Inelastic Nuclear Interactions at Crystal Collimation of Proton Beams

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1. Babaev A and Dabagov S B, On proton multiple inelastic nuclear interactions in bent crystals *Preprint* LNF-11/18(R), 2011. www.lnf.infn.it/sis/preprint/

2. Babaev A and Dabagov S B, J.Phys: Conf.Ser. **357**, 2012

1. Angular distributions of deflected protons

E_{kin} = 400 GeV protons in Si crystal bent over the angle α_R = 162 μrad along (110) planes (the curvature radius R = 1852 cm). The critical proton channeling angle is θ_L = 10.2 μrad. The angular divergence of beam is $\Delta\theta$=8 μrad.

Experiment:

W. Scandale, *et al.*, Phys. Rev. Lett. **98** (2007) 154801.

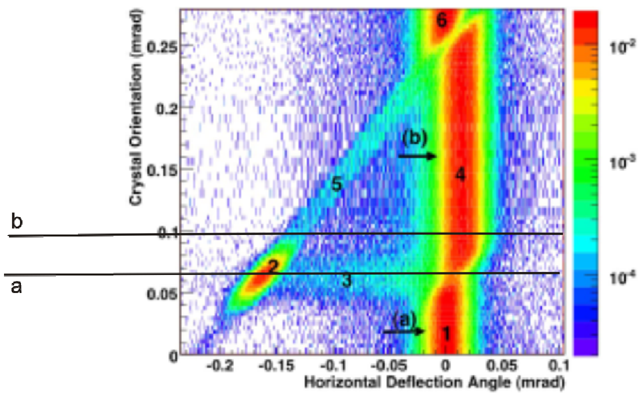
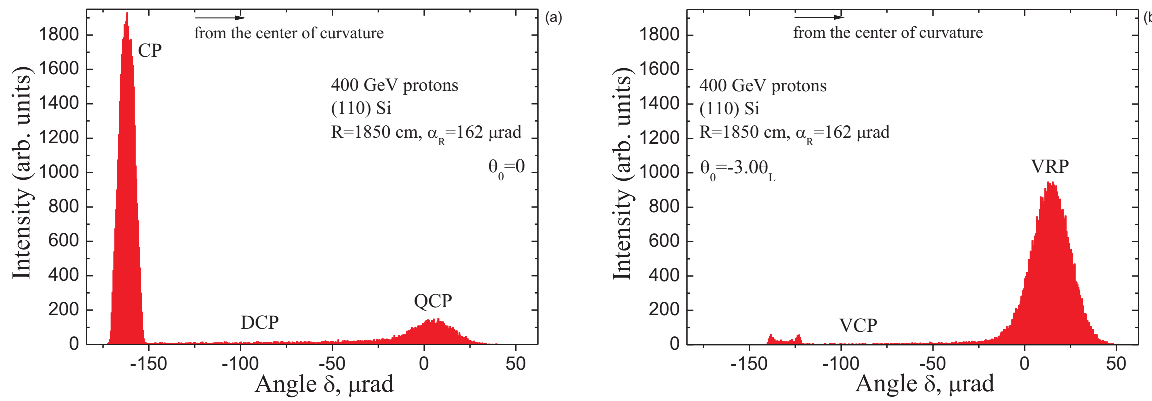


FIG. 3 (color online). Beam intensity recorded by the silicon microstrip detectors as a function of the horizontal deflection angle (x axis) and the crystal orientation (y axis). Six regions can be distinguished: (1) and (6) nonchanneling mode; (2) channeling; (3) dechanneling; (4) volume reflection; (5) volume capture. The wider angular acceptance of volume reflection compared to channeling is clearly visible in the figure.

black solid lines – approximate positions of simulated distributions on experimental angular scan

Our Simulations:



δ is the angle between the proton motion direction in the outgoing beam and the direction corresponding to the center of the incident beam;

CP — channeled; QCP — quasichanneled non-reflected; DCP — dechanneled; VRP — quasichanneled reflected; VCP — captured protons.

2. Inelastic nuclear interactions

It is well-known:

The beam directed along the planes of bent crystal under the channeling or quasi-channeling conditions is split onto two beams in a crystal. The first beam corresponds to channeled particles, which deflect down to bent channel at large angles from the initial direction of motion, while the second one - to quasi-channeled particles.

Hence:

The possibility to use bent crystals in the accelerator technique to manage the beam.
But the projectiles can interact with the nuclei of crystal =>
- Particles leave the beam;
- The produced fragments can damage the experimental setup.

Hence:
The inelastic nuclear interactions must be investigated.

3. Experiment

The detector is mounted near the crystal to register fragments produced by INI. The number of counts evidently is proportional to INI number Z.

W. Scandale *et al.*, Phys. Lett. B **692**, 78 (2010)

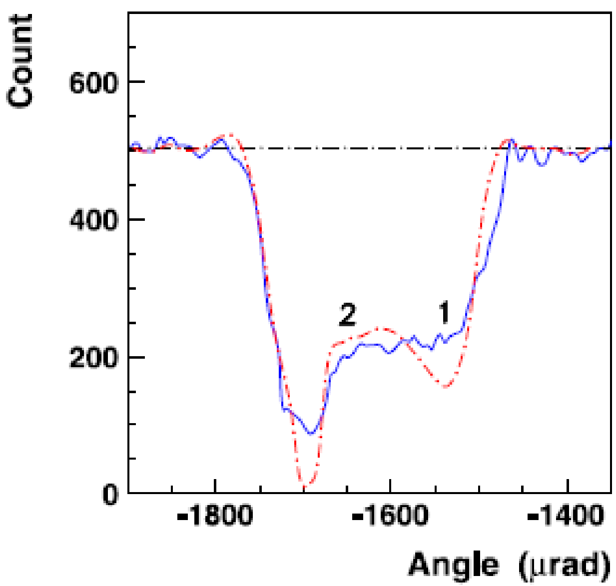


Fig. 3. (Color online.) (1) The dependence of the S1–S2 telescope count on the angular position of the crystal 1; (2) The dependence of the number of inelastic nuclear interactions of protons in the crystal on its orientation angle obtained by simulation. The dot-dashed line shows the level of the beam losses for the amorphous orientation of the crystal.

- The experiment shows the strong dependence of INI intensity on crystal orientation.
-The simulations in reference predict the minima, which is not observed in experiment.
- The model presented here explains the discrepancy. This deep is purely the effect of beam collimation. The effect can be more or less enhanced in dependence of cut-off angle θ_b.
- The model is based on the new-developed code to evaluate angular distributions of projectiles

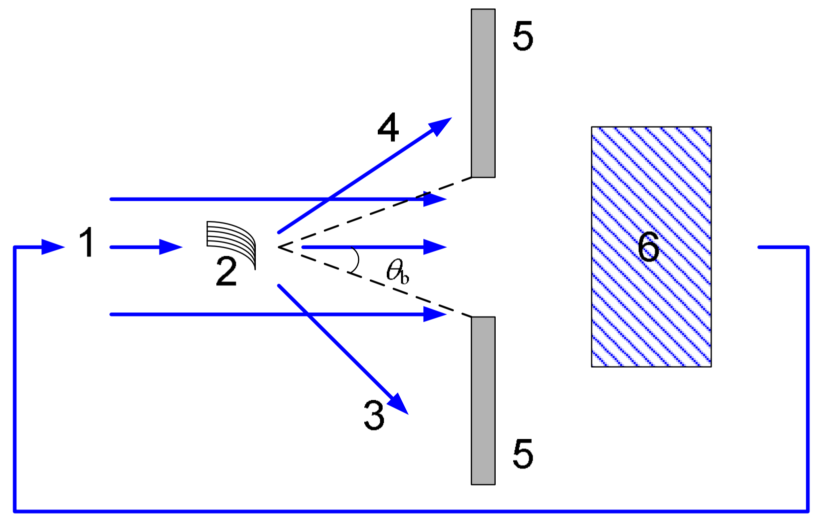
4. Aim of the work

The use of a bent crystal in channeling mode for projectiles allows splitting, deflecting, steering the beams in accelerators.

Multiple passages of projectiles through the crystal take place. Some projectiles interact with nuclei of crystal .

Aim of the work:
To estimate the number of inelastic "proton – nucleus of crystal" interactions (inelastic nuclear interactions, INI) at multiple passages of proton beam through the bent crystal collimator.
We'll try to do this analyzing the angular distributions at given crystal orientation.

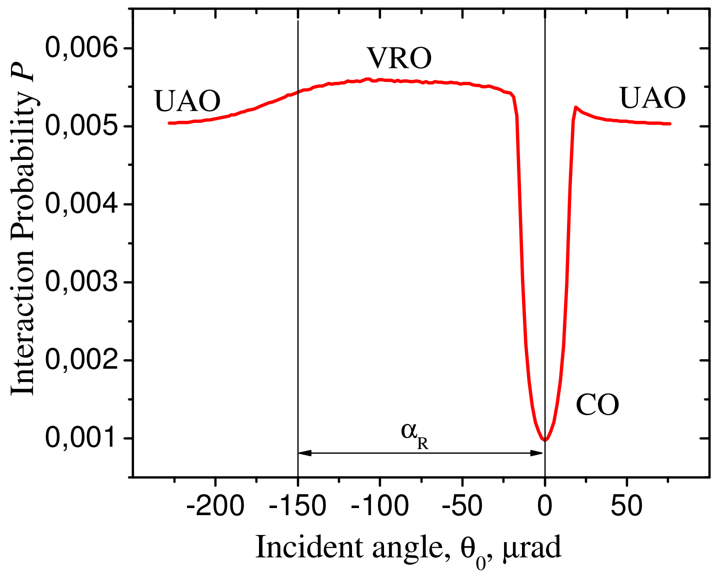
Idealized scheme of bent crystal collimator:



1 – the initial parallel proton beam, 2 – the bent crystal, 3 – the channeled protons, 4 – the reflected protons, 5 – the absorber, 6 – the focusing system making the beam parallel, restoring initial beam profile; θ_b – cutting angle; the particles deflected at angles $|\theta| > \theta_b$ hit the absorber and leave the beam.

5. Averaged probability of INI

120 GeV protons moving through Si crystal bent along (220) planes at the angle α_R=150 μrad with the radius R=1333 cm was considered. The crystal thickness is z_{cr}=2 mm. The critical channeling angle is θ_L=19 μrad.



UAO – unaligned orientation; the deflection of protons - due to the multiple scattering;
VRO – volume reflection orientation; the deflection of protons - due to the volume reflection;
CO – channeling orientation; the deflection of protons - due to the channeling.

The probability of INI at one passage (P<<1):

$$P = \sigma \langle N \rangle_0 z_{cr}$$

σ=0.506·10^{-24} cm^2 – INI cross-section for the single proton-nucleus interaction;
$\langle N \rangle_0$ - averaged nuclear density (over all proton trajectories) at given crystal orientation (angle θ_0).

CP move in the area where nuclear density is suppressed;
QCP and VRP move in the area where nuclear density is significant;

6. INI number

Coefficients:

α – the part of particles hitting the crystal in single turn;

β – the part of particles deflected by crystal at angles $|\theta|<\theta_b$ (passing to the focusing system).

Number of projectiles:

$I_0 >> 1$ – initial number of particles in beam;

$I_{0,i}$ – number of particles in a beam before the crystal for *i*-th turn;

$I_{t,i}$ – number of particles passing to the focusing system for *i*-th turn.

$$I_{t,i} = (1-\alpha)I_{0,i} + \alpha\beta I_{0,i}$$

$$I_{t,i} = I_{0,i+1}$$

INI number for i-th turn:

$$Z_i = P\alpha I_{0,i}$$

Total INI number over T turns:

$$Z = \sum_{i=1}^{T} Z_i = P\alpha I_0 \sum_{i=1}^{T} (1-\alpha+\alpha\beta)^{i-1}$$

=>

$$Z = \frac{1-(1-\alpha+\alpha\beta)^T}{1-\beta} P I_0 \qquad \beta < 1$$

$$Z = TP\alpha I_0 \qquad \beta = 1$$

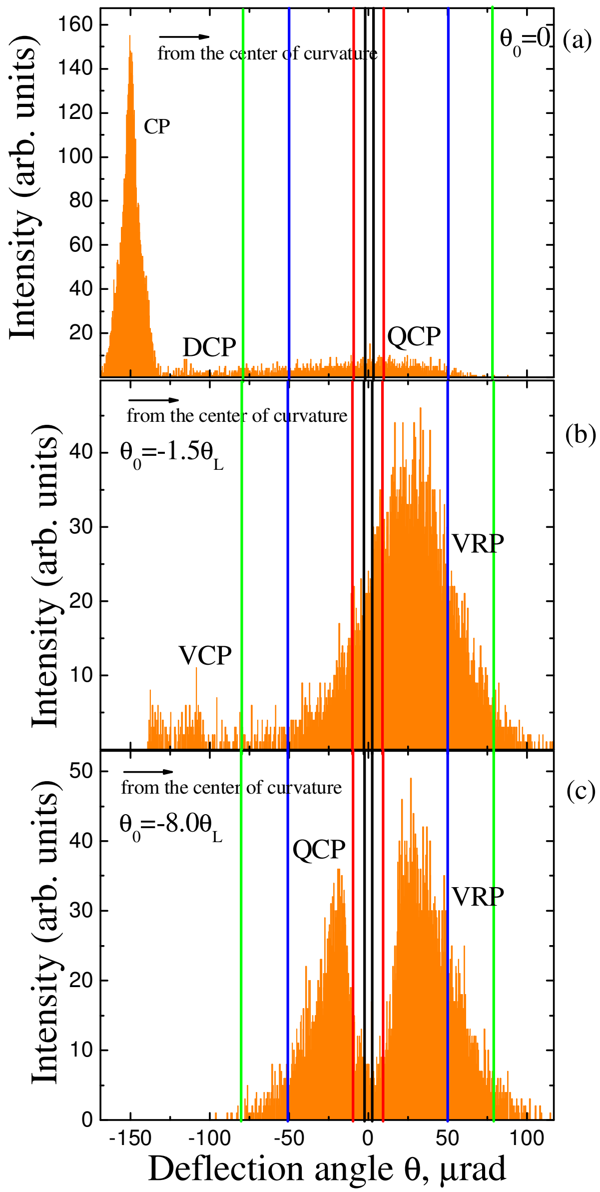
$\beta = 1$ - all projectiles pass to the focusing system

7. Coefficient β

CO

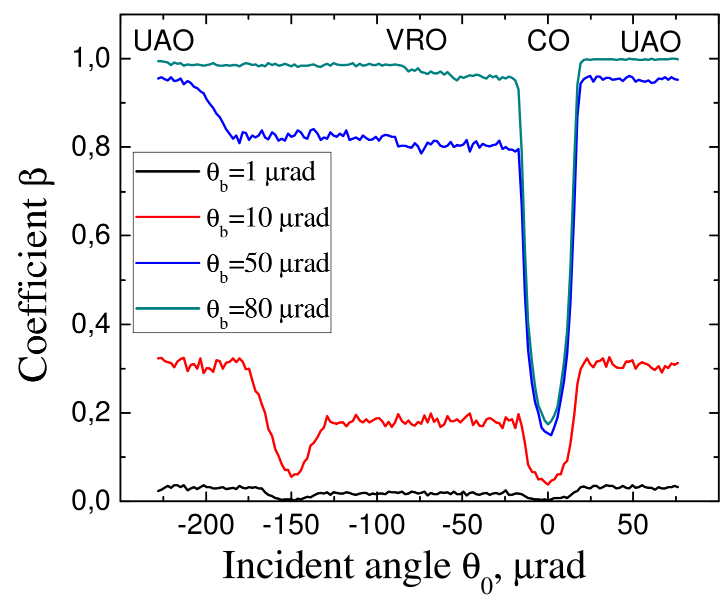
VRO

VRO
↓
UAO



β – the part of angular distributions located between the vertical lines of identical color:

- θ_b=80 μrad;
- θ_b=50 μrad;
- θ_b=10 μrad;
- θ_b=1 μrad;

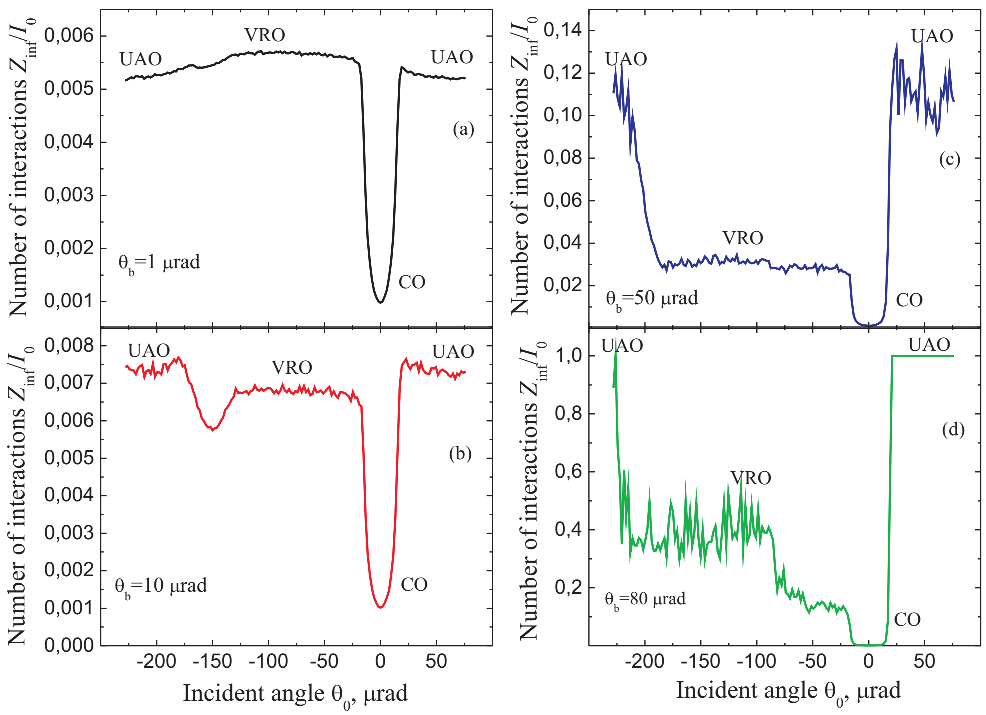


- the deep at CO <= the deflection over large angles under channeling
- the deep at θ_b=50 μrad, $\theta_0=\alpha_R$ <= the splitting at area VRO → UAO

8. Saturation regime

$\beta < 1$ $T \to \infty$

$$Z_{inf} = \frac{P}{1-\beta} I_0$$ - not depending on α



Curves Z_{inf}:

- At small θ_b (a) – is quite similar to curve $P(\theta_0)$ because every proton passes through the crystal one time only;
- At moderate θ_b (b) – has deep in VRO → UAO, area, it is the effect of $\beta(\theta_0)$, i.e., the angular distribution, shape;
- At large θ_b (c,d) – have strong oscillations, here $\beta \approx 1$, small oscillations of the angular distribution shape change Z_{inf} significantly;

- It is difficult in experiment to achieve values shown in figures at large θ_b, because the huge number of turns T is necessary to obtain the saturation.

9. Before the saturation

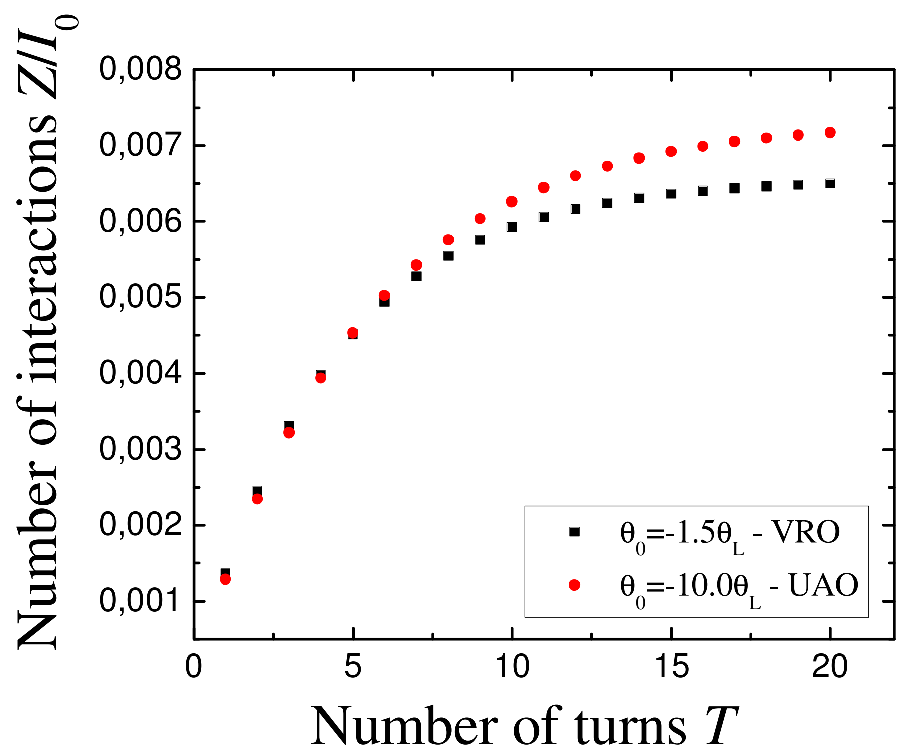
When projectiles pass through the crystal one time, the INI probability is more at VRO than at UAO.

At multiple passage at UAO protons are deflected on the fewer angles with respect to the case of VRO. Therefore, a proton has a chance to make more turns before it will be deflected by the angle $\theta > \theta_b$ at UAO than at VRO.

Hence:

INI number initially is more in the VRO than in the UAO, but the situation becomes inverted starting from the 5-th turn

INI number Z with respect to the initial number of protons I_0 as the function of the turns number T at α=0.25, θ_b=10 μrad; 120 GeV protons passing through Si crystal bend along (220) planes over the angle α_R = 150 μrad with the radius R=1333 cm.



10. Finally

1. We have new models and new codes to model the angular distributions and INI;
- We have not the necessity to model the trajectory at every passage of proton through the crystal;
- We need only to simulate the angular distribution one time.

2. Obtained results are in qualitatively agreement with experiment;

3. The deep in VRO → UAO area observed (or not) in experiments can be more or less enhanced, or can be absent in dependence on experimental condition, namely in dependence on cutting angle θ_b at the setup exit;