CRYSTALOPTICS OF HIGH ENERGY PARTICLES

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Introduction

Since their start in the 60s experiments studying particle channeling in single crystals have been developed in many directions. On the basis of the channeling effects for low-energy particles in the 70s numerous techniques have been proposed and implemented to study the crystal structure and the degree of crystal perfection, as well as various physical processes taking place inside crystals.

Then, however, the interest has shifted toward studies of channeling for high- and ultra-high energy particles. Theoretical predictions made in the 80s of new physical phenomena associated with the channeling effect further stimulated experimental studies. These have included the possibility of controlling trajectories of channeled particles by means of elastic bent crystals (E.N.Tsyganov, 1976) and so on. However, for observation and, the more so, for practical implementation of the above effects about 20 years of intensive activity in Russia and abroad have been required.

Some aspects of these investigations, such as studying the capture of charged particle into channeling regime by a bent crystal [1–5], working out and application of the crystaloptical elements prepared on the basis of bent crystals for high energy particles [6–12], as well as working out the method for measuring the magnetic moments of short-lived particles using the effect of spin precession of the particle channeling inside bent crystal [13–15] performed with participation of PNPI (LNPI) in 1980–96 are presented in this review.

Effect of the volume capture into channeling regime by bent crystal

A first experimental realization of the idea to control trajectories of charged particles with a bent crystal was performed in 1979 at the Dubna synchrophasotron (E.N.Tsyganov et al.). In this experiment the process of controlling the trajectory (turning) was created by the following way – being captured into the channeling regime through the end of the unbent part of the crystal, a particle got into the region with the nonzero curvature of atomic planes and deflected by the angle depending on the length and bending shape of the crystal.

However, real high energy beams have an angular divergency much larger than the Lindhard angle. Naturally, there was a question what would happen with this beam inside volume of a bent crystal. The study of the possibility for a particle to be captured into the channeling regime by bent channel directly both at the end of the crystal (the crystal had no plane part in contrast with the crystal used in Dubna work) and inside the volume of the crystal was the main goal of the experiment with the bent crystal performed at the PNPI (LNPI) synchrocyclotron [2].

The principle scheme of the experiment is pictured in Fig. 1. The proton beam (p) passed through the proportional wire chambers PWC1, PWC2 and the scintillation counter S1 was then transmitted through a cylindrically bent silicon crystal (C). The counter S1 had a 10×0.4 mm^2 slit and was operated in anticoincidence with the counter S2. This arrangement made it possible to separate from the straight beam the protons which reached the entrance face of the crystal and to determine their entrance angle (the angular resolution 0.19 mrad). On the bent

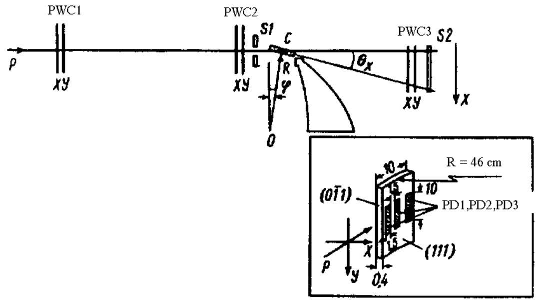

Fig. 1. Schematic diagram of the experiment setup to study the volume capture of 1 GeV protons in the channeling regime by bent silicon crystal.

single crystal 25 × 10 × 0.4 mm^3 made of semiconductor silicon three independent detecting structures (PD1, PD2, PD3) were realized. The passage of particles through the crystal was registered by measuring the energy losses in these sensitive regions. The proportional chamber PWC3 measured the angular distribution of particles leaving the crystal (the angular resolution 0.41 mrad). With the help of a goniometer it was possible to rotate the crystal by the angle φ (with the accuracy of 0.01 mrad) around the axis O of a cylinder coaxial with the crystal curvature, so that the region where the beam came in contact with the curved surface could be located on the crystal face as well as in any point inside the volume of the crystal.

The main advantage of this apparatus was the possibility to combine (for the first time) the functions of a bent crystal target, in which the channeling took place, with a semiconductor multidetector, which separated channeling particles according to their specific ionization losses. The use of three sensitive regions on the same crystal made it possible to follow the motion of a particle in the crystal at all stages: capture, channeling, and dechanneling.

Since no information was available concerning the possibilities and methods of operation of workable semiconductor detectors on a crystal with elastic deformation, the authors together with colleagues had to investigate theoretically and experimentally how an elastic deformation of the crystal influences the energy and time characteristics of the detector [2,3]. Other technological and operational conditions for utilization of such detectors were established experimentally [3]. The multidetector created on the bent crystal had good enough energy resolution – 30–35 keV at 300 K. The measurement process involved the determination of the spectrum of ionization losses in various regions of the crystal (those are PD1–PD3) and observation of the angular distributions of particles leaving the crystal as a function of the orientation angle φ. Particles were considered as channeled when they had abnormally low (less than 0.74 of the most probable losses for the "straight" beam) ionization losses in the detectors PD1–PD3.

The main conclusions obtained from these experiments were published in a series of articles describing different physical phenomena and processes [2–6]. It was demonstrated for the first time that the region, where particles were captured into the channeling regime by the bent crystal, was not limited to the region near entry face but was distributed over entire length (1 cm) of the crystal. The total angular interval of capture was about 20 mrad (see Fig. 2) whereas the Lindhard angle was 0.12 mrad and the angular divergence of the beam was about 1 mrad [4].

This physical process was called by the authors as the "effect of volume capture" into the channeling regime [1,2]. The term "volume capture" was introduced into scientific terminology,

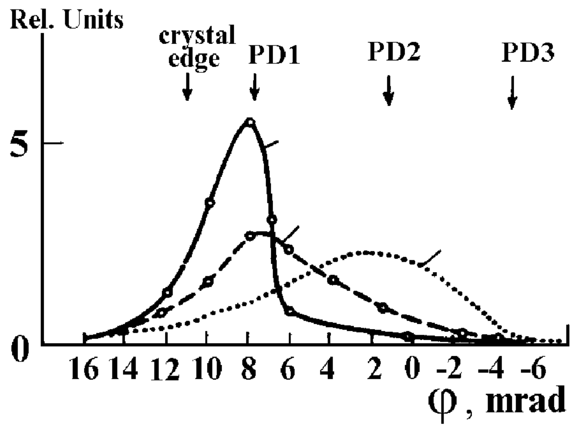

Fig. 2. Fraction of the particles (in percentage of the incident beam) with small amplitudes in PD1, PD2, PD3 as a function of the angle of crystal orientation (φ) relatively to the incident beam. Also the positions of the edge ends of the crystal and detectors PD1–PD3 are shown.

and physics of this process was developed by subsequent works (experimental and theoretical) of many authors (see Sov.J.UFN, 1994. V.164. P.1017).

The deflection of the proton beam with the lowest energy of 1 GeV by the angle of 11 mrad was demonstrated for the first time [4]. The realization of the multidetector semiconductor structures on the bent crystal for the first time made it possible to observe the state of the particles at all stages of their passing through the crystal by means of the ionization losses measurement. So, the mean value of an electron gas density ($\rho = 0.24 \pm 0.02$ electron/$\AA^3$) and the value of an ionization potential ($I = 1.9 \pm 1.4$ eV) for this gas were evaluated from the spectra of ionization losses for channeling particles. Using the calculated dependence of the most probable losses and their experimental values for the observed channeling particles, it was possible to estimate the most probable value of the energy of transverse motion of these particles ($0 \leq E \leq 8.1$ eV at the confidence level of 95%) [6,7].

Using information about the fraction of the particles channeling in different parts (detecting zones) of the crystal and comparing it with calculated dependence allowed to conclude that the case of a dynamic equilibrium between channeling and chaotic phases of the beam (predicted theoretically by M.N.Strikhanov et al., 1989) took place in this experiment. The existence of this effect means increasing the "lifetime" of the channeling phase and, respectively, allows to deflect particles by larger angles.

The high angular resolution of the experimental apparatus allowed to separate the effects for different crystallographic planes and to estimate the magnitude of the probability of volume capture of 1 GeV protons into the channel of (111) plane bent with radius $R = 46$ cm ($\beta_0 = 9.2 \pm 1.4\%$) and, correspondingly, the length of dechanneling ($\lambda = 1.26 \pm 0.09$ mm) [2].

Unique characteristics of the experimental setup allowed us to test the principle of reversibility for such processes as capture, channeling, and dechanneling. Consequently, it was possible to obtain specific information on the transverse energy dissipation in the volume capture process. It was shown that the principle of reversibility was realized for 97% of the particles. It means that for describing the effect of volume capture one can use models, for example, with processes of elastic scattering [5].

Angular focusing and beam deflection by bent crystals

The existence of volume capture should produce the effect of angular focusing, that is particles captured into the channeling regime from a wide angular interval should have a narrower angular distribution. With the experimental apparatus [2–4], the possibility was demonstrated to convert the wide angular distribution of the incident beam (FWHM = 7.2 ± 0.1 mrad) to narrow one at the exit end of the crystal (FWHM = 1.6 ± 0.1 mrad) due to the effect of the volume capture (effect of angular focusing). Accordingly, the phase volume of the beam of channeled particles was decreased by 1.8 times [6].

The possibility to use a bent crystal simultaneously as a semiconductor detector and a focusing collimator for channeling particles was studied [7]. The experiment was carried out at the PNPI synchrocyclotron on the 1 GeV proton beam. The single crystal bent to conform a cylinder ($R = 2$ m) having the orientation of the crystallographic planes (111) perpendicular to the concave (convex) crystal face and serving at the same time as surface-barrier detector (PD1, PD2) was used in this experiment (see Fig. 3).

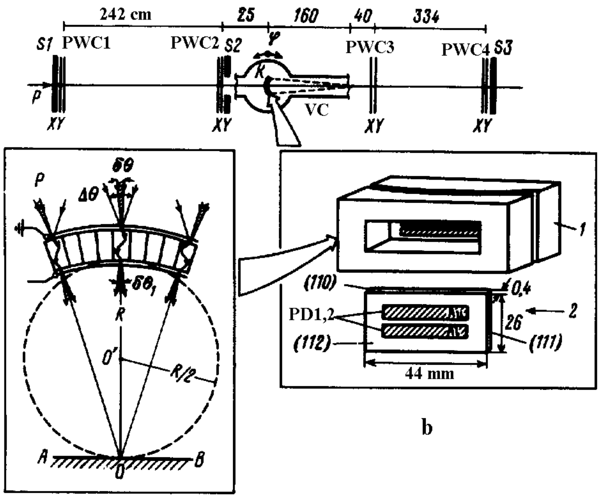

Fig. 3. Schematic diagram of the experimental setup: p – proton beam; S1,S2 – scintillation counters; PWC1–PWC4 – proportional chambers; VC – vacuum vessel; C – crystal. a – principle of spatial focusing; b – construction of bending device, dimensions of the crystal, and location of detecting zones.

Two independent detectors (PD1, PD2) having the p-n junctions on opposite faces of the crystal were located at different levels of height. This geometry of locating the detectors excluded the possible influence of the near-surface regions ("dead" layers).

The wide (covering the whole crystal) incident beam had the angular divergence of 8 mrad. The use of the crystal as a semiconductor detector allows to separate ("mark") channeling particles due to their abnormally small ionization losses. In our case of the cylinder bending the crystallographic planes are perpendicular to the crystal faces, it means that these planes are directed to the centre lying at the distance equal to the radius of bending and the channeling particles are focused to point O (see Fig. 3a). Note that because of approximate equality of the corresponding angles on the focal circle (circle of the radius $R' = R/2$ with the centre in the point O' and being tangent to surfaces of the bent crystal) the inclined (to the big facets) planes and particles channeling along them are focused too. The width of the focus is determined by the angular divergence $\Delta\theta_1$ of the particles outgoing the channels of the crystal.

The process of measurement consisted in separating the particles passing through the crystal with small ionization losses (0.3–0.6 of the most probable value for chaotic phase) and observing the spatial distribution of these particles with PWC3 placed in the focus of the bent crystal. As a result of such separation (see Fig. 4, curve 1), the peak of 0.65 ± 0.05 mm width was obtained, which corresponds to the angular divergence being defined by the Lindhard angle for the crystallographic plane under consideration.

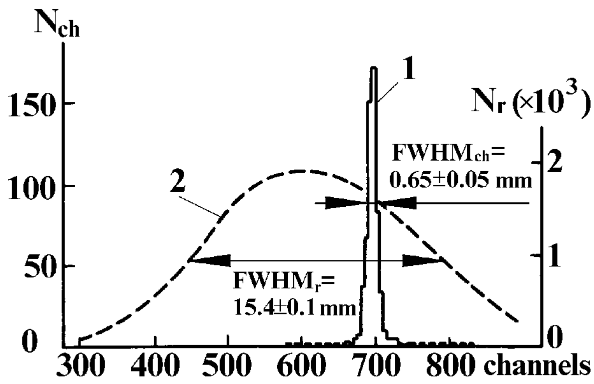

Fig. 4. Spatial location of the beam in the X-plane (PWC3): 1 – with selection of small amplitude of a signal from detector (in the interval of 0.3–0.6 of the most probable energy loss for chaotic phase); 2 – without any selection (incident beam).

The contrast of the focus (the ratio of an effect to a background) was about 34. The turning of the crystal caused the shift of the focus at PWC3 [3]. Natural consequence of this result is the possibility to investigate the distribution of an intensity of the particles emitted along the extended source with the same apparatus but with the reverse direction of the particles motion. Since the width of the focus is proportional approximately to $E_p^{-\frac{1}{2}}$, it will be of several microns for high energy particles. Due to the volume capture effect, the use of the bent crystal with deformed crystallographic planes allows to realize the spatial-angular collimator focusing the channeling particles. During the experiment this effect was observed for inclined (110) planes (see Ref. [3]).

In the middle of 80s one of the authors proposed a perspective idea to focus a parallel beam into a strip with simultaneous deflecting the beam by rather large angle. This allows to get pure focused beams. The idea of this method [8] is that the surface of the exit end face of the bent crystal should have a specific shape, so that the tangents to the crystallographic planes on this surface cross one and the same line, and, hence, particles in the plane of deflection were gathered in the linear focus due to the difference in angles of deflection. In the case of crystallographic planes bent to follow a cylinder of radius R (see Fig. 5), it is necessary that the line with the centres of curvature was placed on the surface of the cylinder by the shape of which the crystal end face was treated.

Described method of focusing was applied in the joint IHEP–PNPI experiment on the proton beam of the U-70 accelerator [8]. The specialists of PNPI worked out the technology of bending of focusing crystals, and several examples of focusing devices were built. Three silicon crystals

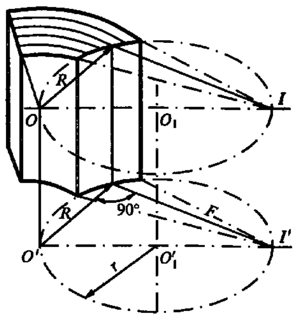

Fig. 5. The principle of focusing the beam by the crystal: OO' - the line on which the centers of curvature of the crystallographic planes are located; O_1O_1' – the axis of the cylinder of radius r by which the shape of the crystal end face was treated; II' – the focal line in which the tangentials to the bent planes meet according to the well-known geometrical theorem.

with dimensions of $2 \times 15 \times 70$ mm^3 (width, height and length along the beam) and orientation (111) were used in this experiment. The crystals were bent to conform to a cylinder of radius $R = 2.7$ m over a length of 65 mm. To have different focusing lengths, the exit end faces were treated so as to conform to cylinders of different radii (the angles of cutting the focusing edge were changed too in accordance with the geometry shown in Fig. 5).

A beam of $\sigma_x = 2$ mm width having the small angular divergence of $\sigma_\theta = 0.1$ mrad was incident on this crystal. The focusing effect was recorded by a few layers of nuclear photoemulsion placed at different distances from the exit end face of the crystal. The intensities of the direct beam and of that bent by the crystal by the angle of 24 mrad were measured with scintillation counters. Fig. 6 demonstrates the image of the beam focused by the crystal #3 at the distance of 0.5 m (the most rigid focusing) from the exit end face of the crystal. The right-hand side of Fig. 6 shows the image of the focused beam for the crystal #3 under microscope.

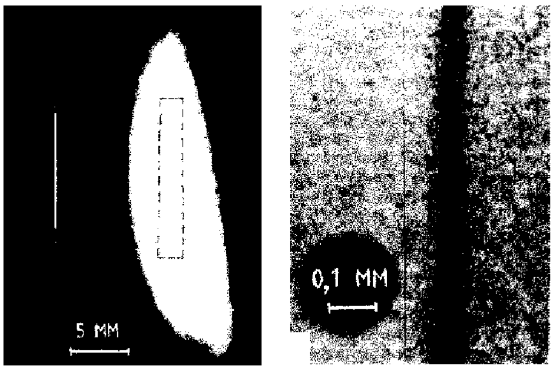

Fig. 6. The image of the beam focused by the crystal #3. The profile of the deflected and focused beam is seen on the left-hand side. Dashed line shows the cross section of the crystal. The right-hand side shows the microscope picture of the focused beam (focusing at the distance of 0.5 m).

The way of the focusing technique implemented in this work may be used to obtain pure micron-size beams of TeV energy at a new generation of accelerators.

Another important application of a focusing crystal may be related to the reverse motion of particles – transformation of the beam diverging from a point-like source into a parallel one. To do this, the crystal entry end face must have a special shape.

The experimental investigation of the efficiency of capture and deflection of the beam diverging from a point-like source was made on the extracted 70 GeV proton beam of the IHEP accelerator [9]. The experiment used bent by 6 mrad silicon crystal with dimensions of $2 \times 20 \times 30$ mm^3. The focusing length of entry end face was 2.5 m (angular acceptance of ± 400 μrad). According to measurement, the beam at the exit of the crystal was of 40 μrad divergency and contained 15% of the protons incident into its end face.

The achievements reached in the study of the processes of channeling high energy particles in a bent crystal stimulated an interest to application of a bent crystal for an extraction of beams of TeV energy accelerators (LHC and SSC). It was proposed to use the Tevatron at Fermilab as a test tool for the beam extraction (see Fig. 7) [10].

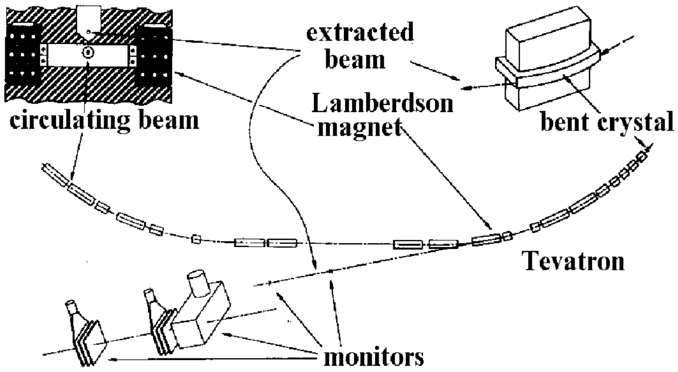

Fig. 7. The scheme of the experiment E853 on beam extraction from Tevatron (Fermilab, USA).

In order to carry out this experiment, principally new solutions in an accelerator technique and a goniometer equipment were needed; besides, new requirements for perfection of a crystal and for quality of its treatment have arisen.

To solve these tasks, new methods of studying the purity of a raw material (silicon) and the perfection of its crystal structure, as well as the new methods of treating crystals, their precise orientation and cutting along the crystallographic directions, removing the destroyed layers from the crystal surfaces were worked out and tested at PNPI [11].

As a result of several experiments performed during 1994–1996, the possibility to extract the 900 GeV beam with the intensity up to 10^9 1/s for the impulse mode (or up to 10^6 1/s for the "expanded" mode) without disturbing the main collider experiments was demonstrated [12] – see Fig. 8.

Fig. 8. The picture of the extracted beam on the monitor screen.

The effect of spin precession of channeled particles in bent crystals

Besides application for the deflection of high-energy beams, bent single crystals open new possibilities to measure magnetic moments of short-lived particles.

In 1979 Baryshevskii pointed out that spins of particles should precess if the particles were channeled in a bent crystal. In such a crystal an electrostatic field of the atomic planes deflecting the particle transforms into a magnetic field in the particle's rest frame. Thus, the spin precession angle φ is $\varphi = 1/2\gamma\theta(g-2)$ (for $\gamma \gg 1$), where γ is the Lorentz factor, g is the gyromagnetic ratio, and θ is the deflection angle of the channeled particle. From the measurement of φ and θ of the channeled particle one can determine g and, hence, the particle's magnetic moment $\mu = geS/2mc$, where e, m and S are the charge, mass and spin of the particle, respectively. Because of superstrong fields inside a crystal, the angle of precession of the particle's spin in the crystal of several centimeters length can be of several radians, that is of a measurable value.

In the experiment [13] the spin precession of channeled Σ^+ hyperon in a bent crystal was observed for the first time. The apparatus consisted of a hyperon spectrometer (one dipole magnet and three sets of silicon strip detectors) and a baryon spectrometer (two dipole magnets and four sets of multiwire proportional chambers). The mean Σ^+ beam momentum was determined by the hyperon channel geometry and by the value of magnetic field to be 375 GeV/c with a full momentum spread of $\Delta p/p = 7\%$. The measured polarization of the Σ^+ hyperon was $12 \pm 1\%$. At 10 m from the target the beam composition was about 1% of Σ^+ hyperons, the rest being mostly pions and protons.

Two bent Si crystals (see Fig. 9) were installed downstream of the hyperon spectrometer at the beginning of the decay region. The crystals oriented along their (111) planes were $25 \times 0.4 \times 45$ mm^3 in dimensions and were bent accordingly to the three-points scheme [14]. The upper crystal deflected the beam down and the lower crystal deflected the beam up. The deflection angles were the same. As anticipated, the spins in the two crystals precess in opposite directions (see Fig. 9).

The vertical beam size (FWHM) at the Z-position of the crystal was 1.8 cm with the vertical divergence of 1.4 mrad. Only a small fraction, $\sim 2.5 \cdot 10^{-4}$, of the beam particles was channeled.

The eight semiconductor detectors implanted on the surface of each crystal (each of them

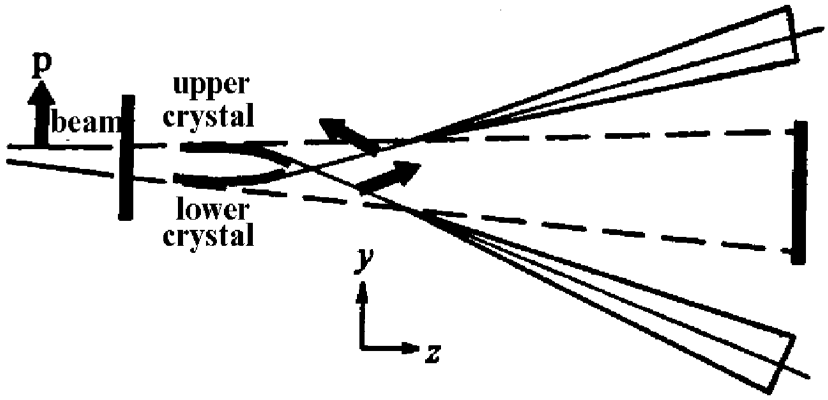

Fig. 9. The scheme explaining the effect of spin precession in bent crystal.

was 2.5 mm along the beam) allowed to measure the ionization losses of particles traversing the crystal.

The channeled particles were identified by deflection angle θ and relatively low ionization losses inside detecting structures of the crystals. The deflection of the channeled particles was measured to be $\theta = 1.649 \pm 0.030$ mrad and 1.649 ± 0.043 mrad for the up-bending and down-bending crystals, respectively (the spin of the Σ^+ hyperons should precess by $\varphi \sim 1$ rad).

For the measurement of the polarization, the mode $\Sigma^+ \longrightarrow p\pi^o$, responsible for 52% of the Σ^+ decays, was separated. The precision of the decay vertex measurement in the 10 m decay region was 50 cm. Selection criteria using restrictions on kinematics variables left 2167 ± 47 events in the final sample.

The $\Sigma^+ \longrightarrow p\pi^o$ decay mode has a large asymmetry parameter $\alpha = -0.98$ making it a sensitive analyzer of Σ^+ polarization. The Σ^+ polarization components were determined for each crystal. These polarizations are plotted in Fig. 10 in comparison with calculated vectors. The measured precession angles for the up-bending and down-bending crystals were $+51° \pm 23°$ and $-72° \pm 26°$, respectively. The average of the experimental value of $60° \pm 17°$ is consistent

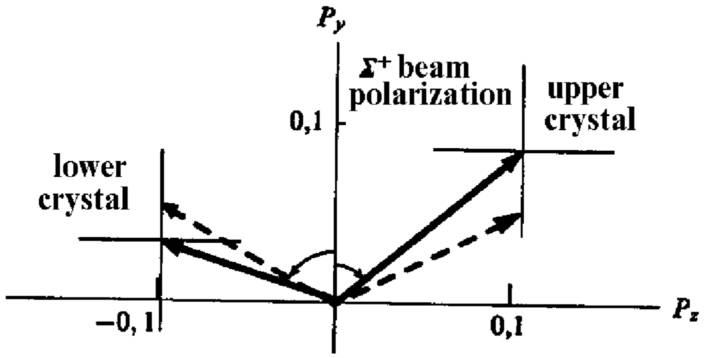

Fig. 10. Measured polarizations and uncertainties (1σ statistical errors) after spin has been precessed by the two crystals. The dashed arrows show the expected precession.

with the theoretically predicted value of $62° \pm 2°$.

For the two crystals the average of the absolute values of the polarization vectors is $P = 11.8 \pm 3.6\%$ consistent with the value of $12 \pm 1\%$ measured without the Σ^+ precession by the crystal. It means that there is no evidence of depolarization during channeling.

The Σ^+ magnetic moments derived from the up-bending and down-bending crystals are $2.15 \pm 0.61\,\mu_N$ and $2.74 \pm 0.71\,\mu_N$, respectively ($\mu_N = eh/m_p$ is the nuclear magneton). Their average of $\mu = 2.40 \pm 0.46\ \mu_N$ is consistent with the experimental world average of $2.42 \pm 0.05\ \mu_N$. Systematic uncertainty was not more than $0.40\ \mu_N$. This experiment has confirmed the effect of spin precession for particles channeled in bent crystals. It has been proposed to use this method for measurement of the magnetic moment of Λ_c^+ baryon [10].

Conclusion

Observed effect of volume capture has enriched our knowledge on process of passing the particles through a bent crystal, and it is taken into account when one chooses and optimizes different crystaloptical devices for particles of high and super-high energies. The methods, devices, and technologies developed at PNPI during many years of activity have allowed to realize in practice different crystaloptical elements to control beams of high energy particles. Experimental observation of the effect of spin precession of channeled particles in a bent crystal has allowed to create the method for measurement of the magnetic moment of short-lived particles such as charm baryons.

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