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Volume reflection efficiency for negative particles in bent crystals

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A B S T R A C T

We suggest a formula for the efficiency of a single volume reflection of negatively charged particles in bent crystal planes and compare it to recent experiments at SLAC, MAMI and CERN with electrons and negative pions in the energy range from 0.855 to 150 GeV in Si crystals. We show that Lindhard reversibility rule provides sufficient basis for quantitative understanding of these experiments.

1. Introduction

The increased interest to interaction of electrons with bent crystals has lead over the recent years to several important experiments on the so-called volume reflection [1–6]. While the full understanding of the process may be gained by the use of computer simulations taking into account both the electron motion in the field of bent crystal atomic planes and the scattering on the crystal constituents, it would be quite useful to obtain simple approximate formulas describing basic features of electron volume reflection in bent crystals.

The volume reflection is caused by interaction of an incident particle with the potential of the bent crystal atomic planes, which give the particle an angular kick of the order of a critical channeling angle θ_C in the direction opposite to the crystal bending. Such a reflection is not 100%-efficient as some particles "stick" to the atomic planes (so called volume capture caused by scattering) instead of bouncing back. The "stuck" particles are trapped with the bent atomic planes in the channeled states and thus are steered away.

The purpose of this paper is to understand the efficiency of volume reflection of electrons. We will show that the Lindhard reversibility rule [7] provides sufficient basis for its understanding. First, we follow the ideas of refs. [8,9] and repeat the derivation of the efficiency of particle reflection off the bent crystal plane.

According to the Lindhard' reversibility rule, the probability for a channeled particle to be scattered from a certain channeled state to certain unchanneled state equals the probability for the opposite process. This rule was proven in the experiments with GeV-beams [10–12], where the state of each particle was detected by means of solid state detectors placed along the crystal length. In 1982 a PNPI experiment observed the effect of 1 GeV protons volume capture into channeling mode in the depth of the bent crystal [12], in the region where the particles' trajectories are tangent to the crystallographic planes.

2. Formula for the reflection efficiency

The reversibility rule allows to consider the feed-in (volume capture or rechanneling) and feed-out (dechanneling) processes from the unified point of view. The rate of particle transitions from the channeled to random states is set by the dechanneling length L_D. Over the distance dz, the transition probability equals dz/L_D. According to the reversibility rule, the rate of the opposite transitions from random (over-barrier) to channeled (under-barrier) states is set by the same quantity L_D.

In a crystal bent with radius R, the non-channeled particle stays near the channel (on the phase plane) along the length of the order of $R\theta_C$. Therefore, the probability of transition to channel over the all interaction time amounts to about $R\theta_C/L_D$. Respectively, the efficiency of volume reflection f_{VR} is reduced by this value:

$$1 - f_{VR} \approx \frac{R\theta_C}{L_D}, \qquad (1)$$

This formula, which is in fact the result of the reversibility rule, has agreed with the experiments where the volume-capture probabilities were measured at 1 GeV and 70 GeV [13]. Also, the 70-GeV experiment has confirmed the linear dependence of the probability on the crystal bending radius.

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Table 1
The bending radius R, critical angle θ_C, measured dechanneling length L_D, measured inefficiency of volume reflection, and the calculated efficiency, Eq. (1), for the experiments with electrons and negative pions at MAMI, SLAC and CERN.

				E, GeV	R, cm	θ_C, μrad	Measured L_D, μm	Measured $1-f_{VR}$	$R\theta_C/L_D$
2014	MAMI	e^-	Si (111)	0.855	3.35	217	38	23.3%	19%
2015	SLAC	e^-	Si (111)	3.35	15	122	55.4	33%	31%
2015	SLAC	e^-	Si (111)	4.2	15	109	45.2	27%	34%
2015	SLAC	e^-	Si (111)	6.3	15	89	65.3	16%	19%
2015	SLAC	e^-	Si (111)	10.5	15	69	57.5	16%	17%
2015	SLAC	e^-	Si (111)	14	15	60	55.8	19.3%	15%
2014	CERN	e^-	Si (110)	120	271	19	744*	4.5%	7%*
2009	CERN	π^-	Si (110)	150	2279	17	930	23.3%	42%
2009	CERN	π^-	Si (111)	150	1292	18	930*	17.26%	25%*

For protons, a typical probability of volume capture to stable channeled states is order of 0.2% at 70 GeV. For electrons, we expect the capture probability to be higher by two orders of magnitude because of stronger scattering. Channeled protons move (and scatter) mostly in electronic gas as they are trapped between atomic planes, while channeled electrons move across atomic plane (and hence scatter on nuclei).

While R and θ_C are well known in each case, the dechanneling length L_D for electrons is not so straightforward to obtain. Many experiments with electrons at low energies (MeV up to a few GeV) show rather flat dependence on energy, see refs. [1–4] and references therein, whereas a simple theory expects a linear dependence on energy [14]. This is why in the present paper we rely on measured L_D values.

3. Comparison to the experiments

Several experiments performed at MAMI, SLAC and CERN have measured both the efficiency and the dechanneling length of the particles in these crystals at the involved energies. These measurements were done in a broad energy range from sub GeV to 150 GeV with electrons and negative pions. Our idea in this paper is to use both measured quantities and check whether they agree with our formula (1).

Table 1 shows the bending radius, critical angle, measured dechanneling length, measured efficiency of volume reflection and the calculated efficiency, Eq. (1), for the experiments with electrons and negative pions at SLAC [1,2], MAMI [3,4] and CERN [5,6]. We take L_D values from ref. [2] for SLAC, ref. [15] for CERN, and ref. [4] for MAMI. We use no free parameters at all, no fitting whatsoever. We just take the quantities R, θ_C, and L_D reported in the papers and produce $R\theta_C/L_D$. This is compared then with the measured inefficiency of volume reflection $1-f_{VR}$. Two cases are marked by (*). The 120-GeV L_D was not measured so we used the 150-GeV value scaled down linearly in proportion 120/150. For Si(111) at 150 GeV the L_D value was not measured, so we tentatively assumed that is the same as for Si(110); actually it may differ somewhat.

We see surprisingly good agreement between the measured inefficiencies of volume reflection and Eq. (1) in Table 1. On average, for the 9 experimental points of MAMI, SLAC and CERN experiments, the data are lower than prediction of Eq. (1) by a factor of 0.82:

$$1-f_{VR} \approx 0.8 \cdot \frac{R\theta_C}{L_D} \tag{2}$$

For the SLAC data that is most complete, we can compare the experiment and the theory, $R\theta_C/L_D$, as a function of energy in Fig. 1. Notice that the comparison is with Eq. (1), not (2).

Eq. (1) suggests a functional dependence on bending radius R. We believe, however, that real values should deviate from the linear R proportion of Eq. (1) both at too large R and at too small R.

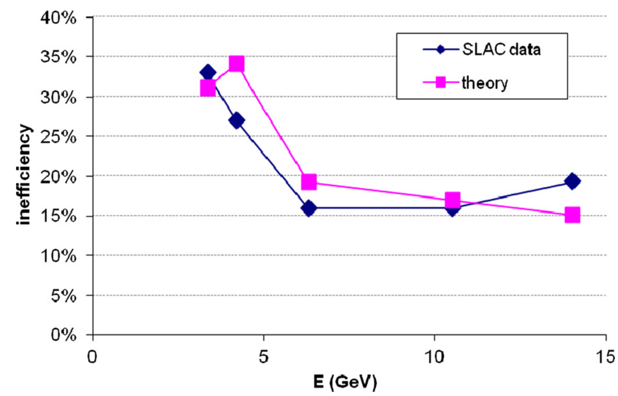

Fig. 1. Inefficiency of a single volume reflection $1-f_{VR}$ in Si(111) as a function of energy. The SLAC data and theory, Eq. (1).

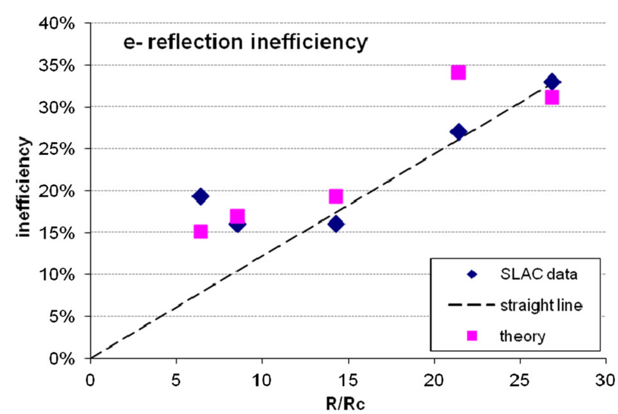

Fig. 2. Inefficiency of volume reflection $1-f_{VR}$ as a function of the ratio R/R_C. The SLAC data for electrons and theory, Eq. (1). Straight line is a guide to the eye.

At large R the efficiency cannot grow above 100% and thus the real values start to saturate below the values given by Eq. (1). At small R, that is R comparable to the critical radius R_C, the effective potential well shrinks (due to centrifugal effect) thus starting to affect the L_D value in Eq. (1) (and θ_C value to lesser extent). This should place the real values above the Eq. (1), at small R.

There is no measured dependence on R for electrons. However, as the energy runs over a broad range with a constant R, the ratio R/R_C spans over a broad range from small values where the potential well is distorted to large ones where the potential well is unchanged. This span for SLAC data can be seen in Fig. 2.

The dependence of the volume reflection inefficiency, measured and calculated, on the R/R_C ratio can be also plotted for CERN data, see Fig. 3.

Notice some big differences between the experimental conditions of SLAC and MAMI versus CERN: