SCATTERING OF 5–40 keV PROTONS BY MOLYBDENUM SINGLE CRYSTALS

B. G. AKHMETOVA, Yu. M. PLETS, and A. F. TULINOV

Nuclear Physics Institute, Moscow State University

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The shadow effect observed by bombarding a molybdenum crystal with 5–40 keV protons is described. The dependence of the effect on the state of the target surface and on its temperature is investigated.

In the scattering of fast charged particles by a single-crystal target one observes in the angular distribution of the scattering products in the directions of the crystallographic axes and planes peculiar "shadows" due to the Coulomb interaction of the scattered particles with the ordered nuclei of the lattice. This phenomenon has been investigated at various energies. In [1-4] it was observed at a proton energy of 3–6 MeV. Investigations carried out on a number of single crystals at lower energies (200–500 keV)[5,3,6] showed that at those energies the effect is not only present, but the conditions for observing and studying it are for a number of reasons improved. The general picture of the angular distributions of protons at such energies is particularly conveniently observed from the blackening of photographic emulsion. A system of shadows—"white lines"—appears on the photographic plate; each of these lines is the intersection of one of the crystallographic planes of the target with the plane of the photographic emulsion.

Inasmuch as the range of protons in a solid is relatively small, the produced "proton pattern" reflects the crystallographic structure of a relatively thin layer of the target near its surface. Thus, at a proton energy ~ 300 keV the thickness of this layer in the case of molybdenum is $\sim 0.2\,\mu$. This circumstance and also the fact that the range of heavy charged particles is rather well defined for a given energy, allows one to hope that the shadow effect can be successfully employed for an investigation of various surface phenomena. For a more detailed analysis of the possibilities of this method, there is considerable interest in experiments on the scattering of charged particles by single crystals in a most extensive energy range, including the region of quite low energies where literally a few atomic layers of the target take part in the scattering. In this paper we present the results of one of the stages of these investigations—the study of the shadow effect with a molybdenum single crystal for elastic proton scattering in the region of 5–40 keV.

The measurements were made on the electromagnetic separator of the Nuclear Physics Institute of Moscow State University. A beam 1 mm in diameter with an intensity of $\sim 0.01\ \mu$A was separated with the aid of diaphragms from a broad flux of protons incident on the separator collector (Fig. 1). This beam was directed at a single-crystal target at a certain angle φ to its surface. To obtain 15–40 keV protons we used an atomic beam, and for energies of 5–15 keV—a molecular beam, with an energy of the molecules of 10–30 keV respectively. The scattered protons were registered with type-MK nuclear photographic plates. The photographic plates were placed 57 mm from the target center in such a way that their normal was at an angle $\theta = 90°$ to the beam axis. The exposure was chosen such that the maximum blackening of the irradiated emulsion should not be outside the limits of the linear region of its densitometric characteristic.[7] The surface of the single crystal was electrolytically polished before irradiation in order to remove surface contamination.

A number of proton patterns in the 5–40 keV energy range were obtained. Negatives of proton patterns corresponding to the scattering of 15 and

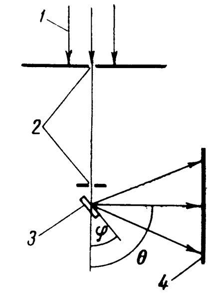

FIG. 1. Diagram of the experiment: 1 – proton beam, 2 – diaphragms, 3 – target (single crystal of molybdenum), 4 – photographic plate.

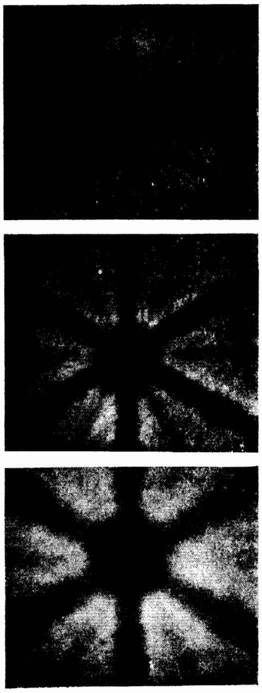

FIG. 2. Proton patterns obtained for molybdenum at incident-proton energies (keV); a – 300, b – 40, and c – 15.

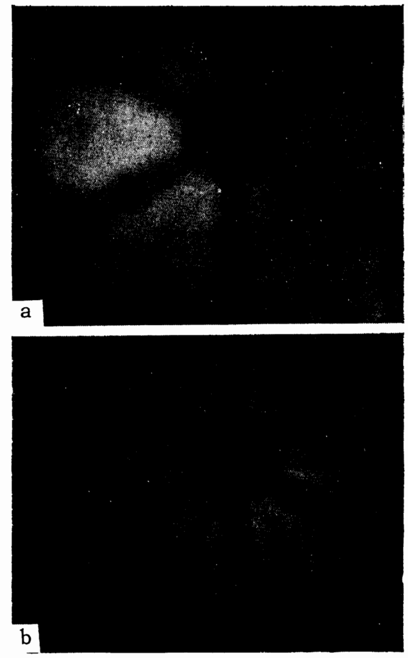

FIG. 3. The effect of treatment of the crystal surface on the quality of the proton pattern: a – pattern obtained before electrolytic polishing, b – after electrolytic polishing.

40-keV protons are shown as examples in Fig. 2. (For comparison we also show a proton pattern obtained under analogous geometrical conditions at 300 keV; see [5].) In all instances the crystals were oriented in such a way that the [111] axis was perpendicular to the photographic emulsion. The general tendency towards increasing geometric dimensions of the shadows with decreasing proton energy in the beam is clearly manifested in all obtained proton patterns.

At the same time, it follows from the results of the experiment that in the energy region 5–15keV the contrast of the images decreases as a rule. This phenomenon is apparently mainly connected with the effect of surface contamination or with the presence on the surface of the crystal of a layer with a disturbed structure. In the region of energies of the order of several keV, the scattering takes place in layers about 100 Å thick; the presence on the surface of an amorphous layer of about 10 Å is sufficient to affect the sharpness of the shadows. The high sensitivity of the effect to the quality of the target surface is illustrated in Fig. 3 which shows proton patterns obtained at 15 keV before and after electrolytic treatment of the crystal surface.

The results described above were obtained with

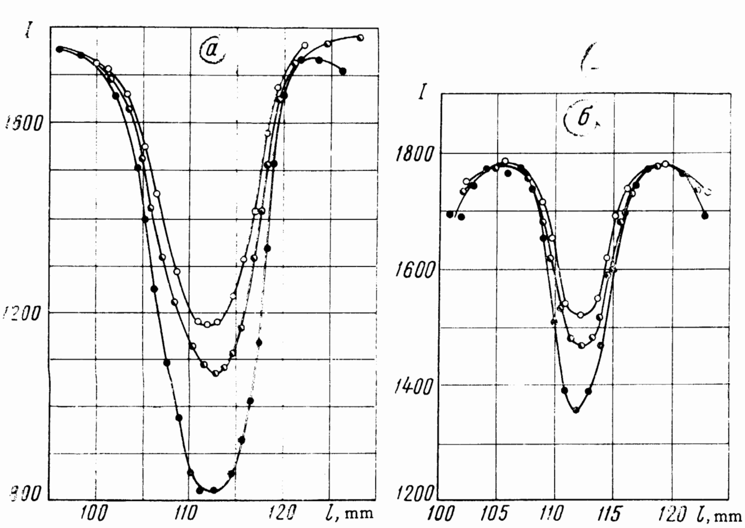

FIG. 4. Temperature dependence of the shape of the shadow: a – for the [111] spot, b – for the (110) line; ● – T = 300°K, ◐ – T = 500°K, and ○ – T = 900°K.

the crystal samples at room temperature. We also investigated the dependence of the effect on the temperature of the target. The measurements were carried out as before on a molybdenum crystal which was heated to 300, 500, and 900°K. The temperature of the sample was measured with a thermocouple. The target was bombarded with a 30-keV beam of molecular hydrogen. The resulting patterns were processed with an MF-4 microphotometer. The result of such photometry are shown on Fig. 4. The number of protons per unit area of emulsion is plotted in arbitrary units on the ordinate axis; the readings of the scale on the microphotometer table are plotted on the abscissa. The curves shown in Fig. 4a were obtained by photometry of the spot corresponding to the [111] axis along the direction of the trace due to the (112) crystal plane. The curves of Fig. 4b were obtained at the intersection of the trace of the (110) plane at a distance of 2 cm from the center of the [111] shadow.

The nature of the change in the pattern with increasing temperature is the same in both instances, namely: an increase of the temperature leads to a decrease of the depth of the shadow. The same behavior as was noted at energies of ~ 3 MeV[3] has thus also been noted in this case.

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