SOVIET PHYSICS JETP VOLUME 17, NUMBER 1 JULY, 1963

NON-PAIR COLLISIONS IN THE INTERACTION OF SLOW POSITIVE IONS WITH THE SURFACE OF A METAL

V. I. VEKSLER

Tashkent State University

Submitted to JETP editor June 8, 1962

J. Exptl. Theoret. Phys. (U.S.S.R.) **44**, 14–16 (January, 1963)

A study was made of the maximum energies of Rb^+ and Cs^+ ions scattered from a molybdenum target in a direction making an angle of 120° with the direction of motion of the primary ions. The results obtained can be interpreted by assuming that the primary ions are scattered: 1) by four target atoms (for primary-ion velocities $v_0 > 1.4 \times 10^6$ cm/sec), and 2) by the lattice as a whole ($v_0 < 1.4 \times 10^6$ cm/sec).

In previous work [1] the present author investigated the energy spectra of Rb^+ and Cs^+ ions scattered from the surface of molybdenum. It was found that in the range of incident-ion energies investigated ($U = 15–250$ eV) the scattering cannot be described within the framework of the theory of elastic pair collisions between the incident ion and a single atom of the lattice. However, the question of whether the scattering is due to simultaneous collisions with several atoms of the lattice, or due to the forces binding individual atoms, remained unanswered.

The present paper reports results which may help to answer this question. Measurements were carried out using the previous apparatus [2]. The retarding field method was used. Careful measurements were made of the maximum energies W_m of Rb^+ and Cs^+ ions scattered by the surface of a molybdenum target ($T = 1400–1450$° K) as a function of the primary-ion energy ($U = 15–250$ eV). The apparatus permitted measurement of an ion current i amounting to 0.1% of the total current of recorded scattered ions i_0. This governed the precision of the determination of the magnitude of W_m. Compared with the results obtained by the usual spherical capacitor method, the data given here are more reliable and their precision is higher since 1) the study was limited to ions scattered at an angle $\theta = 120°$ with respect to the direction of motion of the primary ions, and 2) secondary electrons were prevented from entering the receiver.

If it is assumed that the primary ion is scattered by a group of the metal atoms in the lattice, each of mass M, and this collision process is replaced by a pair collision between an ion of mass m and an atom of some effective mass M_{eff} ($M_{eff} > M$), then using the theory of pair collisions we can easily find the maximum value of the effective mass

$$M_{eff} = m\,(U + W_m - 2\sqrt{UW_m}\cos\theta)\,(U - W_m)^{-1}. \quad (1)$$

Figure 1 shows the dependence of the ratio M_{eff}/M, corresponding to the measured values of W_m, on the square of the primary-ion velocity v_0^2. From Fig. 1 it is apparent that at $v_0 > 1.4 \times 10^6$ cm/sec the results are almost identical for Rb^+ and Cs^+, although the corresponding values of W_m differ by about 60% (see, for example, Fig. 2). Obviously this indicates that in the range of velocities considered here the values of W_m are governed by the collision of an ion with several lattice atoms simultaneously, and the atomic lattice binding forces are not yet important. The observed slow fall of the ratio M_{eff}/M on increase of v_0 is probably governed by the dependence of a quantity equivalent to the effective elastic-scattering cross section (non-pair collision) on the velocity of the colliding particles [3]. At $v_0 < 1.4 \times 10^6$ cm/sec the nature of the curves changes and the curves themselves diverge. This can be interpreted as a consequence of the influence on ion scattering of the interatomic binding energy in the lattice. This

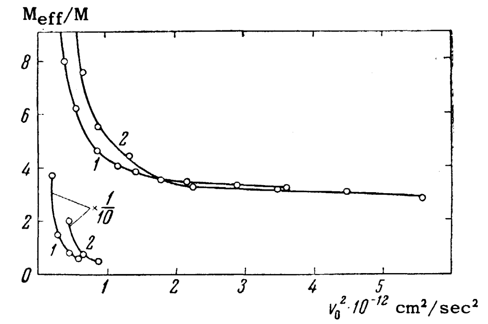

FIG. 1. Dependence of the ratio M_{eff}/M on the square of the incident-ion velocity: 1) Cs^+, 2) Rb^+.

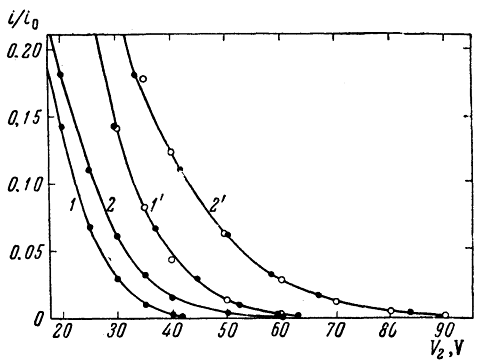

FIG. 2. High-energy part of the current-voltage retardation curves of scattered Cs^+ ions (1, U = 150 eV; 2, U = 250 eV) and Rb ions (1′, U = 150 eV; 2′, U = 250 eV, open circles). The black dots on curves 1′ and 2′ were obtained from the points on curves 1 and 2 by increasing the abscissa scale by factors of 1.50 and 1.67 respectively.

assumption agrees with the observed approach of curves 1 and 2 in Fig. 1 when the variable v_0^2 is replaced by U (then the right-hand parts of the curves diverge).

It should be noted that in the work on Cs^+ ions the primary ion beam contained not more than 0.1% K^+ and Rb^+ ions, while in the work on Rb^+ ions the beam contained 1–2% K^+ ions. This may have raised the experimentally determined values of the maximum energy of the scattered Rb^+ ions. However, the results given are not greatly affected when the calculations are based on the unlikely and least favorable assumption that all the scattered K^+ ions have energies greater than the maximum energy of the scattered Rb^+ ions; with this assumption the value of M_{eff} decreases by only 8–15%. In practice this decrease is considerably smaller, since the position of the maximum W_0 in the energy spectrum of K^+ ions scattered by the surface of molybdenum, calculated on the assumption of elastic pair collisions corresponds to the condition $W_0 \ll W_m$, and most of the K^+ ions possess energies $W < W_0$ [4]. The unimportance of the influence of the K^+ ions is also indicated by the fact that the current-voltage retardation curves of the scattered Rb^+ and Cs^+ ions [2] coincide satisfactorily at high values of W when the scale of the retardation potential (V_2) axis is altered by a constant factor differing slightly for different primary-ion energies (Fig. 2).

The molybdenum target contained not more than 0.5% W atoms and 0.1% Ta atoms.

In the scattering of a primary ion by n atoms of the lattice the effective mass of the latter is always smaller than nM. Consequently, as shown by Fig. 1, the quantity W_m corresponds to $n > 3$. On the other hand at $v_0 > 1.4 \times 10^6$ cm/sec it is difficult to imagine a strong interaction between the incident ion and more than four atoms of the molybdenum lattice (body-centered cube). Thus at $v_0 > 1.4 \times 10^6$ cm/sec the maximum energy of the scattered ions is determined by collision with four lattice atoms. This is corroborated by the weak dependence of the effective mass on the ion energy and the quite large values of the scattering coefficient for Rb^+ and Cs^+ ions incident on molybdenum [1].

The interaction of the incident ion with each of the four lattice atoms is determined by their kinetic energy E_0 in the center-of-mass system. If the ion interacts with each of the atoms in the same way, then

$$E_0 = MU\,(m + 4M)^{-1}. \tag{2}$$

For $v_0 \approx 1.4 \times 10^6$ cm/sec ($U \approx 100$ eV) we have $E_0 \approx 20$–30 eV, which is of the same order of magnitude as the threshold E_d of atom displacement in the lattice. It is probable that this is the reason why a marked penetration of ions into the lattice begins at $U > 80$ eV [1]. At $E_0 < E_d$ the factor which determines the value of the maximum energy of the scattered ions is the interatomic binding in the lattice.

[1] V. I. Veksler, JETP **42**, 325 (1962), Soviet Phys. JETP **15**, 222 (1962).

[2] V. I. Veksler, FTT **4**, 1419 (1962), Soviet Phys. Solid State **4**, 1043 (1962).

[3] O. V. Roos, Z. Physik **147**, 184 (1957).

[4] M. A. Eremeev, Trudy, Leningr. Polyt. Inst. **181**, 157 (1955).

Translated by A. Tybulewicz
3