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FIRST RESULTS OF CRYSTAL DEFLECTOR INVESTIGATIONS AT THE NUCLOTRON EXTERNAL BEAMS

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First results of the experiments on the particle deflection by bent crystals at the external proton and deuteron beams of the Nuclotron are discussed. The modified method of the particle deflection registration is proposed and studied by simulation.

Обсуждаются первые результаты экспериментов по отклонению частиц изогнутым кристаллом на выведенных пучках протонов и дейтронов нуклотрона. Предложен и исследован моделированием усовершенствованный метод регистрации отклонения частиц.

INTRODUCTION

First investigations on the deflection of relativistic charged particles by a bent crystal and on the application of bent crystals for particle extraction from a cyclic accelerator were performed at JINR [1, 2]. The investigations were made with silicon crystals, the growing technology of which allows getting the crystals with very small dislocation density. A channeling length for such perfect crystals is primarily determined by multiple scattering of particles on the crystal electrons. Many investigations with silicon crystals as particle deflectors were fulfilled afterwards (see in [3]), and these crystals are used now to form particle beams for experiments on high-energy physics.

The investigations with crystal deflectors are renewed at JINR, using the nuclear beams of the Nuclotron, few years ago [4]. Their purpose is a study of a tungsten crystal as a deflector, which possesses stronger inner fields than a silicon crystal. The test experiments with silicon crystals on a deflection of the external beams of protons and deuterons of the Nuclotron were performed recently. As a result, a new goniometer device and a system of deflected beam registration were tested.

In this work the experimental results are discussed, and the modified method for deflection registration is proposed. In this method the telescope of counters is installed relative to a beam direction at the angle, which is smaller than the crystal bending angle. The simulation results illustrating this registration method are also presented.

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1. EXPERIMENTAL RESULTS

Figure 1 shows the experiment layout. Here G is the goniometer device with a bent crystal. The main telescope of scintillation counters S_1–S_2 was installed along a deflected beam path, the angle of which relative to the incident beam direction equals the crystal bending angle α. The background telescope S_3–S_4 was installed symmetrically. The plastic scintillators with dimension $30 \times 30 \times 5$ mm were used for the telescope counters. The picture generated by deflected particles at the scintillation screen TV can be observed with a distant monitor. The ionization profilometers M_x and M_y were used for the beam monitoring.

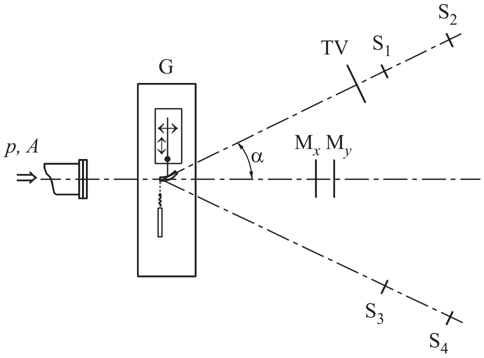

Fig. 1. The schematic layout of the experimental setup. Here G is the goniometer with a bent crystal, S_1–S_2 and S_3–S_4 are the telescopes of scintillation counters, TV is the scintillation screen observed with a distant monitor, M_x and M_y are the ionization profilometers, α is the crystal bending angle

The goniometer can move a crystal in a transverse direction to a beam and can change the crystal angle relative to a beam direction. The accuracy of the coordinate and angle motions of a crystal are better than 0.1 mm and 0.1 mrad, correspondingly. The preliminary crystal alignment is realized by using a laser beam.

The (110) silicon plate, which thickness is 278 μm, was bent and glued on the cylindrical surface of a duralumin holder. The holder radiuses were 270 and 277 mm. The bending angle of a crystal is usually smaller than the calculated one because of a glue layer thickness. Besides, the crystal surface directions near the entrance and exit faces of the crystal are different at different positions along the crystal height (the crystal is placed vertically). A typical value of this angular spread was about 1 mrad in our case. The silicon plates were prepared in Moscow State Institute of Electronic Technology (Zelenograd). The orientation accuracy of the crystal side faces relative to the (110) planes was about $3'$.

The measurements were made with a beam of 5 GeV/c protons. The particle number per the acceleration cycle was about 10^{10}, the extraction time was varied. The angular beam width has to be about 1 mrad according to the profilometer data. This is considerably bigger than a critical channeling angle $\Theta_c = 72$ μrad. A crystal orientation angle Θ_o (see Fig. 2) was changed every acceleration cycle. The counter coincidence numbers for the main and background telescopes, N_1 and N_2, were registered every cycle, and their ratio N_1/N_2 was calculated.

Figure 3 shows the deflection dependence on the crystal orientation measured for the crystal with a length of 1 cm. This is the dependence of the ratio of the event numbers registered by the main and background telescopes on the crystal angle Θ_o. The bending angle of the crystal is about 28 mrad. This is smaller than the calculated bending angle, which is about 37 mrad for the crystal holder with a bending radius of 270 mm.

The maximum observed is stipulated by the particles deflected at the bending angle when the crystal plane direction is perfectly aligned with the beam direction. The full width of the

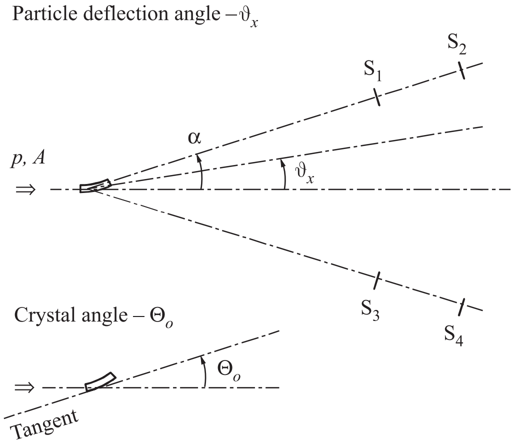

Fig. 2. The schematic picture on the determination of the relevant angles. Here the telescope installation angle $\Theta_t = \alpha$

deflection dependence at its half height is 1.1 mrad. It is determined by the angular width of the beam incident on the crystal. The opening of the telescope angle is bigger than 4 mrad; therefore, it does not influence the dependence formation. There is a small asymmetry of the deflection maximum, which can be stipulated by a volume capture of particles at $\Theta_o < 0$ and by the spread of the plane directions at the crystal entrance.

The telescope count ratio is about 0.4 outside of the maximum when the crystal is not aligned and there is no particle channeling. This says about some asymmetry of the beam halo particles, which is not connected with a particle scattering in the crystal. This ratio increases 3.5 times at the dependence maximum and achieves the value of 1.4. The same growth is observed for the ratio of the main telescope count to the particle number of the beam, which increases from $0.6 \cdot 10^{-5}$ to $2 \cdot 10^{-5}$. The number of the deflected particles is about 10^5 per the acceleration cycle at the perfect alignment of the crystal.

Figure 4 shows the deflection dependence on the crystal angle, which was observed in our experiment when the beam of 2.11 GeV/u deuterons was used. The beam particles were

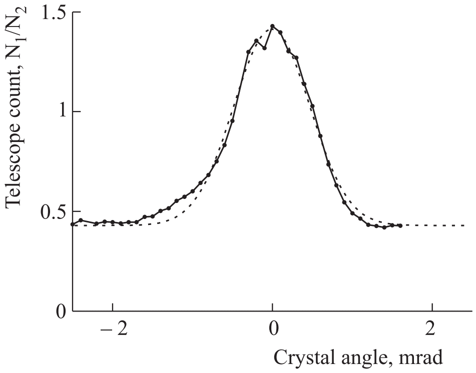

Fig. 3. The dependence of the ratio of the event numbers registered by the main and background telescopes on the crystal angle Θ_o. For 5-GeV/c protons incident on the 1 cm length (110) Si crystal with the bending angle $\alpha = 28$ mrad. The dotted line is the Gaussian fit with $\sigma = 0.48$ mrad

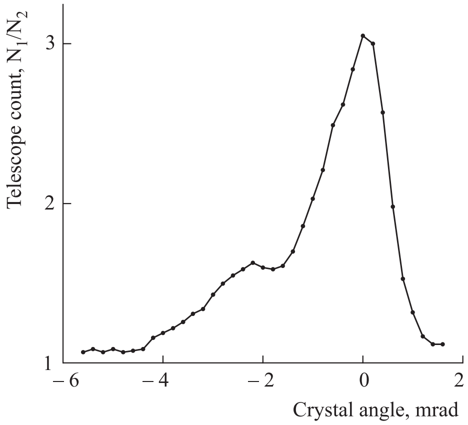

Fig. 4. The same as Fig. 3 for 2.11 GeV/u deuterons incident on the 1.8 cm length (111) Si crystal with $\alpha = 56.2$ mrad

incident on the 1.8 cm length (111) silicon crystal with the bending angle $\alpha = 56.2$ mrad. At the dependence maximum the count ratio increases 2.72 times. The deflected fraction of the beam was about $3 \cdot 10^{-6}$ for this case. A bigger tail at $\Theta_o < 0$ is stipulated by the larger plane direction spread at the crystal entrance for this crystal.

2. SIMULATION RESULTS

Many particles leave bent planar channels and do not achieve the exit face of a crystal; that is, they are dechanneled. The deflection angles of these particles are smaller than a crystal bending angle. So, the particles fill in a whole angular region between the straight beam direction and the bending angle one. The angular unfolding of the dechanneling process occurs. If the counter telescope is placed along any direction from this angular region, it will register dechanneled particles. Their number will be also changed with changing the crystal orientation. This can be used for the registration of particle deflection by a bent crystal too.

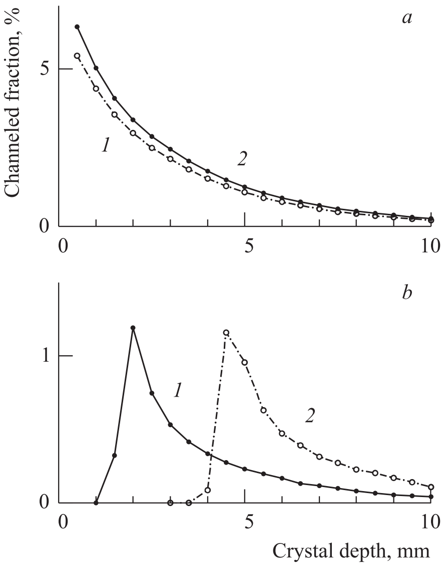

Fig. 5. The dependencies of the channeling fraction on the beam penetration depth into the crystal. *a*) $\Theta_o = 0$, the curve *1* for particles captured at the crystal entrance, *2* taking into account the particles captured in the volume; *b*) $\Theta_o = -6$ mrad (*1*) and $\Theta_o = -16$ mrad (*2*)

The simulation was performed for analysis of the deflection dependence on the crystal orientation and the role of volume capture of particles into the channeling regime for the cases when the telescope orientation angle is smaller than a crystal bending angle. Our simulation model was used [5]. The trajectories of particles are calculated in the continuum potential of atomic planes, which is modified by a centrifugal force. Multiple scattering by the crystal electrons and nuclei is calculated after the particles travel a distance, which is much smaller than the period of particle oscillations in the channel. It was accepted that the angular distribution of the beam is a Gaussian with $\sigma = 0.5$ mrad, which is close to the deflection dependence observed in our experiment.

Figure 5 shows the dependencies of the channeling fraction on the beam penetration depth into the crystal. The particles were considered as channeled if they do not approach to the channel walls at the distance smaller than 2.5 u_1, where $u_1 = 0.075$ Å is the amplitude of thermal vibrations of the crystal atoms. The particles with bigger amplitudes of oscillations in the channels are dechanneled faster. The conditions for particle capture into the channeling regime at the entrance face of the crystal (so-called surface capture) are fulfilled for the biggest part of incident particles, about 8 %, when the crystal angle $\Theta_o = 0$ (Fig. 5, *a*). The channeled fraction is reduced with the crystal depth due to multiple scattering mainly by the crystal electrons. The dechanneling length L_d is about 3 mm. Multiple scattering evokes also a reverse process of particle capture into the channeling states in the crystal volume (volume capture). In the considered case the volume capture of particles near the entrance face gives some increase of the channeled fraction (curve *2*).

Channeled particles appear in the crystal only due to the volume capture when the crystal angle is big enough and $\Theta_o < 0$ (Fig. $5, b$). The volume capture probability is about 1.5 % in our case, that is not much smaller than the surface capture probability. The estimation of the volume capture probability can be made according to the relation $P_{\rm vc} = 2R\Theta_c/L_d$, where $2R\Theta_c$ is the length of the volume capture region. It gives a close value to the simulation result. The volume capture probability does not depend on the crystal angle. The capture region is shifted deep into the crystal with increasing Θ_o (Fig. $5, b$).

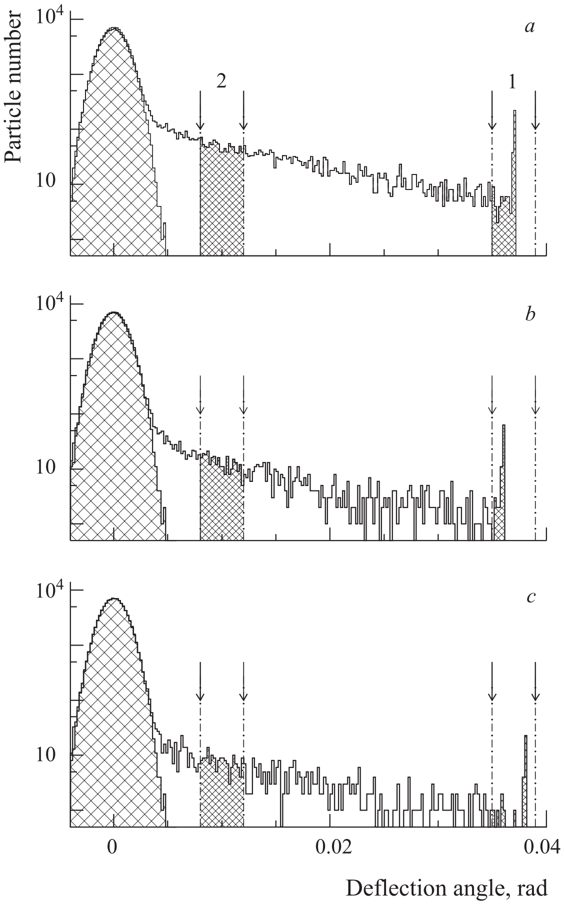

Fig. 6. The angular distributions of particles for small angles of the crystal orientation $\Theta_o = 0$ (*a*), $\Theta_o = -1$ mrad (*b*), $\Theta_o = 1$ mrad (*c*). It is also shown that the distribution of the beam crossed the crystal without channeling (rare hatching) and the regions observed with the telescope when its angle $\Theta_t = \alpha$ (1) and 10 mrad (2)

Figure 6 shows the angular distributions of particles for small angles of the crystal orientation Θ_o, when the surface capture works mainly. The distribution tail stretched to the bending side excepting a maximum at the end is stipulated by the particles, which are followed by the bent channels only during some part of the crystal length. The distribution of the beam crossed the crystal without channeling taking into account its broadening due to multiple scattering is shown by a rare hatching. The angular regions, which are observed with the telescope installed at the bending angle (1) and at 10 mrad (2), are shown by dot-dashed lines and dense hatching. It was accepted that the opening of the telescope angle is 4 mrad. The telescope at the bending angle registers mainly particles, which passed a full crystal length being channeled. These particles form the maximum at the distribution tail. This maximum has the biggest value for $\Theta_o = 0$ (Fig. $6, a$). When the crystal orientation is not perfect, $\Theta_o \neq 0$, this maximum reduces and shifts but it remains in the opening of the telescope angle (Fig. $6, b, c$). When the telescope is placed at the angle $\Theta_t < \alpha$ it registers particles dechanneled in the crystal. In this case the number of registered particles changes significantly with Θ_o too.

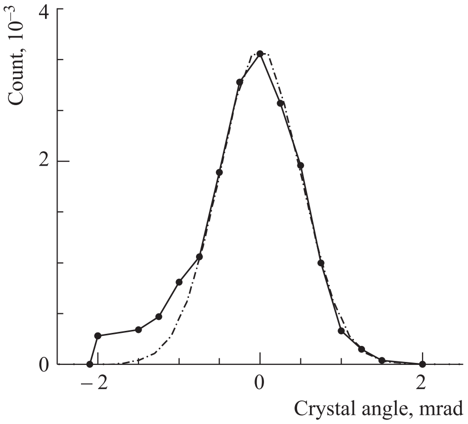

Fig. 7. The dependence of the event number registered by the telescope at $\Theta_t = \alpha$ on the crystal angle. The dot-dashed line shows the angular distribution of the incident beam

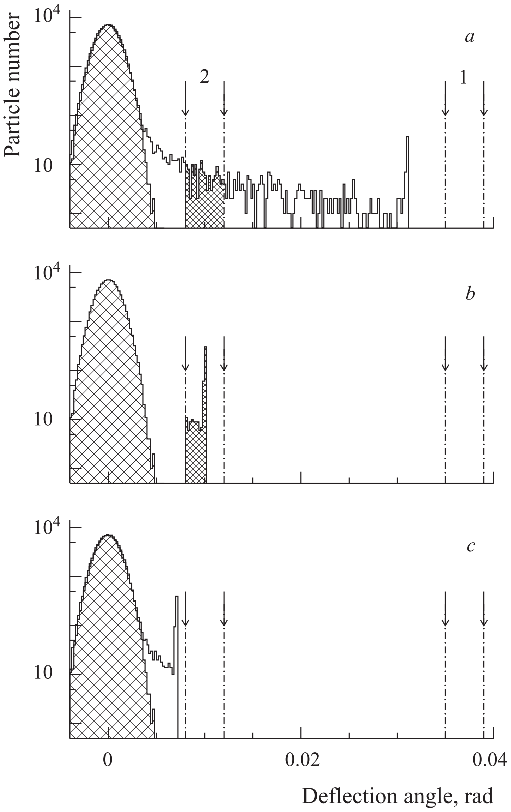

Fig. 8. The same as Fig. 6 for large angles of the crystal orientation Θ_o: *a*) −6 mrad; *b*) −27 mrad; *c*)−30 mrad

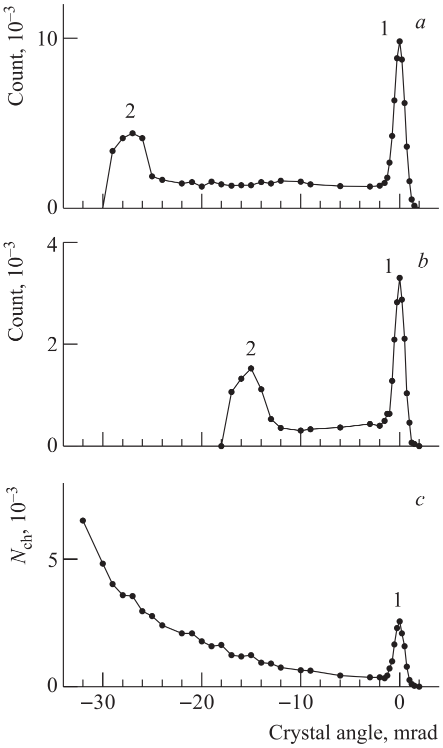

Fig. 9. The dependencies for the event number registered by the telescope at $\Theta_t = 10$ mrad (*a*) and $\Theta_t = 22$ mrad (*b*). The figure *c* is the dependence on the crystal angle for the channeled fraction at the exit face of the crystal

In Fig. 7 we show the dependence on the crystal angle for the event number registered by the telescope at the bending angle. The event number (count) is measured in the part of the beam incident on the crystal. The dot-dashed line shows the angular distribution of the incident beam. The width of the dependence is completely determined by the width of the angular distribution of the beam. The increase of the telescope count near the distribution tail for $\Theta_o < 0$ is stipulated by the contribution of the volume capture.

Figure 8 shows the angular distributions of particles for the big angles of the crystal orientation when $\Theta_o < 0$. In this case the distribution tail stretched to the bending side is stipulated only by the volume capture of particles into the channeling regime. It is natural that the maximum angle at which particles can be deflected by the crystal is smaller, $\Theta_d = \alpha - |\Theta_o|$. The telescope 2 registers either a part of dechanneled particles (Fig. 8, a) or the particles passed in the channeling states all the way from the capture region to the exit face of the crystal (Fig. 8, b). The telescope can register nothing when $\Theta_t > \Theta_d$ (Fig. 8, c).

The dependencies on the crystal angle Θ_o for the telescope count when it is placed at the angle $\Theta_t < \alpha$ are shown in Fig. 9, a, b. The maximum 1 is stipulated by dechanneled particles. The capture into the channeling regime is mainly a surface one for these particles. The width of this maximum is determined by the angular width of the beam. The other part of the dependencies is explained by the volume capture of particles in the crystal. Besides, the maximum 2 at the angle $\Theta_o = \Theta_t - \alpha$ is stipulated by the particles which were channeled up to the exit face of the crystal. This maximum width is determined by the opening of the telescope angle. The level of the telescope count between two maximums is stipulated by the particles dechanneled between the capture region and the exit face of the crystal. Figure 9, c shows the dependence of the channeled fraction at the exit face of the crystal on the crystal angle. This dependence corresponds to the specific case of the deflection registration with using the telescope when the telescope installation angle is changed with changing the crystal angle; that is, one can say that the telescope «looks» always at the exit face of the crystal.

CONCLUSION

The particle deflection by a bent crystal is traditionally registered by finding a sharp maximum for the count dependence of the telescope on the crystal orientation angle. The telescope is always installed at the crystal bending angle. The deflection dependencies received in our experiment demonstrate the possibilities of this method for our background conditions. By using a background telescope, the deflection registration is even possible when there is a high level of background from the beam halo and secondary particles. However, for the crystals which length is much bigger than a particle dechanneling length this method is problematic for the deflection registration. The difficulties of this registration method can appear for quite short crystals of heavy metals, which possess a relatively high density of dislocations.

In the proposed method for the deflection registration the telescope is placed at the angle smaller than a crystal bending angle. In this case the count dependence of the telescope on the crystal orientation is formed by particles, which passed in the channeling states only some part of the crystal length. Their number can be considerably higher. Therefore, the dependence maximum height can be bigger. The proposed method can be useful for the investigation of a particle deflection by the crystals, in which the particle channeling length is small because of some lattice defects. However, it is necessary to note that we are closer to the beam, and the background count of the telescope increases when the telescope is placed at smaller angles. Therefore, the proposed method for registration of particle deflection by a bent crystal can be useful when the suppression of background will be successful.

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