Exercise 13.3. At temperatures around 2500°K and somewhat higher, noble gases (such as argon, for example) are essentially un-ionized. In order to make such a gas electrically conducting, a more easily ionizable seed material (such as cesium or potassium) may be added. At a temperature $T$, the electron and neutral seed number densities $n_e$ and $n_s$, respectively, are related by Saha's equation in the form $n_e^2 = n_s K(T)$, where $K(T)$ is a function only of the temperature. Derive a simple criterion involving just collision frequencies for the amount of seed which yields the maximum electrical conductivity for such a seeded mixture. Assume the noble gas number density $n_n$ is given.

Exercise 13.4. The electrical conductivity of a sample of Cs vapor at a temperature of 2000° and at a pressure of 1 mm of Hg was measured to be 10 mhos m$^{-1}$. When some H$_2$ was added to the sample, the measured conductivity dropped to 2 mhos m$^{-1}$. What was the partial pressure (approximate) of the added H$_2$? (Assume the Cs to be weakly ionized and that there is negligible dissociation of H$_2$.)

Exercise 13.5. Compare the Lorentzian value of the electrical conductivity with that given by the mean-free-path model, for the case where $\bar{v}_e$ is a constant.

14. REPRESENTATIVE CROSS-SECTION DATA

For the most part, information on cross sections is scattered in the scientific literature. Compilations of data by Brown (1959, 1967), by Laborie, Rocard, and Rees (1968), and by Kieffer (1969a, 1969b, 1971) are available and many references are cited by Massey and Burhop (1952, 1969), McDaniel (1964), Hasted (1964), and Massey (1969). (See also Sec. 4.) The quality of experimental measurements varies over a wide range. Estimates of accuracy are probably best inferred from the differences in the results of independent investigations. For example, Kieffer states that uncertainties in the values of the maxima of electron impact ionization and excitation cross sections range respectively between about 15 percent and factors of 2 or 3 and between about 35 percent and factors of 10. With respect to the dependence of cross sections on energy, it is necessary to distinguish between the broad features which vary on an energy scale of the order of a few electron volts, and the fine structure which varies on a scale of less than 0.1 eV. It has been only since about 1963, as a result of refinements in experimental techniques, that the latter aspects have become evident.

It is important for those concerned with partially ionized gases to have
a general appreciation of the processes for which cross section data are available, for the range of magnitudes of these cross sections, and for regularities that may exist. It has been with this objective in mind that the cross section data of this section have been selected. It should be noted that these examples constitute a very small sample of the information that exists. For the results presented, atomic systems may be regarded as being initially in the ground state while molecules may be presumed to be in an initial condition corresponding to that of a gas in equilibrium at room temperature. Only data on the broad features are presented. The references cited in the figure captions refer to the sources from which the data were obtained and are not always the original papers. To aid the reader, the cross-section data are presented sequentially in accordance with the classification scheme shown in Table 11.

### Table 11  Guide to Some Selected Cross Section Data

<table>
<thead>
<tr>
<th>Elastic collisions</th>
<th>Fig. Nos.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Electron-atom total cross sections</td>
<td>20–23</td>
</tr>
<tr>
<td>2. Electron-atom momentum transfer cross sections</td>
<td>24–25</td>
</tr>
<tr>
<td>3. Electron-atom differential cross sections</td>
<td>26</td>
</tr>
<tr>
<td>4. Electron-molecule cross sections</td>
<td>27–28</td>
</tr>
<tr>
<td>5. Energy-averaged cross sections</td>
<td>29</td>
</tr>
<tr>
<td>6. Ion-atom cross sections</td>
<td>30–31</td>
</tr>
<tr>
<td>7. Ion-molecule cross sections</td>
<td>32</td>
</tr>
<tr>
<td>8. Atom-atom cross sections</td>
<td>Table 12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nonelastic collisions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Electron-atom processes</td>
</tr>
<tr>
<td>1.1 Collisonal processes</td>
</tr>
<tr>
<td>1.1.1 Ionization</td>
</tr>
<tr>
<td>1.1.2 Excitation</td>
</tr>
<tr>
<td>1.2 Radiative processes</td>
</tr>
<tr>
<td>1.2.1 Radiative recombination</td>
</tr>
<tr>
<td>1.2.2 Radiative attachment</td>
</tr>
<tr>
<td>2. Electron-molecule processes</td>
</tr>
<tr>
<td>2.1 Processes involving changes in electronic levels—similar to electron-atom processes</td>
</tr>
<tr>
<td>2.2 Rotational and vibrational excitation</td>
</tr>
<tr>
<td>2.4 Dissociative ionization</td>
</tr>
<tr>
<td>2.5 Dissociative recombination</td>
</tr>
<tr>
<td>2.6 Dissociative attachment</td>
</tr>
<tr>
<td>3. Ion-atom and atom-atom processes</td>
</tr>
<tr>
<td>3.1 Charge transfer</td>
</tr>
<tr>
<td>3.2 Atom-atom ionization</td>
</tr>
</tbody>
</table>
Figure 20. Total elastic collision cross sections of electrons in H, H₂, and He (after Brackmann, Fite, and Neynaber, 1958; and Brode, 1933).
Figure 21. Total elastic collision cross sections of electrons in the noble gases Ne, A, Kr, and Xe (after Brode, 1933).

Figure 22. Total elastic collision cross sections of electrons in the alkali metals Na, K, Rb, and Cs (after Brode, 1933). (For more recent data see Visconti, Slevin, and Rubin, 1971.)
Figure 23. Total elastic collision cross sections of electrons in Cd, Zn, and Hg (after Brode, 1933).

Figure 24. Comparison of momentum transfer cross sections (---) with total elastic cross sections (-----) for electron collisions with He, Ne, and A (after Massey and Burhop, 1969, p. 48).
Figure 25. Comparison of low-energy momentum transfer (--- and ----) and total elastic (-----) cross sections for electron collisions with argon (after Golden, 1966).
Figure 26. Differential elastic scattering cross sections $I(\chi)$ of electrons in He, Ar, Xe, and Hg (after Massey and Burhop, 1969, p. 335).
Figure 27. Total elastic collision cross sections of electrons in the molecular gases \( \text{O}_2, \text{N}_2, \) and CO (after Brode, 1933).
Figure 28. Total elastic momentum transfer cross sections of electrons in the polar molecular gases H$_2$O, NH$_3$, N$_2$O, and in CO$_2$ (after Biondi, 1963, p. 90).

Figure 29. Energy-averaged momentum transfer cross sections for electron collisions with argon (based on Golden, 1966, for low energies, and on Frost and Phelps, 1964, for high energies—see Fig. 25), nitrogen (based on Engelhardt, Phelps, and Risk, 1964—see Fig. 43), and potassium (based on Brode, 1933—see Fig. 22).
Figure 30. Total elastic collision cross sections of ions of Cs, Rb, K, Na, and Li in argon (after Delcroix, 1960, p. 21).

Figure 31. Total elastic collision cross section of cesium ions in cesium (after Bullis, 1963, p. 8).
Figure 32. Total elastic collision cross sections of potassium ions in the molecular gases N₂, O₂, and H₂ (after Ramsauer and Beeck, 1928).

Table 12 Total Elastic Collision Cross Sections (in $10^{-16}$ cm²) of Alkali Metal Atoms with Noble Gas Atoms at Energies of Order 0.1 eV (after Massey and Burhop, 1952, p. 397).

<table>
<thead>
<tr>
<th>Scattered atom</th>
<th>Helium</th>
<th>Neon</th>
<th>Argon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li</td>
<td>106</td>
<td>120</td>
<td>303</td>
</tr>
<tr>
<td>Na</td>
<td>130</td>
<td>213</td>
<td>401</td>
</tr>
<tr>
<td>K</td>
<td>165</td>
<td>259</td>
<td>580</td>
</tr>
<tr>
<td>Rb</td>
<td>152</td>
<td>268</td>
<td>572</td>
</tr>
<tr>
<td>Cs</td>
<td>162</td>
<td>287</td>
<td>572</td>
</tr>
</tbody>
</table>
Figure 33. Ionization cross sections for H, H\textsubscript{2}, and He by electron impact (after Fite and Brackmann, 1958; and Smith, 1930).
Figure 34. Total ionization cross sections for the noble gases Ne, A, Kr, and Xe by electron impact (after Kieffer, 1969a).
Figure 35. Ionization cross sections for the alkali metals Na, K, Rb, and Cs (after McFarland and Kinney, 1965).
Figure 36. Excitation cross sections for the first excited level of atomic hydrogen by electron impact (after Fite, Stebbings, and Brackmann, 1959; and Hils, Kleinpoppen, and Koschmieder, 1966).
Figure 37. Excitation cross section for the $2^1 P$ level of He by electron impact (after Kieffer, 1969b, p. 5).

Figure 38. Excitation cross sections for the $2p_8$ levels (Paschen notation) of A, Kr, and Xe by electron impact (after Zapesochnyi and Feltsan, 1966).
Figure 39. Excitation cross sections for the alkali metals Na, K, Rb, and Cs (after Zapesochnyi and Shimon, 1965).
Figure 40. Radiative recombination cross section for electron capture to the ground level of H (after Massey, 1969, pp. 1071 and 1073).

Figure 41. Radiative recombination cross sections for electron capture to the ground levels of K and Cs, calculated from photoionization data (after Massey, 1969, p. 1129; and Marr, 1967, pp. 113 and 115).
Figure 42. Radiative electron attachment cross sections for H⁻ and O⁻ (after Branscomb, 1962).

Figure 43. Rotational, vibrational, and electronic excitation cross sections, and ionization and momentum transfer cross sections of N₂ by electron impact (after Engelhardt, Phelps, and Risk, 1964).
Figure 44. Dissociative electron attachment cross section for O₂ (after Biondi, 1963, p. 126).
Figure 45. Charge transfer (charge exchange) cross sections. Resonant charge transfer for $A^+$ in argon and $\text{He}^+$ in helium, and nonresonant charge transfer for $\text{H}^+$ in xenon and $\text{H}^+$ in argon (after Hasted, 1951; and Massey and Burhop, 1952, p. 529).
Figure 46. Atom-atom ionization cross sections for the noble gases He and A (after Hayden and Amme, 1966), and Ne and Kr (after Amme and Haugsjaa, 1969).

REFERENCES


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Laborie, P., J.-M. Rocard, and J. A. Rees, 1968, Electronic Cross-Sections and Macroscopic Coefficients. 1—Hydrogen and Rare Gases, Dunod.


[Image 0x0 to 611x792]