Orientation Effects Accompanying the Propagation of Ultrarelativistic Electrons through Crystals

S. V. Blazhevich*, **G. L. Bochek**[1)], **W. I. Kulibaba**[1)], **N. I. Maslov**[1)], and **B. I. Shramenko**[1)]

Belgorod State University, Studencheskaya ul. 12, Belgorod, 308007 Russia

Abstract—The results obtained by experimentally investigating the dynamics of the propagation of 1.2-GeV electrons through a thin silicon single crystal are discussed. The orientation dependences of electron scattering into a small solid angle, which are measured at various scattering angles, under conditions where the effects of crystallographic axes and planes manifest themselves are interpreted. It is shown that there are such electron-scattering directions for which the orientation "independence" of the scattering intensity with respect to a specific crystallographic plane is observed and that there also exists a crystal-axis orientation for which the region of a uniform angular distribution of the intensity is observed.

1. INTRODUCTION

Experimental investigation of the dynamics of the propagation of electrons with an energy of about 1 GeV is of interest in connection with the possibility of using the instructive classical approach for its description. At the same time, relativistic effects in the propagation and scattering of fast particles and in radiation from them are pronounced at such energies.

In this study, we present the results obtained from an experimental investigation of orientation effects in the scattering of ultrarelativistic electrons in a silicon single crystal. The experiments were performed at the 2000-MeV linear electron accelerator of the Kharkov Institute for Physics and Technology.

A typical experimental procedure was used in electron-scattering experiments. A crystalline target was placed in a chamber equipped with a goniometer that made it possible to orient the target with respect to the axis of incident electron beam to within 5×10^{-5} rad. The particles that had traversed the target were detected by a small germanium detector (0.5×0.5 mm) positioned at a distance of 15 m from the target; this corresponded to measuring the flux of particles scattered into a solid angle of about 1×10^{-9} sr. The angular distribution of scattered particles was measured by scanning the scattered beam in the transverse plane by displacing the detector. In this study, we measured the angular distributions of particle-flux density versus the orientation of a given crystallographic axis or a given plane with respect to the axis of the incident-particle beam; we also explored orientation dependences.

2. ELECTRON PROPAGATION AT SMALL ANGLES TO A CRYSTALLOGRAPHIC AXIS

The propagation of ultrarelativistic electrons was experimentally investigated by using a 1200-MeV electron beam incident at small angles with respect to a crystallographic axis on a silicon single crystal 10 μm thick cut along the (111) plane. The incident beam was collimated to a diameter of 0.3 mm and had an angular divergence of 10^{-5} rad. At the detector position fixed on the axis of the incident-particle beam, we measured the dependence of forward electron scattering (at zero angle θ) on the orientation of the $\langle 111 \rangle$ crystal axis. Fixing the detector in a position displaced in the transverse plane, we measured the corresponding orientation dependences of scattering. The dependence of forward electrons scattering on the angle ψ of orientation of the $\langle 111 \rangle$ crystal axis is depicted in Fig. 1 (solid curve), which shows a narrow region of orientation angles near the incident-beam axis. Here, the transmission intensity is normalized to that corresponding to the transmission through a disoriented crystal. It can be seen that a strong scattering effect is observed in the region of small orientation angles, where we have $I_\psi \ll 1$ for the transmission intensity. Coherent effects in the interaction of fast charged particles with an ordered atomic medium are pronounced in thin crystals. In the orientation dependence of transmission, the present experiment revealed here a new feature, a local transmission-intensity minimum at small orientation angles, which

[1)]Kharkov Institute for Physics and Technology, ul. Akademicheskaya 1, Kharkov, 310108 Ukraine.

*e-mail: `blazh@belgorod.bpqu.su`

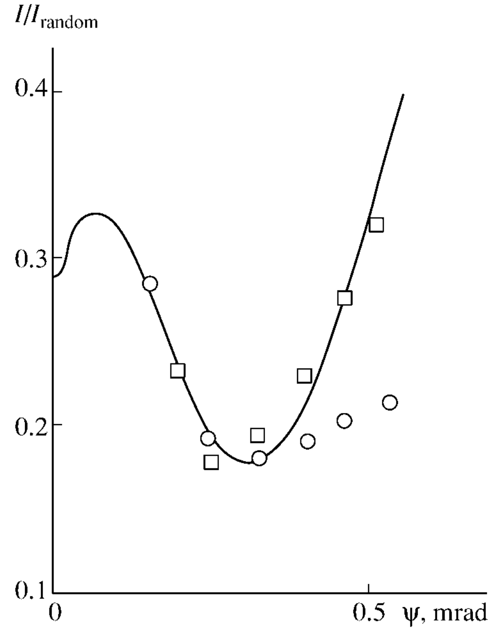

Fig. 1. Orientation dependence of the forward-transmission intensity for 1200-MeV electrons incident on a Si crystal 10 μm thick at small angles to the ⟨111⟩ axis.

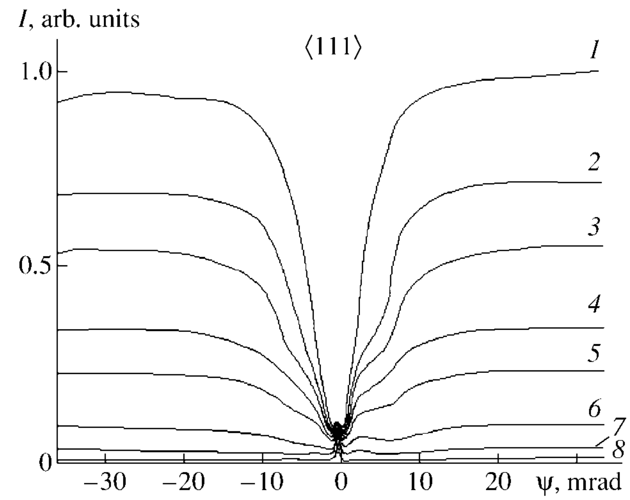

Fig. 2. Orientation dependence of scattering and transmission for 500-MeV electrons incident on a Si crystal 10 μm thick at scattering angles θ of (*1*) 0, (*2*) 0.08, (*3*) 0.12, (*4*) 0.16, (*5*) 0.18, (*6*) 0.23, (*7*) 0.27, and (*8*) 0.3 mrad. The root-mean-square angle of incoherent scattering is $\theta_s = 0.15$ mrad. Data presented in this figure and in Figs. 3, 5, and 6 are normalized to the transmission intensity for a disoriented crystal (see main body of the text).

resembles the well-known effect of blocking. This feature was not previously predicted, so that it calls for an adequate theoretical description. Another feature in the measured orientation dependence manifests itself in a comparison with the results of a calculation based on a theoretical model that takes into account the multiple azimuthal scattering of relativistic electrons by atomic chains in a crystal [1]. It turned out that the calculation (Fig. 1, open circles) yields a much more gently sloping orientation dependence than that measured experimentally. A qualitative explanation for this discrepancy is provided by a model that takes into account the scatter of particles in the polar angle [2] and which leads to an additional reduction of the transmission intensity at small orientation angles. In Fig. 1, open squares represent this dependence with allowance for the scatter in the polar angle.

Figures 2 and 3 display experimental results obtained by measuring the transmission (curve *1*) and the scattering of electrons at various angles in the plane whose normal is aligned with the axis of crystal rotation. Figure 2 shows the results of measurements performed with a 500-MeV electron beam under the same conditions as those described above. The results from [3], which were obtained with a 760-MeV electron beam incident on a crystal 80 μm thick under the conditions of a much poorer angular resolution (the detection solid angle was 1.2×10^{-8} sr) are shown in Fig. 3 for the sake of comparison.

Special attention should be given to the relationship between the intensity of transmission through a disoriented crystal and the intensity of transmission through an analogous crystal oriented in such a way that one of its crystallographic axes is aligned with the incident electron beam. At a local peak, a typical transmission curve for an oriented crystal at a low angular resolution has an intensity that is commensurate with that of transmission through a disoriented crystal. As to the measurements carried out with a high angular resolution, they give much larger ratios of these values. This circumstance agrees well with the concept that the electrons undergo multiple azimuthal scattering on atomic chains in a crystal. From Figs. 2 and 3, it can be seen that there exists a crystal-axis orientation such that almost all orientation curves intersect; that is, there is a scattering-angle region where the angular distribution of the intensity is uniform.

3. PROPAGATION OF ELECTRONS AT SMALL ANGLES TO A CRYSTALLOGRAPHIC PLANE

Experimental investigation of the influence of atomic planes in a crystal on the propagation of relativistic charged particles is aimed at clarifying some orientation effects that differ geometrically from

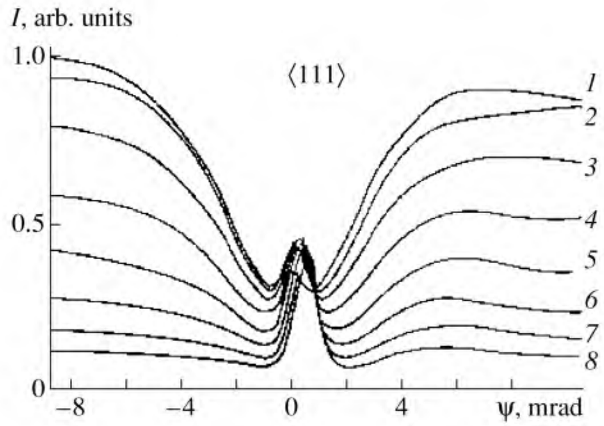

Fig. 3. Orientation dependence of scattering and transmission for 760-MeV electrons incident on a Si crystal 80 μm thick at scattering angles θ of (*1*) 0, (*2*) 0.17×10^{-3}, (*3*) 0.34×10^{-3}, (*4*) 0.51×10^{-3}, (*5*) 0.65×10^{-3}, (*6*) 0.80×10^{-3}, (*7*) 0.89×10^{-3}, and (*8*) 1.03×10^{-3} mrad.

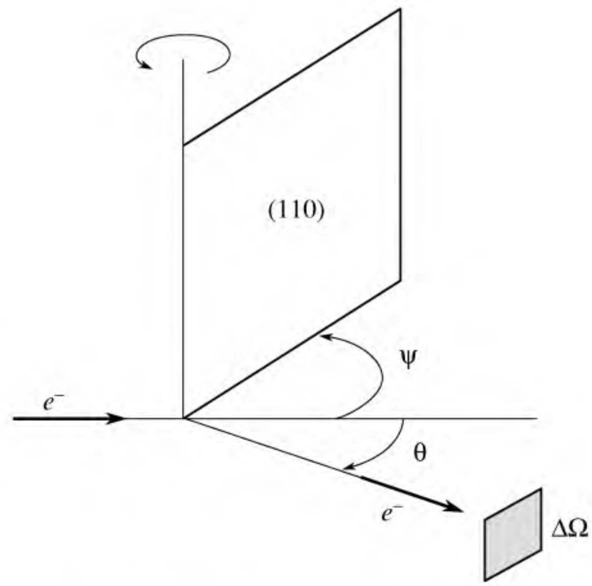

Fig. 4. Geometry of the experiment studying the orientation dependence of transmission ($\theta = 0$) and scattering at specific angles θ for 1200-MeV electrons incident at small angles ψ to a crystallographic plane.

those considered for the case of axes, but which are of no less interest both for fundamental physics and for the possible applications.

In this article, we present the results obtained by measuring the orientation dependence of the transmission and scattering of 1200-MeV electrons by the (110) atomic planes in a silicon crystal 10 μm thick. The crystal was oriented in such a way that the target-rotation axis in the goniometer lay in a plane parallel to the (110) planes and that the orientation angles ψ and the observation angles θ (see Fig. 4) lay in the same plane orthogonal to the (110) atomic planes. The measurements were performed in the same geometry and with the same detector as those described above. The results are displayed in Fig. 5. As can be seen from this figure, the intensity of electron transmission into a small forward solid angle is minimal when the (110) plane of the crystal is oriented along the incident-beam axis; that is, electrons incident on the crystal along atomic planes are scattered more strongly than those in a disoriented crystal. In other words, the electrons are scattered more intensely under the conditions of planar channeling than in the case of a disoriented crystal. It can also be seen that the electrons are scattered symmetrically with respect to the plane. Furthermore, Fig. 5 shows that the intensity of scattering at angles $\theta > \theta_s$ (where θ_s is the multiple-scattering angle in a disoriented crystal) in the region of small orientation angles ψ proves to be greater than that in the case of a stronger disorientation. The position of the intensity peak does not correspond to the orientation of crystalline planes along the incident-beam axis—the orientation dependence becomes asymmetric with respect to the orientation angle of $\psi = 0$. The above effect was also observed by Ermak *et al.* [4], who studied the angular distributions of electrons scattered at various orientations of the crystalline plane; they called this effect a quasirefraction. In the theoretical study of Fomin [5], this phenomenon was explained by the concerted effect of the incoherent multiple scattering of electrons and their planar channeling.

From Fig. 5, it can also be seen that there is an angle $\theta^* \approx \theta_s$ at which the scattering intensity is virtually independent of orientation; this can be used in measurements of orientation dependences for monitoring the beam current.

4. OBSERVATION OF ORIENTATION DEPENDENCE OF THE FORWARD PROPAGATION OF RELATIVISTIC ELECTRONS INCIDENT ON A CRYSTAL AT SMALL ANGLES TO AN AXIS IN THE CASE OF PLANAR CHANNELING

In transmission experiments, it is possible in principle to observe, on a single curve of orientation dependence, the effect of orientation of both crystal planes and axes. Conceivably, this is not a new possibility, but we deem that it is of interest as a demonstration of a crystalline-structure manifestation in the angular structure of a particle flux that has traversed a crystal.

The relevant results of our measurements are illustrated in Fig. 6, which shows the intensity of

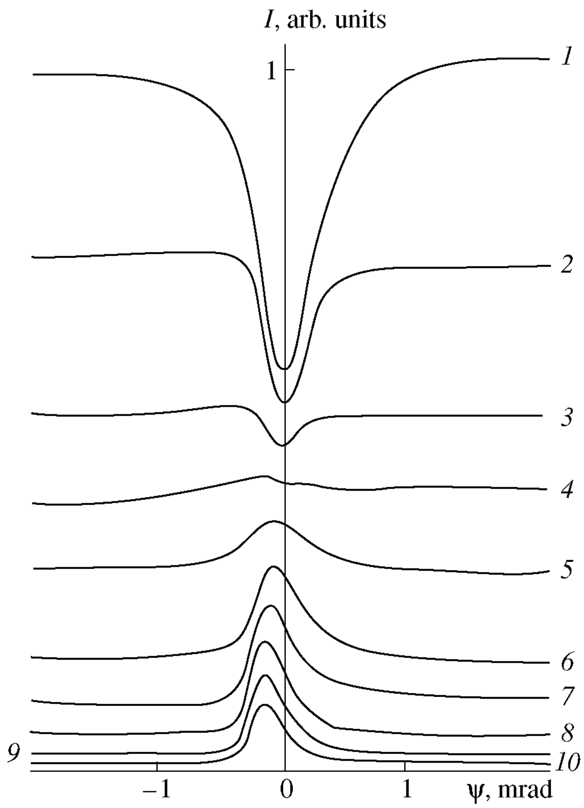

Fig. 5. Transmission and scattering of 1200-MeV electrons into the solid angle $\Delta\Omega = 10^{-9}$ sr that are incident on a Si crystal 10 μm thick versus the angle ψ of orientation of the (110) plane at the observation angles θ of (*1*) 0, (*2*) 0.047, (*3*) 0.067, (*4*) 0.084, (*5*) 0.103, (*6*) 0.13, (*7*) 0.148, (*8*) 0.186, (*9*) 0.231, and (*10*) 0.273 mrad.

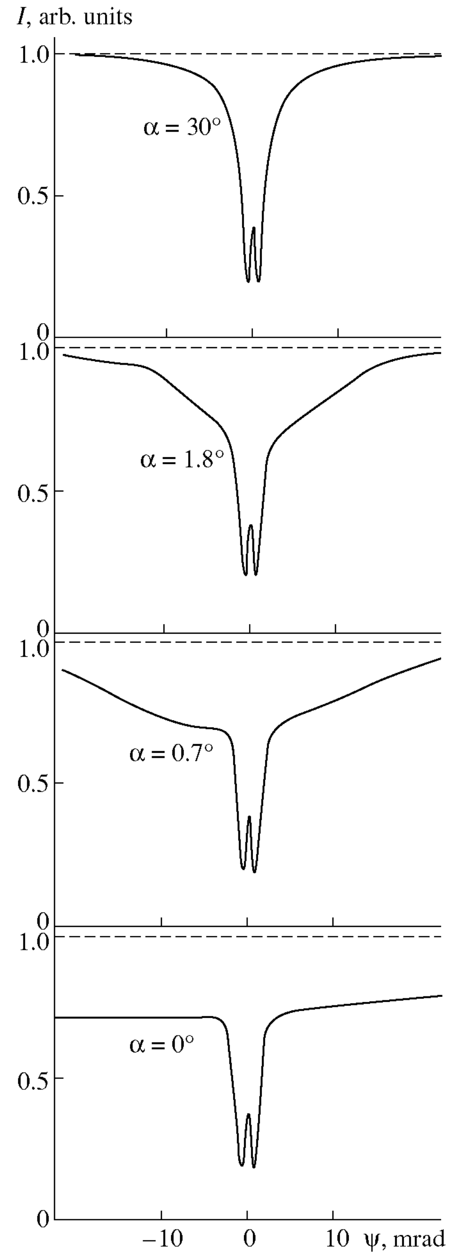

Fig. 6. Manifestation of the (110) crystallographic plane in the orientation dependence of the transmission of 500-MeV electrons into the solid angle $\Delta\Omega = 10^{-8}$ sr that are incident on a Si crystal at small angles to the $\langle 111 \rangle$ axis.

relativistic-electron transmission as a function of the angle ψ of the crystal rotation about a certain axis (orthogonal to the incident-beam axis) for various values of the angle α that specifies the orientation of the normal to one of the planes whose intersection forms the $\langle 111 \rangle$ crystallographic axis with respect to the crystal-rotation axis.

The lower curve in Fig. 6 corresponds to the atomic-plane orientation orthogonal to the crystal-rotation axis in the goniometer ($\alpha = 0°$). In this case, rotation of the crystal rotates the atomic plane without changing the orientation of its normal and the crystal appears to be oriented in such a way that, for all values of ψ, the incident beam lies in the atomic plane. In this case, a disoriented crystal therefore turns out to be in fact oriented, but this orientation is determined by a plane rather than by a crystallographic axis; naturally, the transmission intensity is then lower than that for a “truly” disoriented crystal (see Fig. 6, the upper curve). At small α (second and third curves in Fig. 6), the effect of changing the atomic-plane orientation is observed in the orientation dependence of the transmission intensity, but this effect is much weaker than that of the change in the crystallographic-axis orientation, manifesting itself as a broader minimum on the curve.

5. CONCLUSION

The results obtained from our experimental investigation of the transmission and scattering of relativistic electrons reflect some of the most characteristic orientation phenomena, including new effects like the blocking of particle transmission at very small angles to a crystallographic axis and the asymmetry of scattering by atomic planes. Our results can be of use for studying both the dynamics of particle transmission through an oriented crystal and processes associated with propagation dynamics like photon emission, the production of electron–positron pairs, and nuclear reactions in a crystal.

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