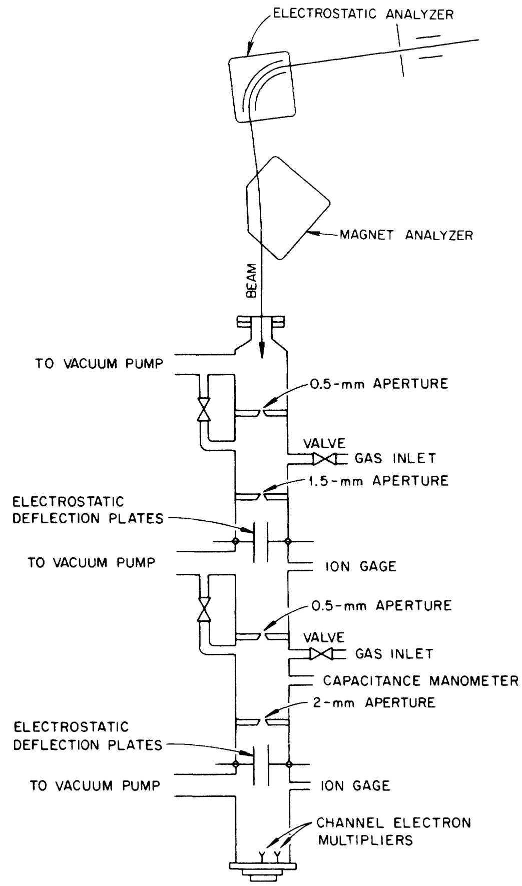

FIG. 1. Schematic drawing of experimental apparatus.

II. APPARATUS

The ions K^+ and Tl^+ were produced in a filament type of ion source. Ions were formed by heating aluminum silicates on a tungsten filament (a well-known process described by Johnson[9] or Septier and Leal[10]). The silicates were diluted in ethyl alcohol, and the filament was covered uniformly. At the exit of the ion source the ions were accelerated with the ORNL Cockcroft-Walton heavy-ion accelerator (Fig. 1). An electrostatic energy analyzer formed by two cylindrical parallel plates of 1 m radius deflected the beam 90° and allowed the selection of the ion charge state at the desired velocity. A stabilized analyzing magnet was placed at the exit of the electrostatic plates, and the desired mass was deflected 8° and passed through the charge-transfer apparatus, which consisted of two differentially pumped gas cells, two electrostatic deflection plates for the separation of beam-charged states, and detectors for the determination of the intensities of the neutral and charged products.

Circular apertures with machined thin knife edges were located at the entrance and exit of the neutralization and charge-changing collision cells. The diameters of the first set of apertures were 0.5 and 1.5 mm, while the diameters of the second set were 0.5 and 2 mm at the entrance and exit, respectively. These aperture dimensions were selected to minimize scattering of the beam from the collision-cell exit apertures. Pumping speeds coupled with these dimensions were such that a pressure differential of approximately 1500 was obtained across the apertures. Alignment of the system was made possible by means of bellows between the apertures.

The geometrical length of the neutralization and gas target cells was 30.5 ± 0.15 cm. In the first collision cell, air was introduced for the production of Tl^0 or K^0 formed by charge exchange of Tl^+ or K^+ incident ions. Pressures less than 0.5×10^{-3} Torr were maintained in this cell. Beam scattering was negligible at this pressure, which was used to produce the neutral beam. After passing through the first collision cell the charged components were deflected from the beam by a transverse electric field, leaving a pure neutral beam incident on the target gas cell. For the K^+ and Tl^+ cross sections the first collision cell was evacuated and the first electrostatic plates were electrically grounded.

After having passed through the target chamber, the charged components of the beam were deflected by the electric field to the side detector, which determined the ion intensity. Neutral intensities were measured in the central detector, and total particle intensities were measured by grounding the electrostatic plates.

The entire vacuum system (excluding the detector assembly) was made from stainless steel and assembled with metal O rings, which allowed bakeout of the system at approximately 200 °C.

Two funnel-type electron multipliers with 0.8 cm^2 of sensitive area were used as detectors. Either with neutral or charged components, the efficiency was 100% at this energy. The detectors were operatred in the charge-saturation mode, as suggested by Ray and Barnett.[11]

The H_2 target gas of ~99% purity was introduced into the collision chamber through a Granville Phillips variable leak valve. The leak rate was constant at a given setting such that the differentially pumped collision cell reaches an equilibrium pressure within a few minutes after the leak rate is set. A calibrated capacitance manometer was used as the secondary-standard pressure-measuring device.

III. MATHEMATICAL DESCRIPTION AND PROCEDURE

The variation of the charge composition of an ion beam penetrating through a gaseous target is described by a system of coupled linear differential equations,

$$\frac{dF}{d\pi} = \sum_{j=-z}^{z}{}' (F_j\sigma_{jm} - F_m\sigma_{mj}),$$

$$m = -z, -z+1, \ldots, 0, 1, \ldots, z, \qquad (1)$$

where F denotes the fraction of the ions which carry the charge (m), and σ_{jm} is the sum over all cross sections in which the ion with charge j is transformed into charge m. The summation is extended over all possible slow-ion charge states with $\sum F_m = 1$. In Eq. (1) the term $j = m$ must be omitted, as was indicated by the prime on the summation. The term π is the number of target gas atoms (or molecules) in a volume of matter of cross-sectional area 1 cm^2 and length equal to the distance traversed along the beam path; π is also represented in the following form:

$$\pi = \tfrac{273}{760} LPl/(273 + T),$$

where $L = 2.678 \times 10^{19}$ molecules/cm^3 is the Loschmit number, P the target gas pressure in Torr, l the effective length of gas target in cm, and T the temperature of target gas in °C.

When only a few charged states are present, a simple, analytical solution of Eq. (1) can be found. If in addition we have "thin" target conditions in which only single collisions occur, a very simple expression results,

$$F_m(\pi) = \pi\sigma_{jm}. \qquad (2)$$

Increasing the target thickness in this single-collision regime results in a linear increase in the fractions F, and the cross section for one charge-changing process can be easily determined from the slope of the linear portion of an F-vs-P plot. Simple calculations provide the cross section σ_{jm} from the slope. In our experiments the slope did not extrapolate through the origin because of charge-changed components which were independent of the gas target density. These background components were due primarily to charge transfer between the incident beam and the residual gas molecules within the vacuum system, or to charge-transfer collisions between the beam and the defining apertures. The data from which the cross sections were calculated were obtained under single-collision conditions.

The equilibrium charge-state fractions were determined by measuring each fraction $F(\pi)$ as a function of target thickness π and were deduced from the flat portion of each curve at large π. When only two components are present, a simple relation exists between the equilibrium fractions and the cross sections; i.e.,

$$F_{1\infty}/F_{0\infty} = \sigma_{01}/\sigma_{10}.$$

This relation permits checking of the internal consistency of the experiment. The results of this comparison will be discussed in Sec. IV.

IV. ERRORS

Experimental uncertainties. Errors concerning the measured fractions were estimated from the reproducibility of the data. A single-particle counting technique was used, and sufficient data were accumulated to reduce counting statistics to less than 1%.

Errors due to the determination of beam intensities and target gas pressures can be evaluated by the uncertainties encountered in obtaining the slope of a straight line through the points of a plot of intensity ratios versus pressure. This uncertainty was estimated to be less than 10%.

Other sources of error, such as the measured target gas pressures and deviations of thin target

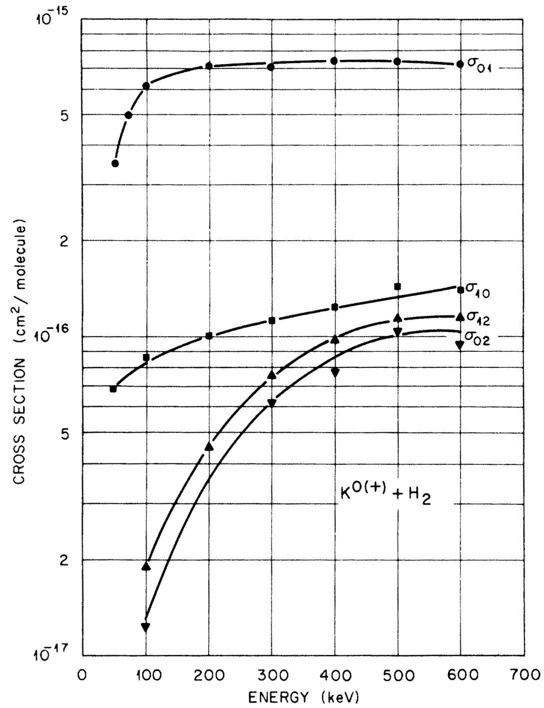

FIG. 2. Capture and loss cross sections for σ_{10}, σ_{01}, σ_{02}, and σ_{12} of $K^{0(+)}$ incident on hydrogen gas.

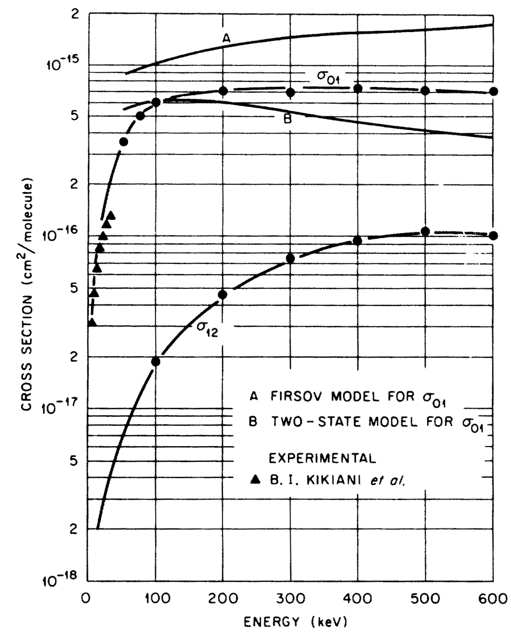

FIG. 4. Stripping cross sections σ_{01} and σ_{12} of $K^{0(+)}$ beam incident on hydrogen gas compared with previous experimental and theoretical values. For experimental points see Ref. 7. For theoretical curves see Refs. 5 and 6.

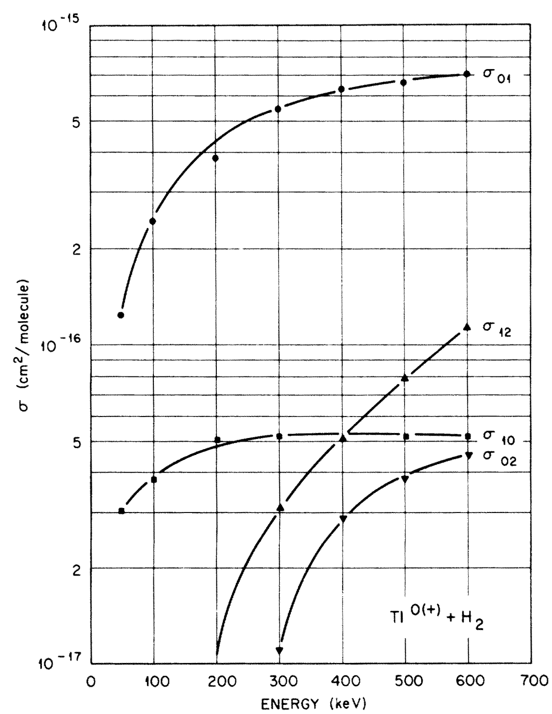

FIG. 3. Capture and loss cross sections for σ_{10}, σ_{01}, σ_{02}, and σ_{12} of $Tl^{0(+)}$ incident on hydrogen gas.

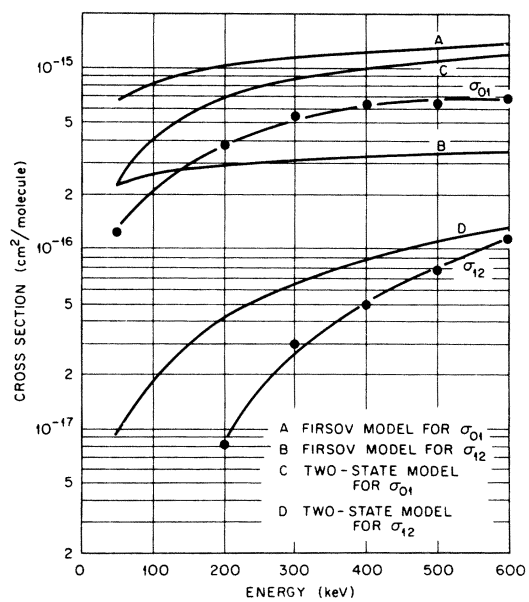

FIG. 5. Stripping cross sections σ_{01} and σ_{12} of $Tl^{0(+)}$ beam incident on hydrogen gas compared with theoretical curves. For theoretical curves see Refs. 5 and 6.

conditions, have been considered. We estimate the total uncertainty to be less than ±12%.

V. RESULTS AND DISCUSSION

Figures 2 and 3 show the measured cross section σ_{10} for the electron capture and σ_{01}, σ_{12}, and σ_{02} for the stripping collisions between fast $K^{0(+)}$ or $Tl^{0(+)}$ and H_2 molecules.

In the velocity range investigated the stripping cross sections increased continuously with the incident particle velocity. From theoretical considerations the maximum of the cross sections should occur at the orbital velocity of the electrons in the target gas. From Figs. 2 and 3 it is seen that the maximum occurs at approximately 10^8 cm/sec, as expected from this adiabatic hypothesis. In general, the capture cross section decreases with increasing Z at the same velocity, and the results reported here agree with this general behavior.

In Fig. 3 the cross sections involving stripping to the 2+ charge state were not measured at energies less than 200 keV for σ_{12} and less than 300 keV for σ_{02}, since the signal counting rates were of the same order as those of the background. In Fig. 2 the lower cutoff energy for K ions and neutrals was 50 keV.

Figure 4 shows a comparison of the experimental data and the Firsov[6] and Fleischmann[7] predictions for the potassium σ_{01} cross sections. The Firsov prediction is, in general, greater than the experimental values. As has been discussed by Kikiani *et al.*,[8] Firsov's theory, which neglected the electron-shell effects involving alkaline-earth atoms, does not agree as well as for collisions involving inert heavy gases. The predictions of the two-state model agree better than Firsov's model at lower energies, but the curve departs at higher energies, being lower than the experimental points. In the same figure, experimental points of Kikiani *et al.*[8] are plotted and the experimental curve is extrapolated.

In Fig. 5 the same comparison is shown for a thallium beam. For these collisions, both theories give higher values than the experimental points, although the two-state model has the same shape as the experimental curve. This feature suggests that the theory should be modified to include the sum of the contributions from all electrons in the outer shell.

It is interesting to compare the electron ionization cross section of Tl^+ with that of the Tl^+ stripping cross section σ_{12} in H_2 gas. Feeney *et al.*[12] have reported the maximum electron ionization cross section of Tl^+ to be 1.8×10^{-16} cm^2 at an electron energy of 80 eV. The cross section decreases to 7.0×10^{-17} cm^2 at 1000 eV. At 600 keV the Tl^+ stripping cross section was 1.1×10^{-16}, and apparently would be greater at increased energies.

Shown in Fig. 6 are the equilibrium fractions of both neutral and singly charged Tl and K beams plotted as a function of the particle velocity. Observations by Ryding *et al.*[13] indicated that a fast heavy ion moving through matter had an equilibrium charge distribution that was dependent only on the particle velocity and nature of the target and was independent of the electronic structure of the incident particle. As observed in Fig. 6, the equilibrium distribution for the higher-velocity Tl particles joins smoothly with that of the lower-velocity K particles. This observation holds for the 0, 1, and 2 equilibrium charge states. Another important feature is that the charge-state 2+ equi-

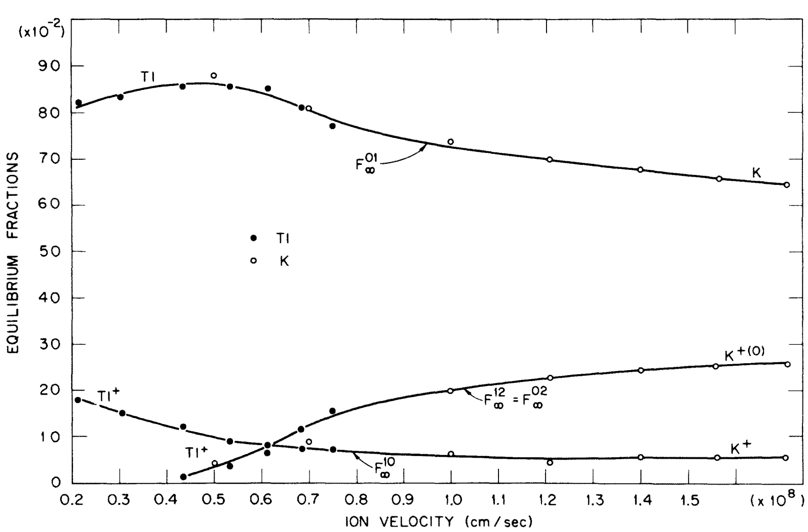

FIG. 6. Equilibrium fraction values (F_∞^{10}, F_∞^{12}, F_∞^{02}, F_∞^{01}) vs ion velocity, obtained with $K^{0(+)}$ or $Tl^{0(+)}$ incident on a high-density hydrogen target gas.

librium fraction was independent of the incident charge state within the experimental error. With a two-component charge system the generalized expression for the equilibrium fractions is

$$F_{m\infty} = \lim_{p\to\infty} F_m = \sigma_{jm}/(\sigma_{jm} + \sigma_{mj}) .$$

As a check of the internal consistency of the experiment, the equilibrium fractions measured directly can be compared with the values given by this equation. For energies less than 300 keV, we can neglect the cross sections involving the doubly charged ions; the following relations apply:

$$F_{0\infty} = \sigma_{10}/(\sigma_{10} + \sigma_{01}) , \quad F_{1\infty} = \sigma_{01}/(\sigma_{10} + \sigma_{01}) ,$$

or

$$F_{1\infty}/F_{0\infty} = \sigma_{01}/\sigma_{10} .$$

TABLE I. Equilibrium fraction ratios ($F_{1\infty}/F_{0\infty}$) and cross-section ratios (σ_{01}/σ_{10}) for $Tl^{0(+)}$ beam incident on hydrogen gas.

Energy (keV)	$F_{1\infty}/F_{0\infty}$	σ_{01}/σ_{10}
50	4.0	4.8
100	6.3	5.6
200	7.6	7.2

Table I compares the ratios of the equilibrium fractions with the ratios of the $Tl^{0(+)}$ cross sections measured directly only at energies such that a two-component charge system is applicable. The difference between the values is only a few percent.

*Operated by the Union Carbide Corporation for the U.S. Energy Research and Development Administration.

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