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Deflection of Charged Particles in the Hundred GeV Regime Using Channeling in Bent Single Crystals*

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Abstract

An experiment has been carried out to observe the deflection of charged particles by planar channeling in bent single crystals with momenta between 12 and 180 GeV and with angular deflections up to 27 milliradians. Anomalous losses of particles from the center point of a three point bending apparatus have been observed at high incident particle energy. This effect has been employed as a "dechanneling spectrometer" to study dechanneling effects caused by bending. The bending losses generally conform to theories of bending dechanneling based on the classical channeling model.

What happens to a particle in a channeled trajectory if the crystal through which it moves is bent? Bending the crystal is equivalent to introducing a rising centrifugal potential, thereby lowering one side of the continuum potential well and raising the other. This causes the equilibrium trajectory to move away from the centerline toward the plane on the outside of the curved channel. In effect, the critical angle for channeling decreases resulting in a loss of channeled particles because of "bending" dechanneling. Tsyganov[1] has calculated the radius of bend at which no particles would remain channeled to be:

$$R_T = E/eE_c \qquad (1)$$

where E is the total energy of the particle and E_c is the interatomic field intensity at the distance from the plane of the crystal lattice where the trajectory of the particle no longer remains stable due to its interactions with individual atoms.

The "Tsyganov radius" for a 100 GeV particle moving in a (110) plane in silicon is about 16 cm so that a 1 cm arc of silicon with constant curvature could deflect particles up to 60 milliradians. More complete analyses such as those of Ellison[2], Kudo[3], and Vorobiev and co-workers[4] suggest that most particles would be lost at radii of curvature considerably larger than the Tsyganov radius.

Tsyganov et al[5] studied channeling in bent crystals for the first time at Dubna looking principally at particle transmission in bent planes. The experiments were performed in an 8.4 GeV proton beam using silicon crystals. An experiment concentrating on axial bending has been carried out by a CERN-Aarhus group[6] using 12 GeV/c particles.

One limitation of these experiments is the short dechanneling length at medium energy. At 10 GeV the planar electronic dechanneling length is on the order of a centimeter based on diffusion theory, measurements at MeV energies scaled to higher energies, and measurements in the Dubna experiment[7]. For characteristic bending arcs many of the particles will be lost to ordinary dechanneling. It is also difficult to approach the Tsyganov radius at medium energy with conveniently thick crystals, (0.5 mm in the direction of bending) because they break.

Carrigan, Gibson, Kim, Sun, and Tsyganov[8] have explored the possible applications of bent crystal channeling. These applications include bends for primary and secondary particle beams, the deflection of charm particles, and the measurement of charm particle magnetic moments. All of these possibilities seem to improve at higher energies[9].

These reasons - less dechanneling, the possibility of approaching the Tsyganov radius, and the enhanced opportunities for applications - are the motivation to carry out studies of bent crystal channeling in the 100 GeV regime. The major objective is to understand the nature of channeling losses as the crystal curvature increases, that is the radius of curvature decreases.

The technique followed in this experiment was similar to that used earlier by the CERN-Aarhus[10] group at medium energy and by our group at the highest energies where channeling has been observed[11]. Two sets of drift chambers with good resolution[12] were placed upstream of the crystal to determine the incident particle direction and the point of impact on the crystal while a third set downstream determined the angular deflection.

The crystals used were slabs of silicon between 0.5 and 1.0 mm thick in the direction of the bend, several centimeters long in the direction of the beam, and approximately one centimeter in height. Typically they were operated with a surface barrier detector near the upstream end with electrodes covering approximately three-quarters of the height of the slab 3 mm along the direction of the beam. These detectors were used to align the crystal and to select particles channeled in the initial, unbent portion of the crystal. Crystals were used with either a (110) or (111) plane parallel to the major face of the slab. The crystals were fabricated so that this plane was characteristically within 1.7 mrad of the geometrical surface of the crystal[13]. This was verified in the experiment both by angular distribution measurements on low energy losses and by noting that narrow slices of incident particles taken near a surface did not exhibit substantially different behavior than slices in the interior for fully deflected particles.

The silicon slabs were clamped near their upstream end just after the detector. The bending apparatus was attached to the downstream end and bent a crystal by deflecting it inside a system of 3 or 4 pins. This arrangement avoided the need for substantial realignment after changing the bending angle. Typically the pin diameter was 3.2 mm. The crystals were mounted in an automated, computer-controlled goniometer with two tilt (θ_X, θ_Y) and azimuthal, ϕ, degrees of freedom. A set of scintilation counters and the detector on the crystal were used to trigger the system.

Measurements were made using several crystals, aligned for planar channeling, for several combinations of bend angle and energy. For each particle passing through the crystal the drift chamber coordinates and the energy loss in the detector were recorded. The incident and emergent particle directions and point of impact relative to the crystal were determined from this information. A range of bend angles was studied for particle momenta between 12 and 180 GeV/c.

In the same experiment data were also obtained for axial bending and for negative particle behavior. These results will be reported separately. More complete information on the experiment appears in the thesis of S.M. Salman[14].

Figure 1a shows typical angular distributions for emergent particles from a three point bending apparatus taken at three energies. Selection of particles that exhibited low energy loss in the semiconductor detector insured that the particles were channeled in the upstream (unbent) region of the crystal in the

(111) wide planes. If it is assumed that the crystal is an elastic beam and that no local distortion is produced by the pressure of the bending pins on the crystal, then the three point bender induces a piecewise cubic shape in the crystal with the smallest radius of curvature at the center pin.

In all cases there is a peak in the forward (undeflected) direction which is due, in part, to channeled particles that dechannel before the bend. At +12 GeV/c there is a prominent peak in the direction corresponding to the full deflection of the crystal. The angular width of this fully deflected peak corresponds to about twice the critical channeling angle indicating that these particles were well channeled during their passage through the crystal. As the incident momentum is increased an intermediate peak emerges at half the total bend angle. For angles somewhat beyond the middle peak but less than the full bend peak there are few particles, suggesting that the particles are very well channeled between the middle and final peak. The middle peak is clearly associated with the center point of the three point bender. As the momentum is increased from 12 to 60 GeV/c the prominence of both the intermediate and full angle peak increases. However, when the momentum is increased to +180 GeV/c both peaks drop substantially. This indicates that the radius of curvature is small enough so that a large fraction of the particles are being lost to bending dechanneling.

Figure 1b shows data for a four point bender for a total angular deflection of 10 milliradians cut on low energy loss. For a four point bender the deflection of an elastic beam between the two inner pins should be a circle. In addition, for the situation in Figure 1 the force exerted by an inner pin is forty times smaller than the middle pin in the three point bender. No middle peak is visible although small losses occur at angular points corresponding to the two inner pins. There is no prominent middle region loss but a gradual loss with angle.

Understanding the origin and intensity of the observed peaks in the emergent direction spectrum as well as the intensity of particles emerging in directions between the peaks is important for practical applications as well as for understanding the fundamental dechanneling processes in elastically deformed crystals.

Measuring the dechanneling of particles due specifically to bending is complicated by several effects. Ordinary "electron" dechanneling occurs in the portion of the crystal after the detector and prior to the bend, but is not included in the present bending dechanneling theories. Crystals bent gradually should produce dechanneling only between the first and second pins of the bending apparatus[15]. There is expected to be no dechanneling due to the bending in regions in which the curvature is constant or decreasing. This is evident in the distributions shown in Figure 1, especially for the three point bender, where a larger emergent particle intensity occurs between the first and second pins

(θ_b=1-2 mr) compared to that between the second and third pins (θ_b=5-6 mr). This type of slowly varying curvature we call "global curvature". The prominent intermediate peaks are not, however, predicted by 'global curvature' dechanneling effects.

For both three and four point benders the intermediate peaks appear at angles corresponding to the position of contact of the pins used in the bending apparatus. Additional dechanneling could arise from the high local pressure exerted by the bending pins either causing local elastic distortion or generating defects in the crystal. We do not believe that the peaks are due primarily to defects induced by the pins. Such defects should remain after the pressure is removed, but measurements in a four point bender of a crystal previously bent in a three point bender did not show a peak at the position corresponding to the middle pin point of contact in the three point bender. However, some contribution from defect generation cannot be excluded.

We believe that the principle origin of the intermediate peaks is local curvature in the region of the pins. Such distortion has been discussed in classical treatises on elastic deformation by Timoshenko and Goodier[16], Love[17], and Frocht[18]. The distortion is greatest near the pin and decreases to zero on the side of the crystal opposite the pin. This dependence on position in the crystal slab can be investigated directly since the point of impact on the crystal can be determined by use of the drift chamber immediately in front of the crystal. The spatial resolution of the drift chambers ($\sigma_x \simeq$ 60 microns at 60 GeV/c) is such that slices of the crystal transverse to the beam can be examined close to and far away from the pin. Figure 2 shows the dechanneled fraction at the middle pin in a 3 point bending apparatus as a function of position away from the middle pin for particles with low energy loss at +60 GeV/c. The dechanneled fraction was computed as the ratio of the particles dechanneled at the pin divided by the sum of the particles dechanneled plus the particles that continued on.

If the local curvature predicted by elastic deformation theory is accepted, then it is possible to utilize the effect as a "dechanneling spectrometer" to compare the observed dechanneling to that calculated from classical continuum models[2,3,4]. We call this the 'local curvature' method. It has the useful feature that it is reasonable to assume that all particles that make it through the crystal to the center peak were well channeled up to that point. This approach minimizes the effects of normal dechanneling and of misalignment since the bending losses occur over a short distance along the crystal.

Figure 3 shows measurements of the dechanneled fraction vs. K (where K is the product of the particle momentum divided by the radius of curvature). Also shown are results of continuum model calculations by Ellison[2] for particles channeled between the (111) planes of silicon. The Ellison theory was developed for a constant curvature configuration. Note that theories of bending are sensitive to the assumed potential and the number of planes used in calculating the potential[3]. Two cases of the Ellison theory are shown. The curve to the right is for the wide planes with no charge smearing for nuclear motion. The left curve includes charge smearing and is averaged over both narrow and wide planes. Note, however, that the average curve should lie somewhat nearer the wide plane case. The curvature is computed using a finite element program. The local distortion is actually quite complex. For example, details of the pin contact may influence the distribution. Several sets of points taken at different distances from the middle pin are shown. The points indicated by squares are for positions very near the pin (a cut where $0.0625W < x < 0.1875W$ and w is the crystal width). In that region most of the curvature is due to local distortion so that the points should be less affected by normal decanneling. On the other hand the curvature is changing rapidly so position resolution becomes an important source of error. The diamond points are from the side of the crystal away from the pin where there should be little local distortion. One of the points is for a 4 mrad bend while the others are for 8 mrad. The experimental points follow the general trend of the theory.

In view of the approximations contained in the "local curvature" analysis there is no support for selecting a particular theory or potential. However the data do show that the continuum calculations give the observed functional dependence and constitue a reasonable basis for estimating the transmission of channeled particles through bent crystals. As the Ellison and Kudo theories have already indicated, there will be major losses prior to reaching the Tsyganov radius.

Comparison of losses in the global region to theoretical predictions is more difficult because of the complicating effects of electronic dechanneling, changing curvature and the distortion of average trajectories by the curvature with a concomittant effect on electronic dechanneling.

Based on these measurements, it appears that the present theory is a useful guide for estimating the loss to dechanneling due to bending. In a practical application[8], it will be necessary to avoid dimpling of the crystal due to the bending pins. This can be done by using more pins or a continuous clamp. Clearly, crystal deflection of particles offers interesting opportunities for experiments, particularly at TeV energies.

Use of the three point bender as a dechanneling spectrometer also offers a unique approach to studying ordinary dechanneling lengths. These will be reported in a later article.

We have also made a number of measurements on possible radiation damage effects. Broadly, no significant degredation of crystal performance is seen at fluences of $10^{17}/cm^2$.

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Figure Captions

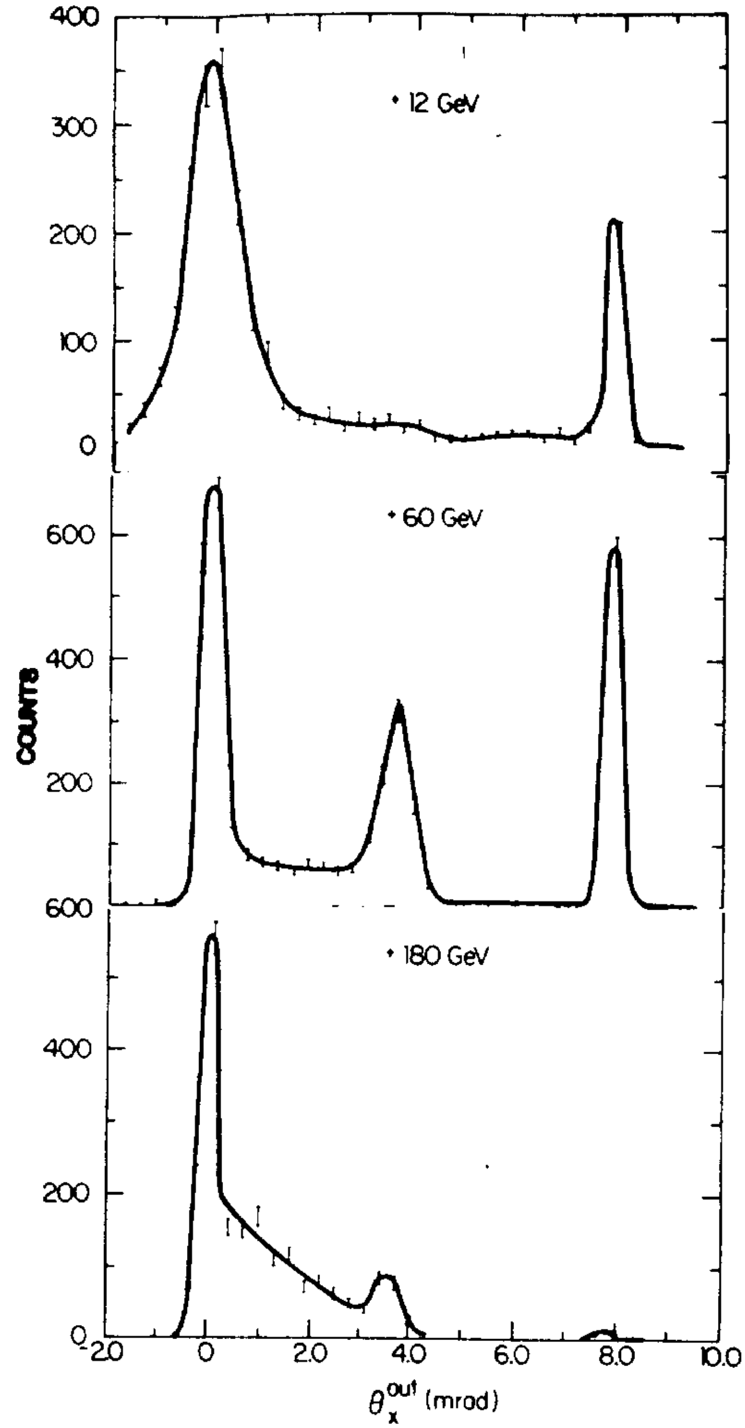
1.a. Angular distribution of outgoing particles which have small energy loss in the detector for a crystal bend of 8 milliradians and incident momentum of +12, 60, and 180 GeV/c using a three point bender. The peak at 0 milliradians, the beam direction, is due mostly to particles dechanneled prior to the bend. Note the peak at approximately 4 milliradians that develops as the energy is increased.

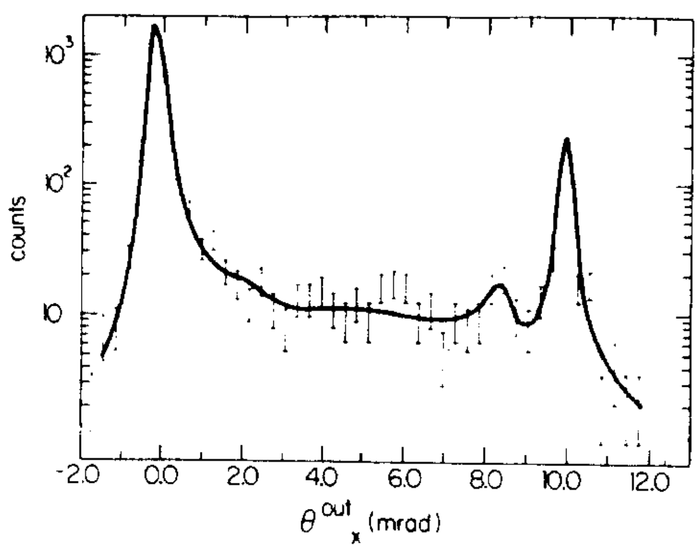
1.b. Angular distribution of outgoing particles which have small energy loss for a four point bender and incident momentum of +60 GeV/c. Note that there is no half angle loss and little loss at the two middle pins. (Note that the y axis is logarithmic.)

2. Dechanneled fraction as a function of position across a crystal in a three point bender for particles with low energy loss at +60 GeV/c. Other momenta exhibit somewhat similar behavior. The line has been drawn to guide the eye. The left hand side of the figure is adjacent to the middle pin. The error bars include only the statistical uncertainties.

3. Comparison of dechanneled fraction as a function of K where K is defined in the text. The theoretical curves are taken from Ellison[2] for the (111) plane in silicon. The right curve is for wide planes with no charge smearing while the left curve includes charge smearing and is avenged over planes. CF shows the point predicted by the Tsyganov centrifugal force calculation for the charge smeared case. Experimental points are based on the losses at the middle pin in the three point bender.

Figure 1


400
300
200
100
0
+ 12 GeV
600
400
200
+ 60 GeV
COUNTS
+ 180 GeV
-2.0
0
2.0
4.0
6.0
8.0
10.0
θ_x^{out} (mrad)


10^3
10^2
10
counts
-2.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
θ^{out}_x (mrad)

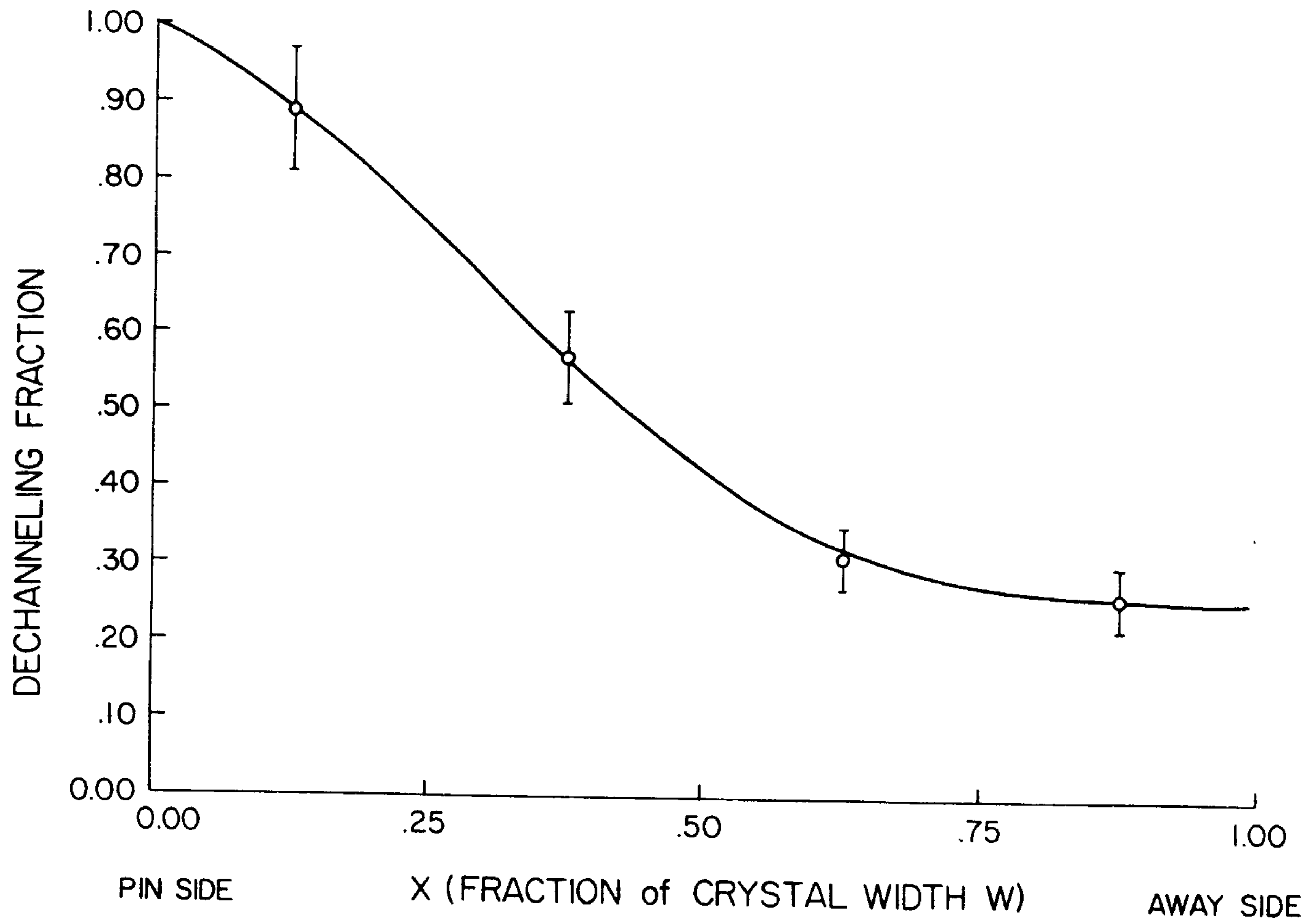

DECHANNELING FRACTION
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0.00
0.00
.25
.50
.75
1.00
PIN SIDE
X (FRACTION of CRYSTAL WIDTH W)
AWAY SIDE

Figure 2