THE EFFECT OF THERMAL LATTICE VIBRATIONS ON THE SCATTERING OF IONS BY CRYSTALS

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Submitted December 2, 1967

Zh. Eksp. Teor. Fiz. 55, 25—38 (July, 1968)

Results are presented of an experimental investigation of the effect of the temperature of a copper single crystal target on the energy and angular distributions of argon ions with initial energies of 10—20 keV scattered by the surface of the target. An oscillographic technique was employed which ensured a high degree of stability of the external parameters (the beam current and target temperature) during the recording time of each spectrum. This facilitated experiments in a broad range of glancing and scattering angles, bombarding ion energies, and target temperatures. The effect of the target temperature on the angular distributions, the width of the energy spectra and dependence of the ratio of the peak intensities of singly and doubly scattered argon ions on the initial energy of the bombarding ions is observed and investigated. The investigations are performed for two different orientations of the ion beam relative to the crystallographic directions on the surface of the target. A result which is characteristic for both orientations is the much greater effect of the target temperature on scattering in the case when both the glancing angle and the scattering angle are small, and the decrease of the effect of the target temperature when the angles increase.

1. INTRODUCTION. METHOD

THE bombarding of a metal surface with 10^3—10^5 eV ions is accompanied by the emission of electromagnetic and corpuscular radiation. The corpuscular radiation includes electrons, target atoms and scattered atoms of the primary beam in various states of ionization.[1] The overwhelming majority of atomic particles consists of sputtered target atoms and their average energies do not exceed 50—100 eV. A small part (usually a few percent) of the particles emitted by the surface of the target has appreciable energies comparable with the initial energy of the bombarding ions. Among these have been observed beam and target ions with energies characteristic of a single pair collision of a bombarding ion with a target atom. In the energy distributions of fast charged particles scattered by the target surface in a given direction these ions produce sharp peaks superimposed on the background due to ions which have experienced multiple collisions with the atoms of the target.[2] Especially interesting results are obtained in bombarding single-crystal targets. In this case, the angular and energy distributions of the scattered ions manifest characteristic features due to the orderly arrangement of the target atoms.[3] Thus, in the energy distributions of ions scattered by the surface of a single crystal in a given direction one observes, along with the ion peak having an energy corresponding to single-pair collision of the bombarding ion with the target atom, an ion peak of higher energy and apparently related with the presence in the spectrum of ions that have experienced more than one collision (in the first approximation—two collisions) with the target atoms.

Experiments with the use of single-crystal targets make it possible to obtain quantitative information essential for setting up a theory of scattering of ions by metals. Particularly valuable in this connection is the information which can be obtained in investigations of the effect of thermal vibrations of the atoms of the target lattice on the process of scattering of ions. So far only one paper[4] is apparently available in which the effect of target heating on the ratio of the single and double scattering components was observed. In it argon ions with an initial energy of 30 keV were used to bombard the surface of a single crystal of nickel; the energy spectra of the scattered ions were investigated only at two fixed target temperatures which differed by 600°C. The effect of thermal lattice vibrations on the angular distributions of the scattered ions has so far altogether not been investigated. In this paper we publish results of a systematic investigation of the effect of thermal lattice vibrations on the scattering process of fast ions by the surface of a metal single crystal.

It follows from simple considerations that for "glancing interaction" of an ion with the target (under the term "glancing interaction" we understand the case when the direction of the bombarding beam makes a small angle with the surface of the target and ions scattered at small angles are recorded) one should expect a relatively stronger effect of changes in the mutual positions of atoms of the surface layer of the target as a result of their thermal motion on the scattering process. On the other hand, in the case when the trajectories of the incident and reflected ions lie close to the normal of the target surface, the thermal vibrations of the target atoms should have a smaller effect on the scattering process. Indeed in the latter case the scattering of the ion occurs as a result of a very limited number of collisions with the atoms of the surface layer. Ions which have not experienced strong scattering in the first collisions with the atoms of the first surface layer of the target have a larger probability of escaping deep into the lattice. To the contrary, in the case of glancing interaction among the scattered particles ions should predominate which have experienced successive scattering on a chain of five or ten atoms of the surface

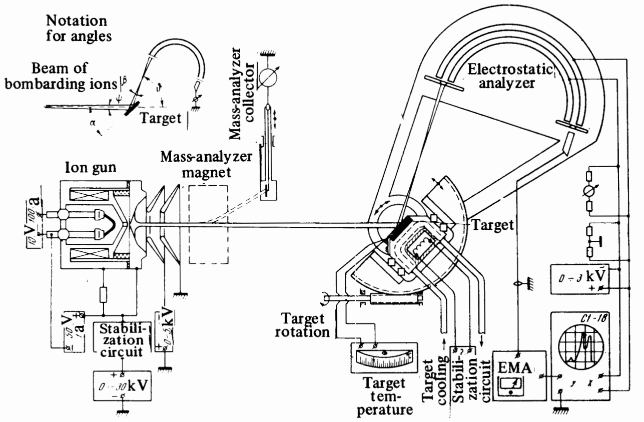

FIG. 1. Schematic diagram of the experimental setup. Details in the text.

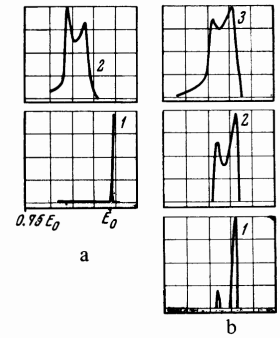

FIG. 2. Typical energy spectra

layer of the target.[5] It was therefore of interest to carry out experiments in the range of scattering and glancing angles including both of these cases.

The measurements were carried out in a rather broad range of scattering and glancing angles, target temperatures, and initial energies of the bombarding ions. Accordingly we used for the investigations of energy spectra of scattered ions an oscillographic method which made it possible to scan the energy spectra rapidly on the oscillograph and to photograph these, as well as to investigate selected sections of the spectra with higher amplification.

A schematic diagram of the experimental setup is shown in Fig. 1. The main units of the setup are: 1) an ion source of the duoplasmotron type with a magnetic mass analyzer for control of the purity of the ion beam; 2) a target with a holder and device for cooling and heating of the target and for temperature control; 3) an electrostatic energy analyzer of the scattered ions (calculated resolution $E/\Delta E \approx 100$, angular resolution of 1°) with a recording system for the spectra.

The current from the collector of the electrostatic analyzer was fed to the input of an electrometer amplifier whose output cascade was connected to the amplifier of the vertical oscillograph deflection. To scan along the X axis, use was made of part of the voltage applied to the plates of the electrostatic analyzer. Application of an oscillographic method instead of the system of recording the readings of two pointer-type instruments usually employed in this type of experiment, made it possible to increase the rate of obtaining information by at least a factor of ten. The time required for recording a spectrum was $\sim 1-2$ min. In all we scanned and recorded in the experiments described below more than 3000 energy spectra corresponding to a change in the initial energy of the bombarding ions between the limits of 8–20 keV, scattering angles between 12 and 45°, and glancing angles between 5 and 20°.

A no less important circumstance is the fact that the oscillographic method employed made it possible to ensure a high degree of stability of the target temperature and the beam current of the bombarding ions during the recording time of each spectrum. A shortcoming of the employed oscillographic method is the lower accuracy in determining the positions of the peaks on the energy scale compared with accuracy provided by a good pointer-type instrument.

In Fig. 2a, curve 1, we present an oscillogram of the energy spectrum of the primary beam ions obtained without the target. When the beam of bombarding argon ions was incident on the entrance window of the analyzer; curve 2 recorded on the same scale is a typical energy spectrum of argon ions scattered by the (100) plane of a single crystal of copper at an angle $\vartheta = 30^\circ$.

The method employed made it possible to measure with high accuracy the ratio of the peak heights in the spectrum, especially of peaks that differed little in their heights. To this end we photographed the peak tops with accurately known amplification, simultaneously compensating with the aid of a calibrated source of compensating voltage for the voltage corresponding to the lower part of the peak. The peaks of the oscillograms 1 and 2 in Fig. 2b were recorded with amplification by a factor of 2 and 5 respectively compared with oscillogram 3.

The subject of this work is the study of the effect of thermal vibrations of the crystal lattice of the copper target on the ratio of the intensities of peaks of singly and doubly scattered argon ions, the nature of the dependence of the ratio of these peak heights on the initial energy of the bombarding ions, as well as the width of the energy and angular distributions of the scattered ions. In this connection one must note the following.

The heights I_1 (of the left-hand "single") and I_2 (of the right-hand "double") peaks measured from the oscillograms do not, strictly speaking, represent the true intensities (fluxes) of ions which have undergone single or double collisions before entering the entrance slit of the analyzer. In fact both peaks are superimposed on a background of multiply scattered ions and it would be more correct to measure the ratio of the peak intensities after reconstructing the contour of each peak from their total envelope. Nevertheless, a presentation of the results of processing of the obtained oscillograms in the form of the ratio I_2/I_1 (or I_1/I_2) is at present apparently the only possible method of characterizing quantitatively the effect of the experimental conditions—the target temperature, the initial energy of the bombarding ions, and the values of the scattering and glancing angles—on the process of scattering of ions by the surface of a metallic target.

The effect of the thermal vibrations of the atoms of the crystal lattice of the target was investigated for two orientations of the bombarding beam relative to the crystallographic directions on the target surface. As

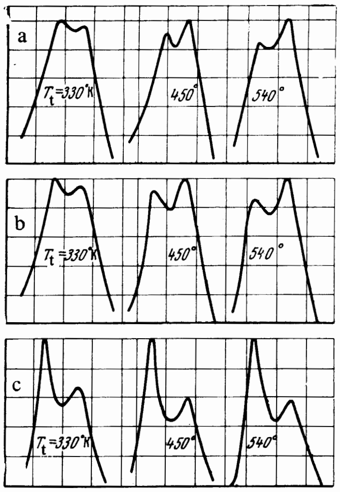

FIG. 3. Effect of the target temperature on the ratio of the intensities of the peaks of "single" and "double" scattering in the spectrum of argon ions with an initial energy of 18 keV scattered at an angle $\vartheta = 27°$ by the (100) plane of a copper single crystal for various glancing angles of the bombarding beam with respect to the surface of the target: a—$\alpha = 5°$, b—$\alpha = 10°$, and c—$\alpha = 14°$. The scattering was investigated in the (100) plane.

will be shown below, a result characteristic of both orientations is the considerably larger effect of the target temperature in the case in which both the glancing angle α as well as the scattering angle ϑ are simultaneously small, and the decreasing effect of the target heating on increasing the angles α and ϑ.

2. THE EFFECT OF THE TARGET TEMPERATURE ON THE RATIO OF THE INTENSITIES OF THE "SINGLE" AND "DOUBLE" SCATTERING PEAKS

The results of the experiments described below were obtained for two target orientations. Different target orientations correspond to different distances between the atoms in the chain lying in the scattering plane on the target surface.

A. (100) Plane. Rotation about the [100] Axis

For this orientation both the target and the analyzer were rotated about the [100] axis lying in the plane of the cut of the target—the (100) plane. The scattering was investigated in the (100) plane perpendicular to the axis of rotation. The primary beam of ions was also in the same plane. The measurements were carried out in the 12 to 45° degree range of angles, the scattering angle being varied by 3—5°. The glancing angles were 5, 8, 10, 14, and 20°. The energy of the bombarding ions E_0 = 18 keV.

The results of the investigation of the effect of the target temperature on the ratio I_2/I_1 characteristic for the scattering angles $18° \leq \vartheta \leq 30°$ are represented by the series of spectra on Fig. 3 ($\vartheta = 27°$). As can be seen from the figure, at a glancing angle of $\alpha = 5°$ and a target temperature $T_t = 330°$K the left-hand peak—the single scattering peak—dominates the spectrum. The height of the right-hand "double" peak is 5 percent lower. Increasing the target temperature by 120°K leads to a considerable change in the ratio of the intensities: the spectrum is now dominated by the right-hand peak and the intensity of the left-hand peak is 10 percent lower. An increase of the temperature to 540°K leads to a further decrease of the relative intensity of the single-scattering peak. The ratio of the peak intensities changes in a similar manner with increasing T_t when $\alpha = 10°$.

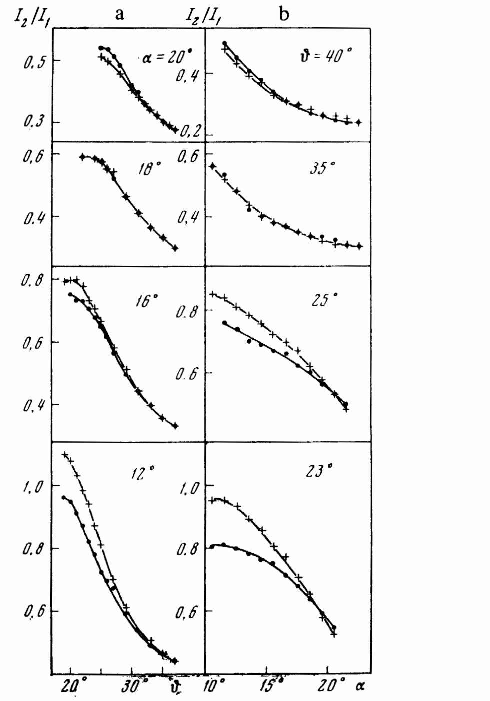

FIG. 4. The effect of the target temperature on the ratio of intensities I_2/I_1 in the spectrum of argon ions with an initial energy of 18 keV scattered by the (100) plane of a single crystal of copper. The scattering was investigated in the (130) plane. O – T_t = 400°K, O – T_t = 600°K.

Increasing the angle α to 14° leads to a considerable weakening of the effect of T_t on the ratio of the peak intensities. Thus, on heating the target from 330 to 540°K the height of the right-hand peak decreases altogether by only 5 percent.

A general result for the region of scattering angles $30° \leq \vartheta \leq 45°$ and glancing angles of 10 and 14° is the practically complete absence of any dependence of the shape of the energy spectrum of the scattered ions on the temperature. No appreciable difference was noted in the ratio of the intensities of the right and left-hand peak in the range of target temperatures of 340 and 400°K. In fact, all the oscillograms obtained on the same scale in the range T_t = 300—500°K which refer to the same glancing and scattering angles coincide fully on being superimposed. Only heating the target to 770—800°K led to a small (~2—5%) change in the ratio of the peak heights in the spectrum of the scattered ions. For the reached maximum target temperature of 1100°K the relative intensity of the right-hand peak decreased by about 10 percent.

B. (100) Plane. Rotation about the [130] Axis

The [130] axis located in the plane of the cut of the target served as the axis of rotation of the analyzer and of the target in this series of experiments; the scattering was investigated in the (130) plane perpendicular to the axis of rotation. The results of measurements carried out with the target in such an orientation are shown in Fig. 4. We recorded and processed a large number of energy spectra and were forced for the sake of compactness to resort to a representation of the results of processing the spectra in the form of graphs where the ratios I_2/I_1 for the two target temperatures 400 and 600°K are plotted as a function of the scattering angle ϑ and the glancing angle α.

It is seen from Fig. 4a that as the scattering angle increases, the ratio I_2/I_1 decreases. In the range of $\vartheta \sim 20-27°$ heating of the target leads to a change in the value of I_2/I_1. For small glancing angles α heating of the target leads to increasing I_2/I_1 values. On going over to large glancing angles, the difference between the values of I_2/I_1 for cold and hot targets decreases for this range of scattering angles and for $\alpha = 18°$ the curves practically coincide. However, on increasing α further up to 20° the curves diverge again in the range of small ϑ, but now the points which correspond to the heated target lie lower than those for the cold target. In the range of scattering angles 27–37° heating of the target does not give rise to any appreciable change in the value of I_2/I_1.

Similar behavior is observed in the case of a smooth change of the angle of incidence of the ion beam on the target at several fixed scattering angles (Fig. 4b). In the range $\alpha \sim 10-15°$ heating of the target leads to a change in the relative intensity of the right-hand peak, the magnitude of this change depending in turn on the angle ϑ and having a minimum near $\vartheta = 30°$.

Thus, the effect of the thermal vibrations of the atoms of the target on the ratio of the peak intensities in the spectrum of scattered ions manifests itself to a large degree in the case of scattering at small angles with glancing incidence of the ions on the target. On going over to large scattering and glancing angles the effect of the target temperature on the energy spectra of the ions decreases.

3. THE EFFECT OF THE TARGET TEMPERATURE ON THE HALF-WIDTH OF THE ENERGY SPECTRUM OF THE SCATTERED IONS ((100) PLANE, ROTATION ABOUT THE [100] AXIS)

A comparison of the energy spectra obtained at various target temperatures T_t indicates that in addition to a change in the ratio of the intensities of the scattering peaks the change of T_t leads to an appreciable change in the half-width of the energy spectrum of the scattered ions in passing through certain temperature ranges which differ for different angles α and ϑ. A general regularity revealed in the analysis of a large number of oscillograms and illustrated by the spectra of Fig. 5 is a considerably larger effect of T_t on the half-width of the spectra obtained when both the glancing and scattering angle are small than on the half-width of spectra corresponding to simultaneously large α and ϑ.

The energy spectra of Fig. 5 are plotted on the same scale and their fronts are shifted for convenience in comparing their half-widths. We compared the two spectra with the maximum difference of widths among those obtained for a given combination of angles α and ϑ on changing the target temperature in the range 200–1000°K by 50–100°K. As is seen from Fig. 5, in the case of scattering and glancing angles $\alpha = 5°$ and $\vartheta = 21°$ the spectra recorded at target temperatures differing by 300°K differ in their width at half-height by 30–40%. However, on going to larger glancing angles

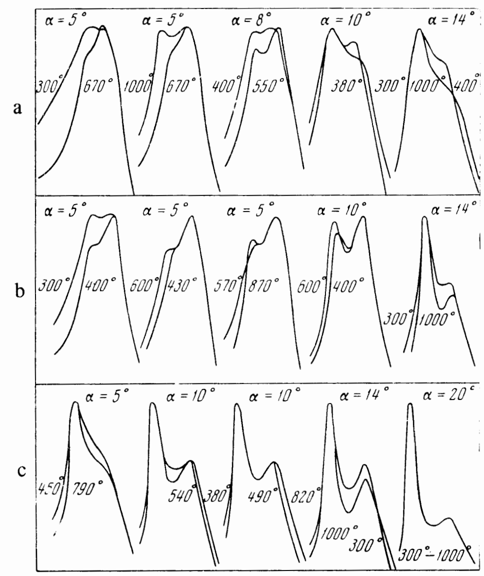

FIG. 5. The effect of the target temperature on the half-width of energy spectra of scattered argon ions. The initial energy was 18 keV. (100) plane of a single crystal of copper. The scattering was investigated in the (100) plane.: a – $\vartheta = 21°$, b – $\vartheta = 25°$, c – $\vartheta = 35°$. The target temperature corresponding to a given spectrum is indicated near the curves.

$\alpha = 8-14°$ (for the same value of $\vartheta = 21°$) the maximum change of the half-width of the spectrum decreases to 15–5%.

An increase in the scattering angle also leads to a decrease in the maximum change of the half-width of the spectrum. Thus for $\vartheta = 25°$ the change in the width of the spectrum does not exceed 25 percent even in the case of a glancing angle $\alpha = 5°$, and decreases rapidly as one goes over to large α. Ion spectra recorded for an angle $\vartheta = 35°$ change their half-width by no more than 3–5%, and the oscillograms of all spectra corresponding to $\alpha = 20°$ and $\vartheta = 35°$ obtained on changing the target temperature within the range of 300–1000°K by 50–100°K coincide fully when superimposed.

In studying the series of oscillograms referring to a given value of the angles α and ϑ one's attention is drawn by the nonmonotonic character of the change in the half-widths of the energy spectra obtained when the target temperature is increased gradually. Thus the half-width of the spectrum of ions scattered at an angle $\vartheta = 21°$ (for $\alpha = 5°$) decreases almost by a factor of two on going from $T_t = 300°K$ to $T_t = 600°K$, and increases by 20 percent on further increasing T_t up to 1000°K. The half-width of the spectrum of ions scattered at an angle $\vartheta = 25°$ first decreases by 25% on heating the target from 300 to 400°K, then increases by 15 percent on changing the temperature close to 600°K, and decreases again on reaching a target temperature close to 870°K.

4. EFFECT OF THE TARGET TEMPERATURE ON THE DEPENDENCE OF THE RATIO I_1/I_2 ON THE INITIAL ENERGY OF THE BOMBARDING IONS

In the course of preliminary experiments it was observed that the ratio I_1/I_2 depends on the initial energy of the ions bombarding the target. In the range of large scattering and glancing angles the dependence of I_1/I_2

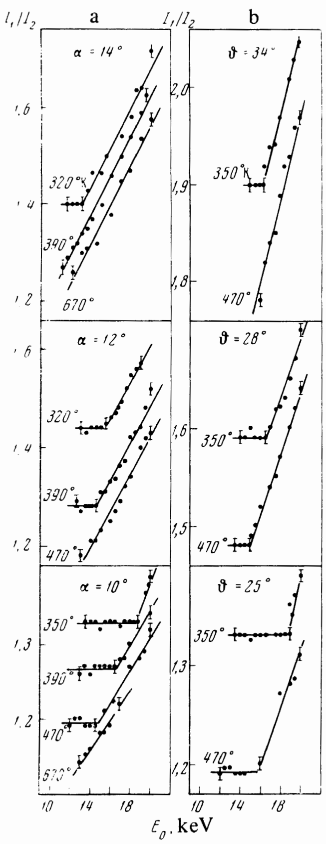

FIG 6. The effect of the target temperature on the nature of the dependence of the ratio I_1/I_2 on the initial energy of the bombarding ions. (100) plane. The scattering was investigated in the (130) plane. a—$\vartheta = 25°$; b—$\alpha = 10°$. The target temperature in degrees Kelvin is indicated near the curves.

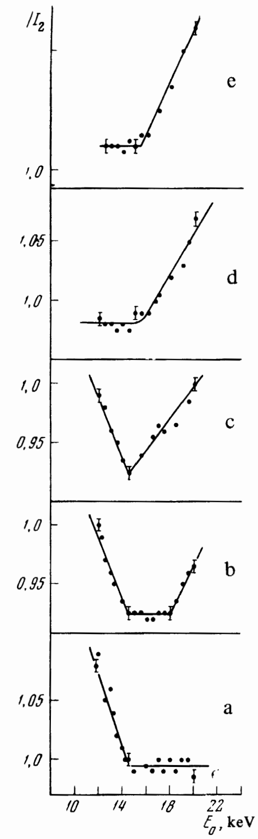

FIG. 7. The effect of the target temperature on the nature of the dependence of the ratio I_1/I_2 on the initial energy of the bombarding ions [(100) plane], the scattering was investigated in the (100) plane; $\vartheta = 20$, $\alpha = 10°$]: a—$T_t = 390°K$, b—$T_t = 470°K$, c—$T_t = 670°K$, d—$T_t = 820°K$, e—$T_t = 970°K$.

on E_0 follows approximately the $I_1/I_2 \propto E_0$ law characteristic of calculations of the I_1/I_2 intensity ratio in the pair-collision model.[6] For small angles α and ϑ the dependence of I_1/I_2 is qualitatively different. In connection with what has been said it was of interest to study the effect of the target temperature on the nature of the dependence of the ratio I_1/I_2 precisely in the region of small glancing and scattering angles where, as was shown above, the effect of the thermal vibrations of the crystal lattice on the scattering process is exhibited to a much greater degree than in the region of large α and ϑ.

In the experiments described below the target was kept at a given, strictly controlled temperature, and the initial energy E_0 was varied from 11 to 20 keV. The glancing angle of the ion beam with respect to the target surface was 10, 12, and 14°. The measurements of the ratio I_1/I_2 were carried out in spectra of ions scattered at angles of 25, 28, and 34°.

The results of the measurements are presented in Figs. 6 and 7. In plotting the curves we used results of measurements which were carried out at target temperatures which did not differ by more than ±5° from the specified value. A weakening of the requirements as to the constancy of the target temperature during the measurements led to a considerable increase in the spread of the experimental points and to a complete masking of the effects described below.

The effect of the target temperature on the dependence of the ratio I_1/I_2 on the initial energy of the bombarding ions was studied for two different orientations of the ion beam relative to the crystallographic directions of the target surface.

A. (100) Plane. Rotation about the [130] Axis

In the measurements whose results are presented on Fig. 6 the (100) plane of a copper single crystal served as the target. In changing the scattering and glancing angles the analyzer and the target were rotated about the [130] axis located in the plane of the target. Incident on the entrance window of the analyzer were ions scattered by the surface of the target whose velocity vector lay in the (130) plane perpendicular to the axis of rotation. The beam of the bombarding ions lay in the same plane.

From the curves of Fig. 6 it is seen that for a given target temperature the dependence of the ratio I_1/I_2 on the initial energy has a qualitatively different character in different intervals of the investigated energy range. Thus for $\alpha = 10°$ (Fig. 6a) and a target temperature of 350°K the ratio I_1/I_2 remains constant on changing the energy of the bombarding ions from 13 to 18.5 keV, whereas in the 18.5—20 keV energy interval it increases with increasing E_0 in accordance with a law which is close to linear. At target temperatures of 390 and 470°K and a glancing angle $\alpha = 10°$, and at temperatures of 320 and 390°K and $\alpha = 12°$ (Fig. 6b), and at $T_t = 320°K$ and $\alpha = 14°$ two sections are also observed with a different course of the energy dependence of I_1/I_2. The small width (~ 0.5 keV) of the interval of initial energies of the bombarding ions within which the change of the nature of the energy dependence takes place is noteworthy.

As is seen from Fig. 6, an increase in the target temperature leads to a decrease of the relative intensity of the left-hand peak for a given energy of the bombarding ions. At the same time the decrease on the "horizontal" section of the dependence is larger by a factor of 1.5–2 than on the section on which the ratio I_1/I_2 depends linearly on the initial energy of the bombarding ions. Heating of the target leads to a shifting of the boundaries of the sections with the different course of the energy dependence of I_1/I_2. Thus, for $\alpha = 10°$ (Fig. 6a) an increase of the target temperature from 350 to 470°K leads to a shift of the transition region from 18.5 to 16 keV, and a further increase of T_t up to 670°K leads to the complete disappearance of the horizontal section of the dependence of I_1/I_2 on E_0.

It is seen from Fig. 6 that for a given target temperature an increase of the glancing angle α leads to the circumstance that the transition region between the horizontal section and the section with the linear dependence is shifted towards lower energies of the bombarding ions. Thus, for T_t = 390°K and $\alpha = 10°$ (Fig. 6a) the transition from the horizontal section to the linearly increasing section occurs at an energy of the bombarding ions of 17 keV, whereas for $\alpha = 12°$ near 15 keV and for $\alpha = 14°$ there is altogether no horizontal section. An analogous shift of the transition region towards lower energies on increasing the glancing angle is observed for target temperatures of 320 and 470°K. Thus, for a large glancing angle one needs to heat the target to a lower temperature for the nature of the E_0 dependence of I_1/I_2 near a given value of E_0 to change from a horizontal to a linearly increasing dependence.

As is seen from Fig. 6b, an analogous conclusion can be drawn regarding the rules governing the change of the nature of the energy dependence of I_1/I_2 with the target temperature and on increasing the scattering angle ϑ.

B. (100) Plane. Rotation about the [100] Axis

Measurements analogous to those described above were carried out on the same target oriented with respect to the ion beam in such a way that the [100] axis lying in the plane of the cut of the target was the axis of rotation of the analyzer and of the target, and the axis of the ion beam and the straight line connecting the center of the target with the entrance window of the analyzer lay in the (100) plane perpendicular to the axis of rotation. The results obtained with such a target orientation for a scattering angle $\vartheta = 20°$ and $\alpha = 10°$ are presented in Fig. 7.

Our attention is drawn by the appearance of a new (compared with the previous orientation) type of dependence of the relative intensity of the right-hand peak on the initial energy of the bombarding ions—a decrease in the value of I_1/I_2 with increasing E_0 observed in the energy interval from 12 to 16 keV at T_t = 390°K (Fig. 7a), from 12 to 14.5 keV at T_t = 470°K (Fig. 7b), and from 12 to 14 keV at T_t = 670°K (Fig. 7c). At target temperatures of 390 and 470°K the graph of the dependence of the ratio I_1/I_2 on E_0 has a horizontal section, the value of I_1/I_2 on this section being 20% lower than at the same target temperatures and the same scattering angles and angles of incidence of the beam on the target for the previous orientation.

Increasing the target temperature to 670°K leads, as is seen from Fig. 7c, to replacement of the horizontal section of the dependence by a linearly increasing section, and further heating to 820°K (Fig. 7d) transforms the section of the linear decrease into a horizontal one. Increasing the target temperature to 970°K does not change the character of the dependence of I_1/I_2 on E_0.

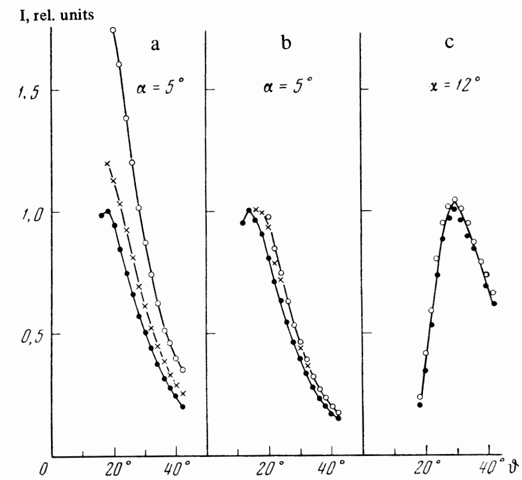

FIG. 8. The effect of the target temperature on the angular distributions of singly scattered ions [(100) plane, the scattering was investigated in the (110) plane]: ○ – T_t = 300°K, × – T_t = 600°K, ○ – 900°K; a – single crystal, b and c – polycrystalline target.

5. EFFECT OF THE TARGET TEMPERATURE ON THE ANGULAR DISTRIBUTIONS OF THE SCATTERED IONS

For these measurements the target was the (100) plane of a single crystal of copper. The target and the analyzer were rotated about the [110] axis lying in the plane of the target. The scattering was investigated in the (110) plane perpendicular to the axis of rotation. We investigated the effect of thermal vibrations on the angular distributions of scattered ions belonging to the high-energy portion of the spectrum. To this end we recorded the energy spectra of the ions corresponding to various scattering angles at a fixed target temperature and angle of incidence of the ions on the target; the scattering angle was varied by 1–2°. Such measurements were carried out in the form of the dependence of the height of the left-hand peak I_1 or of the right-hand peak I_2 on the scattering angle ϑ.

Examination of the obtained $I(\vartheta)$ dependences showed that a change of the target temperature changes the magnitude of the ion flux at the maximum of the angular distribution and shifts the position of the maximum itself. These changes manifest themselves to a larger degree at glancing incidence of the beam of ions on the target and decrease rapidly as the glancing angle is increased. Results referring to the angular distributions of the right-hand peak obtained at glancing angles of 5, 10, and 12° are shown in Fig. 8. It is seen that for $\alpha = 5°$ an increase in the target temperature from 300 to 900°K leads almost to a doubling of the intensity at the maximum of the distribution. At the same time the position of the maximum shifts towards higher scattering angles. For glancing angles of 10 and 12° the position of the maximum is shifted by a smaller angle, and

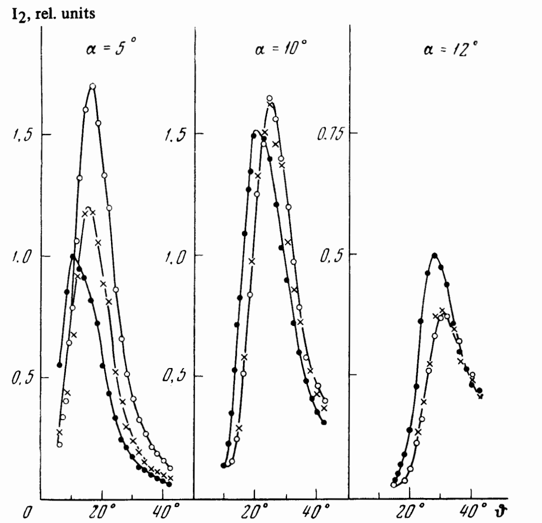

FIG. 9. The effect of the target temperature on the angular distributions of doubly scattered ions [(100) plane, scattering in the (110) plane]: O – T_t = 300°K, X – T_t = 600°K, O – T_t = 900°K.

the change in the intensity at the maximum amounts to ~ 20%.

6. DISCUSSION OF THE RESULTS

An adequately developed theory of scattering of fast ions by the surface of a solid, which would explain the effect of thermal vibrations of the atoms of the target on the energy distributions of the scattered ions, does not exist at present. The attempts now being made of producing such a theory are based on two essentially different approaches. One of these[7] consists in solving the kinetic equation applied to the case of the motion of a charged particle in a gas of metal atoms, omitting however the effect of the crystal structure of the target and the effect of the thermal vibrations of the lattice.

The other approach consists in carrying out numerical calculations of the scattering of fast ions by the atoms of a solid on the basis of the model of pairwise single and multiple collisions. It was shown in[8] that carrying out such calculations using a Firsov potential to characterize the screening of Coulomb repulsive forces between the ion and the atom of the metal makes it possible to explain the basic features of the scattering of fast ions by the surface of a solid. In particular, such calculations predicted the subsequently experimentally observed existence of a structure of the energy spectrum of the ions scattered by a single crystal due to double collisions.[3]

A further development of this approach is the calculation of the reflection of an ion by a chain of atoms located on the surface of the target when each scattering atom is screened by the preceding one and itself screens the atoms with which the subsequent collisions occur. This calculation corresponds to the experimental setup in which the incident and reflected ion beams lie in a plane passing through one of the crystal axes with low Miller indices, and the bombarding of the target is carried out with glancing incidence of the ion beam on the target. Under such conditions before they enter the analyzer slit the ions undergo in the scattering plane a series of small-angle deviations resulting from successive collisions with the atoms of the chain. One of the results of this theory is the double-valued nature of the energy of the ions which have undergone scattering in a given direction. The calculation leads to the appearance in the energy spectrum of ions scattered at a given angle ϑ two energy peaks close to the energies of single and double scattering, but generally differing from these somewhat.

The calculations carried out in[8] of the effect of thermal lattice vibrations of the target on the conditions of mutual screening of atoms in the chain on which the scattering of a fast ion occurs showed that both the ratio of the intensities of these peaks and their position on the energy scale can change with changing target temperature. In certain temperature ranges both peaks may turn out to be in an energy range between the limits E_1 and E_2 (E_1 and E_2 are the energies of ions which have undergone "true single" and "true double" collisions respectively with the target atoms). In another temperature range both these peaks may move outside the limits of the energy range delimited by the values E_1 and E_2. If the experimentally obtained peaks are difficult to resolve, then the mutual approach or separation of peaks can reveal itself in a narrowing or broadening respectively of the entire high-energy portion of the spectrum of the scattered ions, similar to that observed in the experiments described above (see Fig. 5).

It was noted[8] that under certain conditions the thermal vibrations of the atoms of the lattice can lead to a decrease in the mutual screening of the atoms in a chain and to such a change in the scattering conditions that independent pair collisions are realized overwhelmingly. In the limiting case of a total absence of screening and the realization of pure pair collisions the estimate given in[6] for the ratio of the intensity of the flux of doubly and singly scattered ions is correct; according to this estimate the ratio $1/R = I_1/I_2$ is proportional to the initial energy of the bombarding ions. Possibly the change of the energy dependence of the ratio I_1/I_2 to a linearly increasing one observed on increasing the target temperature in the experiments described above (see Figs. 6 and 7) is also related to the change of the scattering conditions towards overwhelming pair collisions of ions with the atoms of the target.

The fact that there exist sections with a qualitatively differing course of the energy dependence of I_1/I_2, as well as the sharpness of the transition from one dependence to another, have no explanation within the framework of presently existing scattering theories.

The author is grateful to S. Yu. Luk'yanov for interest in the work, and to S. N. Zvonkov and V. A. Snisar' for help in the work.

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Translated by Z. Barnea
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