Structure in the orientational dependences and radiation spectra produced as a result of transmission of ultra-relativistic electrons through diamond and silicon single crystals

V. B. Ganenko, L. E. Gendenshtein, I. I. Miroshnichenko, V. L. Morokhovskiĭ, E. V. Pegushin, V. M. Sanin, and S. V. Shalatskiĭ
Physicotechnical Institute, Ukrainian Academy of Sciences

(Submitted 3 June 1980; resubmitted 21 August 1980)
Pis'ma Zh. Eksp. Teor. Fiz. **32**, No. 6, 397–401 (20 September 1980)

A heretofore unobserved structure was detected in the orientational dependences of the transmission of 1.2-GeV electrons through diamond and silicon single crystals near the ⟨110⟩ crystallographic axis and the (001) plane. The results of an experiment for the axial case indicate a logarithmic dependence of the potential.

PACS numbers: 61.80.Mk

As a result of observation of the electromagnetic radiation of channeled and above-the barrier ultrarelativistic particles,[1–3] which was theoretically predicted in Refs. 4–6, and also as a result of the possibilities of practical utilization of this radiation, a study of the dynamics and radiation of ultrarelativistic particles in crystals is of special interest.

A transmission of positively charged particles through crystals has usually been associated with the channeling effect. At the same time, the coupled motion of negatively charged, high-energy particles in crystals is still unclear because of a paucity of experimental data.

We have carried out experiments to investigate the transmission of 1.2-GeV electrons through diamond (0.3 mm) and silicon (0.24 mm) single crystals near the ⟨110⟩ crystallographic axis and the (100) plane, and measured the spectral characteristics of the produced gamma radiation. The experiments were conducted on the linear electron accelerator of the Kharkov Physico-technical Institute. The divergence of the electron beam did not exceed 7×10^{-5} rad, and its dimensions at the target were 1×1.5 mm^2; the energy spread was $\Delta E/E\approx0.2\%$.

We measured in the transmission experiment the intensity of the electrons, which were collimated at an angle of $\sim10^{-4}$ rad in the direction of the incident beam and transmitted through the crystal, as a function of the angle ϕ between the beam direction and the axis or plane of the crystal. Figure 1 shows the orientational dependence for the (100) plane of the diamond cyrstal. An anomalous transmission of electrons is observed within a wide range of angles $|\phi|\leqslant7\phi_c$, where ϕ_c is the critical channeling angle [$\phi_c\approx1.3\times10^{-4}$ rad for the (100) plane], and the maximum intensity is greater than that of a disoriented crystal. Such a broad peak indicates that the motion of an appreciable fraction of electrons is regular even when they are moving relative to the planes at angles that are much greater than the channeling angle and that the dechan-

 0021-3640/80/180373-05$00.60

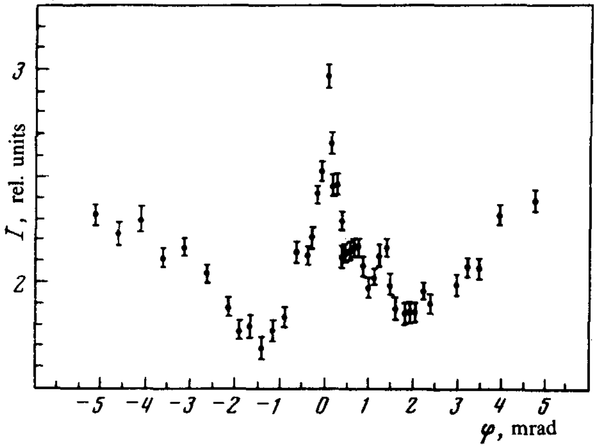

FIG. 1. Orientational dependence of electron transmission near the (100) plane of a diamond single crystal.

neling factors decrease with increasing energy.

In studying the electron transmission near the 110 axis in a diamond (Fig. 2a) and silicon (Fig. 2b), we observed a fine structure of the orientational dependence in the form of two pairs of symmetrically arrranged peaks. The peaks at the smaller angles are apparently due to the limitation on the minimum and maximum distance to the axis for the "rosetan" motion. An estimate of their location gives $\phi_1 \approx \phi_c^R (a/R)^{1/2}$, where $\phi_c^R = (2\,Ze^2/Ed)^{1/2}$, a is the shielding radius, and R is equal to the radius of the axial channel for electrons ($R_{Si} \approx 0.95$ Å and $R_C \approx 0.65$ Å). We associate the second pair of peaks with the anomalously large contribution of circular (and nearly circular)

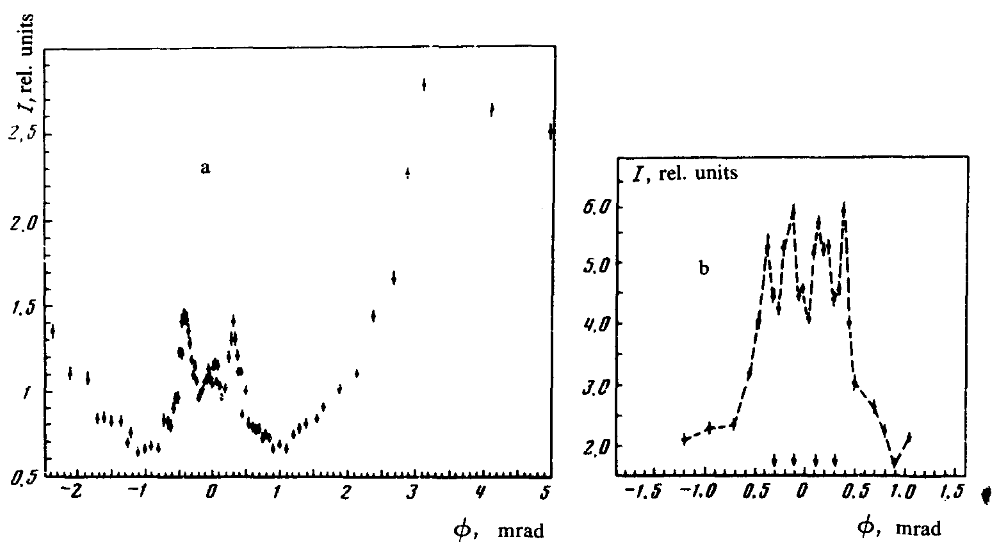

FIG. 2. Orientational dependence of electron transmission near the ⟨110⟩ axis of a diamond single crystal (a) and a silicon single crystal (b).

trajectories, which occurs when the axial potential $U(r)$ varies logarithmically in a certain region. For circular trajectories $v_\perp^2 = rU'(r)/E$, and, if $rU'(r) \approx$ const, the transverse velocity does not depend on the orbit radius. According to Ref. 7, the $U(r)$ dependence can be satisfactorily approximated by $U(r) = (2Ze^2/d)\ln(Ca/r)$. We obtain from this the estimate of $\phi_2 \approx \phi_c^R$ for the location of the second maxima. The calculated locations of the peaks are indicated by the arrows in Fig. 2b. We can see that the two pairs of peaks predicted theoretically are observed in the experiment, although a quantitative agreement between the theory and the experiment requires further investigation.

Thus, the experiments on the transmission of ultrarelativistic electrons through crystals apparently indicate the existence of a regular electron motion near the crystallographic planes even for entrance angles that are much greater than the critical channeling angle. The orientational dependences in the axial case, which are very sensitive to the axial potential, allow us to determine its characteristics.

The expermentally observed peculiarities in the transmission of electrons through single crystals can give valuable information about the relationship between certain characteristics of the radiation of channeled particles and the dynamics of particles in crystals and about the ratio of this radiation for channeled and above-the-barrier electrons. The spontaneous gamma radiation of channeled electrons was experimentally confirmed for 56-MeV electrons.[2] The results of previous studies at high energies [8–14] indicated a large increase in the electron-radiation intensity in the crystal in the low-energy region of the spectrum ($E_\gamma < 100$ MeV) for motion at small angles with respect to the crystallographic axes and planes. However, the discrepancies in the existing data and in the absolute radiation intensities, and the use of photon-beam collimation make it very difficult to interpret the obtained results, although the authors of most of the cited papers interpret the observed radiation as channeled-electron radiation.

One of the problems in our investigation involved making absolute measurements of the cross sections for radiation of electrons in crystals.

The measurement results indicate several characteristic features of the radiation spectra of electrons in the crystals. First, the spectral distributions of the radiation intensity have a maximum near the photon energies $E = 20$ and 30 MeV for the silicon and diamond crystals, respectively. Second, the ratio of the maximum electron-radiation intensity in the crystal to the bremsstrahlung in an amorphous medium obtained by us is equal to 16–17 for silicon and 20–25 for a diamond. Third, the measurement results indicate a possible existence of a definite structure in the radiation spectra in the form of narrow peaks at photon energies in the range of several MeV to several tens of MeV (Fig. 3). The peaks observed in Ref. 2 in the radiation spectra of 56-MeV electrons moving in a silicon crystal in the planar channeling mode were associated with the gamma radiation produced as a result of the transitions between the levels. We can give a reason for the presence of quantum levels in the case of higher (1.2 GeV) energies. A difference between the real potential of the chain of atoms and the Coulomb potential removes the degeneracy of the energy levels in a Coulomb field. For the higher-lying levels the group of levels is approximately equidistant after the removal of degeneracy. In the dipole approximation the main transitions are those between the

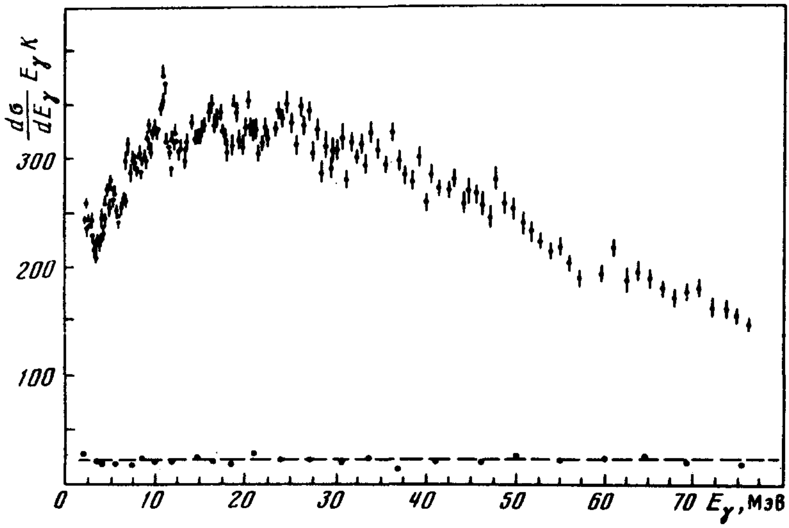

FIG. 3. Low-energy part of the radiation spectrum of electrons moving near the ⟨111⟩ axis in a silicon crystal;...disoriented crystal.

adjacent levels, and in the considered case all the transitions within one group are accompanied by gamma radiation of identical frequency. Since these frequencies are different for different groups of levels, the observed structure can appear in the radiation spectrum.

The fraction of the flux due to the chain can be decreased by increasing the entrance angle of the particles into the crystal relative to the axis; the radiation is determined primarily by the above-the-barrier particles beyond the limits of the critical angle. The results of measurements at $\phi = 5\times 10^{-4}$ (this corresponds to $1.7\phi_c$) show that the spectral radiation intensity for $E_\gamma < 80$ MeV, which reaches 15–20%, decreases. This is attributable to a decrease in the contribution of channeled particles to the radiation. At energies $E_\gamma > 80$ MeV the spectral distributions are identical for angles $\phi = 0$ and $\phi = 1.7\phi_c^R$. Thus, the experimental results indicate that under these conditions the observed large increase in the radiation intensity is caused by above-the-barrier particles. This also applies to other experiments,[8–14] when an increase in the radiation intensity was appreciable.

The absence of photon-beam collimation is crucial for measurement of the true shape of the spectrum. A collimation produces a large monochromatization of the spectrum because of a large decrease in the radiation intensity at higher energies than the maximum in the spectral distribution. This indicates that the radiation in the vicinity of the intensity maximum, where the contribution of the channeled particles is the greatest, has a sharper direction than the radiation of the above-the-barrier particles.

The authors thank V. A. Vishnyakov, V. M. Kobezskiĭ, V. I. Popenko, and S. F. Shevchenko for their assistance in determining the required beam parameters, V. E.

Storizhko, A. Ya. Golovna, B. A. Nemashkalo, and L. Ya. Kolesnikov for making the experimental equipment available, and N. F. Shul'ga for a discussion of the results.

[1]I. I. Miroshnichenko, J. J. Murray, R. O. Avakyan, and T. Kh. Figut, Pis'ma Zh. Eksp. Teor. Fiz. **29**, 786 (1979) [JETP Lett. **29**, 722 (1979)].
[2]R. L. Swent *et al.*, Phys. Rev. Lett. **43**, 1723 (1979).
[3]M. J. Alguard *et al.*, Phys. Rev. Lett. **42**, 1148 (1979).
[4]M. A. Kumakhov, Zh. Eksp. Teor. Fiz. **72**, 1489 (1977) [Sov. Phys. JETP **45**, 781 (1977)].
[5]A. I. Akhiezer, I. A. Akhiezer, and N. F. Shul'ga, Zh. Eksp. Teor. Fiz. **76**, 1244 (1979) [Sov. Phys. JETP **49**, 631 (1979)].
[6]N. F. Shul'ga, Pis'ma Zh. Eksp. Teor. Fiz. **32**, 179 (1980) [JETP Lett. **32**, 166 (1980)]
[7]I. Linkhard, Ukr. Fiz. Zh. **99**, 250 (1969).
[8]S. A. Vorob'ev *et al.*, Pis'ma Zh. Tekh. Fiz. **4**, 1340 (1978) [Sov. Tech. Phys. Lett. **4**, 539 (1978).
[9]B. N. Kalinin *et al.*, Phys. Lett. **A70**, 447 (1979).
[10]S. A. Vorob'ev *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **29**, 414 (1979) [JETP Lett. **29**, 376 (1979)].
[11]Yu. Adishchev *et al.*, Phys. Lett. **A75**, 316 (1980).
[12]V. I. Vit'ko *et al.*, Pis'ma Zh. Tekh. Fiz. **5**, 1291 (1979) [Sov. Tech. Phys. Lett. **5**, 541 (1979)].
[13]G. L. Bochek *et al.*, VAIT, Seriya: Tekhnika Fizicheskogo Eksperimenta No. 2(4) (1979).
[14]A. O. Agan'yants, Yu. A. Vartanov, G. A. Vartapetyan, M. A. Kumakhov, Kh. Trikalinos, and V. Ya. Yaralov, Pis'ma Zh. Eksp. Teor. Fiz. **29**, 554 (1979) [JETP. Lett. **29**, 505 (1979)].

Translated by Eugene R. Heath
Edited by S. J. Amoretty