ANOMALOUS ANGULAR CHARACTERISTICS OF SHADOWS ON PROTONOGRAMS OF BISMUTH

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Anomalously small axial and planar shadow widths have been detected on Bi protonograms. The Bi protonograms have been compared with those for W and Mo obtained under similar conditions. Cooling of the Bi single crystal results in a considerable increase of the shadow width. The high sensitivity of the protonogram to thermal oscillations of the lattice atoms is discussed.

DURING the course of study of the protonograms[1] of single crystals of a number of heavy elements, we have noted that in the case of Bi the widths of both the axial and planar shadows on the protonograms are anomalously small. We present here a brief description of the experiment and of the obtained results.

The investigations were carried out with the electrostatic Van de Graaf generator of the Ural Polytechnic Institute, at a proton energy 650 keV. The experimental setup is shown in Fig. 1. The Bi single crystal 1 was mounted at the center of the vacuum chamber 2. The irradiated surface of the single crystal was the {111} plane, along which the crystal was cleaved in liquid nitrogen. No additional surface treatment was used. A round diaphragm 4, of 0.15 mm diameter, was placed ahead of the crystal in the path of the beam 3; the current passing through the diaphragm was $\sim 1 \times 10^{-8}$ A. The vacuum in the chamber was maintained at a level of $\sim 3 \times 10^{-6}$ Torr.

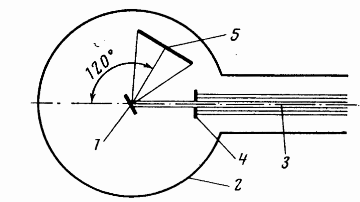

FIG. 1. Experimental setup.

The scattered protons were registered with the type MR photographic plate 5, the center of which was located 114 cm from the irradiated section of the single-crystal surface; the normal to the plate was at an angle of 120° to the primary-beam direction. The length of the exposure was chosen such that the density of the emulsion in the non-shadowed sections did not go beyond the limits of the linear section of the densitometric characteristic.

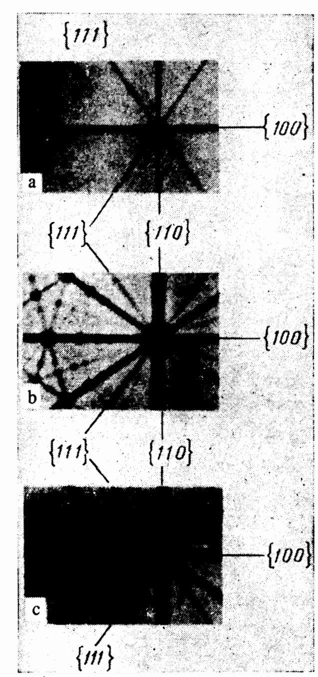

FIG. 2. Protonograms of Bi (a), W (b) and Mo (c), obtained at a proton energy $E_p = 650$ keV. The ⟨110⟩ axial shadow is seen at the point of intersection of the {100}, {110}, and {111} planar shadows.

One of the protonograms obtained is shown in Fig. 2a. It reveals the shadow in the direction of the ⟨110⟩ axis and the planar shadows {100}, {110}, and {111}. Attention is called to the anomalously small width of all these shadows. Figures 2b and 2c show for comparison the protonograms of W and Mo with an image of the axial shadow ⟨110⟩. These protonograms were obtained under the same conditions as that of Fig. 2a.

It is well known that the average width of an axial shadow on a protonogram is approximately proportional to $\sqrt{Z/l}$, where Z is the atomic number of the element of the single crystal and l is the distance between the neighboring nuclei in the corresponding chain. For the ⟨110⟩ axis in the case of Bi and W this quantity is equal to 4.16×10^{-4} and 4.08×10^{-4} cm$^{-1/2}$, respectively, i.e., the values are approximately equal. At the same time, the experimental widths turn out to be significantly different. Moreover, the shadows of Bi turn out to be even narrower than those of Mo, for which $\sqrt{Z/l}$ is much smaller (3.08×10^{-4} cm$^{-1/2}$). This is particularly clear in Fig. 3, which shows the results of photometry of the ⟨110⟩ axial shadows for W, Mo, and Bi. We present below the values of $\sqrt{Z/l}$ and the experimental values of the half-width Ψ, taken from Fig. 3:

	Mo	W	Bi
$\sqrt{Z/l}$, 10^{-4} cm$^{-1/2}$:	3,08	4,08	4,16
Ψ_{exp}, deg:	1,8	2,3	1,2
$\Psi_{exp.}/\sqrt{Z/l}$, 10^4 deg.cm$^{1/2}$:	0,58	0,57	0,29

It is seen from the foregoing data that whereas the relative experimental values of the width turn out to be "normal" for Mo and W, i.e., they are proportional to $\sqrt{Z/l}$, in the case of Bi there is a significant ano-

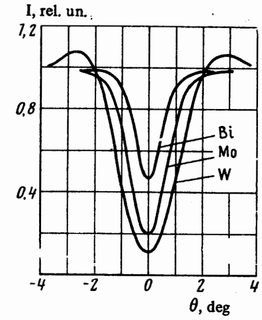

FIG. 3. Curves obtained by photometry of the ⟨110⟩ axial shadows for the single crystals of Bi, W, and Mo.

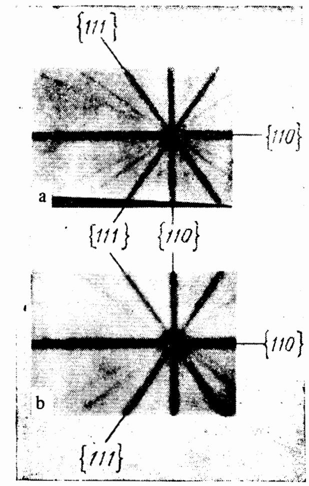

FIG. 4. Protonograms of Bi with image of the ⟨110⟩ axial shadow, obtained at temperatures of −100 (a) and −190°C (b).

maly, in that the width of the shadow is in this case approximately half the expected value.

It should be noted that the scattering of fast charged particles by Bi single crystals had been investigated earlier: namely, Ellegaard and Lassen[2] investigated the scattering of protons of energy 5 MeV and of α particles with energy 20 MeV by a single-crystal target. To be sure, unlike in our experiment, the incident particles in the experiment of Ellegaard and Lassen were in the channeling mode. In this case they observed not the "direct" shadow as in our experiment, but the "inverse" one. At the present time it is known that the widths of the "direct" and "inverse" shadows are approximately equal, and therefore the anomaly described in the present paper should, in principle have appeared in the results of Ellegaard and Lassen. It was not, however, observed.

The discrepancies between our results and those of[2] may be due to the following causes: bismuth has a very low melting temperature (271°C) compared with such high-melting-point metals as W and Mo. As a result, at a fixed temperature, say room temperature, the amplitude of the vibrations of the atoms is much larger in the Bi lattice than in the W and Mo lattices. It has been shown in a number of papers[3-5], on the other hand, that the shadows broaden with decreasing vibration amplitude, and vice versa. One of the reasons why the anomaly of the shadow width was not observed in[2] for Bi is the fact that that the quantity compared with the theoretical estimates was the width obtained at reduced temperature. This is not all, however.

The sensitivity of the shadow width on the protonogram to the temperature is due to two causes. On the one hand, when the vibration amplitude increases the "primary" shadow, i.e., the shadow that can be observed, say, in the case when a thin single-crystal target is used, becomes narrower. On the other hand, if the back scattering occurs at a considerable target depth, the particles experience multiple scattering as they move towards the surface, and this leads to a narrowing of the shadow. With increasing atom-vibration amplitude, the role of the multiple scattering increases. In[2] the measurements were carried out with a semiconductor detector that separated a narrow section of the energy spectrum of the scattered particles near its upper end. With the experiment so performed, the second narrowing factor hardly comes into play; this can also lead to a suppression of the anomaly.

It follows from the foregoing that if the shadow picture is obtained by means of photographic plates, the sensitivity of the shadow parameters to the temperature turns out to be much higher than the case when the particles are registered with counters that separate the upper section of the energy spectrum.

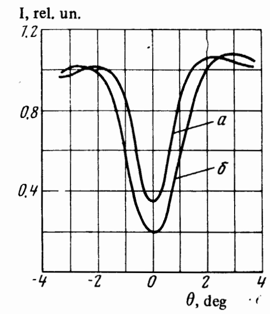

FIG. 5. Curves obtained by photometry of the ⟨110⟩ axial shadow of Bi single crystal, corresponding to the temperatures −100 (a) and −190°C (b).

In order to demonstrate the high sensitivity of the Bi protonograms to the temperature, Fig. 4 shows protonograms with an image of the ⟨110⟩ axial shadow, obtained at low temperatures (−100 and −190°C). The corresponding curves obtained by photometry are given in Fig. 5. From an examination of these curves we see that the shadow widths greatly increase when the crystal is cooled.

The results obtained in the present investigation indicate that great interest attaches to study, with the aid of protonograms, of the shadow parameters in the immediate vicinity of the melting point. In this case the shadows should be extremely narrow. Such measurements are now under way.

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