Satisfaction of the reversibility principle for the "volume" capture of particles into channeling in a curved crystal

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It is shown experimentally that a reversibility principle holds for at least 97% of the particles participating in "volume" capture into channeling in a curved crystal. "Volume" capture into channeling has been discussed previously {A. V. Andreev *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **36**, 340 (1982) [JETP Lett. **36**, 415 (1982)]}.

We have previously reported[1,2] the experimental observation of a "volume" capture of particles into channeling in a curved crystal[1] and a consequence of this volume capture: an angular focusing with a decrease in the phase volume for the beam of channeled particles.[2]

The capture of a particle into channeling in a crystal is a result of a decrease in the energy of its transverse motion. Since we are dealing with changes in the transverse energy, rather than the total energy, the capture process may result from not only inelastic but also elastic proceses. In principle, as a particle passes through a crystal, it participates in many interactions. As a result, there may be changes in the energy of the transvere motion. These interactions are elastic scattering by individual atoms[3,4] and by fluctuations of the crystal field, an inelastic interaction with the electron and the ion subsystems of the crystal through ionization processes, the emission of plasmons and phonons,[5] and (possibly) a quantum tunneling through a potential barrier formed by one of the atomic planes, etc.

To specify the mechanism for the dissipation of the transverse energy, it is of fundamental importance to know which processes—reversible or irreversible—cause this dissipation. The experimental results reported previously,[1,2] however, do not furnish information on the mechanism (reversible or irreversible) for the dissipation of the energy of the transverse motion in the event of volume capture. Even the observed decrease in the phase volume of a beam of channeled particles[2] is not conclusive evidence that the dissipation of transverse energy is inelastic and directed (i.e., irreversible) in this process, since the data referred to only a small part of the beam particles: the channeled phase.

In the present letter we report additional experimental information on the nature of the sequence of processes—capture, channeling, and dechanneling (from the experiments of Ref. 1)—which can yield definite information on the mechanisms for the dissipation of the transverse energy in the event of volume capture.

The details of the experimental apparatus are described in Ref. 1. Here we simply note that experiment used a beam of protons with an energy $E_p = 1$ GeV and a large angular divergence (a square distribution with a width $\Delta\theta_x \simeq 44$ mrad). The crystalline silicon target had a constant radius of curvature $R = 46$ cm, a wafer thickness of 0.4 mm, and a total length of 10 mm. The wafer was cut in such a manner that the large face coincided with the (111) plane, while the end of the crystal coincided with the (110) plane.

The circumstance that makes it possible to test the reversibility principle for the processes listed above is the presence of three "detector regions"[1)] of identical geometric and physical charactristics in the same crystal. These detector regions are separated by equal distances, which are greater than the dechanneling length (see the inset at the right in Fig. 1).[2)]

For the case at hand, the reversibility principle should mean that if the event (the process of the decrease in the energy of the transverse motion) in which the particle is captured into a channeling regime in the interior of the crystal occurs as the result of reversible processes of some sort (e.g., elastic scattering), then the particle should return (should be dechanneled, i.e., should experience an increase in the energy of its transverse motion) to its original state by the same path as in the case of the direct process (capture). If irreversible processes, which can occur spontaneously in only a single direction, are acting, the particle does not have to return to its original state.

In accordance with these arguments, if we select those particles which are channeled through the region of the second detector (e.g., on the basis of their ionization loss), and if we compare their state in the symmetric first and third detectors (also on the basis of the ionization-loss spectra), we should find identical distributions if the

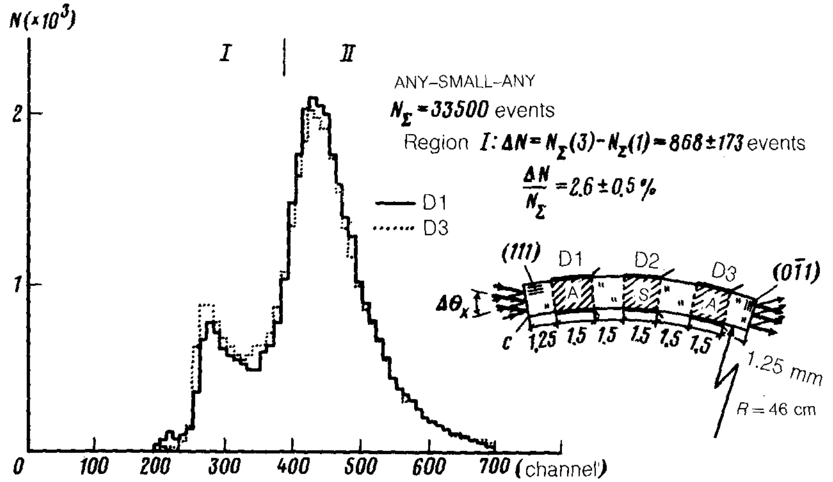

FIG. 1. Pulse-height spectra in $D1$ (solid line) and $D3$ (dashed line) for particles which have small amplitudes (less than 0.74 of the mode of the distribution for a random phase) in $D2$. The events were selected by "ANY–SMALL–ANY" technique: any amplitude in $D1$, a small amplitude in $D2$, and any amplitude in $D3$. Here $D1$, $D2$, and $D3$ are surface-barrier detectors, and C is the silicon crystal.

reversibility principle holds. Also shown in Fig. 1 is experimental information, specifically, the total spectra in detector region 1 (the solid line) and $D\,3$ (the dashed line) of particles which had a small ionization loss (less than 0.74 of the most probable value for a random phase) in $D\,2$ (this was an "ANY-SMALL-ANY" selection of events). Our previous experimental data[1,2] showed that a selection on the basis of this condition of a low ionization loss is a reliable criterion for identifying a channeling regime of the particle.3) The shape of the $D\,1$ spectrum is evidence that the particles which are channeled in the region of the second detector were captured into channeling primarily in the region between the first and second detectors (volume capture); only a small fraction entered channeling from the end region of the crystal. It can be seen from the spectrum from $D\,3$ that the shape is essentially the same. It thus follows from a comparison of the spectra that the rates of the processes of capture and dechanneling are identical, so that these processes are caused by a reversible mechanism. A numerical calculation and a comparison of the number of particles in the first and third detectors in region I (low amplitudes) in Fig. 1 shows, however, that the spectra are not absolutely identical: In $D\,3$ we are left with a few more channeled particles ($\Delta N/N_\Sigma = 2.6 \pm 0.5\%$) than were found in the first detector.4) This result might be an indication of a slight admixture of irreversible processes resulting in the dissipation of the energy of the transverse motion (upon volume capture or as the particles move in a channeling regime—a "cooling" of the beam), but at this level we cannot rule out some asymmetry of the crystalline target itself which has not been allowed for.

In summary, it can be concluded that the reversibility principle holds in the experiment described above for 97% of the particles. This result is evidence that the mechanism by which the particles are captured into channeling in the volume-capture event is reversible, for the most part. These results place a limit on a possible admixture of irreversible capture processes5): $\lesssim 3\%$.

1) Surface-barrier detectors $D\,1$, $D\,2$, and $D\,3$.

2) It is easy to see that a wide (44-mrad) square angular distribution of the incident beam is also a necessary condition for symmetry of the problem.

3) This is a result of the substantial difference between the ionization losses for a random phase ($\Delta^r_{mp} = 516 \pm 5$ keV is the mode of the distribution, and $\mathrm{FWHM}^r = 143 \pm 1$ keV is the half-width of the distribution) and for a channeled phase ($\Delta^c_{mp} = 271 \pm 25$ keV, $\mathrm{FWHM}^c = 48 \pm 3$ keV) and also the relatively high energy resolution of the detectors which were used ($\Delta E = 29 \pm 1$ keV at $E_\alpha = 5.486$ MeV).

4) $\Delta N/N_\Sigma = [N^I_\Sigma(3) - N^I_\Sigma(1)]/N_\Sigma$, where $N^I_\Sigma(1)$ and $N^I_\Sigma(3)$ are the total numbers of particles in region I in the spectra of $D\,1$ and $D\,3$, respectively, and N_Σ is the total number of particles in regions I and II (the total area of the spectrum).

5) For definiteness, we should also point out that all the comments here apply to particles which have an ionization loss in the second detector which is less than 0.74 of the loss of a random phase. This loss corresponds to a transverse-motion state with $E_\perp \lesssim 14$ eV, i.e., rather deep levels (the total depth of the well is 24 eV).

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

[2] V. A. Andreev, V. V. Baublis, E. A. Damaskinskiĭ, A. G. Krivshich, *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **39**, 58 (1984) [JETP Lett. **39**, 67 (1984)].

[3] A. M. Taratin and S. A. Vorob'ev, Zh. Tekh. Fiz. **55**, 1598 (1985) [Sov. Phys. Tech. Phys. **30**, 927 (1985)].

[4] V. A. Muralev, Tezisy dokladov XV Vsesoyuznogo soveshchaniya po fizike vzaimodeĭstviya zaryazhen-

nykh chastits s kristallami (Proceedings of the Fifteenth All-Union Conference on the Physics of the Interaction of Charged Particles with Crystals) (Moscow, 27–29 May, 1985), p. 14.

[5] E. A. Mazur and M. N. Strikhanov, Tezisy dokladov XV Vsesoyuznogo soveschchaniya po fizike vzaimodeĭstviya zaryazhennykh chastits s kristallami (Proceedings of the Fifteenth All-Union Conference on the Physics of the Interaction of Charged Particles with Crystals, Moscow, 27–29 May, 1985), p. 5.

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