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MODIFIED METHOD FOR REGISTRATION OF PARTICLE DEFLECTION BY BENT CRYSTAL

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1. Introduction

Investigations of particle channeling and deflection effect in a bent crystal demand the measurements of angular distributions of particles behind the crystal. The co-ordinate detectors are necessary for these measurements. However, the application of the co-ordinate detectors is only possible at the beams with a low intensity.

The fact itself of particle deflection by a bent crystal can be registered without any co-ordinate detectors. For this purpose, the telescope of counters is installed at the bending angle of the crystal α relative to the beam direction. The observation of a sharp maximum for the count dependence of the telescope on the crystal orientation angle will speak about the particle deflection by the bent crystal. This was widely used in the experiments with bent crystals. The particles passed the whole crystal length in channeling states are registered.

The dependence on the crystal orientation was used not only for the deflection effect registration but also for the investigation of volume capture of particles into the channeling regime [1]. In the experiment [1], the registered particles were also in channeling states up to the exit from the crystal.

The application of the telescope when the bending angle of the crystal is big allows to install the telescope counters at a large distance from the beam what gives possibility to use high intensity beams. Therefore, there is possibility for fast search and observation of particle deflection in the experiment when the crystal pre-alignment is fulfilled before the work with the beam.

The dechanneling length of particles is small for the crystal of heavy metals, which possess high dislocation density. Therefore, it is difficult to hope that many particles can be registered at the bending angle even when the crystal is not so long. On the other hand, bent crystals also deflect dechanneled particles although their deflection angles are smaller than the bending angle α. If the telescope is installed at the angle $\theta_t < \alpha$ it will register dechanneled particles. Their number will be also changed with changing the crystal orientation.

This article describes the experimental results on the investigation of the deflection dependencies on the crystal orientation for the case when the telescope angle $\theta_t < \alpha$ and analysis of the dependencies by simulation. The external beam of 5 GeV protons of the Nuclotron, JINR was used in the experiment.

2. Experimental results, $\theta_t = \alpha$

Fig.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 bending angle of the crystal α. The background telescope S_3–S_4 was installed symmetrically. The plastic scintillators with dimension 30×30×5 mm^3 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.

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 with using a laser beam.

The (111) silicon plate 18×9.5×0.3 mm^3 was bent and glued on the cylindrical surface of a duralumin holder. The holder radius was 277 mm. The bending angle of the crystal equals 56.2 mrad that is smaller than the calculated angle 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. A typical value of this angular spread was about 1 mrad in our case.

The particle number per the acceleration cycle was about 4×10^9 in the external beam. 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. The crystal orientation angle θ_o 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.

Fig.2 shows the received deflection dependence on the crystal orientation. 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 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 deflection dependence at its half height is 1.15 mrad. It is determined by the angular width of the incident beam. The opening of the telescope angle is about 3 mrad, therefore it does not influence on the dependence. The dependence is well fitted by a Gaussian with $\sigma = 0.49$ mrad. However, there is a small asymmetry of the deflection dependence, 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 increases about 7 times at the dependence maximum. The deflected fraction of the beam is about 1.9×10^{-6} at the perfect alignment of the crystal. This value is mainly stipulated by a small beam part crossed the crystal.

3. Experimental results, $\theta_t < \alpha$

Many particles captured into channeling at the crystal entrance are dechanneled further in the crystal. The deflection angles of these particles are smaller than the bending angle of the crystal. Therefore, the particles fill in completely the angular region between the straight beam direction and the bending angle one. The angular unfolding of the dechanneling process occurs in the bent crystal.

What we receive if the telescope will be installed at the angle, which is smaller than α? The preliminary simulation study [2] showed the character of the dependence on the crystal orientation angle, which can be observed. The dependence has to be with two maximums.

Fig.3 shows the deflection dependence received in our experiment when the telescope angle was 0.75 α. The dependence has two maximums in fact. It is different from all dependencies received in the experiments before. The maximum 1 at $\theta_o = 0$ looks like for the traditional scheme of registration. The deflected part of the beam in the maximum is $P_I = 1.8\times10^{-6}$. The width of the maximum equals the beam width.

The second maximum is realized at $\theta_o = \theta_t - \alpha$. Its width equals the telescope width, that is 3 mrad. There are also deflected particles in the intermediate area of the crystal angles. However, the deflected beam part P_{I2} is much smaller for these intermediate angles.

Fig.4 shows the deflection dependence received for the telescope angle 0.5α, when the telescope was more close to the beam direction. There are the same two maximum in this case too. The deflected part of the beam in the first maximum $P_I = 2.8\times10^{-6}$ is higher than for $\theta_t = 0.75\alpha$. On the other hand, the background level, which is registered by the telescope S_3-S_4, becomes higher too.

The schematic picture in fig.5 shows three cases, which are realized for different crystal angles θ_o when the telescope angle $\theta_t < \alpha$ (here $\theta_t = \alpha/2$). At $\theta_o = 0$ when the maximum 1 is formed (fig.5a) the telescope registers the particles, which were captured at the crystal entrance and dechanneled further at the crystal depth near $S_t=\theta_t{\cdot}R$. At $\theta_o = \theta_t - \alpha$ when the maximum 2 is formed (fig.5b) the telescope registers the particles, which were captured in the crystal volume and remained in channeling states up to the exit face. For the intermediate angles of the crystal, $\theta_t - \alpha < \theta_o < 0$, the registered particles were captured in the crystal volume and then dechanneled.

The same telescope angle determines the same crystal length, which is passed by the registered particles in the channeling states, $S_t = \theta_t{\cdot}R$. The cases (a) and (c) are only different by the capture process. Therefore, the ratio P_{12}/P_1 contains the information about the ratio of the volume capture and surface capture probabilities. However, the channeled fraction evolution is different in these cases because the initial distributions of channeled particles in the transverse energy are different. Therefore, one can estimate the volume capture probability from these experimental data only comparing with simulation data.

4. Simulation results

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 $\theta_t < \alpha$. Our simulation model was used [3]. 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.

Fig.6 shows the dependencies of the channeled 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 fast.

When the crystal angle $\theta_o = 0$ (fig.6a) the conditions for particle capture into the channeling regime at the crystal entrance (so-called surface capture) are fulfilled for the biggest part of incident particles, about 5.65%. The channeled fraction is reduced with the crystal depth due to multiple scattering by the crystal electrons mainly. The reduction of channeled particles is stronger at small depth then the dependence becomes close to the exponential one. The dechanneling length L_d is about 5 mm. Multiple scattering evokes also a reverse process of particle capture into the channeling states in the crystal volume (volume capture).

Channeled particles appear in the crystal only due to the volume capture when the crystal angle is big enough and $\theta_o < 0$ (fig.6b). The captured beam fraction that is the volume capture probability is about 1% in our case. It is not much smaller than the surface capture probability. The estimation of the volume capture probability can be done according to the relation $P_{vc}=2R\theta_c/L_d$, 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. However, the capture area is shifted deep into the crystal with increasing θ_o (fig.6b). The capture area location is near the depth $R\theta o$. Here also a fast decrease of channeled fraction occurs after the capture and then the exponential reduction with approximately the same dechanneling length as for the surface captured fraction.

Fig.7 shows the angular distributions of particles behind the crystal for different crystal angles θ_o. For the case of the perfect crystal alignment $\theta_o = 0$ (fig.7a) the maximum at α presents particles which are registered in the traditional scheme of the experiment when the telescope is installed at the angle α. The distribution tail stretched to the bending side excepting the maximum at α is stipulated by the particles, which followed by bent channels during only some part of the crystal length. A rare hatching shows the distribution of the beam crossed the crystal when its orientation is random.

The areas shown by arrows and dense hatching present the particles which will be registered by the telescope when its angle $\theta_t = 0.5\alpha$. They are dechanneled particles for the cases shown in fig.7a,b. However, when θ_o is close to $\theta_t - \alpha$ (fig.7c) they left the crystal in channeling states.

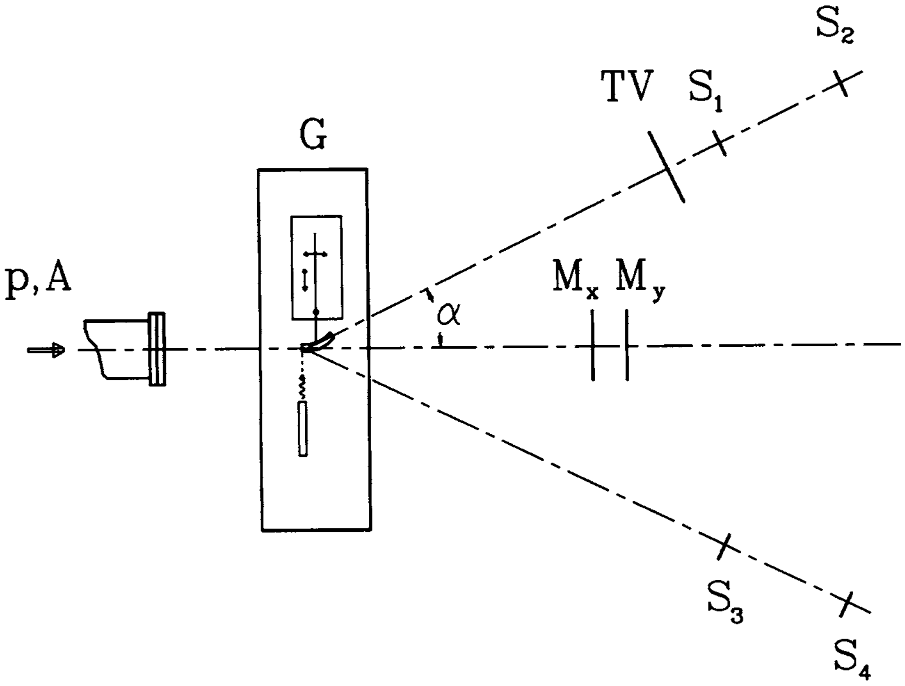

Fig.1. The schematic layout of the experimental setup. Here G is the goniometer with a bent crystal, S_1–S_2 and S_3–S_4 are the telescopes of scintillation counters (main and background), TV is the scintillation screen observed with a distant monitor, M_x and M_y are the ionization profilometers, α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

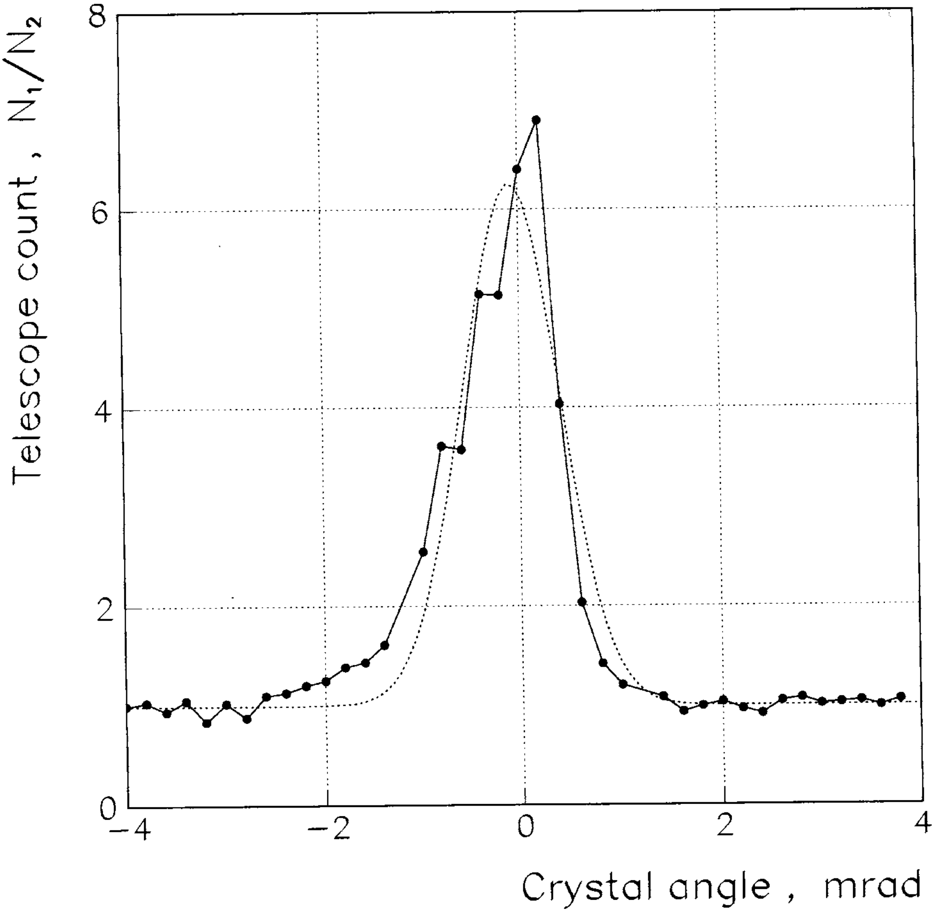

Fig.2. The dependence of the ratio of the event numbers registered by the main and background telescopes on the crystal orientation angle θ_o. For 5 GeV protons incident on the 18 mm length (111) Si crystal with the bending angle α = 56.2 mrad. The telescope angle equals α. The dotted line is the Gaussian fit with σ = 0.49 mrad.

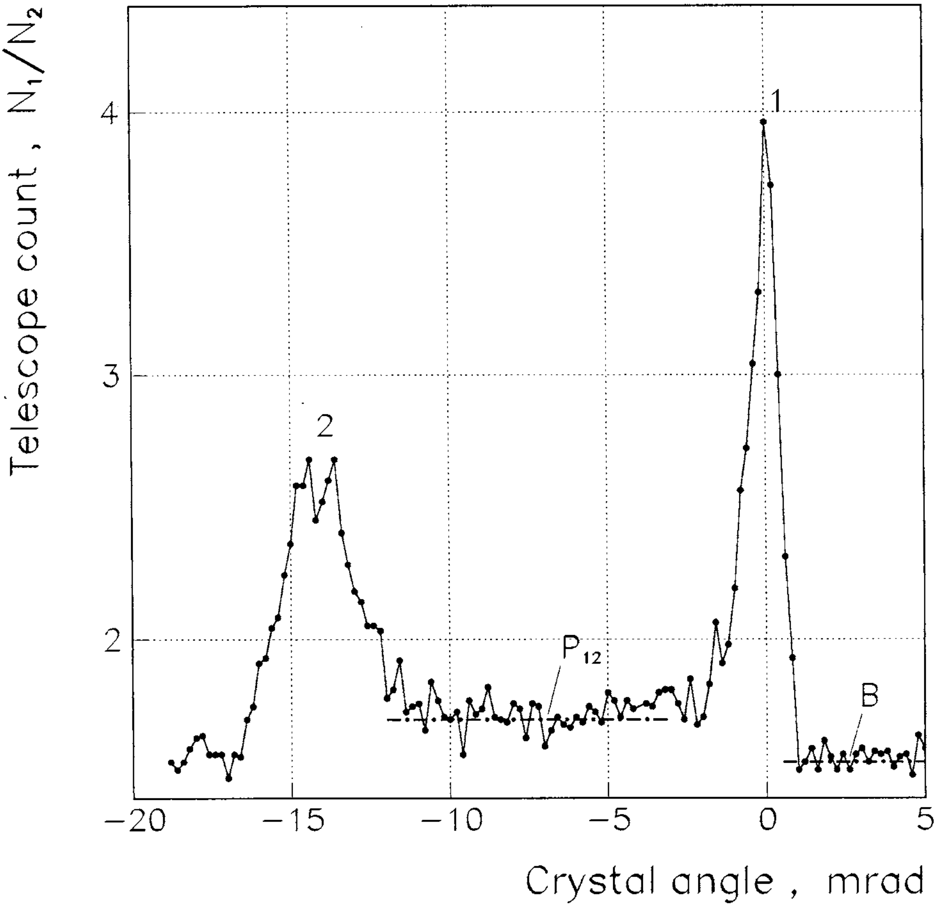

Fig.3. The same as in fig.2 for the case when the telescope angle is 0.75α. Here B is the background level of the count and P_{12} is the count level for the intermediate angles.

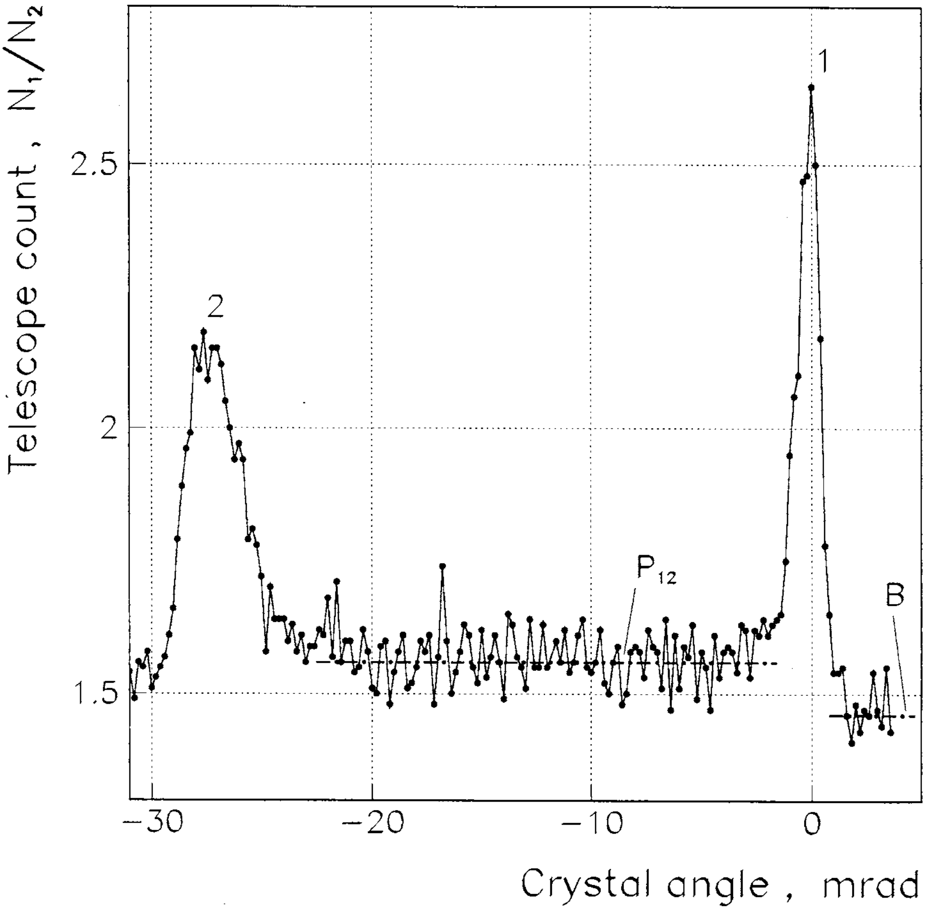

Fig.4. The same as in fig.2 for the case when the telescope angle is 0.5α.

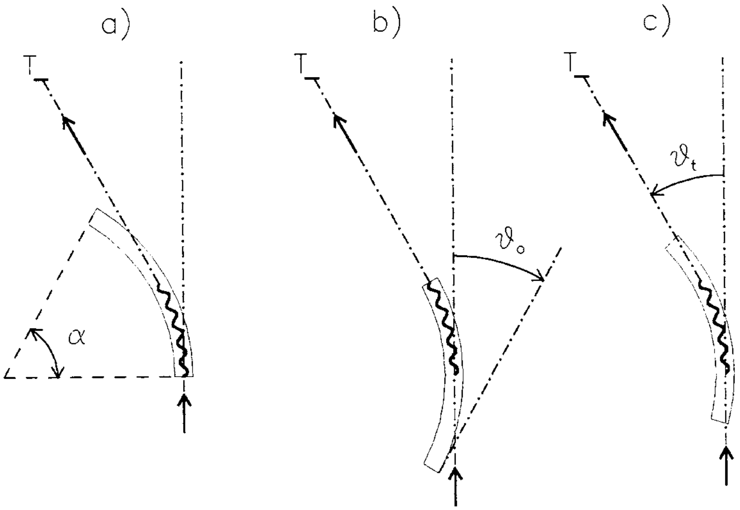

Fig.5. The schematic picture of particle registration by the telescope T shows three cases, which are realized for incident beam particles for different crystal angles θ_o when the telescope angle $\theta_t < \alpha$ (here $\theta_t = \alpha/2$). The sinusoidal curves show the part of particle trajectories in a bent crystal, which they pass in channeling states.

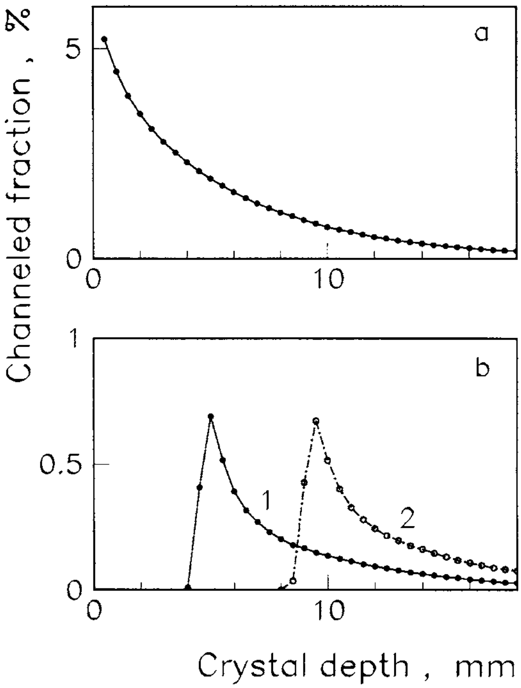

Fig.6. The dependencies of the channeled fraction on the beam penetration depth into the crystal received by simulation. (a) for the crystal orientation angle $\theta o = 0$, (b) for $\theta o = -14$ mrad (1) and -28 mrad (2).

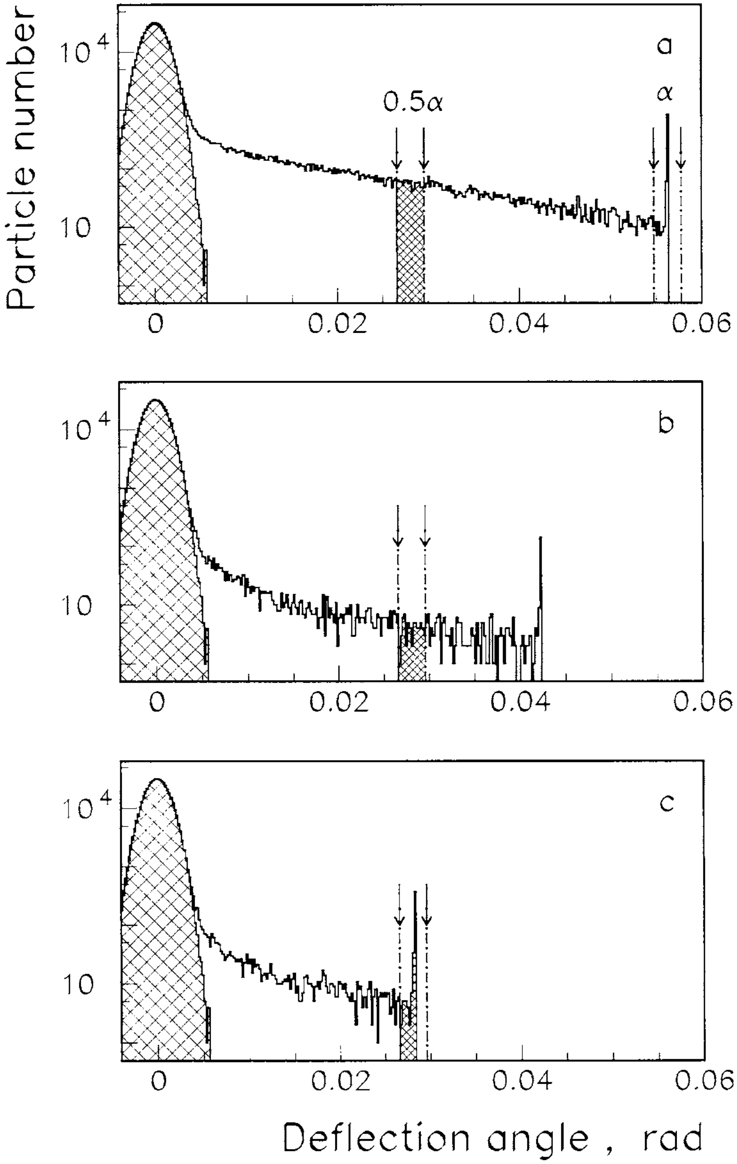

Fig.7. The angular distributions of particles behind the crystal received by simulation for different crystal orientation angles θ_o: 0 (a), -14 mrad (b), -28 mrad (c). The rare hatched histogram is the distribution for the random case. The areas shown by arrows and dense hatching present the particles which will hit the telescope installed at the angle $\theta t = 0.5\ \alpha$.

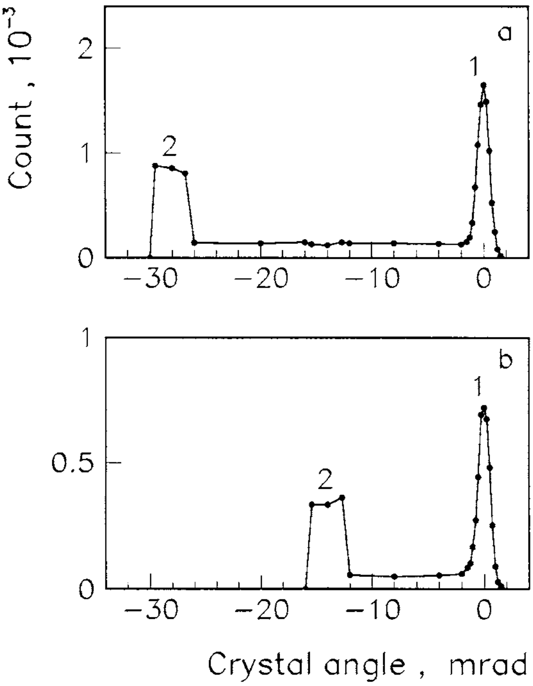

Fig.8. The beam deflection dependencies on the crystal orientation angle θ_o received by simulation when the telescope is placed at the angles $\theta_t = 0.5\alpha$ (a), 0.75 α (b).

Fig.8 shows the beam deflection dependencies on the crystal angle θ_o received in our simulation when the telescope was placed at the angles $\theta_t < \alpha$. The deflection efficiency increases with decreasing θ_t. The dependencies are in good agreement with the experiment. The ratio of the deflection probability for the intermediate angles and $\theta_o = 0$ is the same as in the experiment, P_{12}/P_1=0.084. That is our model describes well the process of the particle passage through the crystal (capture and dechanneling). Therefore, the simulation result concerning the value of volume capture probability can be accepted.

5. Conclusion

The deflection dependence on the crystal orientation has two maximums when the angle of the telescope of counters relative to a beam direction is smaller than the bending angle of the crystal, $\theta_t < \alpha$. The registered particles pass in channeling states only some part of the crystal length. The first maximum at $\theta_o = 0$ is formed by the particles captured into channeling states at the crystal entrance. The second maximum at $\theta_o = \theta_t - \alpha$ is produced by the particles captured in the crystal volume. Thus, there is possibility to receive information about the volume capture of particles too.

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. For example, for the crystals of heavy metals, which possess a relatively high density of dislocations.

The other possible application is a fast alignment of usual silicon crystal deflectors at the particle beams with a small divergence. The width of the second maximum of the deflection dependence equals the angular width of the telescope and can be large enough. This allows using a large goniometer step.

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Афанасьев С. В. и др. E1-2003-204
Модифицированный метод для регистрации отклонения частиц
изогнутым кристаллом

Предложен и изучен модифицированный метод для регистрации отклонения частиц изогнутым кристаллом на выведенном протонном пучке нуклотрона. Телескоп сцинтилляционных счетчиков размещался под углом, который был меньше угла изгиба кристалла. Изучалась зависимость счета телескопом частиц, которые проходили в режиме каналирования только часть длины кристалла, от ориентации кристалла. В полученной зависимости наблюдались два максимума, связанных с частицами, захваченными в каналированные состояния на входе в кристалл и в его объеме.

Используя телескоп и пучки высокой интенсивности, можно получать полезные данные о каналировании частиц и о кристалле, что обычно требует более сложной регистрации с использованием координатных детекторов. Предложенный метод может быть полезен для исследования отклонения частиц кристаллами, длины каналирования частиц в которых малы из-за дефектов решетки.

Работа выполнена в Лаборатории высоких энергий им. В. И. Векслера и А. М. Балдина ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 2003

Afanasiev S. V. et al. E1-2003-204
Modified Method for Registration of Particle Deflection
by Bent Crystal

The modified method for registration of particle deflection by a bent crystal was proposed and studied at the external proton beam of the Nuclotron. The telescope of scintillation counters was placed at the angle that was smaller than a crystal bending angle. The count dependence of the telescope on the crystal orientation was formed by the particles, which passed in channeling states only some part of the crystal length. Two maximums were observed in the dependencies due to particles captured into the channeling states on the crystal surface and in the crystal volume. This allows one to obtain, using the telescope and high-intensity beams, useful data about the particle channeling and the crystal, which usually demands more complicated registration by means of the coordinate detectors. The proposed method can be useful for the investigation of particle deflection by the crystals in which the particle channeling length is small because of some lattice defects.

The investigation has been performed at the Veksler and Baldin Laboratory of High Energies, JINR.

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