Reflection of helium ions from polycrystalline platinum

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The results of an experimental study of the energy distribution of helium ions (initial energy from 10 to 35 keV) after reflection from polycrystalline platinum are presented and compared with the approximate multiple scattering theory developed by Firsov. A considerable discrepancy between theory and experiment is found.

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This paper is devoted to an experimental study of the reflection of 10–35 keV helium ions from polycrystalline platinum. The purpose of the work was to conduct an experimental test of the second variant of the theory developed by Firsov[1,2] to account for the reflection of atomic particles from solid surfaces. There are two variants of Firsov's theory. In the first variant[1] it is assumed that the interaction between the incident particles and the target atoms may be represented by a potential similar to the Coulomb potential, while in the second variant[2] the interaction is represented by an inverse square potential. In other words, the first variant is applicable when the atomic number of the target material is not too large, while the second variant is applicable to targets having large atomic numbers. In both variants the reflection is treated as an essentially multiple process and the kinetic equation is solved to obtain the angular and energy distribution function. The theory is therefore a priori unable to reproduce the high-energy peak in the energy distribution of the reflected particles (the so-called single peak). In both variants the small-angle approximation is used and charge exchange between the incident particles and the target atoms is neglected.

The theory starts from the equation

$$\frac{\partial f}{\partial t}+\mathbf{v}\,\mathrm{grad}\,f+\frac{\partial \mathbf{v}}{\partial t}\frac{\partial f}{\partial t}=I, \tag{1}$$

in which f is the energy and angular distribution function for the particles and I is the collision integral. It is assumed that the energy of the incident particles is fairly large and that the glancing angle of the incident particles and the escape angle of the reflected particles are small. The problem was solved in two different approximations: in the diffusion approximation in velocity space, in which the potential for the interaction between the incident particles and the target atoms is approximately Coulombian and the collision integral is replaced by the Laplace angular operator (first variant), and in an approximation in which the interaction potential is inversely proportional to the square of the distance and the collision integral is given by formula (2) of Ref. 3 (second variant). The problem was reduced to integral equations of the second kind (Fredholm equations) that can be solved numerically on a computer. To obtain analytic solutions, the integral term on the right hand side of the equations was dropped and the distribution function was equated to the free term. Physically, this means that particle trajectories that intersect the surface more than once are included in the treatment, although there can be no such trajectories in an actual reflection. The resulting formulas show that in both variants the shape of the reflected-particle energy distribution is determined, other conditions being the same, by the quantity $g_0\tau_0$, where

$$g_0=\frac{\pi}{2}\frac{nZ_1^2Z_2^2e^4}{E_0^2}\ln\left(1+\frac{0.7E_0}{30\,\mathrm{eV}\cdot Z_1Z_2(Z_1^{2/3}+Z_2^{2/3})^{1/2}}\right) \tag{2}$$

(n is the concentration of the scattering centers, Z_1 and Z_2 are the atomic numbers of the incident particle and the target atom, and E_0 is the energy of the bombarding particles) and τ_0 is the total range of the incident particles in the target:

$$\tau_0=\int_0^{E_0}\frac{dE}{dE/dx}, \tag{3}$$

where dE/dx is the specific energy loss. It was assumed that inelastic losses predominate in the slowing down process and that these losses are given by the Lindhard-Scharff formula[4]:

$$-dE/dx=k_LE^{1/2}. \tag{4}$$

The two variants of Firsov's theory yield different energy distributions for the reflected particles. The first variant gives a cupola shaped distribution. The second variant predicts a monotonic energy distribution for the reflected particles, the peak of the distribution corresponding to the initial energy E_0 of the incident particles:

$$N(E)\sim\{4\pi^2(g_0\tau_0)^2[1-(E/E_0)^{1/2}]^2+\varphi^2+4(\delta^2-\alpha\delta+\alpha^2)\}^{-2}; \tag{5}$$

here α is the glancing angle of the incident particles and δ is the escape angle of the reflected particles (see Fig. 1), while φ is the azimuthal scattering angle.

Both variants of the theory have been tested experimentally. The first variant was tested for reflection of helium ions with energies of tens of keV from graphite, aluminum, copper, and germanium targets.[1] It was found that the first variant of the theory reproduces the shape of the energy distribution of the reflected particles well enough provided the stopping number k_L in formula (4) is increased by the factor $c=1.3$–1.5, i.e. if formula (4) is replaced by

$$-dE/dx=ck_LE^{1/2}. \tag{6}$$

We note that the necessity of increasing the stopping

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number beyond its theoretical value k_L is not in conflect with the results of other studies of the interaction of particles with solid bodies. In particular, the value $c=1.6$ was used in Ref. 5 to reconcile the measured and calculated distributions of radiation defects produced in silicon by 10–40 keV protons. The value $c=1.6$ was also used in Ref. 6 to reconcile experimental and calculated range and energy-deposition distributions in the bombardment of amorphous niobium with helium ions having energies from 0.1 to 20 keV.

The second variant of Firsov's theory has been tested experimentally only for a silver target.[7,8] The shape of the low-energy part of the energy distribution of the reflected particles was found to vary considerably, depending on the experimental conditions. In particular, under some conditions the energy distribution of the reflected particles was found to be a monotonic function of energy clear up to the energy of the single peak. In this case the low-energy part of the distribution could be represented by Eq. (5) with $c=1.8$. On the other hand, there are experimental conditions under which the low-energy part of the distribution has the shape of a small cupola and is thus in conflict with the predictions of Firsov's theory. It would accordingly be of interest to use a target of a material having a considerably larger atomic number than silver, so that the second variant of the theory would be more nearly valid. In the present work we used a platinum target, for which $Z_2=78$.

The experimental technique was as follows. The primary ion beam was directed onto the target surface at the glancing angle α, and the ions reflected in a direction making an angle δ with the target surface were analyzed with an electrostatic analyzer having an angular aperture of $\pm 1°$ and an energy resolution of 0.5%. The energy E_0 of the primary ions was varied from 10 to 35 keV, the angles α and δ were varied from 0 to 30°, and the reflection was investigated in the plane of incidence of the primary beam, i.e. the azimuthal scattering angle φ was zero. The target was rotated in azimuth during the experiment to avoid any effects due to the microtopography of the target. The target was first cleaned by sputtering with 30 keV argon ions and its temperature was held at 1000–1200 °C during the experiment to avoid contamination by residual-gas atoms.

The dependence of the energy distribution of the reflected ions on the energy of the incident ions and on the geometry of the experiment was investigated. The energy distribution of the reflected ions was found, generally speaking, to be a superposition of a cupola and the high-energy (single) peak. Increasing the incident-ion energy E_0 and the escape angle δ of the reflected particles broadens the cupola and reduces the relative height of the single peak. Data illustrating the effect of the incident-particle energy on the energy distribution of the reflected ions are presented in Fig. 1. It will be seen that decreasing the incident-ion energy from 30 to 10 keV leads to a decrease by more than a factor than two in the half-width of the cupola shaped part of the distribution and to a considerable increase in the relative height of the single peak.

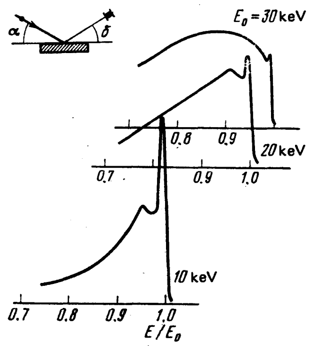

FIG. 1. Definition of the angles α and δ (inset) and energy distributions of reflected ions for $\alpha=20°$, $\delta=20°$.

Before undertaking a comparison of the experimental data with the theoretical results we must analyze the changes in the charge states of the ions during reflection. Actually, when gaseous ions are reflected from a surface, a considerable fraction of them become neutralized. As was noted above, Firsov's theory yields the angular and energy distributions of all the reflected particles, regardless of their charge states. Moreover, the experimental technique used in our work permits us to investigate only the ionic component of the reflected-particle stream. Before comparing the experimental results with the theoretical conclusions, therefore, we must establish a relation between the energy distribution of the total reflected-particle stream and that of its ionic component. Although the neutralization problem has been under study for many years,[9-15] it is not a simple matter to apply the results of those studies to the situation facing us here. Actually, in all the studies cited above it was essentially only the probability for the charge state of the ion to change while the ion was outside the solid target, i.e. while the ion was approaching or receding from the target surface, that was investigated. In other words, the initial charge state of the ion was assumed to be known. On the other hand, in the case under consideration here the change in the charge state of an ion (both by stripping and by neutralization) may also take place while the ion is moving within the material of the target. An attempt to take this circumstance into account was made in a recently published paper,[16] in which the authors proposed a formula for the degree of ionization of the reflected stream (i.e. for the ratio of the number of reflected particles in the ionized state to the total number of reflected particles). This formula, however, contains four adjustable parameters and is therefore ill suited for practical use. We therefore felt it reasonable to base our analysis on the results of the still very few experimental studies in which the energy distributions of both the total reflected-particle stream and of its ionic component has been determined and analyzed under experimental conditions similar to ours.

In an experimental study[17] carried through at the Max Planck Institute of Plasma Physics, Federal Republic of Germany, the reflection of helium ions with energies from 1.5 to 15 keV from a polycrystalline nickel target was investigated. The glancing angle of the incident ions and the escape angle of the reflected particles were $\alpha=90°$ and $\delta=45°$, respectively. The ionic component of the reflected stream was analyzed with an electrostatic analyzer. The method of stripping in gases developed by Chicherov[18] was used to analyze the reflected neutral particles. The ratio Y^+/Y of the number of particles reflected in the ionized state to the total number of particles reflected in a given direction, i.e., the degree of ionization of the reflected stream, was determined as a function of the energy of the reflected particles by dividing the energy distribution of the ionic component of the reflected stream by the energy distribution of the total stream. The results are presented in Fig. 2. It will be seen that, within the experimental errors, $\ln(Y^+/Y)$ is a linear function of the reciprocal velocity of the reflected particle over a wide range of velocities. Deviations from linearity are seen only near the single peaks of the energy distributions. A linear dependence of the degree of ionization of the reflected particles on the reciprocal velocity of the reflected particles was also obtained by processing the results of Ref. 19 (the upper left-hand points in Fig. 2) on the reflection of helium ions with energies E_0 of 120 and 200 keV from a gold target at the glancing angles $\alpha = 45°$ and $\delta = 85°$. The reflected particles were energy analyzed with a surface barrier detector. Thus, both Refs. 17 and 19 yield an exponential dependence of the same type for the ionization of the reflected stream as a function of the velocity of the reflected particles:

$$Y^+/Y \sim \exp(-\text{const}/v). \tag{7}$$

It is interesting that the experimental dependence of the degree of ionization on the velocity of the reflected particles is much like the dependence predicted by theories that only take account of the changes in the change

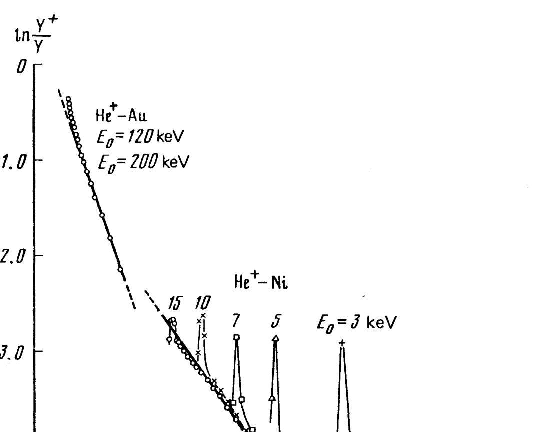

FIG. 2. Logarithm of the degree of ionization Y^+/Y vs reflected-particle velocity.

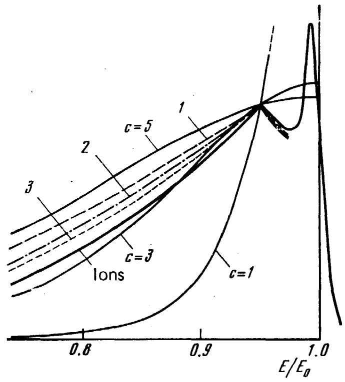

FIG. 3. Experimental energy distribution of He^+ ions scattered from platinum ($E_0 = 15$ keV, $\alpha = 20°$, $\delta = 20°$) together with distributions calculated with formula (5) using the indicated values of c in Eq. (6). Curves 1, 2, and 3 are energy distributions of the total scattered-particle stream calculated using the formula $Y^+/Y \sim \exp(-a/v)$ with the following values of the neutralization constant a (in units of 10^8 cm/sec): 1—3.2, 2—2.2, 3—1.5.

states of the ions that take place outside the target, even though, as was mentioned above, the situation considered here is more complicated. As an example, we show in Fig. 3 the energy distribution of ions (initial energy $E_0 = 15$ keV) reflected from platinum together with energy distributions of the total reflected particle stream calculated from it. In calculating the distributions for the total particle flux we used the values 1.5×10^8 cm/sec and 3.2×10^8 cm/sec (taken from Fig. 2) for the neutralization constant, as well as the value 2.2×10^8 cm/sec (taken from Ref. 20). The distributions were normalized to the point corresponding to the top of the cupola. The figure also shows energy distributions of the reflected particles calculated with formula (5) for various values of the coefficient c in Eq. (6). These distributions were also normalized to the point corresponding to the top of the cupola. It is evident that, generally speaking, the low-energy part of the cupola can be represented by Eq. (5), but only by using too large a value of c ($3 < c < 5$). It is also evident from the figure that the observed discrepancy between theory and experiment cannot be attributed to any uncertainty in calculating the total distribution from the ion distribution resulting from differences among the neutralization constants. It must be pointed out that the second variant of Firsov's theory does not yield even a qualitative description of the high-energy side of the cupola. The reasons for such a considerable discrepancy between theory and experiment are not yet clear.

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