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102

ENERGY LOSS OF LIGHT IONS AND NEUTRALS FROM SURFACE SCATTERING

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The energy spectra of He scattered at grazing incidence from a clean metal surface are measured by a time-of-flight method. The results are interpreted in terms of the dielectric response function of the metal. It is shown that surface effects and straggling have a major influence in the energy range under consideration (1–10 keV). There is also a basic connection between energy loss and charge state, such that these phenomena must be dealt with by the same formalism. It is shown that Auger neutralization is the dominating process and hence the energy loss depends on how long the incoming particle interacts with the surface as an ion or as a neutral.

1. Introduction

The energy loss of particles in matter is a classical subject of radiation physics [1–4]. Recently, the dynamic aspects of the interactions of a moving charge with the electronic system of a solid have found new attention taking into account the progress in the field of solid-state physics, i.e. the theory of the electronic properties of metals [5–7]. An interesting part of the results in point of view of surface physics is the treatment of the charge exchange processes within the framework of the theory of the electronic stopping power. Since at low ion energies (≤ 10 keV) neutralization is the dominating process of ion–surface interaction [8,9] we performed experiments aimed at the application of the new theoretical concepts to understand the charge exchange and the energy loss of slow particles interacting with surfaces [10–12]. In this contribution we discuss energy loss spectra of He scattering at grazing incidence off Ni in the energy range of 260 eV to 14 keV. It is shown that charge exchange processes and energy loss are closely related in the system under investigation.

2. Experimental results

For the experiments we use an ultrahigh-vacuum system equipped with a magnetically separated ion beam and a time-of-flight (TOF) system [13]. The TOF system includes a postacceleration part such that neutrals and ions can be measured. Fig. 1 is a TOF spectrum for He^+ incident on Ni(110) in a random direction at an angle of incidence (glancing angle) of 5°. The detector is placed at a laboratory scattering angle of 10° with an angle of acceptance of 1.2° (full width). Note the logarithmic scale of the ordinate, and the reversed time axis, such that fig. 1 shows essentially an energy spectrum. The ion yield is low (0.67%) and the shape and energetic position of neutral and ionic spectra are identical within the experimental error.

Converting the TOF spectra to energy spectra yields (for Ni(111)), e.g., fig. 2 for three primary energies, i.e. 260 eV, 2.5 keV and 12 keV. We chose a linear scale for

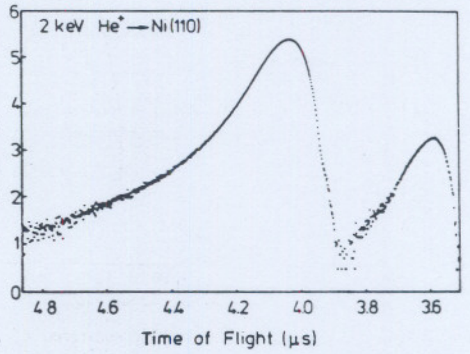

Fig. 1. Time-of-flight spectrum of He ions (right-hand data) and neutrals (left-hand data) scattered off Ni(110) in a random direction. The glancing angle of incidence is 5°, the scattering angle is 10°. The intensity scale is logarithmic, the time scale runs from right to left. The ions appear at shorter times because they have been postaccelerated.

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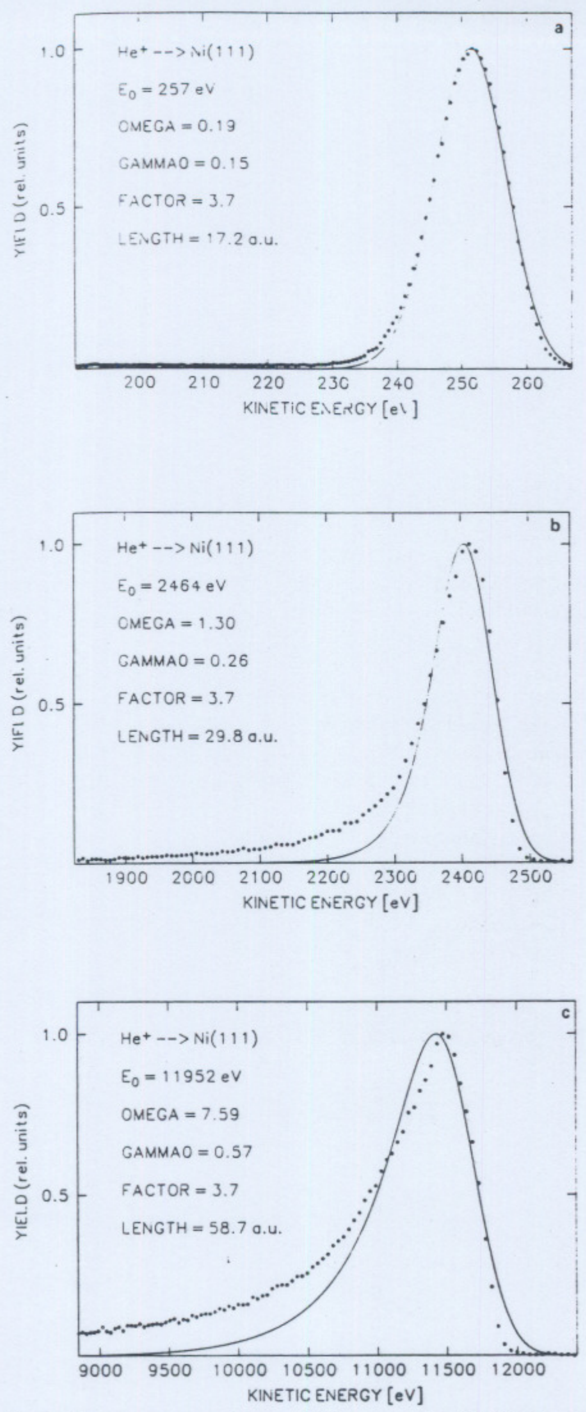

Fig. 2. Energy spectra of neutral He scattered off Ni(111) at grazing incidence (glancing angle 5°, scattering angle 10°). The dots are experimental data, the solid lines are calculated. The parameters used in the calculation are: E_0 the primary energy, Omega = Ω_2 the straggling parameter, Gamma 0 = γ_s^0 the average surface friction coefficient, Factor = γ^+/γ^0, the ratio between ion and neutral friction coefficient [10] and Length = L, the trajectory length.

the intensity in order to demonstrate the change of the peak shape from almost Gaussian at 260 eV to strongly skewed at 12 keV.

Fig. 3 gives the energy dependence of the peak energy loss, i.e. peak position of the energy spectrum with respect to the (measured) primary beam energy. The elastic energy loss can safely be neglected, since $E/E_0 = 0.998$ for single scattering of He off Ni into a scattering angle of 10°, which is of the order of 10% of the observed losses. Furthermore, the He particles follow essentially channeled trajectories such that the elastic losses are even smaller. The slope of the experimental results in fig. 3 shows a proportionality of $Q_0 \propto v^3$.

3. Theory

The incoming He^+ ions will be neutralized at the surface and may be re-ionized by the interaction with the surface. Depending on the particle velocity the scattered particle will have a charge state distribution and a distribution of the population of excited states. In our energy range, the most important processes are the neutralization by Auger capture and the ionization by dynamic resonant loss [6]. However, the Auger capture cross section is much larger than the resonant loss cross section, in qualitative agreement with the experiments where mainly neutralized He is observed [11]. Taking into account the Auger neutralization only, we write the rate equations for the yield of ions and neutrals, respectively:

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}t}n(\mathrm{He}^+) &= -\frac{1}{\tau^{\mathrm{A}}}n(\mathrm{He}^+);\\ \frac{\mathrm{d}}{\mathrm{d}t}n(\mathrm{He}^0) &= \frac{1}{\tau^{\mathrm{A}}}n(\mathrm{He}^+).\end{aligned} \tag{1}$$

where τ^{A} is the Auger lifetime, which was estimated previously [10]:

$$\begin{aligned}\frac{1}{\tau^{\mathrm{A}}} = \sum_{R_j}\int\frac{\mathrm{d}^3q}{(2\pi)^3}\int_0^\infty\frac{\mathrm{d}\omega}{2\pi}\,\frac{16\pi^2}{q^2}\\ \times\sum_a\int_{-\infty}^{E_\mathrm{F}}\rho_a(E)\,\delta(E+\omega-E_0)\,\mathrm{d}E\\ \times\mathrm{Im}\left[-\frac{1}{\epsilon(q,\omega)}\right]\\ \times|\langle\phi_a(r-R_j)|\mathrm{e}^{-\mathrm{i}qr}|u_0(r)\rangle|^2.\end{aligned} \tag{2}$$

where $\rho_a(E)$ is the density of states associated with the orbital [14] Φ_a of site R_j, $u_0(r)$ the He 1s wavefunction and E_0 its energy. The Auger lifetime is $\tau^{\mathrm{A}} = 1.7 \times 10^{-15}$ s. Hence the ion survival length is 5.2 Å only for a 2 keV He^+ ion. We also estimated the Auger decay length to be $d_s = 1.3$ Å for the interaction with the

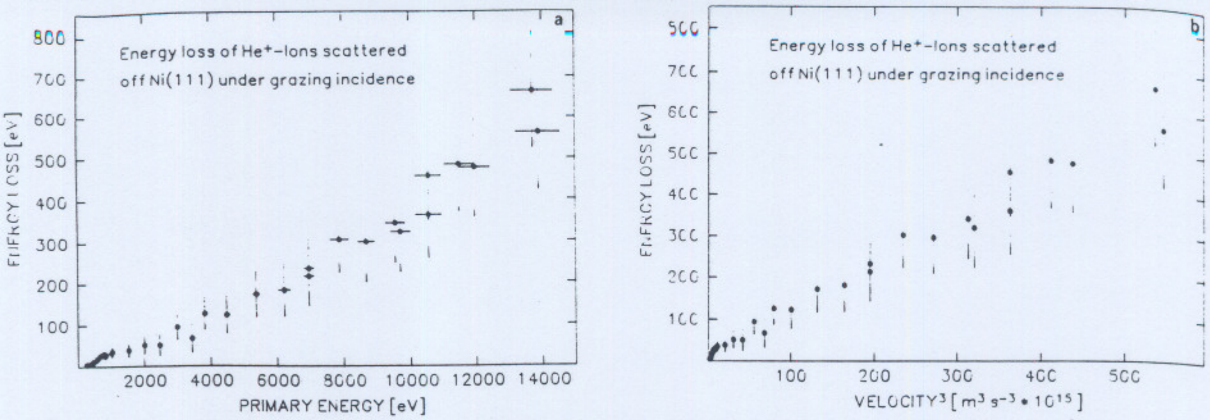

Fig. 3. Energy loss of He scattered off Ni(111) as a function of the primary energy (a) and of the (velocity)^3 (b).

s-electrons and $d_d = 0.4$ Å for the d-electrons. Both values are within the image plane $d_{im} = 1.42$ Å [15].

For the inelastic energy loss per unit length dQ we have two contributions:

$$dQ_s^+ = \gamma_s^+ \nu\, dl; \quad dQ_s^0 = \gamma_s^0 \nu\, dl. \qquad (3)$$

The index s denotes the surface, γ_s^+ and γ_s^0 are the surface friction coefficients for the ion and the neutral, respectively, and v is the particle velocity.

Combining eqs. (1) and (3) yields

$$\frac{dn(\mathrm{He}^0)}{dQ} \propto \exp\left[-(Q-Q_0)/\left(\gamma_s^+ - \gamma_s^0\right)v^2\tau^A\right] \times\theta(Q-Q_0). \qquad (4)$$

Note that $\gamma_s^+ > \gamma_s^0$, such that with increasing v the energy loss due to the He$^+$ will increasingly contribute to the energy loss of the He^0.

In eq. (4), Q is the energy loss, $Q_0 = \overline{\gamma_s^0} vL$ and θ the step function, $\overline{\gamma_s^0}$ is an average friction coefficient and L the trajectory length. The energy loss spectrum is asymmetric, "skewed" owing to the change of the charge state of the particle. The average trajectory lengths L are calculated using the code MARLOWE [11,16].

Finally, taking into account the energy loss straggling [17,18] by convoluting eq. (4) with $\exp[-(Q-Q')^2/2\Omega_2^2]$, where $\Omega_2^2/v^2 dl$ is the straggling parameter, we obtain the theoretical (solid) lines in figs. 2a–c. The next moment of the energy loss, i.e. Ω_3, has been neglected so far since we are studying a low-energy "thin"-target case [15,19].

4. Discussion

Comparison of the calculated energy loss spectra with experiment (fig. 2) shows good agreement. The skewness of the curves is due in part to the charge state distribution along the incident trajectory. From the equality of the loss spectra for ions and neutrals (fig. 1) we conclude that the detected ions are reionized by dynamic resonant ionization. The $Q_0 \propto v^3$ dependence (fig. 3b) agrees with the theoretical ansatz $Q_0 = \overline{\gamma_s^0} vL$, where $\overline{\gamma_s^0}$ and L increase linearly with the velocity [16,19]. This is qualitatively to be expected as long as the He particles have not enough momentum perpendicular to the surface, i.e. the perpendicular energy component is too small to overcome the surface potential barrier. The motion of the He particles can hence be understood as proper planar channeling.

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