ANGULAR DEPENDENCE OF THE ENERGY SPECTRA OF HEAVY IONS SCATTERED BY SINGLE CRYSTALS OF LIGHT ELEMENTS

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Abstract

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In ([1,2]) it was shown that, even in the region of low energies (1–5 keV), the energy spectrum of ions scattered by the surface of a single crystal possesses a structure caused by double collisions. An anisotropy of scattering was also observed as a function of the angle of incidence of the ions, which is explained by the coincidence of the direction of the primary-ion beam with the crystallographic axes of the single crystal.

It was established ([3]) that, in the energy spectrum of secondary ions, scattered ions are found with energies greater than those of ions that have undergone a double collision. It was also found ([4,5]) that the character of the energy distribution of this group of ions and the change in the distribution with increasing angle of incidence and energy of the primary ions do not contradict the assumption that it arises as a result of collisions of high multiplicity. In addition, it was shown that at angles of incidence and emission close to grazing, an apparent disappearance of the peak of single collision is observed against the background of peaks corresponding to multiple collisions. The latter is well explained by an increase in the multiplicity of ion collisions as a result of successive collisions of primary ions with chains of atoms on the surface, which confirms the conclusions ([6]) made by E. S. Parilis et al. in considering a model of ion reflection from a chain of atoms on the surface of a single crystal when the direction of the incident beam approaches a grazing angle.

However, these results were obtained in the bombardment of the (100), (110), and (111) faces of W and Mo single crystals by Na^+, K^+, and Rb^+ ions. In the bombardment of targets of light elements by heavy ions (Cs^+ on Mo), in the case of a polycrystal it was shown ([7]) that the energy spectrum obtained at scattering angles β far from the limiting angle $\beta_{1\ \mathrm{lim}}$ following from the relation for a single collision differs from the spectrum obtained within $\beta_{1\ \mathrm{lim}}$. Therefore it is of considerable interest to investigate the angular dependence of the energy spectra of secondary ions in the bombardment of different faces of a Mo single crystal by Cs^+ ions, to which the present work is devoted.

Fig. 1

Figure 1: Fig. 1

Results of measurements. Figure 1 gives three oscillograms of the energy distributions of secondary ions obtained in the bombardment of the (100) face of a Mo single crystal, annealed to 1800°K, by Cs^+ ions with energy $E_0 = 2000$ eV, at angles of incidence of the primary ions $\Phi = 0$, 50, and 80°. Secondary ions propagating in a direction making an emission angle $\theta = 60°$ with the normal to the surface of the (100) Mo face were considered. The orientation of the target was such that the incident and scattered beams lay in the plane passing through the [010] axis of the Mo single crystal.

From Fig. 1a it is seen that in the energy spectrum, besides the peak of evaporated ions, there is also a maximum in the energy region of 50 eV. This peak of slow ions, as is seen from the oscillogram, falls off not steeply toward higher energies, and its width clearly exceeds the natural width because of the presence of ions with energies exceeding the energy of ions corres-

corresponding to this peak. The presence of a smoothly decreasing "tail" of the peak of slow ions, as is also known in the case of bombardment of targets of light elements by heavy ions, is associated with multiple collisions of the bombarding ion with target atoms ([7]). The absence here of a fine structure caused by the ordered structure of the single crystal is apparently connected with the difficulty of resolving it in the present case ($\Phi = 0°$).

Fig. 1. Oscillogram of the energy distribution of secondary ions, obtained upon bombardment of the (100) face of a Mo single crystal ($T = 1800°$) by Cs^+ ions with energy $E_0 = 2$ keV, $\theta = 60°$, at $\Phi = 0°$ (a), 50° (b), and 80° (c)

Indeed, the value of the limiting scattering angle $\beta_{1\,\mathrm{lim}}$, following from the relation for an elastic single collision,

$$\beta_{1\,\mathrm{lim}} = \arcsin m_1/m_2, \tag{1}$$

in the case of Cs^+ on Mo is $\beta_{1\,\mathrm{lim}} = 47°$ (m_1 is the mass of a target atom, m_2 is the mass of the ion). Therefore, when the faces of a Mo single crystal are bombarded by Cs^+ ions, the possible range of deflection angles of singly scattered Cs^+ ions from the initial direction, with energy

$$E_1 \geq E_0(m_1 - m_2)^2(m_2^2 \cos\beta_1)^{-1},$$

lies in the region $0° < \beta_1 \leq 47°$. However, under perpendicular incidence this range of scattering angles β_1 mainly includes atoms lying beneath the near-surface layers. Therefore, when bombardment is perpendicular to the Mo faces ($T = 1800°$K) by Cs^+ ions, the energy spectrum of secondary ions consists

Fig. 2

Figure 2: Fig. 2

mainly of evaporated and slow ions. In this case the number of ions with energies greater than the energies of ions corresponding to the peak of slow ions is small, but increases sharply with increasing angle of incidence of the primary ions. In the case of Fig. 1b, in the energy spectrum, in addition to the peaks of evaporated and slow ions, peaks corresponding to doubly scattered ions are observed in the region of comparatively high energies. Calculations show that the outermost peak corresponds to Cs^+ ions rescattered on an atom in the [010] direction, and the peak close to it corresponds to the energy of ions that have undergone double collisions on an atom in the [031] direction; with increasing energy of the primary ions E_0, between the peaks corresponding to scattering on atoms [010] and [031], there are also shoulders (peaks) apparently associated with ions doubly scattered on atoms located in different directions relative to the atom with which the first collision occurred ([8]). It is of interest here that the peak of a single collision is absent in the energy spectrum. The latter is explained by the fact that at $\Phi = 50^\circ$ the region $\beta_{1\,\mathrm{lim}}$ still does not include the angle θ at which the secondary ions were analyzed by energy. However, the presence here of peaks of double collisions is due to the fact that the region $\beta_{1\,\mathrm{lim}}$ in the present case ($\Phi = 50^\circ$) already includes atoms lying on the (100) face of Mo, which leads to double collisions of the bombarding ion with atoms of this face, giving them the possibility of being deflected through an additional angle $\beta_{2\,\mathrm{lim}}$, which already includes the angle θ.

In this case the ion can leave the target with energy

$$E_2 \gtrless \frac{E_0(m_1 - m_2)^4}{m_2^4 \cos^2 \beta_{1\mathrm{pr}} \left[\cos \beta_2 + \sqrt{(m_1/m_2)^2 - \sin^2 \beta_2}\right]^2}, \tag{2}$$

where β_2 is the angle of deflection of the ion after the second collision. Verification shows that the experimental data agree well with the calculations.

From the oscillogram in Fig. 1b it is also seen that, as Φ increases, the peak of the slow ions shifts toward higher energies. In Fig. 1b, in the energy spectrum, in addition to the peaks observed on the oscillogram of Fig. 1b, a [000] peak is detected, corresponding to ions that have undergone single collisions, which is analogous to the spectrum of secondary ions obtained when the face of a Mo single crystal was bombarded with Na^+, K^+, and Rb^+ ions ([4]). The presence of a single-collision peak in the present case is explained by the fact that at $\Phi = 80^\circ$ the region $\beta_{1\mathrm{pr}}$ already includes the angle θ.

Fig. 2. Dependences of $\eta_{[000]}$, $\eta_{[010]}$, and η_m on the scattering angle β, obtained for Cs^+ on Mo (100)

Further investigation showed that the angular and energy characteristics of the spectrum obtained within β_{1pr} are analogous to the angular and energy characteristics of the spectrum obtained for direct mass ratios of the colliding particles (K^+ on Mo) (4).

From the oscillograms of Fig. 1 it is also seen that, as Φ increases, the intensity of the evaporated ions decreases sharply and at $\Phi \gtreqless= 80°$ is absent, indicating the possibility of cleaning the target surface by ion bombardment.

Figure 2 gives the dependences of $\eta_{[000]}$, $\eta_{[010]}$, and η_m on the scattering angle β ($\eta_{[000]}$, $\eta_{[010]}$, η_m are the ratios of the energies of secondary ions that have undergone one, two, and more collisions, respectively, to E_0). For comparison, the dependences η_{T_1} and η_{T_2} on β are also given there (where η_{T_1} and η_{T_2} are the calculated values of the ratios of the energies of Cs^+ ions that have undergone single and double collisions with a Mo atom to E_0). The curves $\eta_{[000]}(\beta)$ and $\eta_{[010]}(\beta)$ coincide with the calculated curves $\eta_{T_1}(\beta)$ and $\eta_{T_2}(\beta)$.

Thus, consideration of the angular regularities of the energy spectra of ions scattered by the surface of single crystals shows that in the cases $m_1 > m_2$ (1–4) and $m_1 < m_2$ the spectrum reveals peaks of single and multiple collisions. In the case $m_1 < m_2$, the single-collision peak is detected only within a certain limiting scattering angle. At the same time, the angular dependence of the energy spectra in the case $m_1 < m_2$ indicates the presence of peaks of multiple collisions at angles β that considerably exceed the limiting scattering angles β_{1pr}. In addition, the energy spectrum of secondary ions also indicates the presence of scattering of ions with energies greater than those of ions that have undergone double collisions. The nature of the distribution of these scattered ions in energy and the change in the distribution with increasing angle of incidence and energy of the primary ions, both in the cases $m_1 > m_2$ and $m_1 < m_2$, do not contradict the assumption that they arise as a result of collisions of higher multiplicity. Thus, the results we have obtained show that

that the model of pairwise single and multiple collisions is also applicable in the case of bombardment of a single crystal of light elements by heavy ions.

In addition, the results of previous works (1-4) and of the present work indicate the possibility of using ion bombardment of solids at glancing angles as a method for effective cleaning of the target surface, and the study of the energy spectra of secondary ions as a method for investigating the structure and composition of the surface layers of a solid.

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Note: Figure translations are in progress. See original paper for figures.