Observation of quantum states of fast electrons in planar channeling

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A preferred population of discrete quantum states of channeled electrons was observed in the measurements of the orientational dependences of angular distributions of the 4.9-MeV electrons transmitted through a 2-μm silicon crystal along the (110) atomic planes. This opens the possibility of controlling the electron flux in the crystal and establishing spontaneous and induced processes in the radiation and absorption of energy by the original, free beam.

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In recent years, an interest has increased in a broad class of phenomena associated with channeling of fast, charged particles in single crystals. The motion of heavy, positively charged particles in the transverse direction to the planes of the atoms, which at small angles of entrance of the particle into the crystal corresponds to a discrete spectrum of eigenvalues of the transverse energy, was investigated in terms of quantum mechanical theory of channeling.[1] However, the quantum states due to channeling were not observed in many experiments (see, for example, Ref. 2), probably because of quasi-continuous system of levels in the periodic potential of the planes of atoms. Because the electrons and positrons have a smaller mass, a small number of levels of transverse motion is formed as a result of their channeling in the crystals. The quantum nature of the transverse motion basically distinguishes the channeled particle flux, which has a certain link with the crystal lattice, from the initially free beam. For example, after quantization of the transverse motion in the planar channeling, Kalashnikov *et al.*[3] predicted a new effect of quasi-characteristic radiation of channeled electrons. In any case, the interaction of electrons with a single crystal is now determined by the quantum states that are preferentially populated. If it can be reliably demonstrated that the transverse energy and the process of preferred population of the states of the flux through the crystal are quantized, then the prospects are good that the relativistic, electron, crystal, emitting and beam-control devices can be built on this physical principle, by using in addition to the spontaneous processes also the induced processes for the emission and absorption of energy.

In this paper we clearly observed for the first time at certain crystal orientations discrete quantum states in the planar channeling of fast electrons. In the experiment we measured the angular distributions of 4.9-MeV electrons transmitted through a $\sim$2-μm-thick silicon crystal. The divergence of the electron beam obtained in the microtron, $<\Delta\theta/2\leqslant 0.03°$, was smaller than the critical angle of channeling $\theta_c = 0.12°$. The beam size at the target was smaller than 0.5 mm and the accuracy of rotation of the single crystal was within 0.01°. The scattered electron beam was recorded on a FT-31 photographic film with a low sensitivity to the background bremsstrahlung. Figure

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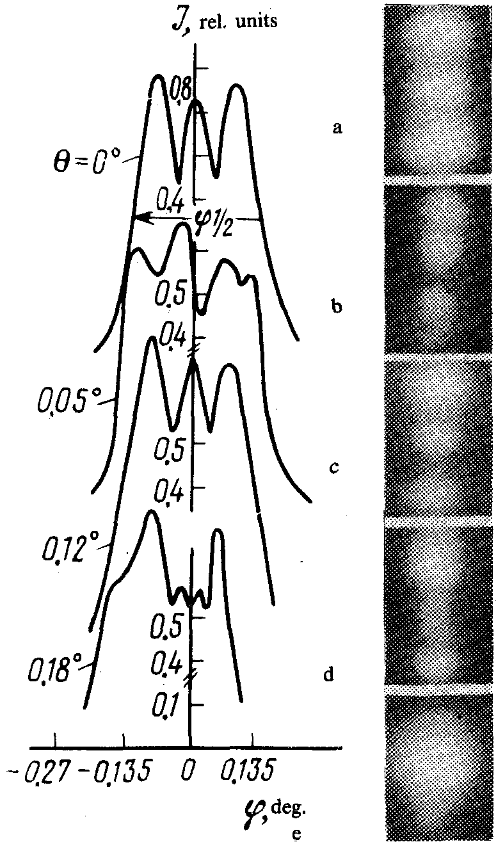

FIG. 1. Angular distributions for different angles θ of incidence of the electron beam relative to the (110) plane of the silicon crystal: a, 0°; b, 0.05°; c, 0.12°; d, 0.18°; e, 0.29°.

1 shows the curves for angular distributions, which were obtained by scanning photometrically the electron-diffraction patterns, for different angles θ of direction of the electron beam relative to the (110) plane of atoms of the silicon crystal. At $\theta = 0°$ we can see a central peak and two lateral intensity peaks. We note that the half-width of the entire angular picture is consistent with the value θ_c of the critical channeling angle. At $\theta = 0.05°$ there are already four intensity peaks at the angles that differ from the corresponding locations in the preceding case. For the orientation $\theta = 0.12°$ we again see the three-peak pattern. The case $\theta = 0.18°$ represents the four-hump intensity curve with maxima at locations that are different from $\theta = 0.05°$. Finally, at $\theta = 0.29° = 2.4\,\theta_c$ there was no evidence of channeling, and the obtained angular distribution (Fig. 1e) is characteristic of multiple, random scattering of electrons. We can assume that the observed "switching" effect of the angular distributions of the scattered beam is determined by modification of the interaction with the crystal due to preferred population of any states from the discrete spectrum of levels (bands) of the transverse motion of channeled electrons.

In the channeling of heavy particles such "switching" of angular distributions was not observed because of the large level density in the potential well, i.e., the transverse motion in this case is quasi-classical. We calculated the band structure of

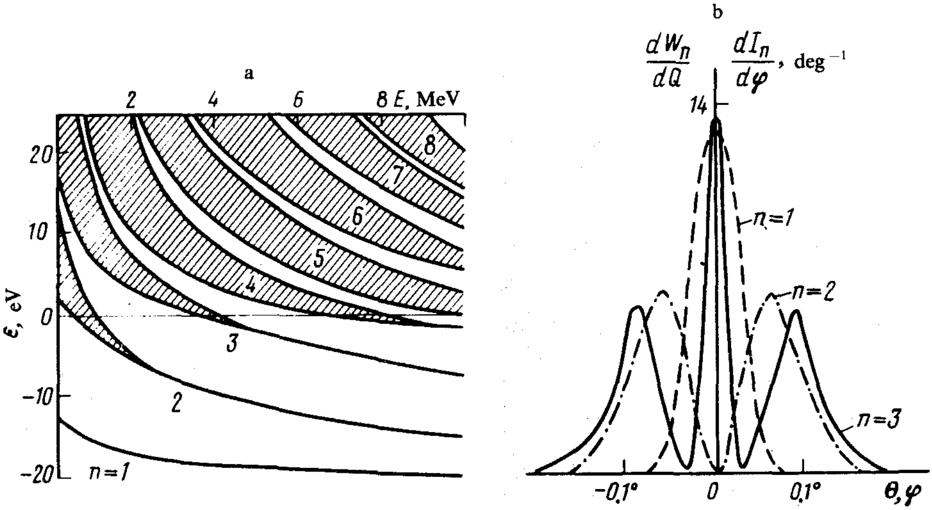

FIG. 2. (a) Band structure of the spectrum of transverse energy ϵ for (110) of the Si crystal and electrons with different energies E; (b) calculated angular distribution for (110) of the Si crystal and electrons with an energy $E = 4.9$ MeV in the ground state $n = 1$, first excited state $n = 2$, and second excited state $n = 3$.

the spectrum of transverse energies of the channeled electrons (Fig. 2) with an energy up to 10 MeV in the Kronig-Penney-type potential with a distance between the potential wells $d = 1.92$ Å, whose depth is $u_0 = -21$ eV and width is $a = 0.43$ Å. The result of the calculation shows that at $E = 4.9$ MeV there are three very narrow, subbarrier bands. These subbarrier states are strongly localized in the planes of the atoms. The expression for the angular distribution $dI_n(\phi)/d\phi$ of electrons in the n state can be obtained by using the momentum representation of the wave function of the transverse component of motion of an electron in the field of the plane of an atom. Figure 2b shows the calculated angular distributions for the ground state and for the first two excited states. The ground state has a maximum at $\phi = 0°$, but it is wider than that observed in the experiment by approximately a factor of two. This state contributes little to the formation of the angular picture behind the crystal, since the electron flux is localized most strongly near the plane of an atom, and the given state can be easily perturbed. Since the orientational dependences of the population of the bound states are identical to the angular distributions $dW_n(\theta)/d\theta \sim dI_n(\theta)/d\phi$, we can see that at $\theta = 0°$ in addition to the ground state the third excited state, which accounts for the appearance of the three maxima in the angular distribution, is also populated. As follows from $dI_n(\phi)/d\phi$ in Fig. 2b, the second excited state, which is responsible for the two internal, symmetrical, intensity maxima in the electron-diffraction pattern, is excited as a result of sloping the beam (Fig. 1b). At the same time, a flux, which accounts for the lateral maxima at $\phi = 0.12°$, is also produced in the bands above the barrier. At $\theta = 0.12°$ mainly the third excited state is again excited, in agreement with the calculation, and we have an angular picture similar to the case of $\theta = 0°$. These two orientations of the crystal are preferable for the formation of this state. At $\theta = 0.18°$ the subbarrier states are not formed, and only the states of the bands above the barrier determine the formation of the electron-diffractions patterns.

The effect of preferred population of the transverse-energy bands observed by us can be effectively used to control the flux of channeled electrons, which produces excitations or defects in the crystal. This effect may also be useful for controlling the frequency characteristics of the recently observed hard x-radiation produced as a result of channeling.[4] By populating a certain group of states, we can produce radiation in a specified region of the spectrum. At an energy of several tens of MeV a strongly anharmonic potential, which is controlled by the channeled electrons, has only several radiative transitions with good energy resolution. The location of the lines in the spectrum of channeled radiation at different energies gives us sufficient information to determine the depth and shape of the average potential of the plane of an atom. Using the methods of Fourier analysis, we can determine the potentials of the individual atomic series or atoms in the crystal. Therefore, we can say that the development of a new experimental method for studying channeled relativistic electrons is promising. Since the "fast electron-crystal" quantum system is a sufficiently good model of an atom moving with almost the speed of light, if the conditions for channeling are fulfilled, we have also the opportunity to study the effects of both spontaneous and induced emission and absorption of energy by fast-moving objects in external magnetic and electric fields. For example, by placing a crystal in an electric field, we can observe the relativistic analog of the Stark effect—shift of the maximum in the emission spectrum of channeled particles. This shift may reach a value of several percents due to the Doppler effect.

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