Box 5: Charge Exchange and Electron Stripping

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1 Charge Exchange Processes

Charge exchange processes, where the capture or loss of electrons in a target medium changes the electrical charge state of swift ions, are of central importance for electrostatic tandem accelerators. For example, such processes are employed for:

– The formation of negative ions prior to injection into the accelerator, which is commonly used to produce He^- ions and in this case involves double electron capture by low-energy He^+ ions in an alkali-metal vapor.
– The conversion of negative to positive ions by *stripping* electrons from the injected negative ions by a target medium in the high-voltage terminal of the tandem accelerator.
– The second stripping of positive ions to create highly positive charge states, either at some point along the high-energy tube of the tandem accelerator or after acceleration. The latter may improve the suppression of background ions by the analyzing magnet or may be required to match the ion charge state with that required by a second accelerator such as a cyclotron (see Chap. 10).
– The fragmentation of molecular ions in the high-voltage terminal of the tandem accelerator. This is a crucial tool of accelerator mass spectrometry (AMS), discussed in Chap. 23. It can also be used to produce beams of elements which do not form stable negative ions. A typical example is ^{14}N, which, for example, may be accelerated by injecting the molecular ion $^{14}NH^-$ into the tandem accelerator. Electron stripping in the high-voltage terminal then renders the molecular ion unstable and releases a positive nitrogen ion.

Two fundamental charge exchange processes can be distinguished, which are *electron capture* and *electron loss*. In electron capture, the discrete charge state q of an ion with atomic number Z_1 decreases by unity through the acceptance of an electron from the target medium, according to

$$Z_1^q + e^- \rightarrow Z_1^{q-1} \qquad \text{for } q \geq 0$$

Conversely, in electron loss, an electron is stripped off and the ion charge state increases by unity:

$$Z_1^q \rightarrow Z_1^{q+1} + e^- \qquad \text{for } q \geq -1$$

The conditions on q account for the fact that ions do not carry more than one negative charge. Generally, the change of the ion charge state in a target medium, such as a stripping gas or a thin, solid stripping foil, is the consequence of a multiple combination of these two fundamental processes.

Charge-State Equilibrium

As a swift ion penetrates a target medium it undergoes a large series of ion–electron collisions. The statistical probabilities for electron capture and electron loss generally differ and depend on the current charge state, the current excitation state and the velocity of the ion. This, coupled with the discrete changes of the charge state by ± 1, implies that, as the ion traverses the medium, q changes in a stepwise manner towards a *charge-state equilibrium* q_{eq}. This is shown schematically in Fig. B5.1(a) for the case of an initially negative ion with $q = -1$ penetrating a stripping gas or foil. It is apparent that the charge-state equilibrium is a pseudoequilibrium, because the ion continues to undergo electron capture and loss processes [1]. The fluctuation of the actual charge state about the charge-state equilibrium q_{eq} results in a charge state distribution, as illustrated in Fig. B5.1(b).

The development of the charge-state distribution before equilibration can be verified experimentally. Figure B5.2 shows results for ^{12}C ions accelerated in a tandem accelerator with an N_2 gas stripper and a terminal voltage of 2.4 MV. The charge-state equilibrium q_{eq} is reached after the initially negative ^{12}C ions have traversed $\sim 0.6\,\mu\text{g/cm}^2$ of the gas. In the pre-equilibrium phase, the fraction of low charge states is necessarily large, because the ions pass through the $q = 0, +1, +2$ states before equilibration with an charge-state equilibrium $q_{eq} = +2.8$. A number of useful compilations of experimentally measured charge-state distributions are available in the literature [3–8].

The charge-state equilibrium q_{eq} of a swift ion with atomic number Z_1 can be estimated from an expression based on the Thomas–Fermi effective-charge model. This expression has the form [4, 9–12]

$$q_{eq} = Z_1 \left[1 - \exp\left(-\frac{0.97 v_1}{v_{TF}} \right) \right]$$

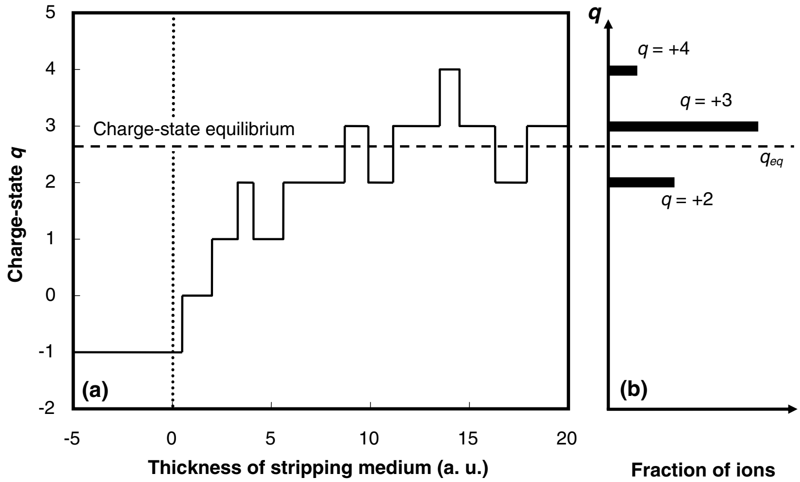

Fig. B5.1. Schematic illustration of the charge exchange processes for a negative ion penetrating a stripping gas or foil. (**a**) The approach to charge-state equilibrium. (**b**) The relation between the discrete distribution of exit charge states and the charge state equilibrium q_{eq}

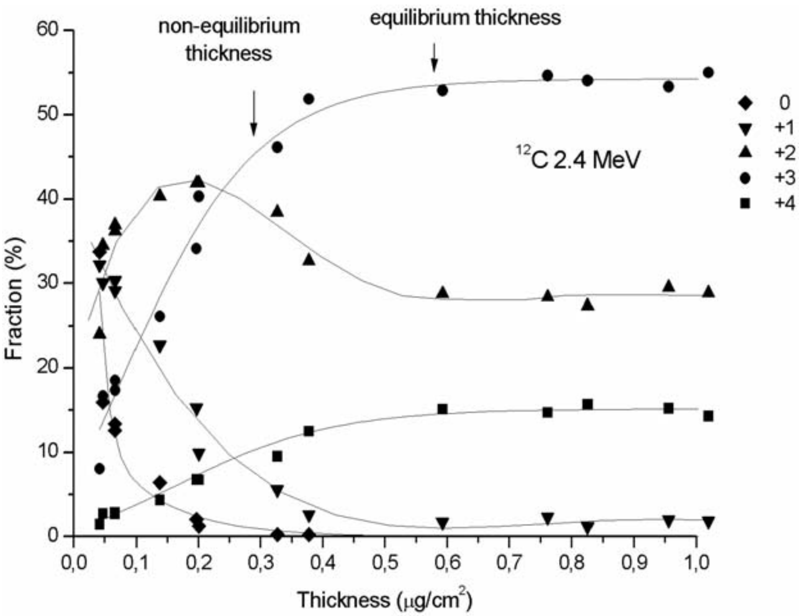

Fig. B5.2. The measured fractions of the charge states $q = 0, +1, \ldots, +4$ for ^{12}C ions exiting an N_2 gas stripper in a tandem accelerator. The initial charge state and ion energy were $q = -1$ and 2.4 MeV, respectively (Reprinted from [2], copyright 2002, with permission from Elsevier) which compares the ion velocity v_1 with the Thomas–Fermi velocity $v_{TF} = Z^{2/3}v_0$, where v_0 is the Bohr velocity. In terms of SI units, $v_0 = e^2/(4\pi\epsilon_0\hbar) = 2.188 \times 10^6\,\mathrm{m\,s^{-1}}$. More sophisticated expressions for the charge-state equilibrium have been proposed [12]; however, over the energy range accessible with electrostatic accelerators (0.1–5 MeV per nucleon), this simple form is generally adequate. For a representative selection of ions, Fig. B5.3 illustrates that the charge-state equilibrium q_{eq} calculated in this way is proportional to the ion atomic number Z_1 and increases with increasing ion velocity to approach the fully stripped condition $q_{eq} = +Z_1$ asymptotically. Figure B5.3 also shows that the formation of He^- ions via double electron capture by He^+, via $\mathrm{He}^+ + e^- \rightarrow \mathrm{He}^0$ and then $\mathrm{He}^0 + e^- \rightarrow \mathrm{He}^-$, is more easily achieved at low energies.

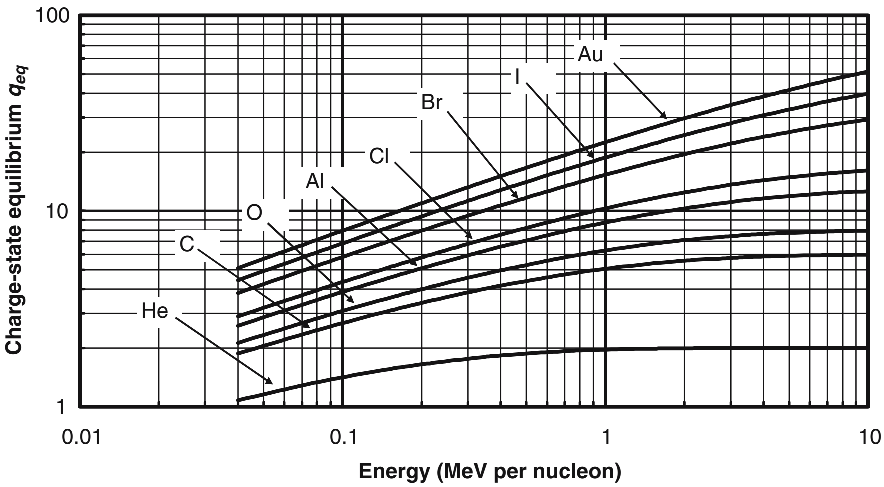

Fig. B5.3. The dependence of the charge-state equilibrium q_{eq} on energy for a range of ion species, calculated using the Thomas–Fermi effective-charge model

Gas and Foil Stripping

Foil stripping achieves a higher charge-state equilibrium than does gas stripping. As an example, Fig. B5.4 presents measured equilibrium charge-state distributions for $^{79}\mathrm{Br}$ ions with an incident energy of 0.05 MeV per nucleon and an original charge state of $q = -1$ after passing through different target media, which include various gases and solid carbon. The measured charge-state equilibrium for carbon foils exceeds that for all of the gases, while also being in excess of the q_{eq} calculated using the Thomas–Fermi effective-charge model. This observation is generally attributed to the *density effect*. In dense

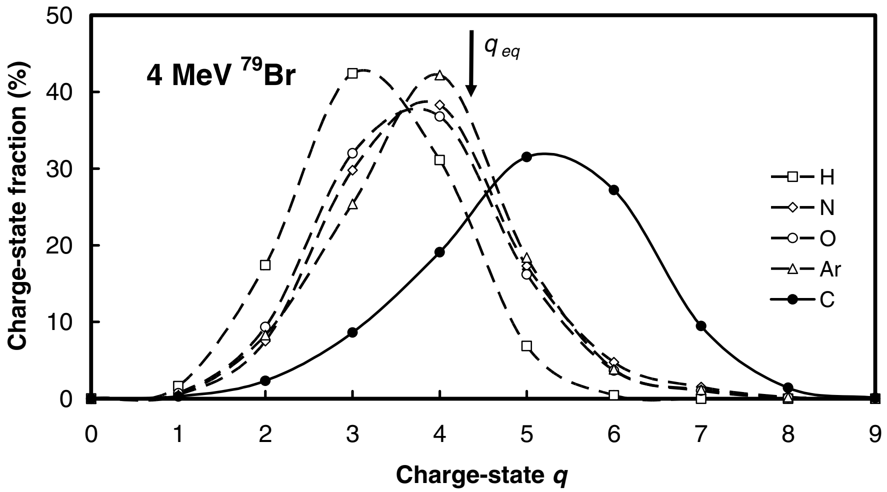

Fig. B5.4. Equilibrium charge-state distributions for 4 MeV ^{79}Br ions for various gases and for carbon-foil stripping (after Wittkower and Ryding [13]). The vertical arrow denotes the calculated q_{eq}. The curves are to guide the eye. The dashed curves denote gaseous stripping media, while the solid curve represents carbon-foil stripping

target media the electron loss of ions is enhanced, because when they are in excited states, deexcitation to the ground state may not take place before subsequent ion–electron collisions [5]. The fact that the charge-state equilibrium for the gases tends to be lower than the calculated q_{eq} has been explained, in the case of low-density gases, to arise from electron capture by doubly excited states that subsequently decay by Auger emission [5, 14]. Foil media, discussed in Box 6, are therefore, owing to their greater densities, better suited for the production of high charge states than are gases. This difference is most pronounced for heavier ions. Likewise, foils are more effective than gases for fragmenting tightly bound molecules.

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