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Charge and Momentum Exchange in an Ion Beam

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Introduction

Ion-beam measurements and calculations are complicated by charge-exchange and momentum-exchange collisions. In charge exchange, an energetic ion passes near a background neutral. An electron leaves the neutral and goes to the ion, resulting in a low-energy ion and an energetic neutral. The energetic neutral will continue to the target and perform most or all of the functions that the ion would have performed, but it cannot be detected by simple beam probes. The low-energy ion will gain pre-sheath energies (on the order of 1-2 eV) and can be detected by simple probes, but will generally be unable to perform the functions expected of an energetic beam ion.

The momentum loss of energetic beam ions, or the energetic neutrals resulting from charge exchange, is not important at typical operating pressures and distances. But two common mistakes are made in evaluating this process. The first mistake is to use an ambient-temperature path length. The outer electrons in an atom have a binding energy of at least several eV. From the equivalence, 1 eV = 11600 K, the thermal energy at 20° C corresponds to about 0.025 eV.

Collisions at ambient temperature thus cause minor perturbations to the outer electrons in atoms. Beam ions are much more energetic, typically having hundreds of eV. The outer electrons will offer little resistance to collisions at beam energies, and the cross sections should be much smaller than for ambient-temperature collisions.

Someone may recognize that beam ions have energies much higher than ambient, search for experimental data on energetic ions colliding with ambient-temperature neutrals, and make the second common mistake. There are ion-neutral cross sections obtained under these conditions, and they are close to the ambient-temperature values. Unfortunately, these experiments measure the cross section for deflections of one to several degrees – far less than the ~90° deflection required for the loss of forward momentum.

Basic Theory

The mean free path length, λ, for an energetic particle passing through a background of much lower energy particles is given by

$$\lambda = 1/(n_o\sigma), \qquad \textbf{Eq. (1)}$$

where n_o is the density of the background particles and σ is the cross section for the process of interest. If the incident particle and the background particles are in the same thermalized energy distribution, the incident particle is as likely to be struck by, as it is to strike, a background particle. In that case,

$$\lambda = 1/(2^{1/2}n_o\sigma). \qquad \textbf{Eq. (2)}$$

The particle flux, I that escapes collisions is

$$I = I_o\exp(-L/\lambda). \qquad \textbf{Eq. (3)}$$

where I_o is the incident flux, L is the path length covered, and λ is the mean free path for that collision process.

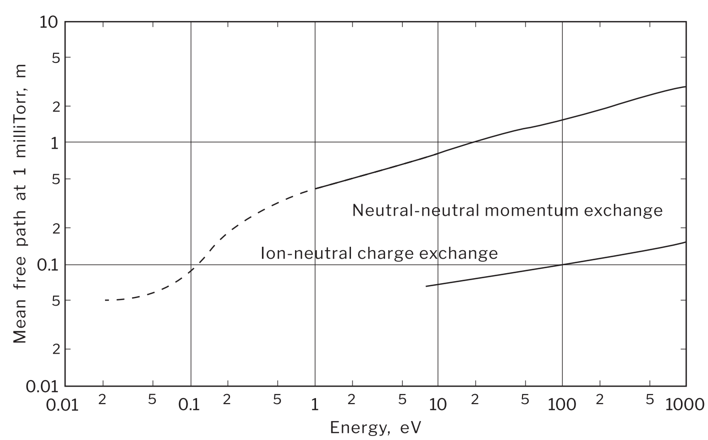

Figure 1. Charge-exchange and momentum-exchange path lengths for argon.

Charge Exchange

Charge exchange between ions and atoms of the same specie is called resonant charge exchange. The "resonant" is often omitted. But remember that the charge-exchange cross section is greatly reduced when the two particles have different ionization potentials.

Charge-exchange cross sections are predicted with good accuracy using a theoretical equation, which requires an iterative approach to a transcendental equation for solution. The authors of this publication [1] found a closed-form solution for ionization potentials, Φ_i, of 4-26 eV and ion velocities of 1-10×10^4 m/s that was accurate to ±3%. That equation is modified here to use ion energy, E_i, in eV rather than ion velocity. The charge-exchange cross section, σ_{ce}, in m^2 is

$$\sigma_{ce} = 6.30\times10^{-18}(w/E_i)^{0.14}/\Phi_i^{1.07}, \qquad \textbf{Eq. (4)}$$

where w is the atomic weight of the atom or ion in amu and the ionization potential, Φ_i, is in eV. Equation (2) was used to calculate the charge-exchange cross section for argon, and Eq. (1) was used to calculate the path length at a 20˚C background temperature shown in **Figure 1**.

Momentum Exchange

Experimental momentum-exchange cross sections are not available at ion-beam energies. The best available values have been calculated from the pair-interaction potentials of neutrals [2] and are presented in **Table 1**. The absence of an outer electron should not be important at beam energies.

The momentum-exchange cross sections for argon from **Table 1** were used with Eq. (1) to calculate the path length shown in **Figure 1** for energies greater than 1 eV. The ambient-temperature path length, Eq. (2), is shown near 0.025 eV. The dashed line between 0.025 and 1 eV is an arbitrary interpolation.

E, eV	*Ar*	*Kr*	*Xe*
1	7.17	9.04	11.50
2	6.07	8.10	10.30
5	4.63	7.03	8.93
10	3.68	6.31	8.02
20	2.97	5.66	7.18
50	2.32	4.86	6.17
100	1.96	4.30	5.47
200	1.65	3.77	4.81
500	1.28	3.12	3.99
1000	1.04	2.66	3.41

Table 1. Momentum-exchange cross sections in Å^2.

Concluding Remarks

The momentum-exchange cross section for argon at ambient temperature is closely related to the size of the atom in the solid state, and thus can be thought of as corresponding to the physical size of that atom. The charge-exchange cross section is roughly half as large (twice the path length) as this ambient-temperature value, which is consistent with an ion having about 50% probability of gaining an electron when it comes within "touching" distance of a neutral.

At ion-beam energies, the momentum-exchange path length for argon and many other elements and molecules is roughly an order of magnitude greater than the charge-exchange path length. An ion beam should thus be mostly charge exchanged (Eq. (3)) before there is significant loss of momentum. A long path length for momentum ex-change is also indicated for sputtered atoms, which have mean energies of several eV.

References

1. D. Rapp and W.E. Francis, "Charge Exchange Between Gaseous Ions and Atoms," *J. of Chemical Physics*, Vol. 37, pp. 2631-2645, 1962.
2. R.S. Robinson, "Energetic Binary Collisions in Rare Gas Plasmas," *J. of Vacuum Science and Technology*, Vol. 16, pp. 185-188, 1979.