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Nanostructures versus crystals in particle channeling

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Abstract

Crystal channeling is a well-established technique at particle accelerators. Nanotechnology offers regular structures of nanochannels, with unique characteristics and with possibilities to vary them over a broad range. Does channeling in nanostructured material offer unique capabilities as compared to channeling in crystal lattices? We address this question with Monte Carlo simulations of channeling in nanotubes of various geometry (SWNT and MWNT) and in crystal lattices. We compare channeling and dechanneling in nanostructures and in crystal lattices.

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1. Introduction

Bent crystal channeling of particle beams at accelerators is a well-established technique [1] demonstrated in the energy range spanning over six decades [1–6]. For instance, bent crystals are largely used for extraction of 70-GeV protons at IHEP (Protvino) with efficiency reaching 85% at intensity well over 10^{12} particle per second, steered by silicon crystal of just 2 mm in length [5]. There has been a strong interest to apply channeling technique in a multi-TeV Large Hadron Collider for beam cleaning [7,8].

While bent crystals have found a good niche for their application, there is a continuing interest in finding better structure for channeling, in order to increase the efficiency of the technique and to widen its span of applications. The bent crystals used were typically made of silicon and sometimes germanium [9,10]. Although one can choose between the existing crystal lattices, paying attention to their quality and physical properties, there has been large interest recently [11–16] to possibility of channeling in the materials produced by nanotechnology. Actually, of all these materials only

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single-wall nanotubes (SWNTs) of carbon were a subject of channeling research so far.

Carbon nanotubes are remarkable in the field of nanostructure, owing to their exceptional mechanical, capillarity, electronic transport and superconducting properties [17–19]. They are cylindrical molecules with a diameter of order 1 nm and a length of many microns [20]. They are made of carbon atoms and can be thought of as a graphene sheet rolled around a cylinder [21]. Creating efficient channeling structures – from single crystals to nanotubes might have a significant effect onto the accelerator world. It is well known that nanotubes can be manufactured of different diameter – from a fraction of nm up to microns, of different length – from tens of microns up to millimeters, of different material-usually carbon but also others [22,23]. This makes nanotubes a very interesting object for channeling research.

With nanotechnology in hands, there is a principle possibility to engineer a channeling lattice from wanted atoms and of wanted configuration, to some extent. Therefore, it would be interesting to understand what kind of channeling structure we would prefer if we could choose. Ideally, we would like to trap particles in two dimensions; to have the channel walls made of densely packed atoms; to make channel size of our choice; to build it with atoms of our choice. And this is about what we are getting from nanotechnology indeed. In order to improve the channeling properties, we would need a larger angular acceptance, lower bending dechanneling, and lower scattering dechanneling for the channeling structure. These characteristics depend on the atomic composition of the channel walls and surface density of atoms and on the geometry of the channel.

The simplest is the angular acceptance, determined by the depth of the potential well U_0. The critical angle for channeling is then about $\theta_c = (2U_0/pv)^{1/2}$, pv is the particle momentum times velocity. In a carbon nanotube with an arbitrary helicity the channeled particles are confined in a potential well $U(\rho, \varphi)$ with the depth U_0 of about 60 eV. This figure does not depend practically on the size of the channel, as the atomic field within the nanotube falls off sharply in a close vicinity of the wall already.

For the particles trapped into channeled states, two mechanisms of particle transfer from channeled to random states (dechanneling) are well known for crystals: scattering on electrons and nuclei and curvature of the channel [1]. Typical nanotube is a few tens of microns in length at present. For such a short channel, the scattering on electrons within the bulk of the tube is quite small. However, a curvature of the tube could quickly (in less than one oscillation) bring much of the channeled particles out of the potential well or into close collisions with the nuclei of the nanotube walls.

For understanding of bending dechanneling in nanotubes of different size and geometry, we did Monte Carlo simulations of particle channeling in bent single-wall and multi-wall nanotubes, aiming to find how useful are the nanotubes for channeling of positively charged particle beams, what kind of nanotubes are efficient for this job, and how nanotubes compare with crystals in this regard. We compare the channeling properties of carbon nanostructures with those of diamond lattice of carbon, namely with one of the strongest planar channels (1 1 0) of diamond crystal. The details of the simulation model can be found in [24].

Dechanneling due to scattering on electrons is a slow kinetic process, discussed and estimated in the last section of this paper. This process is characterised by some dechanneling length over which most of the channeled particles are dechanneled in the process of scattering.

2. Single-wall nanotubes

For assessing the general properties of channeling in nanotubes, we average the potential $U(\rho, \varphi, z)$ of a straight nanotube over the longitudinal coordinate z and angle φ to obtain a potential $U(\rho)$ with cylinder symmetry. As known from crystal channeling, the averaging over z is well justified as a collision of a particle with a nanotube wall under a glancing angle involves many thousand atoms along the particle trajectory. For the same reason, the averaging over φ is equally justified if the nanotube has an arbitrary helicity as defined by the nanotube indices (m, n). In the special