Deflection of MeV Protons by an Unbent Half-Wavelength Silicon Crystal

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The interaction of a 2 MeV proton beam with an ultrathin unbent Si crystal was studied through simulation and experiment. Crystal thickness along the beam was set at 92 nm, i.e., at half the oscillation wavelength of the protons in the crystal under planar channeling condition. As the nominal beam direction is inclined by less than the critical angle for planar channeling with respect to the crystal planes, under-barrier particles undergo half an oscillation and exit the crystal with the reversal of the transverse momenta; i.e., the protons are "mirrored" by the crystal planes. Over-barrier particles suffer deflection, too, to a direction opposite that of mirroring with a dynamics similar to that of volume reflection in a bent crystal. On the strength of such coherent interactions, charged particle beams can be efficiently steered through an ultrathin unbent crystal by the same physical processes as for thicker bent crystals.

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As a charged particle impinges onto a crystal within the "critical angle" θ_c, with respect to a major atomic plane or axis, coherent interactions with the atoms of the crystal take place, resulting in particle capture with high probability via planar or axial channeling regime [1]. The motion of a positive ion confined under a planar channeling regime is characterized by oscillations between neighboring atomic planes [see Fig. 1(a)] [2,3], whose wavelength λ is a function of particle energy. Such oscillatory motion strongly reduces the probability of impact of the channeled particles with the crystal atoms, thus allowing deep penetration into the crystal.

Channeling of low-energy charged particles has found wide application as a powerful tool for ion-beam analysis. Many applications were also found in high-energy accelerator physics [4], i.e., the generation of electromagnetic radiation [5–7] and the realization of electron or positron [8] sources. In recent years, channeling in bent crystals opened up new schemes for beam manipulation and steering [9–13] of high-energy particle beams (a few hundred GeV energy). Beam-trajectory manipulation can be driven by either planar channeling or volume reflection (VR).

In regards to planar channeling, pioneering experiments [14,15] were carried out by using bending schemes with crystals that were as long as many thousand times the channeling oscillation wavelength [$\lambda \sim 58\ \mu$m for protons at 400 GeV channeled in Si (110) planes]. Here dechanneling is one of the factors which limited deflection efficiency. A second generation of experiments [10,12,16] employed thin crystals bent along the beam through anticlastic [17] or quasimosaic [18] effects. Such crystals considerably increased the deflection efficiency for channeling [1,9,11,19,20] because channeled protons underwent only some tens of channeling oscillation wavelengths in the crystal. Such crystals also led to the experimental demonstration of VR [10,16], which was predicted about 25 years earlier by Taratin and Vorobiev [21].

On the strength of their high efficiency for planar channeling or VR regime, thin crystals are currently being investigated for halo collimation of circulating beams at CERN-SPS and LHC [12] and at Tevatron [22].

Baryshevsky and Tikhomirov suggested the use of an "ultrathin" unbent crystal; i.e., a crystal thinner than the planar oscillation wavelength could be used as a source of transversely polarized particles [23]. Tsyganov and Taratin suggested [24] that a crystal as thick as half the planar oscillation wavelength, tilted by an angle less than θ_c with respect to the direction of the incoming beam, would act as a high efficient "mirror" for charged particles [see Fig. 1(b)]; i.e., it was envisaged that even an unbent crystal could be used for beam deflection.

In this Letter we experimentally demonstrate that channeled 2 MeV protons were mirrored by a half-wavelength unbent silicon crystal strictly according to Taratin's predictions. In addition to the effect of mirroring, we experimentally observed that over-barrier particles were deflected to the opposite direction with a dynamics similar to that of VR in a bent crystal.

The Monte Carlo code FLUX [25] has been used to study particle trajectories and transverse momentum evolution of a 2 MeV proton beam interacting with (110) planes of a Si crystal with thickness 17.6 μm. Beam parameters were the same as those for the experimental apparatus described later. We simulated either an unbent crystal or a crystal with a total bending of 1°. This latter case is described in Fig. 1(a) and serves to highlight the features of extensively studied dynamics in a bent crystal [21,26,27] and for comparison with the results for an unbent crystal in Fig. 1(b).

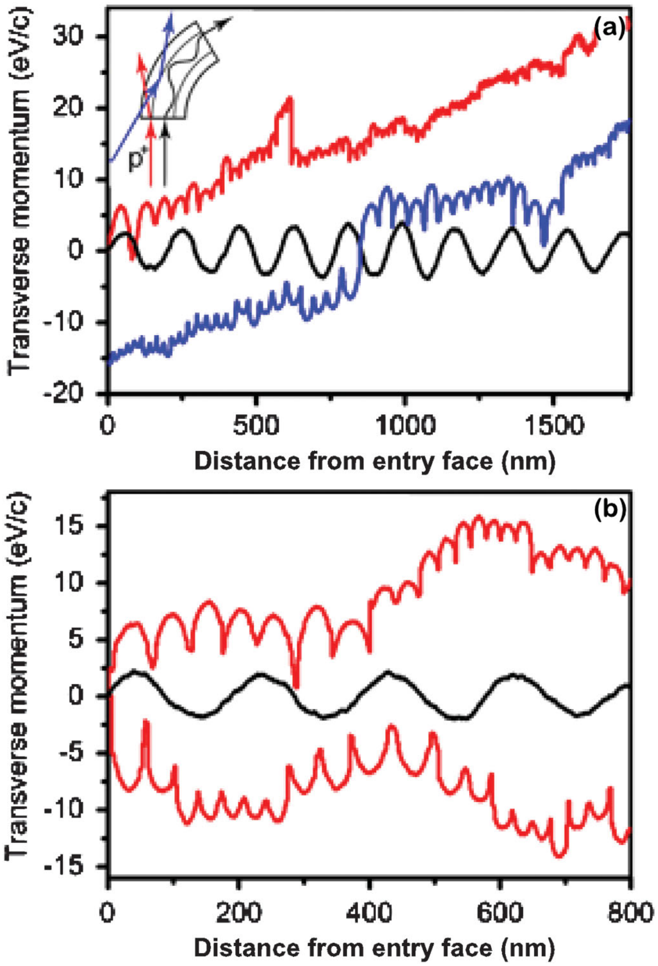

FIG. 1 (color). (a) Simulation of transverse momentum evolution of a 2 MeV proton interacting with a bent Si crystal as a function of the distance from the entry face in the frame comoving with an ideal particle channeled and oscillating with zero amplitude. The black curve describes the oscillations of a channeled particle, the red curve is for an over-barrier particle undergoing VR close to the entrance of the crystal, the blue curve is for VR in the bulk of the crystal. The inset schematically shows the trajectories of particles subject to channeling (black) or VR (red or blue). The bump in the red curve at 550 nm and dip for the blue one at 1500 nm are caused by multiple-scattering events. (b) Same dynamics for an unbent crystal. Here under-barrier particles are channeled (black curve) and over-barrier particles undergo a dynamics similar to that of the particles undergoing VR in a bent crystal.

It is known [28] that in a bent crystal aligned with the incoming beam within θ_c, under-barrier particles are captured in channeling states, perform oscillations, and are deflected by a quantity equal to the whole crystal bending angle (Fig. 1, black curve). Particles in over-barrier states are subject to VR while penetrating in the crystal bulk (red curve) and deflected by $\sim 0.8\theta_c$ [21]. Conversely, if the crystal-to-beam angle exceeds θ_c and the particle's trajectory is tangent at some point with the crystal, all the incoming particles are found in over-barrier states and VR (blue curve) occurs with an inefficiency roughly scaling as $E^{-3/2}$ [29,30], where E is the kinetic energy of the particle beam; thus, VR efficiency approaches unity for high-energy charged particle beams [10,31], being limited only by volume capture [10]. In this case, particles are deflected by $\sim 1.4\theta_c$ [21]. Transverse particle momentum vanishes at the tangency point causing reversal of the sign of VR oscillation concavity.

To date, studies about the motion of over-barrier particles through analytical models [26,27] and Monte Carlo simulations [21] focused their attention only on the interaction with bent crystals and the possibility of deflection of over-barrier particles [10,13,31].

The motion of particles interacting with an unbent Si crystal is described in Fig. 1(b). Under-barrier particles are channeled and oscillate in the same way as for a bent crystal (black curve). Over-barrier particles interact with the atomic planes with oscillations similar to those experienced by over-barrier particles impinging at an angle less than θ_c with a bent crystal, then result in VR. In Fig. 1(b) we depicted two trajectories having different initial condition at the entrance to the crystal. At the end of the crystal each particle may acquire a nonzero component of the transverse momentum.

The deflection mechanisms occurring between a half-wavelength crystal and a charged particle beam becomes clearer as illustrated by real-space trajectories. Figure 2(a) shows some trajectories of 2 MeV protons in the first 500 nm of the crystal studied in previous simulations. Channeled particles (in black) oscillate between atomic planes with wavelength of about of 200 nm according to Ref. [3]. Trajectories in red pertain to the particles that are found in over-barrier states at the entry face of the crystal. Figure 2(b) shows some trajectories in a 92 nm thin crystal tilted by $0.15° \sim \theta_c/2$ with respect to the beam-to-crystal perfect alignment. The proportion of under-barrier and over-barrier particles depends on the tilt angle of the crystal with the beam. By tilting the crystal, it increases the fraction of the particles in over-barrier states. However, since the angular tilt is smaller than the critical angle, channeling is still possible (trajectories in black). For the experimental conditions we used, we calculated that 58.7% of the particles are in fact captured under the channeling regime and see the atomic planes as a mirror, which reverses the transverse momentum and deflects the trajectories by twice the incidence angle. The motion of the remaining particles, which are in over-barrier states, is similar to the dynamics of the particles subject to VR at the entry face of a bent crystal. However, differently from an unbent crystal, the dynamics of VR in a bent crystal causes a transverse drift of the particle's motion with respect to the trajectory of a channeled particle.

For experimental investigation, a Si crystalline membrane of nominal thickness 100 nm and lateral sizes $1 \times 2\ \mathrm{mm}^2$ was fabricated through micromachining

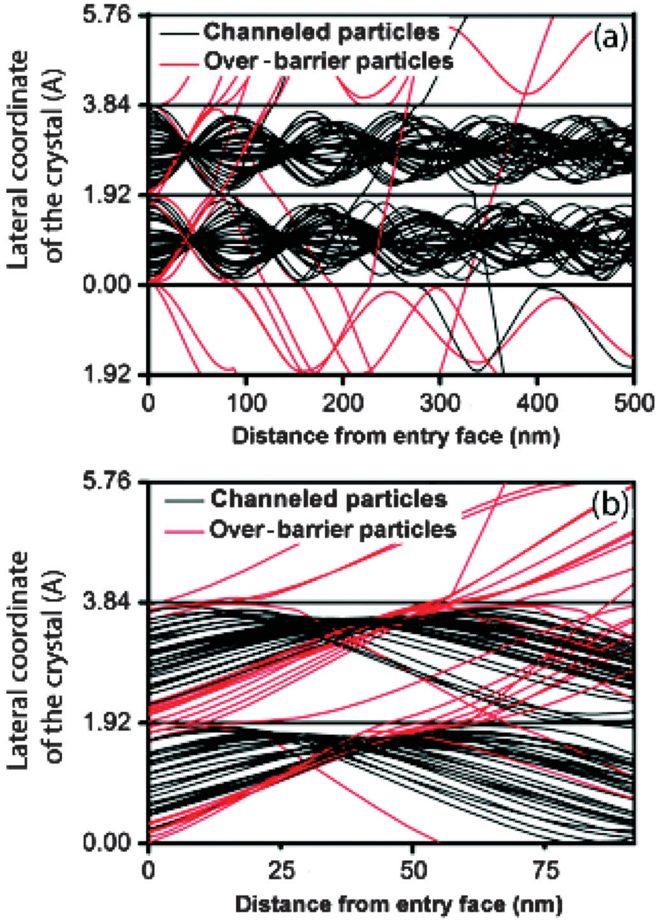

FIG. 2 (color). (a) Simulated trajectories of 2 MeV protons channeled between (110) planes of a Si crystal 500 nm thick. Black trajectories are for under-barrier channeled particles, red trajectories are for over-barrier particles scattered someplace in the crystal. (b) Simulated trajectories of 2 MeV protons channeled between (110) planes (interplanar distance 1.92 A) of a half-wavelength Si crystal 92-nm thick tilted by 0.15° with respect to the incoming particles. A large fraction of particles are captured under channeling regime and deflected by 0.3° with respect to the incoming direction; namely, mirroring onto crystalline planes has occurred. Over-barrier particles are subject to deflection to the opposite side as for mirroring with a dynamics similar to that of VR in a bent crystal. Further tilting of the crystal would increase the number of over-barrier particles (not shown). Thick horizontal solid lines correspond to (110) atomic planes positions.

techniques. The membrane is perpendicular to the $\langle 100 \rangle$ axis and its (110) planes can be used for channeling. The experimental arrangement is shown in Fig. 3(a). A 2 MeV proton beam with divergence less than 0.01° was collimated to a size of 0.2×2 mm^2. The crystal was mounted on a goniometric stage with 0.01° angular resolution. Protons backscattered from the membrane were collected by a standard Si junction detector D2 and analyzed via standard ion-beam analysis technique. Membrane thickness turned out to be 92 ± 4 nm. A fraction of the protons crossing the crystal impinged onto a golden target (Au) of size 0.2×0.2 mm^2, which was mounted on a second independent stage, capable of angular rotation around the crystal with 0.01° resolution and at a distance of 165 ± 1 mm from the crystal itself. Backscattered protons were collected by another Si detector (D1). The angular distribution of the particles scattered by the crystal was reconstructed through an angular scan of the golden target. With the crystal out of the beam, the particles impinged directly onto the target, whose rotation determined the angular resolution of the system, which was measured to be 0.042°.

Figure 3(b) shows the recorded angular distribution of the particles with the crystal tilted by 0.15° with respect to planar channeling alignment (red squares). The beam was clearly split into two components after interaction with the crystal. A two-Gaussian fit provided the positions of the peaks, resulting in $-0.30°$ and $+0.07°$ and the efficiency of the deflection phenomena, which results to be $58.3 \pm 0.4\%$ for particles under the first peak and $41.7 \pm 0.3\%$ for particles falling under the second peak. We simulated the beam profile under previous experimental conditions (black curve), which consisted of a two-peak angular distribution with the higher peak pertaining to channeled particles and with the lower peak due to volume reflected particles. Convolution of the simulated profile with the experimental resolution resulted in the blue curve, which was in good agreement with experimental records.

By varying the angle between the crystal and the proton beam, the beam was still split into a bimodal distribution, whose peak positions are shown in Fig. 3(c). Agreement between experimental results and simulations held true. Since the crystal is unbent, symmetry in the position of the two peaks was recorded while changing the sign of the beam-to-crystal angle.

In summary, a method to deflect charged particle beams through coherent interactions with an unbent ultrathin crystal has been demonstrated through experimental work and simulation. The key factor behind particle deflection is the use of crystals with thickness equal to half the oscillation wavelength, i.e., half-wavelength crystals. Channeling of under-barrier particles is responsible for mirroring and an effect similar to VR in a bent crystal acts on over-barrier particles and determines the fraction of particles diverted to the opposite direction.

Provided the half-wavelength condition is met, deflection by an ultrathin unbent crystal envisages wide application for beam particle manipulation at any energy. In fact, this scheme involves a minimal amount of material for interaction of the particles with the crystal. High-energy experiments [12,22] may use a single or a series of properly aligned ultrathin unbent crystals in a way similar to the scheme being proposed for multiple volume reflection [32]. At low energies, particle steering is normally accomplished through magnetic dipoles; however—if deflection has to be imparted very locally—beam manipulation by

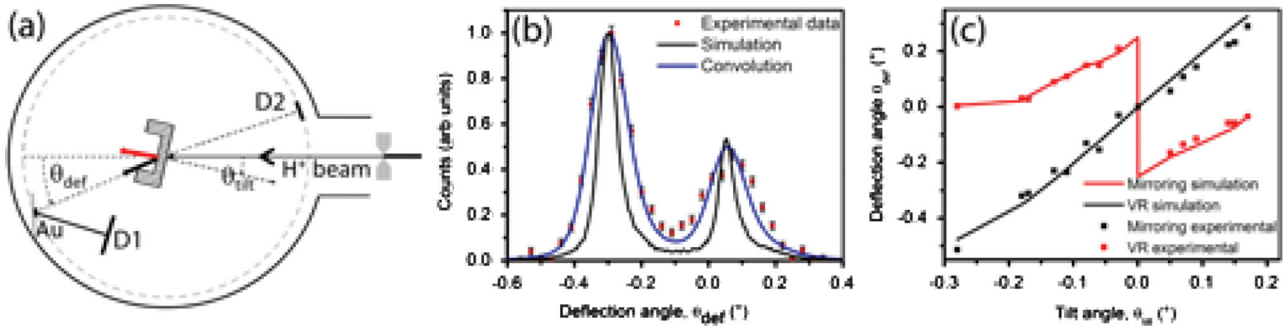

FIG. 3 (color). (a) Schematic of the experimental setup: C is the 92-nm thick Si crystalline membrane, D1 and D2 are pin-diode detectors, Au is the golden target, θ_{tilt} is the angle of the incoming beam with the membrane, θ_{def} is the angle of the outgoing particles after interaction with the crystal as seen by the golden target. (b) Angular profile of outgoing particles versus θ_{def} as a result of simulation (black curve); the same after the convolution with the finite resolution of the experimental apparatus (blue curve). Red points are experimentally recorded values. (c) Deflection undergone by particles versus θ_{tilt} in the cases of under- (black curve) and over-barrier (red curve) dynamics. Black and red points are experimental points for under- and over-barrier cases, respectively.

ultrathin crystals could be a viable technique. Moreover, expensive magnetic structures such as the extractor from a hadron-therapy proton synchrotron could be replaced by a series of ultrathin crystals.

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