Focusing of a 1-GeV proton beam as it is brought into the channeling regime by a curved single crystal

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The possibility of focusing high-energy particles by means of bulk capture of particles in the channeling regime is demonstrated experimentally. Protons with energies of 1 GeV, as they were bulk captured by the (111) plane of a curved silicon crystal from an angular interval with FWHM = 7.2 mrad at the exit from the crystal, had an angular divergence with FWHM = 1.6 mrad. The phase space of the beam of channeling particles in this case decreased slightly (by a factor of 1.8).

In the preceding paper,[1] we demonstrated experimentally that a curved single crystal is capable of capturing particles into the channeling regime in a range of angles much greater than the Lindhardt angle. The essence of this effect, called "bulk capture," consists of the fact that the conditions for capture into the channeling regime for particles can arise within the bulk of the crystal in regions where the particle trajectories coincide with the tangent to the curved crystallographic plane or axis.[1] Thus the particles of the incident beam can be captured within the total angle between the tangents to the curved surfaces inside the crystal.

The purpose of this work is to demonstrate experimentally that particles captured into the channeling regime from a wide angular interval have a narrower angular distribution at the output from the curved crystal, i.e., focusing (with respect to angles) occurs. The results presented below were obtained with further processing of experimental data obtained at the proton synchrotron of the Leningrad Institute of Nuclear Physics and published in part in Ref. 1. The diagram of the experiment and the details of the experimental apparatus were described in a previous paper.[1] A proton beam with angular divergence $\sigma_x = 1$ mrad and $\sigma_Y = 0.4$ mrad was directed onto a single-crystalline silicon plate 1 cm long and 0.4 mm thick, curved along a radius of 46 cm (see Fig. 1e). Three independent sensitive zones, operating as dE/dx detectors (PD1, PD2, and PD3), were realized in the crystal. The sensitive zones are 1.5 mm wide and are separated by 1.5 mm. The distance from the ends of the crystals up to PD1 and PD3 (so-called "shanks") are 1.25 mm.[2)] The crystal rotated around the axis of curvature relative to the primary beam with a step of 2 mrad in a range up to 44 mrad. The conditions under which the experiment was performed permitted modeling the input beam with constant density (2.8×10^4 particles per channel, equal to 0.45 mrad) in the range of 44 mrad with respect to θ_x with $\Delta\theta_y = 0.4$ mrad by combining all informa-

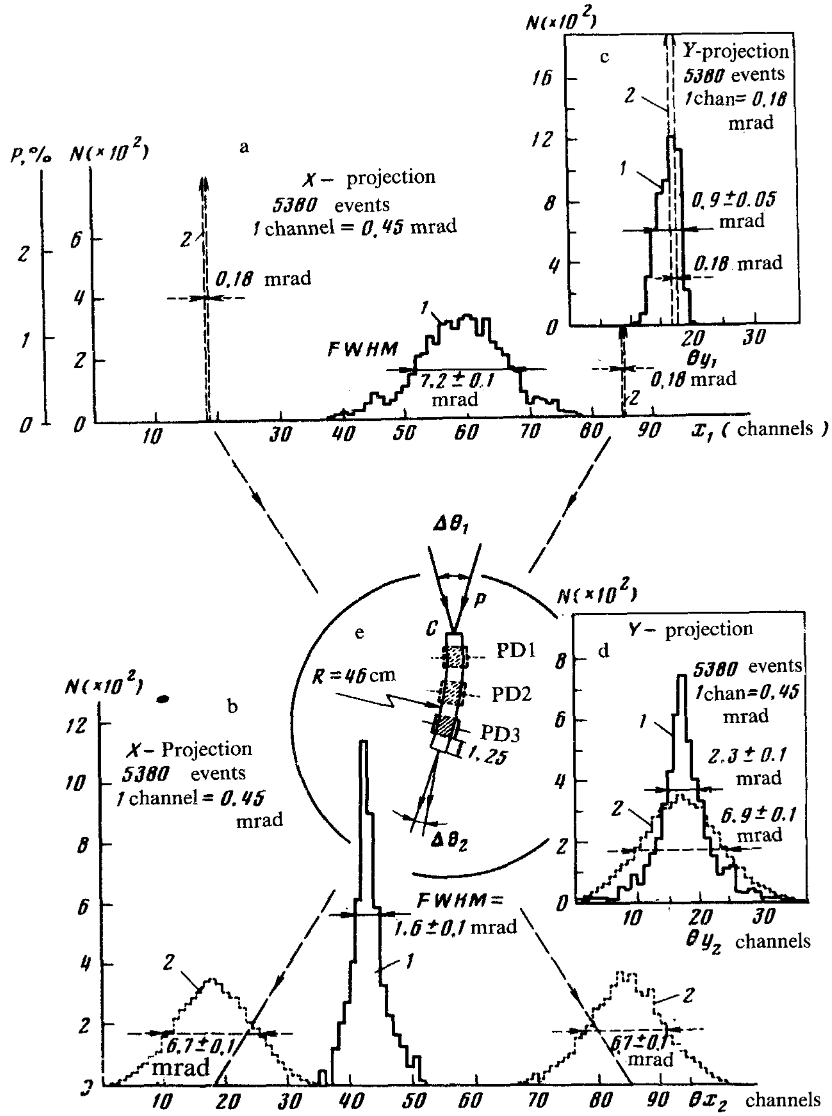

FIG. 1. Angular distributions of particles at the input into the crystal (a,c) and at the output from the crystal (b,d). 1) Selection according to the criterion of low ionization losses in detector PD3; 2) selection according to the criterion of normal ionization losses. *P* denotes the proton beam and denotes the silicon single crystal with detector zones PD1, PD2, and PD3.

tion for different angles of rotation of the crystal. The channeling particles were singled out according to the ionization losses in the detectors (see Ref. 1).

Figure 1 shows the measured angular distributions of the particles in front of the crystal and behind it, selected according to the criterion of "small losses" in PD3. The distributions refer to particle channeling along the curved crystallographic (111) plane, which coincides with the large facet of the crystal and normal to the end face of the crystal.[3] It is evident from the angular distribution of the channeling particles at the input (Fig. 1) that the capture region $\Delta\theta_{1x} = 7.2$ mrad, with total angular width of the exit beam equal to 44 mrad and the possible angular capture range of the crystal (up to PD3) ~ 16 mrad. The fraction of particles (as a percent of the incident beam), captured in the channeling regime from the corresponding section of the angular spectrum of the input beam is plotted on the first scale along the ordinate axis in Fig. 1a (%). The absolute numbers of channeled particles are plotted along the second scale. The distribution is cut off at small angles; the cutoff is due to dechanneling of particles ($\lambda = 1.6$–1.7 mm is the dechanneling length), since the particles from this angular region can be captured only in the initial part of the crystal and, correspondingly, up to PD3 they must traverse a distance $l \gg \lambda$. Figure 1b shows the angular distribution of the channeling particles which leave the crystal. It is evident that the particles, which have an angular distribution of 7.2 mrad at the input into the crystal, are focused at the exit by approximately a 4.5-fold smaller angle. The angular width obtained, 1.6 mrad, is primarily due to instrumental factors: the dechanneling of particles in the "shank" of the crystal and their subsequent multiple scattering, the spread of these particles due to the curvature of the shank, and the angular resolution of the device. For comparison, the dashed curves in Figs. 1a and 1b show the angular distributions of unchanneled particles (i.e., those having normal ionization losses) up to the entrance into the crystal (a narrow distribution 0.18 mrad is chosen) and after passing through the crystal. The distributions obtained at the output (2) have FWHM = 6.72 mrad, which corresponds exactly to the effect of multiple scattering of particles that pass through the silicon (as an amorphous body) with a thickness of 1 cm. Figures 1c and 1d show the Y projections of the angular distributions of the beam of channeled particles before entering and after exciting the crystal. The width of the output beam (~2.3 mrad) is due primarily to multiple scattering before capture in the bulk of the crystal, as well as to multiple scattering of dechanneled particles in the shank of the crystal. The angular distributions of particles having normal ionization losses are also shown in these figures.

It is important that the observed focusing is accompanied by a decrease of the phase space of the beam.The phase space of the beam of channeled particles at the input to the crystal can be estimated at the half-height level of the angular distributions as $\Phi_1 = \Delta\theta_{1x}\Delta\theta_{1y}S_1 = (6.4 \pm 0.3)\cdot S_1$ (mrad^2·mm^2), where $S_1 = 4$ mm^2 is the working area of the input face of the crystal. Analogously, we have for the outgoing beam $\Phi_2 = \Delta\theta_{2x}\Delta\theta_{2y}S_2 = (3.68 \pm 0.2)\cdot S_2$ (mrad^2 cm^2), where $S_2 = S_1$ is the working area of the output face of the crystal. Thus the phase space is decreased by a factor of 1.76 ± 0.17. In the experiment with a crystal without a shank it is natural to expect that the width of the distribution of the outgoing beam will be of the order of the Lindhardt angle $\Delta\theta_{2x} \simeq 2\psi_L = 0.24$ mrad, i.e., the beam can be focused by a factor of ~30. Accordingly, there will be a considerable (~10-fold) decrease of the phase space (increase in brightness) of the distribution of channeling particles. We note in this connection that since the fraction of particles participating in the process amounts under our conditions only to about 1% of the particles incident on the crystal within the limits of the capture angle (see above, % scale in the figure), it would seem that the question of Liouville's theorem should not be raised. It should be pointed out, however, that even when this fraction approaches 100%, the second law of thermodynamics

$$k \ln \beta V_{\mathrm{ph}\,1} \leqslant k \ln \beta_{\mathrm{ph}2} + \frac{\Delta E}{T} , \tag{1}$$

where k is the Boltzmann's constant, $V_{\Phi 1}$, $V_{\Phi 2}$ are the initial and final phase spaces of the beam, and T is the absolute temperature of the crystal, imposes a constraint on the minimum energy losses ΔE (per proton) which must occur in a capture event

$$\Delta E \geqslant kT \ln \frac{V_{\mathrm{ph}1}}{V_{\mathrm{ph}2}} . \tag{2}$$

Substituting $V_{\mathrm{ph}1}/V_{\mathrm{ph}2} \approx 10$, we obtain (with $T \approx 300$ K)

$$\Delta E \geqslant 0.06 \text{ eV}.$$

We hope to study in greater detail in a future publication the question of mechanization of capture and the nature of the friction, which leads to unavoidable losses.

Thus it has been demonstrated experimentally that the existence of bulk capture of particles into the channeling regime permits realizing angular focusing of beams, which can be used in crystal optics of high-energy particles.

1) In a plane crystal, bulk capture can occur due to a change in particle trajectories accompanying multiple scattering.

2) "Shanks" are formed in order to decrease the surface leakage currents.

3) For the orientation of these crystal cut-outs, bulk capture of particles also occurred due to other "oblique" surfaces (see Ref. 1). However, the angular resolution permitted separating out the effect due to the (111) plane.

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[1] V. A. Andreev, V. V. Baublis, E. A. Damaskinskiĭ, *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **30**, 340 (1982) [JETP Lett. **36**, 415 (1982)].

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