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CHARGE-STATE DISTRIBUTIONS IN COLLISIONS OF H AND He WITH MAGNESIUM*

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Charge equilibrium fractions have been measured for hydrogen on magnesium vapors in the energy range 4–40 keV. A large difference is seen to exist between our results and those on charge distributions of H on Mg foils. This is attributed to the fact that charge distributions in solids are determined by surface interactions rather than by multiple charge changing collisions. For He^+ and He projectiles, equilibrium could not be attained even at target thicknesses π of the order of 10^{16} atoms/cm^2. This can be explained assuming a raise and subsequent fall of the population of metastable He with π, these atoms being the main producers of He^+ and doubly excited He^-. Our results indicate that Mg, and probably other alkaline-earths, are most convenient for use in the source stage of tandem accelerators as they are good producers of negative ions at the more efficient injection energies.

1. Introduction

Information on charge-state distributions and equilibrium fractions is useful in experimental physics. Intense beams of neutral atoms are required for atomic collision studies and long-lived engines for space vehicles. The production of negative ion beams is of interest in tandem accelerator technology and basic research in atomic physics.

Most of the previous studies on charge distributions has been done, for H and He projectiles, on gas targets and foils. The use of gases as charge converters presents the difficulty that for high-intensity beams, large-aperture charge-exchange chambers must be employed, which impose a heavy gas load to the vacuum system. They are also relatively inefficient targets for production of negative ion beams. On the other hand, metal foils are undesirable at low energies as they produce a large energy and spatial dispersion in the beam. Metal vapor targets are the best to be used since they are efficient media to produce negative and neutral beams and do not present the problems associated with the use of gaseous and solid targets. They require, however, the use of high temperature ovens.

In a gas or vapor, the evolution of the charged beam components with target thickness π is given by the system of differential equations:

$$\frac{dF_i}{d\pi} = -F_i q_i + \sum_k F_k \sigma_{ki}, \tag{1}$$

where F_j is the fraction of the total beam flux which is in the charge state j, σ_{if} are the cross sections for the collisions which change the charge of the projectile from i to f, and $q_i = \sum_j \sigma_{ij}$.

The solutions of eq. (1) are given by

$$F_i(\pi) = F_i(0)\, e^{-q_i\pi} + e^{-q_i\pi} \sum_j \sigma_{ji} \int_0^{\pi} F_j(w)\, e^{q_j w}\, dw. \tag{2}$$

In the limit of target thicknesses sufficiently large so that the charged beam components come into dynamical equilibrium with each other, the charge equilibrium fractions ϕ_i are given by

$$\phi_i \equiv F_i(\infty) = \frac{1}{q_i} \sum_j \sigma_{ji}\phi_j, \tag{3}$$

which shows that measurements of the equilibrium fractions can be used to determine relations between electron capture and loss cross sections^1). The approach to equilibrium can be seen by expanding eq. (2) at high π values, which gives

$$F_i(\pi) = \frac{1}{q_i}\sum_j \sigma_{ji}\, F_j(\pi) + F_i(0)\, e^{-q_i\pi} -$$
$$- \frac{1}{q_i^2}\sum_j \sigma_{ji}\, F'_j(\pi)\, [1 - e^{-q_i\pi}(1 + q_i\pi)], \tag{4}$$

where $F'_j(\pi) = dF_j(\pi)/d\pi$. If π goes to infinity where the derivatives F'_j vanish, eq. (4) reduces to eq. (3). So, the closeness to equilibrium at a given π depends both on q_i and on the products $\sigma_{ji}F_j(\pi)$ and $\sigma_{ji}F'_j(\pi)$.

The charge-state distributions of ion beams traversing solids is generally thought of as resulting from multiple electron capture and loss collisions inside the solid in a similar manner as would cocur in a dense gas^2). The higher charge states observed for heavy fission fragments in solids as compared with gas targets has been attributed by Bohr and Lindhard^3) to the fact that in solids, the time interval between

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collisions is so short that an excited projectile is more likely to suffer an ionizing collision than to decay radiatively to the ground state.

This model can hold for highly charged heavy ions at high velocities. However, for the lighter atomic particles or at low velocities for which the proportion of neutral particles emerging from the foil is high, it cannot be applied. For those particles, the average extent of the ground and excited electron orbits is comparable with or larger than lattice spacings, the outer electrons cannot be said to belong to the projectile and the concepts of an atomic state, charge and excitation equilibria are therefore meaningless.

In the case of protons in a metal foil, Yavlinskii et al.[4]) have shown that the Debye shielding length inside the metal is so short that the protons are too well shielded to capture an electron. They proposed that the capture process occurs through tunnel recombination at the surface. This process is shown schematically in fig. 1. At very low incident velocities, the ground state of the ion-plus-electron system B is populated mainly by Auger transitions with the ejection of secondary electrons and excited states are formed by resonance neutralization if they lie at an energy lower than φ. At increasing particle velocities the energy levels of B broaden, and electron capture tunneling transitions become possible to increasingly more states of system B[5]).

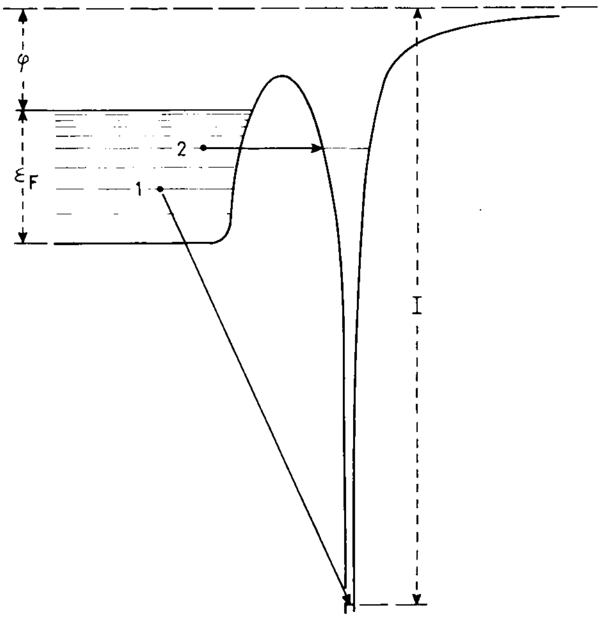

Fig. 1. Energy diagram for an ion close to a metal surface. I – ionization energy of ground state of the ion-plus-electron system, φ – work function; ε_F – Fermi energy. In the Auger neutralization process, electron (1) tunnels directly to the ground state and the excess energy is liberated through secondary electron emission. In the resonance neutralization process, electron (2) tunnels to an excited state isoenergetic to a filled level in the metal.

It can be seen qualitatively that the process is more favoured in the case of low work function materials. This is consistent with the results obtained by Phillips[6]) for charge distributions of hydrogen beams in different metal foils, and with the recent work of Bornstein et al.[7]). On account of this, foils coated with a low work function material (by continuous deposition if ultra high vacuum techniques are not used) could be utilized, as proposed by Bashkin[8]), to increase signals in BFS. The tunneling recombination theory should be improved to take into account the angular momentum and spin multiplicity of the excited particles formed, as beam-foil spectra is known to depend on these factors[9]). It should also be extended to multiple electron capture processes at the surface. Spectra of neutral atoms could, due to the nature of the interaction, be studied through small angle scattering of ions impinging on a metal surface. This would increase the time spent by the particles near the surface and therefore enhance the yield of scattered particles in excited states.

In this work we report measurements of charge equilibrium fractions for H on Mg vapors in the energy range 4–40 keV and compare them with charge distributions of H beams scattered through Mg-coated foils, reported by other workers. Non-equilibrium distributions are observed for 15–45 keV He beams on Mg vapors.

2. Experimental results

The apparatus used is the same as the one described by Baragiola and Salvatelli[10]). For incident protons or hydrogen atoms, the charged fractions F_j did not vary with target thickness for $\pi > 10^{15}$ atoms/cm^2 within experimental errors. Measurements were taken with π set at $4\text{–}6 \times 10^{15}$ atoms/cm^2. At low energies (less than 10 keV), an incident beam of deuterons was used. Data for D is comparable with that for H at equal velocities since isotope effects in charge changing collisions are negligible in our energy range[11]). The error for all points is less than 4% and, on the average, 1%. This accuracy could be obtained by the use of a charge independent detector and by a careful calibration of the electrometer used to measure the beam intensities. Our results are shown in fig. 2 and compared with data of other workers for H and D on Mg vapors[12–15]), and on Mg-coated foils[7]). It can be seen that it is not a good approximation to treat the foil as if it were a dense vapor.

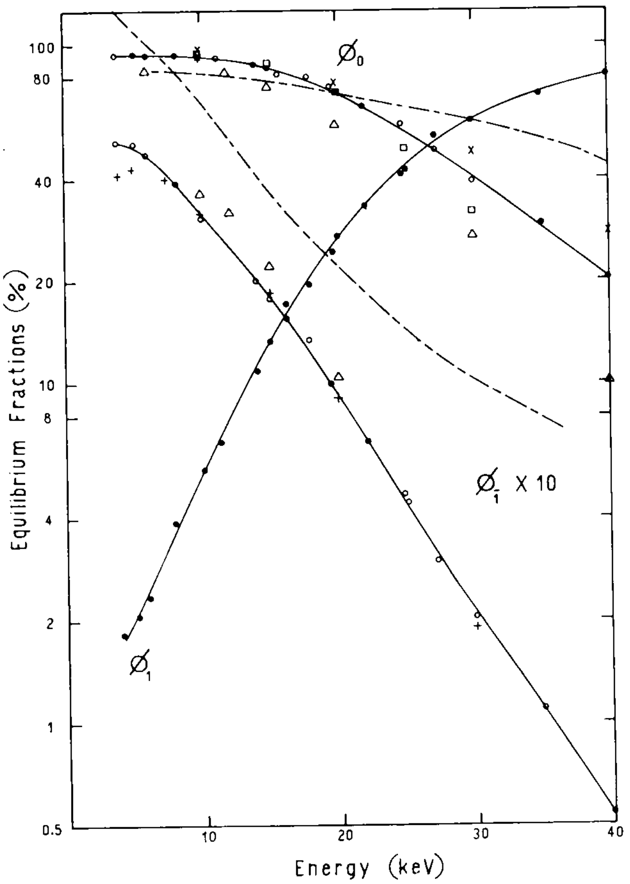

Fig. 2. Equilibrium fractions of H and D on Mg vapors: -○- and ●, present results; +, Moses and Futch[12]); ×, Oparin et al.[13]); △, D'yachkov and Zinenko[14]), □, Panasenkov and Semashko[15]). Charge distributions of D on Mg-coated foils: —·—, Bornstein et al.[7]). The fraction of protons, $\varnothing_1$, is only plotted for the present work. Results for D are presented at ½ of their actual energy, for comparison with protons of the same velocity.

In the case of incident He ions and atoms, equilibrium could not be attained. Fig. 3 shows that for 25 keV He^+ on Mg, $F_{\bar{1}}(\pi)$ is slowly varying at target thicknesses as high as 10^{16} atoms/cm^2. Higher densities could not be reached as the effusing metal vapors would clog the apertures of the target cell. Fig. 4 shows $F_i(\pi)$ curves for 45 keV He^+ and He(1^1S) incident on the target cell. The neutral beam with more than 99% of the particles in the ground state was prepared by charge equilibrating a He^+ beam on He gas and sweeping out the remaining charged particles with an electric field. The approach to equilibrium is seen to be slower for incident ground state He atoms. At $\pi > 10^{15}$ atoms/cm^2, we can neglect in eq. (4) the terms involving $\exp(-q_i\pi)$, getting

$$F_i(\pi) = \frac{1}{q_i}\sum_j \sigma_{ji}\, F_j(\pi) - \frac{1}{q_i^2}\sum_j \sigma_{ji}\, F'_j(\pi). \qquad (5)$$

Our results can be explained, from eq. (5), in terms of a metastable fraction F_m in the neutral beam, as has

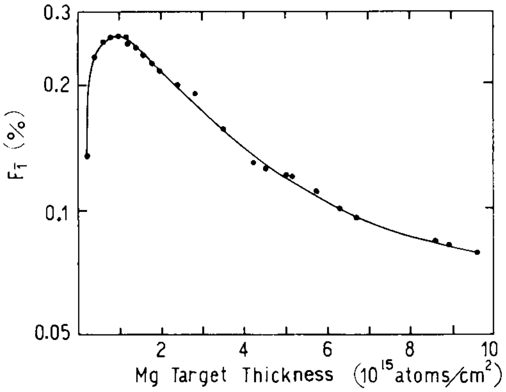

Fig. 3. The He^- fraction $F_{\bar{1}}$ (%) as a function of Mg target thickness for 25 keV He^+.

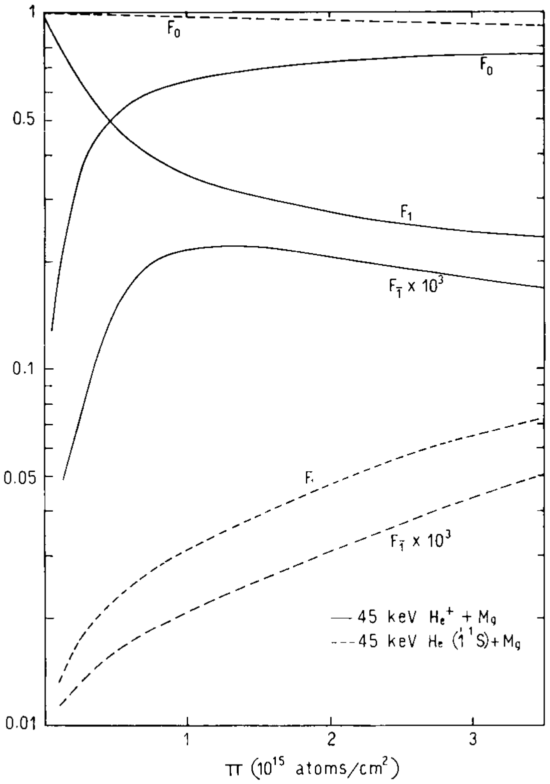

Fig. 4. The fractions of He, He^+ and He^- for 45 keV He^+ and He beams as a function of target thickness π. The He^{++} fraction is negligible at this energy.

been done by Schlachter et al.[16] for He^+ on Cs vapors. Since:

1) the cross sections $\sigma_{1\bar{\rm I}}$ are very small ($< 10^{-19}$ cm^2/atom) in this energy range[17],
2) from fig. 4 it is seen that He^- are formed primarily from He metastables produced mainly by electron capture, as $F_{\bar{\rm I}}(\pi)$ for $He(1^1S)$ incident raises very slowly with π,
3) the cross section for electron loss should be higher for metastable than for ground state He atoms,

eq. (5) can be approximated, for the He^- component, as

$$F_{\bar{\rm I}}(\pi) = \phi_{\bar{\rm I}}\left[\frac{F_{\rm m}(\pi)}{\phi_{\rm m}} - \frac{1}{q_{\bar{\rm I}}}\,\frac{F'_{\rm m}(\pi)}{\phi_{\rm m}}\right]. \qquad (6)$$

Then, for incident He^+, the variation of $F_{\bar{\rm I}}(\pi)$ at large π, can be explained by a large negative value of the derivative $F'_{\rm m}(\pi) \simeq F_1(\pi)\,\sigma_{1\rm m} - F_{\rm m}(\pi)\,q_{\rm m}$, which implies a high collisional quenching cross section $q_{\rm m}$. If the electron loss cross section $\sigma_{\rm m1}$ is an important part of $q_{\rm m}$, then the slow approach to equilibrium of $F_1(\pi)$ is also explained. The shape of the curves for incident $He(1^1S)$ is governed by the slow raise of the fraction of metastable atoms with π which is due to the fact of $q_{\rm m}$ being large and that these atoms are formed primarily by the two-step process $He(1^1S) \rightarrow He^+ \rightarrow He^m$.

Fig. 5 shows the maximum values of $F_{\bar{\rm I}}$ as a function of He^+ energy. They are more than an order of magnitude larger than for He^+ impact on gases[18,19].

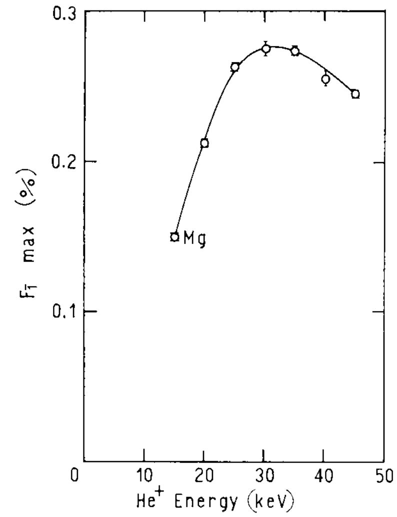

Fig. 5. The maximum values of $F_{\bar{\rm I}}$ for incident beams of He^+ ions.

3. Conclusions

It has been shown that magnesium, and probably other alkaline earths, are very efficient targets for the production of negative ions. As their first two ionization potentials are low they yield large cross sections $\sigma_{0\bar{\rm I}}$ and $\sigma_{1\bar{\rm I}}$, and, in the case of incident He^+ beams, they yield a large number of metastable He atoms which are the main producers of He^-. These vapour targets have also the advantage of having less pumping requirements than gases and of being less reactive than the alkalis, and can, therefore, be used sucessfully as charge converters in the source stage of tandem accelerators.

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