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INFLUENCE OF THE CRYSTAL LATTICE ON SOME ATOMIC AND NUCLEAR PROCESSES

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1. INTRODUCTION

THE problem of the interaction of fast particles with single crystals has been dealt with in numerous papers. At first, the investigations were mostly concerned with the cathode sputtering of various substances. These investigations yielded a number of important results, the most interesting of which is the focusing of collisions, discovered in 1954 by Wehner.[1] There is now a considerable body of literature on the subject, which is, in particular, reflected in a review published recently in the present journal.[2]

Much less investigated, but attracting increasing attention, is the problem of the influence of the lattice on the nature of motion of fast particles in a crystalline medium. Even the initial investigations on this subject have shown that the ordered distribution of atoms in a lattice gives rise to a number of special effects which are not observed in the motion of particles in an amorphous or polycrystalline substance. The problems involved can be usefully divided into two groups in accordance with the nature of the relevant relationships and the possibilities of their utilization in various physical applications. One group includes the problems connected with the motion of particles introduced into a crystalline sample from outside, while the other includes the problems involving particles generated in the crystal itself - in particular, those emerging directly from the lattice sites. These two groups of problems are discussed here separately and we shall deal only with the motion of charged particles.

2. INFLUENCE OF THE CRYSTAL LATTICE ON THE MOTION OF PARTICLES INCIDENT ON A SINGLE CRYSTAL

Theoretical considerations of the nature of the motion of heavy ions of relatively low energies (tens of keV) in a solid have led a number of investigators [3-4] to the conclusion that when an ion beam is incident on a crystal, one should observe an effect characteristic of the capture of particles into channels ('channeling'). The essence of this effect is as follows. If a particle enters a channel (defined as the space bounded by an assembly of neighboring parallel chains of atoms in a crystal) at a sufficiently small angle to the axis of the channel, the particle will move for a relatively long time along the channel, experiencing alternate reflections from the opposite 'walls' of the channel due to the electrostatic interaction with the atoms (Fig. 1). Since this effect is associated with the motion of relatively heavy particles (p, d, α, etc.), their wavelength is usually small compared with the lattice constant l, so that many effects can be analyzed using classical representations. By this means, one can quite easily find the conditions under which this effect should be observed. The most important of these conditions is the smallness of the angle φ. Considerations based on the assumption of a classical trajectory give the value of the maximum angle φ_{max}:[5]

$$\varphi_{\max} = C\sqrt{\frac{b}{l}}, \qquad (1)$$

where $b = Z_1Z_2e^2/E$, Z_1e and E are the charge and energy of the moving particle, Z_2e is the charge of the nucleus in the lattice, and C is a constant which is approximately 1.5. The expression (1) applies to a perfectly rigid lattice. An allowance for the vibrations of nuclei about their equilibrium positions will lead to some reduction of φ_{max}. When $\varphi > \varphi_{max}$, the particle will leave the channel and the nature of its motion will not differ greatly from that in an amorphous medium.

FIG. 1. Schematic representation of a channel and a trajectory of a particle moving in the channel (the image of the trajectory is strongly compressed in the horizontal direction).

When the conditions for the capture of a particle by a channel are satisfied, its trajectory is, on the average, quite close to the channel axis. This 'paraxial' nature of a beam of particles captured by a channel has a number of consequences which are important in the experimental investigations of the details of this effect. We shall mention the most interesting of these consequences.

a) Since the density of electrons near a channel axis is considerably less than the average density of electrons in a sample, the specific energy lost by the particles moving in the channel, when they collide with electrons, will be considerably less than elsewhere. Such particles should have much longer paths.

b) Electron belonging to different atomic shells are distributed in characteristic layers inside a channel. Thus, the K-electrons lie in the peripheral region of the channel, the L-electrons are somewhat closer to the channel axis, etc. At a given particle energy E, the particles corresponding to different values of φ will, on deviating from the channel axis, pass through different shells. This may be reflected, in particular, in the dependence of the yield of x rays on the value of the angle, being different for the K- and L-shells, etc.

c) Since particles captured by a channel move quite far from the nuclei, the probability of reactions caused by such particles is much reduced.

All these conclusions have already been subjected to experimental checks and they all have been confirmed qualitatively.

Let us consider some examples.

1) Reduction in energy losses. Nelson and Thompson [6] used 75 keV protons to bombard a thin single-crystal film of gold which, as is well known, has the fcc lattice. They measured the dependence of the number of protons transmitted through the film on the direction of the incident beam with respect to the crystallographic axes of the target (Fig. 2). The target was rotated about the [111] axis in such a way that the various [110] axes coincided, in turn, with the direction of incidence of the particles. The dependence shown in Fig. 3 indicates that the fraction of protons transmitted through the target rose sharply whenever the direction of the incident beam coincided with a [110] axis. Similar experiments have also been carried out for protons of higher energies.

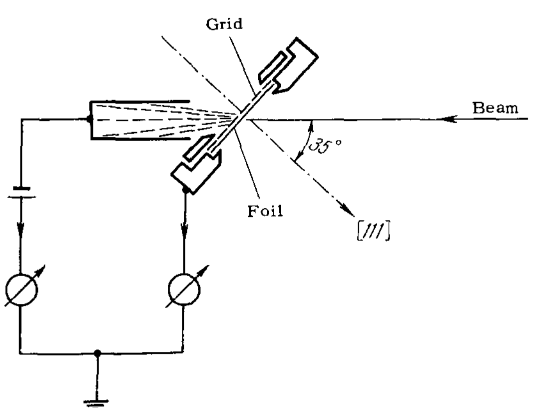

FIG. 2. Experimental arrangement used to investigate the transmission of 75 keV protons through an Au single crystal.

Thus, Erginsoy et al.[7] investigated the influence of the orientation of a silicon crystal on the value of the energy loss by protons. They used 3 MeV protons. The silicon sample was sufficiently thin so that it transmitted practically all the incident particles; for an arbitrary orientation, they observed only a shift of the corresponding energy line toward low energies. When the direction of the incident beam coincided with a crystallographic axis (in this case, a [110] axis), the line had a high-energy tail (Fig. 4), indi-

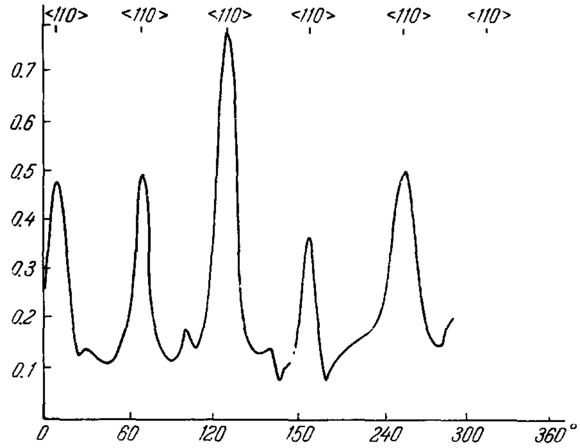

FIG. 3. Dependence of the number of protons transmitted by a single-crystal Au film on the azimuthal angle of the rotation of the target about the [111] axis. The number of protons is given along the ordinate in relative units. The positions of the [110] axes are given at the top of the figure.

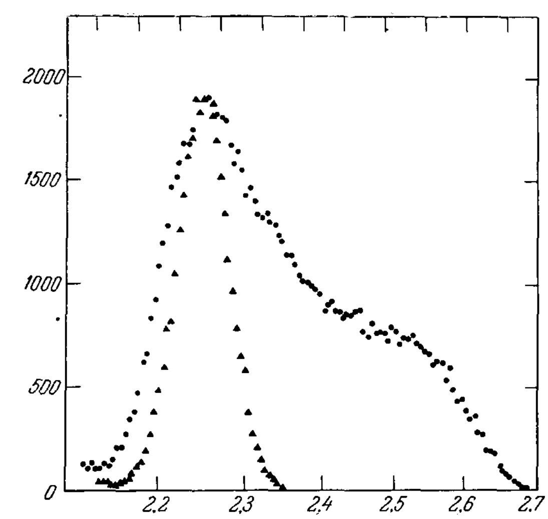

FIG. 4. Energy spectra of protons transmitted by a thin silicon plate. The primary proton energy was 3 MeV; ▲—direction of the incident beam different from those of the crystallographic axes; ●—beam along a [110] axis.

cating that protons captured in a channel suffered a smaller energy loss than other protons.

It is interesting to note that a qualitatively similar effect has been observed during the motion of particles not only along crystal axes, but also along crystal planes.[8]

2) Yield of characteristic x rays. Brandt et al.[9] bombarded Al and Cu single crystals with 75–115 keV protons. They measured the yield of the characteristic x rays from the K- and L-shells as a function of the crystal orientation with respect to the direction of the incident beam. When a [110] axis coincided with the beam direction, the yield of the x rays dropped sharply in both metals and the width of the resultant minima agreed with simple theoretical

estimates based on the effects described in b) above.

3) Reduction in the probability of nuclear reactions. To confirm the conclusion of item c), a resonance reaction (p, γ) was investigated in Al and Si single crystals.[10] The investigators recorded γ quanta, representing the formation of resonance states at E_p = 405 keV in Al^{27} and at E_p = 414 keV in Si^{29}. Measurements were made of the dependence of the yield of γ quanta on the mutual orientation of the directions of the incident beam and one of the crystallographic axes. By way of example, Fig. 5 shows the dependence obtained for a [110] axis and Al nuclei. A sharp reduction in the yield of γ quanta was indeed observed, indicating a reduction in the probability of the reaction when the protons were channelled. Similar, but less clear, results were obtained for the (p, n) reaction in Cu^{65} nuclei (cf.[11]).

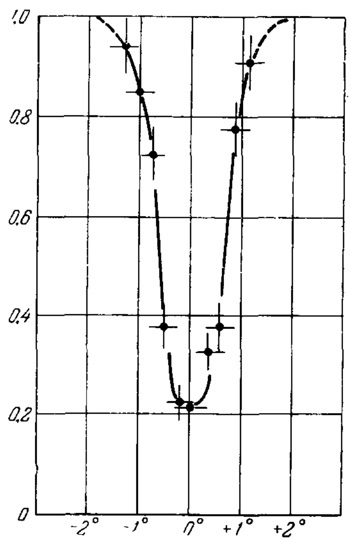

FIG. 5. Relative yield of γ quanta in the (p, γ) reaction in an Al single crystal as a function of the angle between a [110] axis and the incident beam direction. The angle 0° corresponds to the coincidence of these two directions.

Bogh et al.[10] obtained another interesting result. They varied the energy of the incident particles. Consequently, the reaction, due to its resonance nature, took place at different depths of the target. It was then found that the relative yield of γ quanta at the minimum of the curve shown in Fig. 5 increased considerably as the depth of the target increased. The corresponding data are given in Table I.

One may conclude from these data that the fraction of particles captive in channels decreases during their motion in these channels because some of the particles leave the paraxial beam. The reasons for this effect have not yet been investigated. They are obviously associated, to some extent, with the vibrations of nuclei in the lattice. The presence of such vibrations leads to a considerable probability of the 'injection' of nuclei into the channel cavity, which causes—due to a reduction in the impact parameter—a particle to deviate from the channel axis by an angle greater than φ_{max}. In this connection, it would be interesting to repeat the cited experiments at different temperatures of the crystal. So far, such experiments have not been carried out.

3. INFLUENCE OF THE LATTICE ON THE MOTION OF CHARGED PARTICLES WHICH ARE THE PRODUCTS OF NUCLEAR REACTIONS

I. When charged particles leave lattice sites (these particles may be the products of reactions or of scattering through large angles), the situation is different. We can show that the conditions for the capture of such particles by channels are not satisfied; the angle at which they intersect the channel axis is too large. It is this circumstance that leads to another interesting observation, which may be called the 'shadow effect'.[12-15] The principle of this effect can be understood from the following considerations. Let us assume that particles incident on a single-crystal target interact with nuclei located at the lattice sites of the single crystal. The charged scattering or reaction products will fly in all directions, including directions close to the crystallographic axis. In the latter case, the particles will suffer additional Coulomb scattering by the nearest nuclei, which constitute atomic chains.

Thus, the directions along crystallographic axes are closed to the particles leaving the lattice sites; characteristic shadows will be observed along these directions. It is important to stress that, because of the translational symmetry of the crystal lattice, a given crystallographic direction will be closed absolutely, i.e., irrespective of the angle of emission of a particle which may be the product of scattering or of a reaction.

The practical possibility of the observation and utilization of this effect is governed by the absolute values of the angular dimensions of the shadows.

An estimate of the quantities involved was obtained theoretically in [13] for the two limiting cases: the assumption of an absolutely rigid ideal lattice, and the adoption of a model which describes nuclei in a chain as an assembly of three-dimensional classical

Table I

E_p, keV	410	420	435	465
Relative yield at 0°	0.21	0.25	0.38	0.60

oscillators vibrating completely independently of one another. It can be shown that the former model makes it possible to estimate the value of the upper limit of the angular dimensions of the shadow and the latter can be used conveniently to estimate the average angle of deflection of particles by a chain of nuclei.

Assuming that the interaction potential between a particle leaving a lattice site and a nucleus, which is a constituent of the crystal, is in the form of the expression $V(r) = (Z_1/Z_2e^2/r)e^{-r/a}$, where a is the well-known screening parameter, we obtain the following expression for the upper limit of the angular dimensions of the shadow ψ

$$\psi^2 = 2\frac{b}{l}\left[K_0\left(\frac{\sqrt{bl}}{a}\right)+2\right], \qquad (2)$$

where $K_0(x)$ is a cylindrical function of the 3rd kind.

The value of the average angle of deflection φ of a particle, which is emitted from a site along the direction of the chain axis and which is multiply scattered by nuclei forming this chain, is given by

$$\varphi^2 = \left[\frac{3}{2}\frac{l^2}{gl}\ln\frac{a}{b}\right]^{2/3}+2\frac{b}{l}K_0\left(\frac{g}{a}\right). \qquad (3)$$

It is assumed here that nuclei vibrate with an amplitude g.

To illustrate the angular dimensions of the shadows, Table II lists the numerical values of 2ψ and 2φ for the energies 1, 10, and 100 MeV for light (Mg), medium (Mo), and heavy (W) nuclei (at room temperature). It is evident from Table II that the shadow effect may be observed if the detection system has a sufficiently high angular resolution.

We shall describe briefly an experimental investigation of this effect for the elastic scattering of protons by tungsten nuclei.[12,13] A thick (2 mm) single-crystal sample of W was used as a target. The angular distribution of the protons was measured in the vicinity of the [111] axis, whose direction was first determined by the x-ray method. The measurements were carried out using a 3 MeV proton beam from the cyclotron of the Nuclear Physics Institute of Moscow State University. The beam diameter in the region of the target was ≈ 1 mm. The experimental arrangement is shown in Fig. 6. The protons were recorded with a semiconductor counter. The angular distribution for a polycrystalline target was also measured for comparison. The results of the measurements are given in Fig. 7. The points denoted by open circles were obtained for the polycrystalline target, and the black dots represent the single crystal. The ordinate gives the number of pulses in the high-energy end of the continuous spectrum (the threshold was 80% of the maximum signal amplitude). As is evident from Fig. 7, the separation between the two side maxima of the curve is 4°. Using Eq. (2), we obtain $2\psi \approx 3.3°$. The experimental half-width is ≈ 2°; the value of 2φ corresponding to this half-width is, in accordance with Eq. (3), also equal to ≈ 2° at room temperature. The value of the amplitude

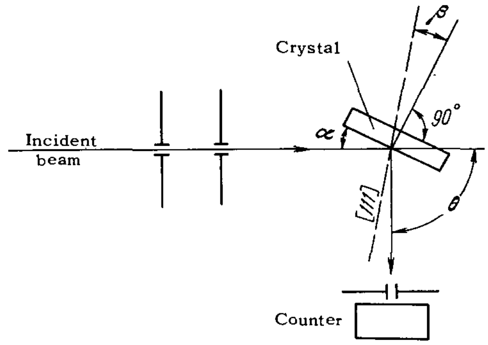

FIG. 6. Experimental arrangement used to investigate the shadow effect in a W single crystal ($\alpha = 30°$, $\beta = 15°$, $E_p = 3-6$ MeV).

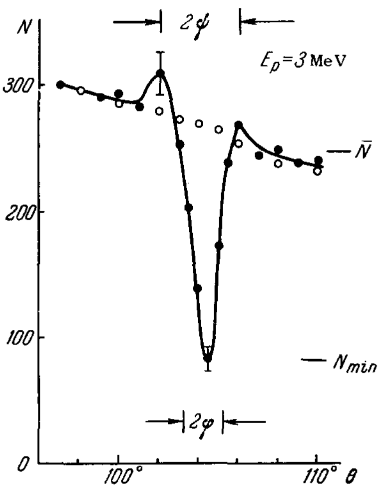

FIG. 7. Dependence of the number of protons, scattered by a W single crystal, on the angle θ (cf. Fig. 6). The crystallographic axis [111] oriented first at an angle $\theta = 105°$. ● – Single-crystal target; ○ – polycrystalline target.

Table II

	1 MeV		10 MeV		100 MeV	
	2ψ	2φ	2ψ	2φ	2ψ	2φ
Mg	1.8°	1.1°	1.0°	0.3°	0.3°	0.09°
Mo	4.2°	2.7°	1.5°	0.7°	0.5°	0.2°
W	4.6°	3.9°	1.7°	1.0°	0.6°	0.3°

of the vibrations of the nuclei was estimated using the Debye model of the lattice. Thus, we found fairly good agreement between the experimentally determined angular dimensions of the shadow and the corresponding results of simple theoretical estimates.

The shadow effect was investigated further by the present author et al.[16] In particular, the dependence of the effect on the crystal temperature was studied. For this purpose, a target (the same tungsten crystal) was cooled to the temperature of liquid nitrogen ($T \approx 80°K$). The corresponding curves are shown in Fig. 8. It is evident that, with cooling, the effect becomes stronger, and the minimum becomes deeper and wider. The cause of the broadening can be easily understood on the basis of the oscillator model; moreover, the use of Eq. (3) gives, at $T \approx 80°K$, a value which is in reasonable agreement with the experimental results.

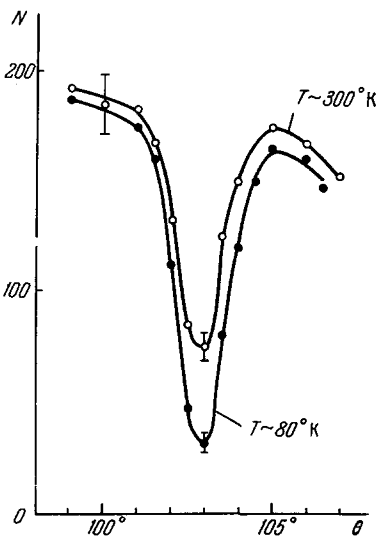

FIG. 8. Dependence of the number of protons, scattered in a W single crystal in the vicinity of the [111] axis, on the angle at room temperature ($T \approx 300°K$) and at the temperature of liquid nitrogen ($T \approx 80°K$).

The dependence of the shadow parameters on the energy of incident protons was also investigated. It was found that when E_p was increased to 6 MeV, the width of the shadow decreased practically in full agreement with the predictions of Eqs. (2) and (3).

The problem of the depth of the minimum has not yet been solved, although there is some experimental evidence about it.[16] For example, using a multichannel analyzer of the AI-100 type, the energy spectra of protons emerging from a crystal were recorded at various points of the shadow. Because the crystal was very thick, the spectra were continuous for all angles, but their behavior varied slightly with angle. Since different energy regions of the spectra corresponded to different depths of the corresponding scattering centers, it was possible to find how the form of the shadow varied with the scattering of protons at different depths in the crystal. It was found that, as the depth increased, the width of the shadow increased somewhat and the relative depth of the minimum decreased considerably. Figure 9 shows the relative intensity of the scattered protons at the center of the minimum as a function of their energy—in other words, as a function of the depth of the scattering layer. It is evident from the curves, obtained both at room temperature and at the temperature of liquid nitrogen, that the deepest minimum corresponds to the scattering of protons by nuclei located quite close to the target surface. The reduction in the depth of the minimum as the depth of the scattering layer increases resembles the situation described earlier: the fraction of particles remaining captive in channels decreases as the depth of penetration increases. It is possible that the cause of the two effects is the same. As already mentioned, one of the possible causes are the vibrations of the nuclei in a lattice. In the case of the shadow effect, these vibrations may have the effect that, when it traverses a sufficiently thick layer of a substance, a particle has a considerable probability of colliding with nuclei which protrude from the chains in the direction of the channel axis. It can easily be seen that scattering by such nuclei may establish conditions under which particles are captured by a channel, which would lead to a decrease in the depth of the minimum. The temperature dependence of the curves shown in Fig. 9 does not contradict such an explanation.

It can be easily seen that the effect of capture by channels, described above, and the shadow effect have a number of common features.

However, there are also considerable differences between these effects. To stress the differences, we shall consider two points.

1) The minimum shown in Fig. 5 represents a

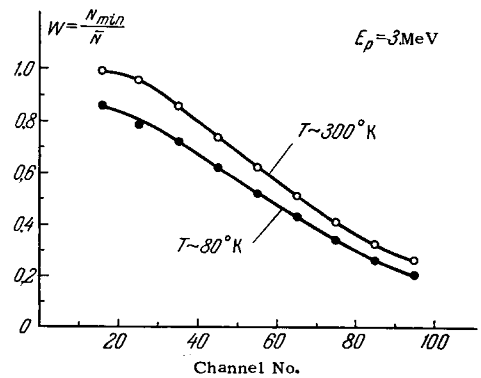

FIG. 9. Dependence of the ratio $W = N_{min}/\bar{N}$ on the number of the analyzer channel (the meaning of N_{min} and $\bar{N}$ can be seen from Fig. 7).

real reduction in the total yield of the reaction products; in the case of Fig. 7, the total yield of the scattering 'products' remains unaltered. There is only a redistribution of the directions of emergence of the products from the target.

2) The multiple scattering of particles by nuclei in the chains is essential for the capture of particles into channels. In other words, a large number of practically identical single collisions establishes the necessary conditions for a prolonged stay of a particle in a channel. We can easily see that in the case of the shadow effect the participation of a large number of nuclei is not essential. In principle, only one neighboring nucleus is needed to produce a shadow for a given center.

The shadow effect in the form just described suggests interesting possibilities of its utilization in various physical investigations. We shall consider some of them.

a) Determination of the duration of nuclear reactions.[12,13] One of the principal difficulties in the investigation of nuclear reactions is the lack of experimental methods which make it possible to separate the reaction mechanisms. As a rule, several processes are taking place in an experiment, which makes it difficult to consider them theoretically. For example, we would point out that the direct reactions are usually accompanied by the formation of compound nuclei, and although the durations of such processes are very different ($\tau \approx 10^{-22}$ sec for the direct reactions, and $\tau \approx 10^{-16}$-10^{-20} sec for the compound nucleus formation), the dearth of methods for measuring such very short intervals prevents our using this difference.

The shadow effect offers, in principle, the possibility of estimating experimentally these very short time intervals. The basis of the method is very simple. If the duration of a reaction is sufficiently short, at the moment of emission of a product particle, the compound system will be within a region defined by the thermal vibrations of the lattice nuclei and the shadow effect will be observed. In particular, this occurs in the Rutherford scattering of charged particles by nuclei at the lattice sites in a crystal. If, during its lifetime τ, a compound system can move, under the influence of the momentum transferred to it by the incident particle, a distance greater than the vibration amplitude of the nuclei, the shadow effect will disappear. Since the relative amplitude of the nuclear vibrations is of the order of $\approx 10^{-9}$-10^{-11} cm, and the velocity of compound systems is $\approx 10^{7}$-10^{9} cm/sec, the method is sensitive to values of τ in the region of 10^{-16}-10^{-20} sec.

b) Investigation of some properties of crystals. The rigid lattice model and the model of independent oscillators, i.e., the complete absence of correlation in the motion of nuclei, represent extreme simplifications of the real situation. In fact, the motion of nuclei is, to a considerable extent, correlated, the degree and nature of the correlation being governed by details of the phonon spectra. It is known that the investigation of these problems meets with certain experimental difficulties. The shadow effect presents us with an additional tool. We can show that the form of the shadow depends strongly on the nature of the correlation in the motion of the nuclei. There should be a very sharp difference between the forms of the shadow for the acoustical-mode and optical-mode vibrations and, therefore, we can, in principle, measure the relative intensities of the corresponding branches of the phonon spectra.

A number of interesting results related to the shadow effect can be obtained not only in the investigation of nuclear reactions, but also in the investigation of the α-decay of nuclei introduced into a crystal lattice. The resultant anisotropy of the α-particles has been described in [17].

II. The discussion given above applies to an isolated shadow associated with one crystallographic axis. In fact, there is a large number of such axes and, therefore, the total angular distribution pattern of, say, elastically scattered particles, should contain a multitude of shadows. The angular dimensions of the shadows depend on the distances between neighboring nuclei in the appropriate chain and, therefore, the shadows associated with the crystallographic directions of low indices should appear most clearly. As the order of indices increases, the shadows should become narrower. The presence of large numbers of axes of relatively high indices will obviously give overlapping shadows which will be manifested experimentally as continuous shadow lines. To observe such a pattern over a wide range of angles, the photographic plate method was used. The measurements were carried out using a multistage accelerator in the proton energy range 200—500 keV.[8] As before, a thick single-crystal sample of tungsten was used as a target. The proton beam was 0.3 mm in diameter in the region of the target. A photographic plate was placed at right-angles to a crystallographic axis [100], which, in turn, made an angle of 90° with the incident beam direction. To make sure that the plate recorded only the fraction of protons in the high-energy end of the continuous spectrum, an organic film was placed directly in front of the plate to act as a filter. Figure 10 shows a pattern obtained for $E_p = 200$ keV. The photograph shows clearly the shadows corresponding to chains of relatively low indices, as well as the lines referred to above. For comparison, Fig. 11 shows the distribution of the shadows in the form of points and lines, plotted on the basis of a purely geometrical consideration of the bcc lattice. The diameters of the points and the thicknesses of the lines represent approximately the nuclear 'population density' of the corresponding directions and planes. Indices are given for some directions. The very good agreement between the experimental and 'theoretical' patterns allows us to conclude that we have a new effective method for investigating the structure of crystals. In contrast to the currently widely used x-ray diffraction and electron diffraction methods, the wave processes have practically no effect in the formation of the points and lines (cf. Fig. 10) and the whole pattern is governed only by the Coulomb interaction of the incident particles with the nuclei. This means that the resolving power of the method is not restricted, in contrast to the limitations imposed by the diffraction broadening of the spots. Moreover, the interpretation of the results is extremely simple. The lines shown in Figs. 10 and 11 are simply lines of intersection of crystallographic planes with the plane of the photographic plate.

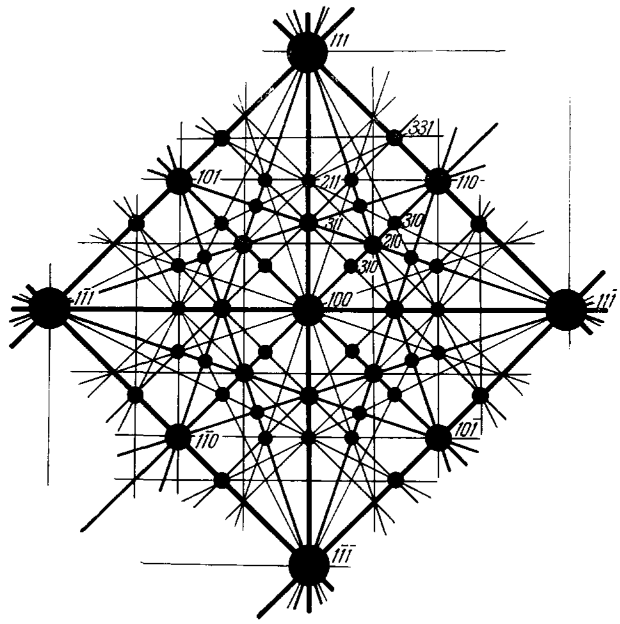

FIG. 11. Geometrical representation of the bcc lattice. The lines represent traces of crystallographic planes on a plane parallel to a [100] axis. The spots represent the intersections of crystallographic axes of relatively low indices with the same plane. The dimensions of the spots and the thicknesses of the lines represent approximately the 'population' of the corresponding axes and planes.

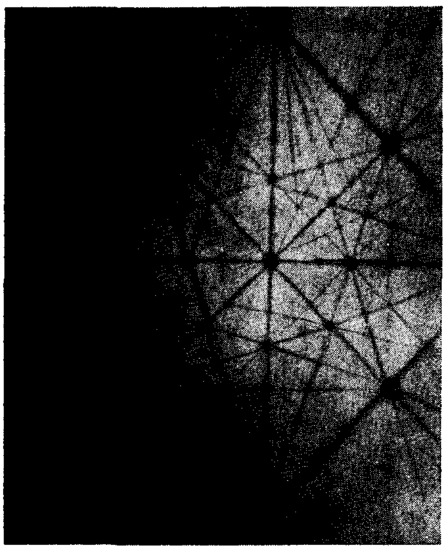

FIG. 10. Image of a system of shadows of crystallographic planes in W obtained by the elastic scattering of 200 keV protons in a W single crystal. The spot in the center is the shadow of the system of chains along a [100] direction. The photographic plate was placed at right-angles to this axis.

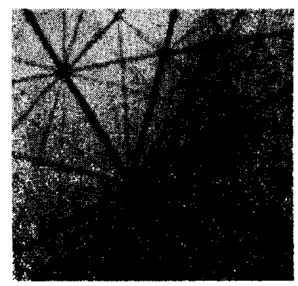

FIG. 12. Image of a system of shadows obtained for a molybdenum single crystal when $E_p = 500$ keV; the regions of different degrees of blackness represent different exposures; the shadow of a fourfold [100] axis is shown in the center.

In addition to the experiments with tungsten, several other substances were also investigated. Figures 12 and 13 show the photographs obtained for single crystals of molybdenum and silicon (in the latter case, the orientation was arbitrary). It is worth pointing out that the photographs show very thin lines; obviously, the thickness of the lines is governed solely by the dimensions of the beam. The satisfactory sharpness of the images of such thin lines makes it possible to use this effect for precision orientation of crystals. In connection with the possibility of investigating the details of phonon spectra using the form of the shadows, an interesting question arises as to what extent a shadow corresponding to a given crystallographic axis is associated solely with that axis, and whether the shadow is not complicated by the presence of a fine structure due to the super-position of the shadows associated with axes of higher indices. The images of shadows shown in Figs. 10, 12, and 13 cannot give a direct answer to this question because the particles recorded in all three photographs covered a very wide range of the energy spectrum; consequently, the form of the shadows was affected by the consequences of the transmission of particles through fairly thick layers of substances (from the scattering centers to the target surface). This last process obviously smooths out the line images. In the case of photographs obtained without an absorber in front of the photographic plate, microphotometry indicates a high degree of homogeneity of the shadow lines. On the other hand, as the thickness of the absorber is increased, i.e., the effective path of scattered particles in the substance is decreased, the relief structure of the lines becomes sharper. When the absorber

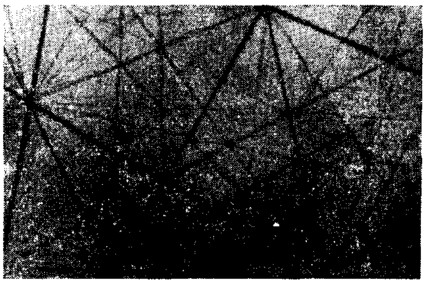

FIG. 13. Image of a system of shadows obtained when 500 keV protons were scattered in a silicon single crystal of arbitrary orientation.

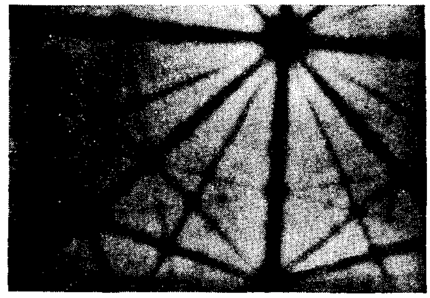

FIG. 14. The same image as in Fig. 10, but obtained using a larger distance between the target and the photographic plate, as well as a filter in front of the plate to absorb all the protons whose energy did not exceed 150 keV.

thickness is such as to ensure a discrimination threshold of 70% of the energy in the incident beam, we obtain a pattern such as that shown in Fig. 14. More detailed investigations, carried out at the energies of 3—6 MeV,[19] lead one to the conclusion that the shadow corresponding to the scattering of protons along the [111] axis at a relatively small depth in a crystal can be regarded as practically independent of the shadows due to axes of higher indices.

The nature of the lines shown in Figs. 10, 12, and 13 indicates that under certain conditions an assembly of nuclei in a given plane can be considered to be a single scattering system. In connection with this, it is useful to point out another effect which should be observed when fast, positively-charged particles interact with single crystals. If the surface of a sample coincides with one of the crystallographic planes, a well collimated beam of particles incident at a sufficiently small angle on such a surface should suffer complete reflection from the surface layer, like light from a mirror, and the monoenergetic nature of the beam should not be affected. Obviously, certain new aspects arise in this case. In particular, due to the spin—orbit interaction of the proton with the Coulomb field of the nuclei and the multiple amplification of this effect due to the identity of the successive collisions, the narrow beam of reflected protons should, in principle, split into the components corresponding to the different spin states. This effect is of interest from the point of view of the formation of beams of polarized particles.

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Naturally, the problems discussed here represent only part of the range of problems associated with the interaction between fast particles and single crystals. Research on these topics is proceeding rapidly in a number of laboratories and along various directions. Thus, the results of very interesting investigations of the β decay of nuclei introduced into single crystals have been published recently.[20] In particular one should stress the great importance of the investigations of the transmission of fast electrons through single crystals. It has been shown theoretically several times that an electron interacting with the periodic field of a lattice behaves as a moving dipole which may emit quasimonochromatic lines of the bremsstrahlung γ quanta. Such radiation was recently detected at high energies ($E_p \approx 1$ GeV) at Frascati [21], and at relatively low energies ($E_p \approx 30-80$ keV) at the Leningrad Polytechnical Institute.[22] This problem deserves a separate review.

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