Charge Exchange in the Io Torus and Exosphere

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Cross sections for charge-exchange reactions of potential importance in the Io torus and the interaction of torus plasma with Io’s atmosphere are estimated with an accuracy of about a factor of 2. The size of the cross sections for a given collision velocity are shown to depend entirely on the spacing of the energy levels between the initial and final states of the reactions. Reaction rates for charge-exchange cross sections, calculated at the corotation velocity in Io’s reference frame, are compared to reaction rates for electron impact ionization and recombination at a number of radii from 5.1 R_J to 7.1 R_J for a model torus. Inside Io’s orbit, charge-exchange processes are the principal mechanism for ionization of neutrals (except Na and K) and the dominant source of ions accelerated to corotation, the primary mode of multiply charged ion recombination, and a major contributor to mass loss via fast neutrals. As a consequence, the ratios of ion concentrations are critically dependent on charge-exchange rates and the neutral densities. Charge-exchange reactions of torus ions with molecular species in Io’s exosphere may yield a net supply of neutrals and plasma to the Io torus. Expressions are given to obtain the velocity dependence of the charge-exchange cross sections and to calculate cross sections for reactions not considered here.

INTRODUCTION

One of the significant discoveries of the Voyager mission during the Jupiter encounter was the Io plasma torus whose existence most likely depends on Io’s volcanic activity (see Science, vol. 204, no. 4396, pp. 945–1008, 1979). It was known prior to the Voyager encounter with Jupiter that neutral sodium atoms and singly ionized sulfur were present in Jupiter’s inner magnetosphere [Brown, 1974; Kuiper et al., 1976]. In the initial analyses of the plasma torus data, most attention was focused on the enormous ultraviolet radiation losses, the required energy sources, ion composition, and ion residence times. The primary interaction of neutrals and plasma was thought to be electron impact. Ion-neutral collisions were for the most part ignored, although Cheng [1980] discussed their potential importance particularly in the context of energetic heavy ions. Brown and Schneider [1981] found evidence for such collisions in observations of episodic occurrences of high-speed neutral. The discovery of an extended neutral cloud of oxygen atoms by Brown [1981] and the probable existence of a neutral sulfur cloud has stimulated interest in charge-exchange collisions in which plasma ions capture electrons from neutrals [e.g., Brown and Ip, 1981; Brown et al., 1982a, b].

Kunc and Judge [1981] estimated electron capture cross sections for corotating ions impinging on Io’s atmosphere. Their estimates for nonresonant reactions were based on an impulse approximation which can be used reliably only at moderate and large relative velocities ($\approx 10^3$ km s$^{-1}$) or for slower collisions involving significant energy transfer. At the $\sim 60$ km s$^{-1}$ relative velocity between neutrals and plasma ions in the torus, the collisions proceed nearly adiabatically with transitions taking place at a well-defined separation between the ion and neutral at which the transition energy is small. It is the purpose of this paper to review the various types of charge-exchange processes and corresponding methods for estimating relevant cross sections, as well as to demonstrate the potential importance of charge-exchange reactions relative to other plasma processes. Cross sections are calculated for neutral and ionized species of Na, K, O, S, SO$_2$, and O$_2$ (Table 1). The cross section estimates should provide guidance in understanding the Io plasma torus until accurate calculations become available.

Inside Io’s orbit we find that charge-exchange processes are the primary means of ionization, the preferred mode for recombination of multiply charged ions, the dominant source of newly created ions which are accelerated to corotation, and a major means of mass loss from the torus via fast neutrals. We also point out that charge-exchange reactions involving multiply charged ions with molecular species may play a role in ejecting neutrals from Io’s exosphere into torus.

In the first section the methods used for calculating the cross sections are given and discussed in some detail. This is done in order to allow the reader to understand the physics associated with the approximations used and thereby make estimates for other processes as the character of the torus is better defined. As the velocity dependence of, particularly, ion-ion collisions may play an important role in understanding, for instance, the O$^{+}$ density [Brown et al., 1982b], we have calculated scaling factors for the cross sections which can be used to obtain this dependence. This is followed by a description of a model torus based on available observations. The calculated cross section and torus densities are

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<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\Delta E$, eV</th>
<th>$I$, a.u.</th>
<th>$R_{c,-}$, a.u.</th>
<th>$\lambda^{-1}\beta^{-1} \gamma^{-1}$</th>
<th>$P_r$</th>
<th>$\sigma$, $\AA$</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1. $O^+ + O \rightarrow O + O^+$</td>
<td>data</td>
<td>0.5</td>
<td>8.1</td>
<td>(2.6)</td>
<td>1/2</td>
<td>15</td>
</tr>
<tr>
<td>R2. $O^+ + S \rightarrow O^+(P) + S^+(C\Pi)$</td>
<td>0.2</td>
<td>0.42</td>
<td>7.1</td>
<td>(0.84)</td>
<td>1/6</td>
<td>1</td>
</tr>
<tr>
<td>R3. $S^+ + S \rightarrow S + S^+$</td>
<td>0.56</td>
<td>scaled to $O^+ + O$</td>
<td>2.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R4. $S^+ + O \rightarrow O^+(D) + S^+(C\Pi)$</td>
<td>-3.25</td>
<td>0.44</td>
<td>4.2</td>
<td>(0.13)</td>
<td>1</td>
<td>$\geq 0.1$</td>
</tr>
<tr>
<td>R5. $S^+ + S \rightarrow S + S^+$</td>
<td>-3.25</td>
<td>scaled to $O^+ + O$</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R6. $O^+ + O \rightarrow O^+(C\Pi) + O^+(D\Pi)$</td>
<td>3.4</td>
<td>0.68</td>
<td>8.0</td>
<td>16</td>
<td>4/9</td>
<td>4.8</td>
</tr>
<tr>
<td>R7. $O^+ + O \rightarrow O^+(S\Pi) + O^+(D\Pi)$</td>
<td>4.7</td>
<td>0.74</td>
<td>10.1</td>
<td>140</td>
<td>4/9</td>
<td>0.8</td>
</tr>
<tr>
<td>R8. $O^+ + O \rightarrow O^+(D\Pi) + O^+(P\Pi)$</td>
<td>4.8</td>
<td>0.74</td>
<td>10.1</td>
<td>140</td>
<td>4/9</td>
<td>0.8</td>
</tr>
<tr>
<td>R9. $O^+ + O \rightarrow O^+(S\Pi) + O^+(S\Pi)$</td>
<td>6.7</td>
<td>1.2</td>
<td>4.2</td>
<td>0.24</td>
<td>1/3</td>
<td>$\leq 0.1$</td>
</tr>
<tr>
<td>R10. $O^+ + S \rightarrow O^+(P\Pi) + S^+(C\Pi)$</td>
<td>3.4</td>
<td>1.2</td>
<td>8.0</td>
<td>560</td>
<td>8/9</td>
<td>0.3</td>
</tr>
<tr>
<td>R11. $S^+ + O \rightarrow S^+(4P) + O^+(C\Pi)$</td>
<td>3.7</td>
<td>0.57</td>
<td>7.4</td>
<td>6.3</td>
<td>1/3</td>
<td>5.4</td>
</tr>
<tr>
<td>R12. $S^+ + O \rightarrow S^+(4S) + O^+(C\Pi)$</td>
<td>3.05</td>
<td>0.56</td>
<td>9.0</td>
<td>49</td>
<td>1/3</td>
<td>2</td>
</tr>
<tr>
<td>R13. $O^+ + N \rightarrow O^+(S\Pi) + Na^+$</td>
<td>-0.67</td>
<td>0.18</td>
<td>$\ldots$</td>
<td>...</td>
<td>5/8</td>
<td>...</td>
</tr>
<tr>
<td>R14. $O^+ + K \rightarrow O^+(S\Pi) + K^+$</td>
<td>-0.25</td>
<td>0.16</td>
<td>$\ldots$</td>
<td>...</td>
<td>3/8</td>
<td>...</td>
</tr>
<tr>
<td>R15. $S^+ + Na \rightarrow S^+(4P) + Na^+$</td>
<td>-0.13</td>
<td>0.16</td>
<td>...</td>
<td>...</td>
<td>5/8</td>
<td>...</td>
</tr>
<tr>
<td>R16. $O^+ + N \rightarrow O^+(3S) + Na^+$</td>
<td>0.9</td>
<td>0.22</td>
<td>14.7</td>
<td>13</td>
<td>6/8</td>
<td>...</td>
</tr>
<tr>
<td>R17. $S^+ + Na \rightarrow S^+(4P) + Na^+$</td>
<td>3.5</td>
<td>0.26</td>
<td>8.8</td>
<td>1.1</td>
<td>2/3</td>
<td>8</td>
</tr>
<tr>
<td>R18. $S^+ + O \rightarrow S^+(4P) + O^+$</td>
<td>3.6</td>
<td>0.26</td>
<td>8.0</td>
<td>0.62</td>
<td>29</td>
<td>2.1</td>
</tr>
<tr>
<td>R19. $O^+ + S \rightarrow O^+(C\Pi) + S^+(C\Pi)$</td>
<td>-0.22</td>
<td>0.18</td>
<td>10.1</td>
<td>10.1</td>
<td>2/3</td>
<td>8</td>
</tr>
<tr>
<td>R20. $O^+ + O \rightarrow O^+(D\Pi) + O^+(P\Pi)$</td>
<td>0.42</td>
<td>4.6</td>
<td>(0.22)</td>
<td>...</td>
<td>$\leq 0.1$</td>
<td></td>
</tr>
<tr>
<td>R21. $S^+ + O \rightarrow S^+(C\Pi) + O^+$</td>
<td>-1.7</td>
<td>0.41</td>
<td>5.3</td>
<td>(0.25)</td>
<td>...</td>
<td>$\leq 0.1$</td>
</tr>
<tr>
<td>R22. $O^+ + S + O \rightarrow O^+(D\Pi) + O^+(C\Pi)$</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
<td>$\leq 13$</td>
</tr>
<tr>
<td>R23. $S^+ + O \rightarrow S^+(C\Pi) + O^+(C\Pi)$</td>
<td>-0.86</td>
<td>-6.3</td>
<td>...</td>
<td>...</td>
<td>$\leq 16$</td>
<td></td>
</tr>
<tr>
<td>R24. $O^+ + O \rightarrow O^+(D\Pi) + O^+(D\Pi)$</td>
<td>-1.3</td>
<td>-5.1</td>
<td>...</td>
<td>...</td>
<td>$\leq 12$</td>
<td></td>
</tr>
<tr>
<td>R25. $S^+ + O \rightarrow S^+(C\Pi) + O^+(C\Pi)$</td>
<td>-0.86</td>
<td>-6.1</td>
<td>...</td>
<td>...</td>
<td>$\leq 15$</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
- Unless otherwise indicated, reactants and products are in their ground terms. $\Delta E$ is the difference in the binding energy of the electron on the two centers. $\Delta E$ negative is an exothermic reaction. $P_r$ is a product of factors determined by the spin and orbital angular momenta of the initial and final states: $P_r = P_1 P_2$. If the ratio of the spin multiplicity $t(2S_1 + 1)(2S_2 + 1)$ in the final state to that in the initial state is less than 1, then $P_r$ is determined similarly from the orbital angular momentum multiplicities.
- $\lambda^{-1}\beta^{-1} \gamma^{-1}$ and $P_r$ are determined similarly from the orbital angular momentum multiplicities.
- $\lambda^{-1}\beta^{-1} \gamma^{-1}$ and $P_r$ are determined similarly from the orbital angular momentum multiplicities.
- If number is in brackets it refers to $\delta^{-1}$, otherwise to $\lambda^{-1}$. Cross section at other velocities is obtained using these parameters and Figure 1. Note: in equations (5), (7), and (8), $\gamma \rightarrow V/|V|$. $\gamma$ in (2) is multiplied by $|1 - V/|V||$ at low velocities.
- The approximate upper limit is obtained by noting that the mismatch in energies requires either the transfer of an electron in a molecular orbital other than the outer orbital (see R5, R7) or an exchange to the ground state orbital of the ion with another electron in an excited state (See R8). Therefore, the ground state energies of the ion are used to estimate $I$ and Figure 3 gives the $R$, for the maximum $\sigma$. Note: double charge transfer will occur as a part of the net cross section.
used to compare the ion and electron reaction rates at a number of radii in the Io torus region. To ascertain the role of charge-exchange, the reader may choose to go directly to the last section.

**Cross Section Models**

Charge-exchange cross sections have been extensively studied both because of their importance in plasmas and the simplicity of detecting the charge-exchanged species in collision experiments. These cross sections are often written by using the impact parameter \( b \) between the incident and target particles and a transition probability (here charge-exchange probability) \( \mathcal{P}_{\text{ee}}(b) \)

\[
\sigma_{\text{ee}} = 2\pi \int_0^\infty \mathcal{P}_{\text{ee}}(b) b\,db
\]  

(1)

If the target particle is initially stopped, then the impact parameter is determined by the angular momentum \( L': b = L'/Mv \), where \( M \) and \( v \) are the incident mass and velocity. The form in (1) is particularly useful when describing slow charge-exchange collisions. In such a collision the electron will be shared by the two centers if they approach within some critical distance \( R_c \). For impact parameters less than \( R_c \), \( \mathcal{P}_{\text{ee}}(b) \) is an oscillatory function of \( b \), which can, quite accurately, be replaced by its average value, and the cross section becomes

\[
\sigma_{\text{ee}} = \mathcal{P}_{\text{ee}}(\pi R_c^2)
\]  

(2)

Therefore a calculation of the cross section involves a calculation of both \( R_c \) and \( \mathcal{P}_{\text{ee}}(b) \). These can generally be estimated from knowledge of the interaction potentials at large separations and the electron binding energy.

The simplest charge-exchange collision is the symmetric resonant process, \( A^{-}\,^0 + A \rightarrow A^{-}\,^1 + A \), in which the centers are identical and therefore \( \mathcal{P}_{\text{ee}} = 1/2 \). In this case the critical impact parameter, \( b = R_c \), is determined roughly by that separation at which the electron exchange frequency \( H_{12}(R)/\hbar \), where \( H_{12}(R) \) is the exchange energy, becomes comparable to the inverse of the collision time \( \sim v/R_c \), where \( v \) is the relative velocity of approach. At large separations \( R \) between the ion and the neutral, the exchange energy (the ability to share an electron) is related to the decay of the electron’s orbital wave function at large distance from the atomic center. For one electron transfer, this is determined by the ionization potential \( I \). General expressions for \( R_c \) are given by Rupp and Francis [1962] and Smirnov [1965]. These indicate that, as orbital wave functions decay exponentially,

\[
R_c = \frac{C}{I^{1/2}} [1 - \ln v]
\]  

(3)

at low velocities, \( v \leq 1 \) a.u. (1 atomic unit of velocity equals \( 2.2 \times 10^8 \) cm s\(^{-1}\)), where \( C \) and \( I \) depend weakly on \( I \). This useful expression, inserted in (2), indicates that \( \sigma \) increases slowly with decreasing velocity at low velocities and scales roughly as \( I^{-1} \) [Hastings, 1972]. In Table I we use this scaling to estimate symmetric resonant collision processes (R3, R5, R7) of importance in the Jovian magnetosphere.

Whereas the symmetric-resonant collision involves no inelastic energy change, nonsymmetric collisions, \( A^{-}\,^0 + B \rightarrow A + B^+ \), usually do. At low velocities the cross sections for such collisions depend on the energy difference, \( \Delta E \), between the final and initial states of both species. Because of the sensitivity of the cross sections to \( \Delta E \), they cannot be calculated reliably, by classical collisions between the incident ions and the electrons in the target atom, contrary to the view of Kunc and Judge [1981]. However, as exothermic and endothermic inelastic processes behave similarly at velocities above those at which the ion and atom are likely to orbit (>10 km s\(^{-1}\) depending on the masses) some simplifications can be made for estimating the cross sections. For instance, as the uncertainty in energy of the states during the collision \( \sim \hbar v/R_c \) is determined by the collision time, the size of \( \Delta E \) for which transitions are likely decreases with decreasing velocity. If \( \Delta E \) is much less than this uncertainty, then this energy difference is unimportant. The cross section now has the form in (2), and the collision is effectively like the symmetric resonant collision with \( R_c \), given by (3) and \( \mathcal{P}_{\text{ee}} = 1/2 \). For much larger values of \( \Delta E \) and/or lower velocities, the cross section rapidly decreases. Finally, at very low velocities, orbiting occurs due to the long-range attractive polarization force. Such orbiting increases the number of passes the particles make with each other, allowing exothermic processes with significant \( \Delta E \) to occur efficiently at very low velocities. Therefore in all nonsymmetric, low-velocity collisions the states of the colliding particles and the evolution of these states at large \( R \) have to be specified. We briefly describe procedures for estimating \( \mathcal{P}_{\text{ee}} \) and \( R_c \) that are useful for particular collision processes occurring in Io’s plasma torus.

For the collision \( A^{-} + B \rightarrow A + B^+ \), at large internuclear separation \( R \), both the initial and final state interactions (\( V_i \) and \( V_f \)) are that of a charge with an induced dipole determined by the polarizability \( \alpha \) of the neutral atom or molecule. Hence the energy difference (initial-final) versus \( R \) is

\[
\Delta V(R) = \Delta E + V_i - V_f
\]  

(4)

where \( \Delta E = (\varepsilon_R - \varepsilon_A) \), \( \varepsilon_A \) and \( \varepsilon_R \) being the binding energies of the electron in particular states on \( A \) and \( B \). For the collision described, \( V_i = -\alpha e^2/2R^2 \) and \( V_f = -\alpha e^2/2R^2 \), where \( e \) is the electronic charge, and these expressions for the potential are valid for \( R \) much larger than the atomic radii.

Since \( \Delta V(R) \) changes slowly at large \( R \), the criterion for establishing whether the energy difference is large or small is found by calculating the ratio

\[
\delta = \pi^2 \frac{\Delta V(R)}{\hbar} \frac{\alpha}{v}
\]  

(5)

To be more precise, \( v \) should be replaced by \( v(1 - (V_f(R_c)/E)^{-1/2} \), which is the velocity at \( R_c \), where \( E \) is the kinetic energy in the center of mass system.) As in the discussion above, \( \alpha e^2/\hbar \) is a collision time, where \( \alpha \) is an average electron radius on the two centers \( \alpha \sim (13.6 \text{ eV})^{-1/2} \omega_B \), with \( \omega_B \) the Bohr radius and \( I = (\varepsilon_A + \varepsilon_R)/2 \) (this is not the standard expression for \( \alpha \), but for problems of interest to us \( \varepsilon_A \) and \( \varepsilon_R \) differ little, and it is adequate). At high velocities when \( \delta^{-1} \lesssim 5 \), the energy difference is small enough that \( R_c \) equals the symmetric-resonant \( R_c \) in (3) and \( \mathcal{P}_{\text{ee}} = 1/2 \). For low velocities, \( \delta^{-1} \lesssim 5 \), \( R_c \) is determined by that distance at which the exchange energy \( H_{12} \) is comparable to energy separation between the states, or

\[
\frac{\Delta V(R_c)}{2} = H_{12}(R_c)
\]  

(6a)
The interaction energy (exchange energy for these processes), has been shown semi-empirically [Olson et al., 1971] to have the form

\[ H_{1z}(R) = \tilde{I} R^* \exp \left(-0.86 R^*\right) \quad (6b) \]

with \( R^* = R/a \). In this velocity region, \( \delta^{-1} \lesssim 5 \). \( P_{a-o} \) changes rapidly with \( v \) (i.e., \( \delta^{-1} \)) and values are tabulated (a quantity \( Q^*(\delta) \) is actually tabulated where \( P_{a-o} = (1/2)Q^* \) [Olson, 1972]) by Olson [1972] and shown in Figure 1. The transition probability, hence the cross section, is seen to increase rapidly with increasing velocities becoming a maximum at \( \delta^{-1} \sim 3 \).

It is seen from Figure 1 that \( P_{a-o} \) remains significant (>0.1) for \( \delta^{-1} \) as small as 1. Therefore from the above expressions we obtain the quite useful result that inelastic charge exchange occurs efficiently only if \( |\Delta E| \gtrsim 0.5 \) eV for ions and atoms having relative velocities characteristic of the Io torus (~60 km s\(^{-1}\)) and a mean ionization potential \( \tilde{I} \sim 13.6 \) eV. The expressions above are used to estimate cross sections in Table 1 (R2, R4, R9, R14, R15, R18, R21). The form for \( H_{1z}(R) \), equation (6b), can also be used with reasonable confidence to estimate \( R \) at high velocity, \( \delta^{-1} \gtrsim 5 \), by using Smirnov's [1965] expression

\[ \frac{H_{1z}(R_c)}{\hbar} = \left( \frac{\alpha R_c}{v} \right)^{1/2} = 0.11 \quad (7) \]

and therefore \( R_c \) has the form in (3).

In contrast to the above, if the interaction potentials between the colliding particles, \( V_i \) and \( V_f \), are very different (e.g., \( A^{12} + B \rightarrow A^{+} + B^+ \)) \( \Delta V(R) \) may go to zero at some large \( R \), i.e., \( R_c \) in Figure 2. New transitions (exchange) will occur rather efficiently in the vicinity of \( R_c \). When this is the case, \( R_c = R_c \) in (2), and the transition probability depends on the speed at which the particles pass through the region \( R_c \) and how steep the slope of \( \Delta V(R) \) is in this region. This is referred to as the Landau-Zener curve-crossing problem and the parameter replacing \( \delta \) is

\[ \lambda = 2\pi \cdot \left| \frac{H_{1z}(R_c)}{\hbar} \cdot \frac{H_{1z}}{[\partial \Delta V/\partial R(0)R_c]} \right| \quad (8) \]

where \( \Delta E = |\Delta V(0)|/|\partial \Delta V/\partial R| \), replacing, within a constant, the quantity \( a \) in (5).

Unlike the previous discussion (for \( \Delta V \) nearly constant), here \( R_c = R \) independent of \( v \) and the probability, \( P_{a-o} \), goes to zero both at high velocities (short collision times) and low velocities (adiabatic collision). \( P_{a-o} \) is tabulated as a function of \( \lambda \) (\( P_{a-o} = 4E_i(\lambda - E_2(2a)) \), where \( E_i \) is an exponential integral, a tabulated quantity) and shown in Figure 1. The maximum in \( P_{a-o} \) of 0.45 occurs at \( \lambda = 0.424 \) in (8).

'Curve-crossing' collisions dominate when multiply charged ions capture a single charge from a neutral, i.e., \( A^{12} + B \rightarrow A^{+} + B^+ \), with \( V_i = -a_b z^2 e^2/2R^2 \) and \( V_f = -z-e^2/R \) in (4). Also, when ions exchange an electron with another ion, \( A^{12} + B \rightarrow A^{+} + B^+ \), with \( V_i = -z^2 e^2/2R \) and \( V_f = -(z-1)(z^2+1)e^2/R \) in (4), curve crossings will occur for \( z < z^* \) (\( z = z^* + 1 \)). If we ignore the smaller polarization potential, then, for these collisions, \( \Delta V(R_c) = 0 \) in (4) implies that \( \Delta E = n e^2/R \), with \( n = (z-1) \) or \( z-z^* \) = 1. It is now seen that \( \Delta E \) and the crossing point are simply related and that exothermic collisions are always preferred for \( n > 0 \), because of the outgoing repulsive potential (Figure 2). Noting that \( |\partial \Delta V/\partial R| = |n| e^2/R^2 \), then for a given \( \tilde{I} \) and \( v \), an optimum \( R_c \) and hence an optimum \( \Delta E \) can be determined by evaluating (8) at \( \lambda = 0.424 \). This can be used to determine those final states (\( \Delta E \)) which are favored. For \( \tilde{I} = 13.6 \) eV, \( n = 1 \), and \( v = 60 \) km s\(^{-1}\), we obtain the useful result that the maximum in \( P_{a-o} \) occurs for exothermic collisions with \( \Delta E = 3.5 \) eV, and reasonably large \( P_{a-o} \) (≥0.1) occur if the colliding pairs have states such that \( +0.27 \) eV < \( \Delta E < 4.3 \) eV). In Figure 3 we graphically show the dependence of the optimum \( \Delta E \) on \( v, \tilde{I} \), and \( |n| \), from which the reader can determine the important final state energy differences for each collision process. Charge-exchange cross sections are calculated in (2) and (8) and Figure 1 for reactions R5, R6, R7, R8, R10–R13, R16, R17, R22–R25 in Table 1.

For very low velocities and/or a high polarizability for atom B (with a high charge z on A), orbiting occurs. Now we assume, if there are a number of exothermic states available, that \( P_{a-o} = 1 \) and \( R_c \) is the orbiting radius, \( R_c = (2a_b z^2 e^2/E_i)^{1/4} \), determined from the attractive polarization interaction. For this model to be applicable, \( R_c \gg a \) and the exothermic states must have crossings within \( R_c \) (i.e., \( R_c < R_c \)). Such a model, here the Langemick model [e.g., Hasted, 1972; Johnson, 1982] is referred to as an absorbing sphere.
model. It is based on the fact that when the colliding pair passes through a transition region many times or passes through many transition regions, the sum of transition probabilities $P_{0\rightarrow i}$ approaches unity. Therefore, one only needs to know a critical radius. The absorbing sphere idea can also be extended to describe charge transfer into a large number of closely spaced states. General models have been developed for collisions $A^{\text{1}^+} + B \rightarrow A^{\text{1}^+} + B$ for $\nu > 4$ [Janey and Hveplund, 1981]. Further, if charge-exchange occurs by crossing with a near continuum of states, one can always use such a model. For instance, estimating that $R_s$, which corresponds to the maximum $P_{0\rightarrow i}$ in a near continuum of final states, then $\sigma \sim \Sigma_{m \not= 0} m \sim \pi R_s^2$, which is applicable to such collisions as $O^{\text{1}^+} + S$ and $S^{\text{1}^+} + S$ (R8 and R12, Table 1).

The above methods have been developed and tested primarily for one-electron processes. However, these results can be roughly extrapolated to processes involving two electrons (charge-exchange plus excitation of a second target electron or double charge-exchange) by replacing $I$ in (3), (5), (6), and (7) by the sum of the $I$ for the two active electrons. These methods, with the exception of the absorbing sphere models, have also been developed to describe collisions involving only two interacting states well separated in energy from other states and with low multiplicity (preferably singlet or doublet S states). When applying them to higher multiplicity problems, care must be taken to satisfy time reversal (or detailed balance). In the absence of a more complete treatment of the angular momentum, one can satisfy this constraint by calculating the multiplicities (spin and orbital angular momentum) of the initial and final state. If those of the final state are higher, the two-state estimates above can be used. If those of the initial state are higher, the cross section calculated above should be multiplied by the ratio of final to initial state multiplicities, the factor $P_f$ in Table 1. Using such a factor implies that transitions only occur between states of the same symmetry. It is known, however, that transitions do occur between states of different symmetry and hence that this procedure gives a conservative estimate. The inclusion of transitions between states of different symmetry would tend to increase the cross section at low velocities, particularly where the energy difference $\Delta E$ is small [Russek, 1971].

For molecular targets the above procedures also apply if $R_s$ is greater than the molecular dimensions. For molecules, however, there is generally a near continuum of vibrational and rotational states existing between the separate electronic levels. Near-resonant collisions, therefore, will occur if the vibrational wave function of the initial state and the final ion state are similar. This similarity is determined by the overlap of the wave functions in the initial neutral state and the final ion state, referred to as the Franck-Condon factor [Hasted, 1972], for which tabulations exist for many molecules. At the velocities of interest here, small changes in vibrational and rotational state are favored, the latter because transitions take place predominantly at large $R$ and, therefore, the torques are small. As the possible final states of the molecule may include electronic states which are nonbinding, dissociation may also be produced efficiently in such collisions, particularly if there is a large mismatch in electron-binding energy of the incident and target species, as in collisions involving doubly charged ions with neutral molecules (e.g., R22–R25).

The above models have been applied to a variety of charge-transfer reactions which were considered to be potentially important in the Io torus and exosphere. The list of reactions, relevant parameters, and calculated cross sections are given in Table 1, along with appropriate footnotes where needed to amplify the above discussion to specific reactions. The parameters are given for each collision process so the reader can follow the estimate of the cross section and also obtain the velocity dependence by using Figure 1. The general trend is a shift in charge from the more weakly bound species to the more tightly bound species. Estimates of cross sections are seen to require specific state information about each collision partner. For example, note the substantial difference in cross sections for reactions R7 and R8 when $O_1$ is a product, as opposed to an educated guess that the cross sections would be comparable. Comparison of Table 1 cross sections with Kunc and Judge [1981] estimates reveals significant differences for reactions R2 and R4, as well as the overall velocity dependence for reactions R1–R4 below 1 keV. The cross sections given in Table 1 are presumed generally to be accurate to within a factor of 2. At low velocities ($\lambda^{-1}$ or $\delta^{-1}$ small) the results are less reliable. Therefore, detailed calculations should be considered for very important reactions when accurate modeling of the torus becomes possible. Further discussion of these models and additional references may be found in Olson [1980], Janey and Hveplund [1981], and Johnson [1982]. In the following sections we describe a model torus and the use of calculated cross sections in Table 1 to assess the importance of charge exchange in the torus.

Model Torus Properties

To evaluate the importance of charge-exchange processes relative to other competing processes, we need to know certain properties such as ion and neutral densities and the electron temperature. In Table 2 their values, which are guess estimates based on observations and theoretical considerations, are specified at 6 radial distances from the center of Jupiter. Since the time constants associated with charge exchange exceed the bounce time and rotation period of the corotating plasma relative to the neutrals, only latitudinal and longitudinal averages are needed. On the basis of the detailed calculations of the neutral oxygen cloud by
Smyth and Shemansky [1982], which satisfy the observational constraint of Brown [1981], adopt their longitudinally and latitudinally (over 1 \( R_J \)) averaged oxygen densities. These are given in Table 2. It should be noted that charge-exchange effects were not included in these calculations. This probably results in overestimates in the oxygen density and the importance of charge exchange in the inner torus. In the case of the neutral sulfur cloud, neither observations nor equivalent calculations were available. Accordingly, the sulfur density was estimated by

\[
n(S) \sim \frac{I(O)}{I(S)} n(O)
\]

where \( I \) is the ionization rate of the indicated atom by electron impact at \( T_e = 5 \) eV, the adopted electron temperature in the vicinity of Io. A comparable average density has been inferred by Cheng [1982].

The electron temperature profile was constructed on the basis of the constraint imposed by EUV radiative loss [Brown et al., 1982a], the evidence for cold, equilibrated ion and electron temperatures in the inner torus [Bagemihl and Sullivan, 1981], and the trends of Scudder et al. [1981] measurements. The longitudinally averaged electron density contours of Birmingham et al. [1981] were adopted to construct the electron density profile. The ion densities were the most difficult to estimate due to the problems associated with interpreting the Voyager EUV spectra [Brown et al., 1982a] and the in situ plasma measurements [Bagemihl and Sullivan, 1981]. Given the optical observational constraints [Brown et al., 1982a] and the in situ plasma science measurements, we have made guess estimates of the required ion density profiles that are consistent with increasing electron temperature at increasing radial distance and the expectation that the most highly ionized species will be concentrated in the outer torus, whereas singly ionized species will predominate in the cold, inner torus. Unfortunately, the entire data base of optical emissions does not yield consistent ion density profiles as discussed by Brown et al. [1982a]. For example, the adopted O\(^+\) density profile is consistent with the Voyager EUV data but not with ground-based forbidden emission line data [Morgan and Pilcher, 1982].

### Importance of Charge Exchange in the Io Torus and Exosphere

In determining the importance of charge exchange in the Io torus we have abandoned the still commonly used artifice of a homogeneous torus with averaged physical properties [e.g., Brown et al., 1982b] in favor of a model with explicit incorporation of the radial dependence of densities and temperatures as advocated in the concluding remarks of Brown et al. [1982a]. This essential framework is necessary as a consequence of the significant radial variation of electron temperature, and hence ionization and dielectronic recombination rates.

Charge-exchange rate coefficients are functions of the relative velocity of the colliding reactants. The relative velocity between the corotating plasma and Io is \( \sim 60 \text{ km s}^{-1} \). The neutral clouds associated with Io are moving at approximately the same velocity, although the leading inner edge of the cloud at 5 \( R_J \) may be moving \( \sim 20 \text{ km s}^{-1} \) faster than Io [Smyth and Shemansky, 1982]. Since the products of cross section and velocity in many of the interesting charge-transfer reactions do not vary significantly over the velocity interval of 40–80 km s\(^{-1}\), we assume a relative velocity of 60 km s\(^{-1}\) in computing charge-exchange rates, except as noted in Table 1. Charge-exchange rates in units of s\(^{-1}\) were evaluated for most of the reactions in Table 1 at the six radial locations in the torus shown in Table 3, where they are compared with the rates of the competing processes of ionization and electron recombination. The electron impact ionization rate coefficients given by Brown et al. [1982a] were used. Dielectronic recombination rates calculated by Jacobs et al. [1979] plus the contribution of radiative recombination were adopted for electron recombination.

In a charge-exchange reaction involving a neutral species the resulting neutral acquires the velocity of the ion (\( \sim 70 \text{ km s}^{-1} \) in the inertial frame of reference), which is sufficient to escape the Jupiter system as noted by Cheng [1980], whereas the newly created ion acquires initially the velocity of the slow neutral (\( \sim 12 \text{ km s}^{-1} \)). In exothermic reactions the light fragment will, in addition, gain most of the excess energy, \( \Delta E \), as random kinetic energy. The slow ion will subsequently be accelerated to corotation and gain the usual pickup energy of \( \sim 280 \text{ eV} \) for oxygen ions and \( \sim 560 \text{ eV} \) for sulfur ions. Therefore charge exchange, like electron processes, is a source of fresh gyration energy and a mass sink for torus material. If we compare the O ionization rates 11 with the charge-exchange rates (C1, C4, C7, and C10), we find that charge exchange dominates the production of O\(^+\) inside Io’s orbit and is still competitive with ionization outside of Io’s orbit [Strobel, 1981]. A similar comparison of the S ionization rate 12 with charge-exchange rates (C2, C3, C5, C6, and C11) leads to a similar conclusion except at the outer edge of the torus where ionization is more important. However, in the case of sodium (and potassium) ionization, I3 is clearly more important than charge exchange (C8, C9) everywhere. With the exception of the reaction O\(^{++}\) + S \( \rightarrow \) O\(^+\) + e + S\(^{++}\), charge exchange does not change the net ionization level of the plasma and therefore in any radial region the net source of ions is due to electron impact and/or diffusion.
<table>
<thead>
<tr>
<th>Reaction</th>
<th>Rate at ( R_L = )</th>
<th>5.1</th>
<th>5.5</th>
<th>5.9</th>
<th>6.3</th>
<th>6.7</th>
<th>7.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>11. ( e + O \rightarrow O^+ + 2e )</td>
<td>( \sigma \langle O \rangle )</td>
<td>3.9(8)</td>
<td>2.2(6)</td>
<td>3.9(6)</td>
<td>4.8(6)</td>
<td>5.6(6)</td>
<td></td>
</tr>
<tr>
<td>12. ( e + S \rightarrow S^+ + 2e )</td>
<td>( \langle S \rangle )</td>
<td>3.9(8)</td>
<td>2.2(6)</td>
<td>3.9(6)</td>
<td>4.8(6)</td>
<td>5.6(6)</td>
<td></td>
</tr>
<tr>
<td>13. ( e + Na \rightarrow Na^+ + 2e )</td>
<td>( \langle Na \rangle )</td>
<td>5.8(5)</td>
<td>4.1(4)</td>
<td>5.8(6)</td>
<td>5.6(6)</td>
<td>4.8(6)</td>
<td></td>
</tr>
<tr>
<td>14. ( e + O^+ \rightarrow O^+ + 2e )</td>
<td>( \langle O^+ \rangle )</td>
<td>3.9(10)</td>
<td>2.2(8)</td>
<td>3.9(8)</td>
<td>4.8(6)</td>
<td>5.6(6)</td>
<td></td>
</tr>
<tr>
<td>15. ( e + S^+ \rightarrow S^+ + 2e )</td>
<td>( \langle S^+ \rangle )</td>
<td>2.3(10)</td>
<td>1.5(6)</td>
<td>2.3(6)</td>
<td>2.8(6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16. ( e + O^{++} \rightarrow O^{++} + 2e )</td>
<td>( \langle O^{++} \rangle )</td>
<td>1.3(10)</td>
<td>1.5(6)</td>
<td>2.3(6)</td>
<td>2.8(6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17. ( e + S^{++} \rightarrow S^{++} + 2e )</td>
<td>( \langle S^{++} \rangle )</td>
<td>2.3(10)</td>
<td>1.5(6)</td>
<td>2.3(6)</td>
<td>2.8(6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18. ( e + S^{+++} \rightarrow S^{+++} + 2e )</td>
<td>( \langle S^{+++} \rangle )</td>
<td>2.3(10)</td>
<td>1.5(6)</td>
<td>2.3(6)</td>
<td>2.8(6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1. ( O^+ + O \rightarrow O + O^+ )</td>
<td>( \sigma \langle O \rangle )</td>
<td>5.9(6)</td>
<td>4.1(4)</td>
<td>5.9(6)</td>
<td>5.6(6)</td>
<td>4.8(6)</td>
<td></td>
</tr>
<tr>
<td>C2. ( O^+ + S \rightarrow O + S^+ (2P) )</td>
<td>( \sigma \langle S \rangle )</td>
<td>3.9(8)</td>
<td>2.2(6)</td>
<td>3.9(8)</td>
<td>4.8(6)</td>
<td>5.6(6)</td>
<td></td>
</tr>
<tr>
<td>C3. ( S^+ + S \rightarrow S^+ + S )</td>
<td>( \sigma \langle S \rangle )</td>
<td>4.1(8)</td>
<td>2.7(6)</td>
<td>4.1(8)</td>
<td>5.6(6)</td>
<td>4.8(6)</td>
<td></td>
</tr>
<tr>
<td>C4. ( O^{++} + O \rightarrow O + O^+ )</td>
<td>( \sigma \langle O \rangle )</td>
<td>3.9(10)</td>
<td>2.2(8)</td>
<td>3.9(8)</td>
<td>4.8(6)</td>
<td>5.6(6)</td>
<td></td>
</tr>
<tr>
<td>C5. ( S^{++} + S \rightarrow S^+ + S^+ )</td>
<td>( \sigma \langle S \rangle )</td>
<td>3.9(10)</td>
<td>2.2(8)</td>
<td>3.9(8)</td>
<td>4.8(6)</td>
<td>5.6(6)</td>
<td></td>
</tr>
<tr>
<td>C6. ( O^{+++} + S \rightarrow O^+ + S^+ )</td>
<td>( \sigma \langle O \rangle )</td>
<td>2.3(10)</td>
<td>1.5(6)</td>
<td>2.3(6)</td>
<td>2.8(6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C7. ( S^{+++} + O \rightarrow S^+ + O^+ )</td>
<td>( \sigma \langle O \rangle )</td>
<td>1.3(10)</td>
<td>0.9(8)</td>
<td>1.3(10)</td>
<td>1.8(8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C8. ( O^{+++} + Na \rightarrow O^+ + Na^+ )</td>
<td>( \sigma \langle O \rangle )</td>
<td>1.3(10)</td>
<td>0.9(8)</td>
<td>1.3(10)</td>
<td>1.8(8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C9. ( S^{+++} + Na \rightarrow S^+ + Na^+ )</td>
<td>( \sigma \langle O \rangle )</td>
<td>1.3(10)</td>
<td>0.9(8)</td>
<td>1.3(10)</td>
<td>1.8(8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C10. ( O^{+++} + O \rightarrow O^+ + O^+ )</td>
<td>( \sigma \langle O \rangle )</td>
<td>1.3(10)</td>
<td>0.9(8)</td>
<td>1.3(10)</td>
<td>1.8(8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C11. ( S^{+++} + S \rightarrow S^+ + S^+ )</td>
<td>( \sigma \langle O \rangle )</td>
<td>1.3(10)</td>
<td>0.9(8)</td>
<td>1.3(10)</td>
<td>1.8(8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C12. ( O^{+++} + S \rightarrow O^+ + S^+ )</td>
<td>( \sigma \langle O \rangle )</td>
<td>1.3(10)</td>
<td>0.9(8)</td>
<td>1.3(10)</td>
<td>1.8(8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D1. ( O^+ + e \rightarrow O^+ + h\nu )</td>
<td>( \sigma \langle O \rangle )</td>
<td>2.3(9)</td>
<td>1.8(8)</td>
<td>2.3(9)</td>
<td>1.8(8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D2. ( S^+ + e \rightarrow S^+ + h\nu )</td>
<td>( \sigma \langle O \rangle )</td>
<td>2.3(9)</td>
<td>1.8(8)</td>
<td>2.3(9)</td>
<td>1.8(8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D3. ( S^{+++} + e \rightarrow S^{+++} + h\nu )</td>
<td>( \sigma \langle O \rangle )</td>
<td>2.3(9)</td>
<td>1.8(8)</td>
<td>2.3(9)</td>
<td>1.8(8)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( * \) For \( e + K \rightarrow K^+ + 2e \), \( \sigma \langle K_{\text{e}} \rangle_\text{e} = 1.4a_{\text{H}}/\text{Na}_{\text{e}}. \)

\( * \) Evaluated at \( v = 20 \, \text{km s}^{-1} \).

\( * \) Ratio of ion gyration energy production rate by charge exchange to electron impact ionization.

Note at the bottom of Table 3 that charge exchange is the dominant source of ion gyration energy \( T_e \) in the inner torus. This conclusion is independent of the assumed neutral densities.

Charge-exchange reactions can be an efficient way for multiply charged ions to recombine \cite{Strobel1981, Brown1982}. For example, \( S^{++} \) can recombine by reaction C7 a factor of 3 times faster than electron recombination D2 inside of 6.3 \( R_L \). Only at the outer edge of the torus does dielectronic recombination become important. Even for \( S^{+++} \), which has the fastest recombination rate D3, charge-exchange recombination dominates inside of 6 \( R_L \). Thus the preferred mode of recombination in the 'inner' torus is charge exchange.

Charge exchange may also lead to an increase in the ionization level as is evident from reaction C12, where \( S^{++} \) is converted to \( S^{+++} \). Its charge-exchange rate exceeds the ionization rate of \( S^{++} \) in the inner torus only if most \( O^{++} \) are hot \( T_e \sim 280 \, \text{eV} \) as a consequence of the strong velocity dependence of the cross section (see Table 1, R10). This reaction may suppress preferentially any superthermal tail in the \( O^{++} \) velocity distribution. \( S^{+++} \) is created at the expense of \( O^{++} \), which has a comparable ionization rate (compare I6 with I8), as \( Brown1982 \) found in their calculations.

The dominance of charge-exchange reactions inside Io’s orbit suggests that the relative distribution of various ions may be controlled by these reactions. For example, from Table 3 we obtain in chemical equilibrium

\[ \frac{n(S^{++})}{n(S^{+++})} = \frac{\sigma_{eO}(O) + \sigma_{eO}(S)n(O)}{\langle S^{++} \rangle n_e} \]

(9)

where the subscript on \( \sigma \) indicates the appropriate reaction in Table 3. From Tables 1–3 we compute this ratio to be 2.6, 0.4, 0.06, and 0.03 at \( r = 5.5, 5.9, 6.3 \), and \( 6.7 \) \( R_L \), respectively. This may be compared with the respective values in Table 2 of 3, 0.4, 3.0, and 0.16. The agreement is surprisingly good in the inner torus. The discrepancies in the outer torus may not be serious, since \( S^+ \) forbidden line emissions which were used to infer \( n(S^+) \) in Table 2 are highly variable. In all probability, outward diffusion by centrifugal interchange maintains the \( S^+ \) concentration in excess of the chemical estimates of \( 9 \) outside of Io’s orbit \cite{Richardson1980, Frohlich1980}.

A similar expression may be derived from Table 3 for the \( n(S^{++})/n(S^{+++}) \) ratios

\[ \frac{n(S^{++})}{n(S^{+++})} = \frac{\alpha_{Oe}(O) + \sigma_{eO}(S)n(O) + \sigma_{eO}(O)}{\langle S^{++} \rangle n_e + \sigma_{eO}(S)n(S^{++})} \]

(10)

with values of 340, 17, 2, 0.9, and 0.4, respectively, at 5.5, 5.9, 6.3, 6.7, and 7.1 \( R_L \). When compared with the respective model torus values of 8.5, 7.1, 1.5, 0.8, and 0.45, we find reasonably good agreement except in the inner torus where
only in situ measurements provide density estimates. Radial mixing of $S^{++}$ may enhance its concentration in the inner torus. In Table 2 the $S^{++}$ densities were based primarily on the strong EUV emission at 745 Å observed by the Voyager UVS [Shevanskay and Smith, 1981] rather than a stringent upper limit on $S^{++}$ densities imposed by IUE observations at 1406 Å [Moses and Clarke, 1981]. The implication of the calculated $n(S^{++})/n(S^{+++})$ ratio in (10) is that charge-exchange processes maintain a very low abundance of $S^{+++}$ except on the fringes of the outer torus.

Similar calculations can be carried out from Table 3 for the $n(O^+) / n(O^{+++})$ ratio, although no simple expression can be given that is valid throughout the torus. The results of these chemical equilibrium calculations are $n(O^+) / n(O^{+++})$ approximately equal to 32, 23, 2, 0.2, and 0.14 at $r = 5.5, 5.9, 6.3, 6.7,$ and $7.1 R_J$, respectively. Thus charge-exchange recombination suppresses both $O^{++}$ and $S^{+++}$ concentrations in the inner torus where neutral O and S densities are largest. Brown et al. [1982b] found larger average $S^{+++}$ and smaller average $O^{++}$ concentrations as a consequence of their assumption of higher $O^{+++}$ temperature, which determines the relative velocity of reactions R9 and R10 in Table 1.

Charge-exchange reactions can also be important processes in the interaction of torus plasma with Io’s atmosphere. An exosphere may be produced on Io, albeit nonuniformly, as a result of volcanoes, sputtering, and/or sublimation with molecular species such as SO₂, SO, and O₂ as components of the exospheric gas. In a charge-exchange collision of a torus ion with a molecular target, multiple products can be produced which may escape Io (e.g., three atoms/ion from SO₂ and two from O₂ and SO). Therefore charge-exchange events in Io’s exosphere are a source of torus ions and neutrals. The neutrals are produced either directly, if an excited molecular-ion dissociates via a repulsive state, or subsequently by electron recombination and electron collisional dissociation (see R22–R25, Table 1). The latter is reasonably efficient as the molecular dissociation energies are of the order of 5 eV, approximately the torus electron temperature, and the excited dissociating electronic states are only a couple of electron volts higher. Although dissociative recombination rates are much faster than radiative and dielectronic recombination rates for atomic ions, dissociative recombination is very sensitive to electron temperature. At $T_e \sim 5$ eV the recombination coefficient is $\lesssim 10^{-8}$ cm$^{-3}$ s$^{-1}$, and dissociation of molecular ions by electron impact is competitive with dissociative recombination. However, if molecular ions only recombined after being accelerated to corotation, then the neutral products would escape the Jovian system. The effect of charge exchange is thus to remove exospheric molecules and contribute a net supply of neutrals and plasma to the Io torus.

CONCLUDING REMARKS

Charge-exchange cross sections and their velocity dependence have been estimated for the most important reactions in the Io torus and exosphere. For symmetric-resonant single and double charge exchange, the cross sections are slowly varying functions of velocity (equation (3)). For inelastic charge-exchange collisions, however, the transition probabilities into a given final state can depend critically on velocity (Figure 1). Therefore in any velocity region charge-exchange reactions are favored for those systems having particular initial–final state energy differences. The models described in the text can be used to estimate both the most rapid charge-exchange processes and those states which play an important role. The latter information will be useful in interpreting spectroscopic data taken on the torus region. By using the calculated cross sections to obtain reaction rates as a function of radial position, the importance of charge exchange has been demonstrated primarily in the inner torus, whereas Brown et al. [1982b] have concluded that charge exchange cannot be ignored in calculating average homogeneous torus densities. The radial variation of the important collision processes, as shown in Table 3, indicates that a spatially averaged description of plasma processes in the Io torus cannot be expected to represent adequately the controlling atomic and molecular collision processes. The validity of our results, of course, depends on the accuracy of the input parameters: the cross sections, neutral and ion densities, and the electron temperature. Our calculated charge-exchange cross sections should be accurate to about a factor of 2 for the larger cross sections and in most cases are probably conservative estimates. The accuracy of the neutral densities which depend on the assumed radial electron density and temperature profiles is discussed in Smyth and Shevanskay [1982]. The neglect of charge-exchange effects may be the largest source of neutral density error.

The ion densities are probably the most uncertain. Even though the rates in Table 3 may be reasonable, they should be regarded primarily as illustrative rather than definitive results. They are sufficiently accurate to defend the principal conclusion of this work, namely, that charge-exchange reactions are of fundamental importance in the inner torus of Io.

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