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Ion slowing down and charge exchange at small impact parameters selected by channeling: Superdensity effects

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Abstract

In two experiments performed with 20–30 MeV/u highly charged heavy ions (Pb^{56+}, U^{91+}) channeled through thin silicon crystals, we observed the original features of superdensity, associated to the glancing collisions with atomic rows undergone by part of the incident projectiles. In particular, the very high collision rate yields a quite specific charge exchange regime, that leads to a higher ionization probability than in random conditions. X-ray measurements show that electrons captured in outer shells are prevented from being stabilized, which enhances the lifetime of the projectile inner shell vacancies. The charge state distributions and the energy loss spectra are compared to Monte-Carlo simulations. These simulations confirm, extend and illustrate the qualitative analysis of the experimental results.

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Keywords: Channeling; Energy loss; Charge exchange; Heavy ions; NII; EII; REC; MEC; Impact parameter

1. Introduction

Channeling of swift heavy ions in crystals is a powerful tool to study particle–solid interactions. In particular, one can study interactions with valence or conduction electrons as channeling conditions restrict the accessible transverse space of projectiles according to their transverse energy. Most experimental channeling studies have dealt with the best channeled projectiles that see the crystal as a quasi-free electron gas target. One can also use the relation between the transverse energy $E_\perp$ and the available transverse space to study how processes as energy loss, secondary electron emission or charge exchange, depend on the projectile impact parameter with respect to atomic rows [1–4]. A particular group of projectiles may deserve attention, that are the projectiles with a transverse energy close to the critical

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transverse energy $E_{\perp c}$. For an incident beam aligned along an axial or planar direction, these "critical" projectiles enter the crystal with an impact parameter (distance to the row) close to the thermal vibration amplitude. After their first glancing collision in the entrance surface region, critical projectiles are deflected by an angle nearly equal to the so-called channeling critical angle Ψ_c and may suffer further glancing collisions on neighboring atomic rows or planes. This group of projectiles is the most abundant when the incident beam and the crystal axis or plane make an angle close to Ψ_c. Those high transverse energy projectiles are the main subject of this paper. In what follows, we will mainly focus on energy loss and charge exchange processes.

Critical channeling has been known for a long time for increasing the rate of energy loss above the "normal" value measured in random conditions. One of the challenges in material science is to understand the relation between the energy deposited in solids by inelastic processes and the creation of defects, in particular the formation of tracks. For this, experimentalists have tried to find conditions where the density of energy deposition by a projectile is maximized. One way is to use a cluster projectile for which energy deposition (before the constituents scatter away) is roughly multiplied by the number of atoms in the cluster [5]. Another way, as shown by Vickridge et al. [6], could be to use projectiles in critical channeling conditions. Using a narrow nuclear resonance the authors showed that 1 MeV protons entering close to [1 1 0] atomic rows of an aluminum single crystal have, during their first glancing collision, an energy loss rate nearly one order of magnitude larger than in random conditions. Applied to the case of heavy ions, this method could allow to reach locally enormous linear densities of energy deposition, above 100 keV/nm. It must be noted that the energy deposition by a charged projectile is much more localized (at most a few nanometers around the ion track) than in the case of intense short-pulsed lasers.

We present here new features observed in the energy loss and charge exchange of fast heavy ions in critical axial channeling through a thin crystal. We describe and analyze (in particular with the help of a Monte-Carlo code) two channeling experiments with thin Si crystals in which we observe energy losses and charge distributions of transmitted heavy ions, secondary electron and/or X-ray emissions. The fingerprints of critical channeling are clearly visible on each of these processes. In particular, charge distributions reveal a new effect of superdensity. It results from a combination of two factors: (i) the impact parameter dependence of the interactions governing charge exchange for high transverse energy ions (non-radiative capture also called mechanical capture, MEC, ionization and excitation by impact on the target nuclei, respectively, NII and NIE) and (ii) the high rate of collisions undergone in atomic rows by critical projectiles (we use here the word "rate" instead of "frequency" to differentiate this effect from the well-known coherent resonant excitation of atomic levels of channeled ions [3,7]).

The effect of the collision rate has been observed [8] since long when comparing equilibrium charge state distributions obtained after crossing gas or dense solid targets. It results in a higher mean charge state in the case of dense targets. The close collisions of the projectile with target atoms may promote electrons to excited states. According to the interpretation of Bohr–Lindhard, whereas in a gas de-excitation takes place before the occurrence of the next collision, in a solid the collision rate may be too high for de-excitation to happen, and then excited electrons have an enhanced probability to be lost. In fact, we are studying in this paper a "superdensity effect" related to the fact that the collision rate of critical projectiles may exceed in part of their trajectories that of "random" projectiles by more than one order of magnitude. We will also show how critical projectiles could be selected and used in specific applications in material science.

2. Ion channeling

Ion channeling is a well-documented subject (see [9] and references therein). In this paragraph, we insist on peculiar aspects of channeling, concerning mainly the behavior of particles with high transverse energy.

2.1. Binary collisions versus transverse potential description

The ion trajectory in a crystal is essentially governed by elastic collisions on the screened target nuclei. For a beam with a direction parallel or nearly parallel to a major crystallographic direction, one generally defines a transverse energy $E_\perp$ associated to the motion of the ions in the transverse plane, perpendicular to the crystallographic direction as

$$E_\perp = U(\mathbf{r}_\perp) + E\varphi^2, \tag{1}$$

where $E\varphi^2$ is a transverse kinetic energy (E is the kinetic energy of the ion, φ is the angle between the ion velocity direction and the crystallographic direction z considered), and $U(\mathbf{r}_\perp)$ a transverse potential energy defined as the 3D interaction potential $U(\mathbf{r})$ between the ion and the crystal, averaged along the z-direction. Such a transverse potential is represented in Fig. 1(a) in the case of the [1 1 0] axis of silicon (diamond structure) per unit ion charge. When one needs to calculate the trajectories of ions channeled in a crystal, two very different approaches may be used: (i) the trajectories may be calculated using the transverse potential $U(\mathbf{r}_\perp)$ and (ii) the motion of the ion may be considered as a succession of binary collisions with neighboring target atoms. The latter approach is the one used in Monte-Carlo calculations. This is a fully justified approach for ions with high $E_\perp$ that may induce small impact parameter collisions with the vibrating target atoms. In the first approach on the contrary, the ion is assumed to move in a static potential averaged over z, a description that reflects neither the discrete series of binary collisions, nor the thermal vibration of the target atoms. This approach may