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Observation of high deflection efficiency and narrow energy loss distributions for 450 GeV protons channeled in a bent silicon crystal

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Abstract

A 450 GeV/c proton beam has been deflected by various angles from 1 to 11 mrad using planar channeling in a (111) silicon crystal which was mechanically bent to achieve the desired beam deflection. High deflection efficiencies of up to 50% have been measured, in good agreement with present theoretical estimates. It is shown that bent crystals are also a unique tool for measurements of energy loss and straggling of channeled particles, without any influence from random particles: Selecting protons which are deflected by increasing angles corresponds to decreasing the transverse energy at the crystal entrance. With this technique energy loss and straggling was measured for protons channeled in the wide and narrow (111) planes in silicon for the first time.

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1. Introduction

Deflection of high energy protons using the channeling effect in bent silicon crystals has been studied since several years [1,2]. While the attractive features of bent crystals as beam splitters to produce low intensity test beams was of prime interest in the earlier studies at FERMILAB [3], the possible application for a new CP-violation experiment lead to more detailed studies with 450 GeV/c protons at CERN [4-7]. Recently, the ultimate limitations of deflecting high energy protons in bent crystals have been much debated in the context of proposals to extract protons for fixed target experiments from the halo in the future multi-TeV hadron colliders SSC and LHC [8,9]. The expected properties of the extracted multi-TeV proton beam depend on simulations of the proton distribution in the halo of the collider [10] and on the theoretical estimates of the deflection efficiency for protons in perfect bent crystals [11].

The present experiment aims at testing the understanding of channeling and dechanneling by a quantitative comparison of measured deflection efficiencies in bent silicon crystals with theoretical estimates for different crystal curvatures. The bent crystal was equipped with an intrinsic solid state detector, which is a unique tool for measuring energy loss and especially straggling for channeled particles. The use of a highly parallel beam allowed for the first time to perform accurate measurements of these parameters and in particular to study the energy loss distributions for proton channeling in the wide and the narrow (111) planes in silicon

2. Theory

Positively charged particles entering a silicon crystal at small angles with respect to a major plane are channeled, i.e. steered away from regions of high electron density, and thus experience less energy loss, multiple scattering, nuclear interactions etc. than particles incident far away from such directions, i.e. at so-called "random directions". In a first approximation, the atomic plane may be described by the Lindhard continuum potential [12],

$$Y(y) = Nd_p \int 2\pi\rho d\rho V(\sqrt{y^2+\rho^2})$$

obtained by averaging the electric potential V from all atoms over a crystal plane. Here, Nd_p is the average number of atoms per unit area, y the distance to the plane and d_p is the distance between planes. The function $Y(y)$ is the potential energy for the transverse motion in the crystal. The kinetic transverse energy takes the form $E_{\perp,kin} = 1/2pv_{in}^2$, where ψ_{in} is the angle to the plane. The total transverse energy $E_{\perp} = E_{\perp,kin} + Y(y)$ of channeled particles is conserved to first approximation. It should be pointed out that this transverse motion may be described classically [12].

For particles incident on a crystal at an angle ψ_{in} to the plane, $E_{\perp}$ equals $1/2pv_{in}^2$ outside the crystal. Upon entrance the particle achieves a potential energy $Y(y_{in})$, where y_{in} is the position at the point of entrance, but the kinetic energy is

unchanged, i.e. $E_{\perp} = 1/2pv\psi_{in}^2 + Y(y_{in})$ inside the crystal. The basic quantity determining the conditions for channeling is the critical angle ψ_p which corresponds to a critical value of $E_{\perp} \leq Y(y_c)$, below which channeling effects set in - the particles are trapped in the potential $Y(y)$. It follows that $\psi_p = (2Y(y_c)/pv)^{1/2}$, where $Y(y_c)$ is the planar potential at a distance y_c to the plane where planar channeling becomes unstable. For 450 GeV protons incident along the wide (111) planes in silicon $\psi_p = 9 \mu\text{rad}$ and for the narrow planes $\psi_p = 3.6 \mu\text{rad}$ (for details see ref. 13). Here it should be remembered that the (111) planes consist of two sets of planes: the wide ones with $d_p = 0.43d_0$ and the narrow ones with $d_p = 0.14d_0$. The lattice constant is $d_0 = 5.431 \text{ \AA}$ in silicon.

As a consequence of the abrupt change of $E_{\perp}$ at the crystal surface, mentioned above, a beam of particles incident on a crystal surface separates into two kinds of particles inside the crystal: The "random" particles, for which $E_{\perp} > Y(y_c)$, and the channeled particles, for which $E_{\perp} < Y(y_c)$. This implies that even for a perfectly parallel incident beam of GeV particles the so-called "surface transmission" amounts, e.g. in the case of the wide (111) planes in silicon, to a maximum of 75% being channeled inside the crystal.

In straight crystals, the protons once channeled can be lost by scattering on electrons and nuclei - they are dechanneled. In a bent crystal, however, additional dechanneling may occur: due to the curvature of the crystal the potential Y is asymmetrically lowered by a centrifugal term,

$$Y_{\text{eff}}(x) = Y(x) - pv\kappa x$$

Here, κ is the curvature of the crystal, x is the distance from the mid-plane between two atomic planes. Clearly in the bent crystal the particles are subject to an additional force, the centrifugal force, perpendicular to the bent planes. In Fig. 1 the potential $Y_{\text{eff}}(x)$ is shown for various κ [2]. Here, the minimum is shifted towards the outer plane for increasing bend angle (i.e. curvature). Furthermore, the outer potential barrier decreases, such that only particles with low transverse energies may remain channeled for the full length of the crystal. When combining the effects of multiple scattering and bending dechanneling (i.e. the result of the centrifugal term), one finds that the efficiency of deflection in bent crystals is determined by the length and the maximal curvature of the crystal [2, 14]. Selecting protons deflected through increasing angles corresponds to selecting smaller and smaller $E_{\perp}$ at the crystal entrance. Since the critical angle $\psi_p \propto (Y(y_c))^{1/2}$, increasing bend angle also corresponds to decreasing the critical angle. Some of the channeled particles entering the bent part of the crystal will be dechanneled in those parts of the crystal where the curvature increases. On the other hand, no dechanneling due to bending is expected in the part of the crystal where the curvature is constant or decreasing [15].

In addition to a detailed study of the parameters influencing the deflection efficiency in a bent silicon crystal, the present experiment provides also accurate results on energy loss and straggling of channeled protons. In previous energy loss measurements for randomly directed and channeled GeV particles [16,17], one issue was to find the best method to measure these quantities. It is well known that at high

particle velocities the energy loss for random incidence receives roughly equal contributions from distant resonant excitations and from more violent close encounters. Channeled positive particles of low $E_{\perp}$ are restricted to crystal regions of low electron densities leading to (1) channeled energy loss being only around half that of the random one, and (2) the energy loss distributions (straggling) being considerably narrower because of fewer close collisions. The channeled energy loss and straggling for GeV particles is however not easily accessible experimentally. Here, single crystals turned into solid state detectors proved to be a major step forward [16,17]. It still remained an open question what experimental parameters would be best suited to characterise the energy loss for the best channeled particles, i.e. those with the lowest $E_{\perp}$. Normally, this quantity is extracted from the low energy loss side either by taking the minimum (the leading edge), the energy loss at half maximum $\Delta E_{1/2}$ (these parameters are proportional to the crystal thickness) or the most probable energy loss. All three parameters were found to be rather insensitive to the angular cuts chosen in the analysis of energy loss for channeled particles [17]. The widths of the energy loss distribution on the other hand are very sensitive to these cuts in angular space. In the detailed investigations of refs. [16,17], where only straight crystals were used, it was not possible to avoid contributions to straggling from random particles. A bent crystal provided with a fully depleted intrinsic solid state detector on the straight part at the entrance has in the present experiment been used for such investigations.

3. Experimental Arrangement

The measurements were performed in continuation of our earlier tests at the H8 beam in the North Area of the CERN SPS [5,6]. The experimental arrangement is schematically shown in Fig. 2a. The bent silicon crystal is mounted on a goniometer turntable with $1.7 \mu\text{rad}$ stepsize. The incident and exit position of the protons are measured in two drift chambers, one 20 cm upstream, the other 4.1 metres downstream of the crystal. Three scintillators are used to trigger on protons passing through or near the crystal. An additional scintillator (SC4) is used to veto events for which the incident proton undergoes a nuclear interaction in the crystal or the bending device, thus reducing the uniform background in the drift chamber beam profiles. The silicon crystal, 50 mm long in beam direction, 10 mm wide and 0.9 mm thick, was cut parallel to one of the (111) planes. It was mounted in a classical 3-point bender for deflection in the horizontal plane (see Fig. 2b). At each end of the crystal there were 10 mm long straight section. The bending was varied by a thumb-screw. A surface barrier detector was produced on the straight entrance part of the crystal, allowing measurements of the dE/dx of protons hitting the crystal. Protons channeled between the wide (111) planes have about 60% of the energy loss of unchanneled ones - therefore, the dE/dx spectrum of this detector allows to align the crystal with respect to the proton beam, and to tune the beam.

In Fig. 3a is shown the energy loss spectrum from the detector measured for all incident particles when the crystal planes are aligned with the beam. Around 65% of the incident beam is captured in the wide (111) planes, as reflected by the larger peak around channel 55. The beam particles giving an energy loss signal corresponding to random incidence consist of those not channeled at the entrance due to the limited surface transmission and a small contribution from those

protons channeled between the narrow (111) planes, having a mean energy loss slightly larger than random (see below).

The 450 GeV proton beam was set up to be highly parallel in the horizontal (deflection) plane and focused in the vertical plane (for further details, see [5]). While observing the fraction of channeled protons in the dE/dx spectrum in the aligned silicon crystal, the horizontal beam size was gradually increased in order to achieve the smallest possible angular spread for the fraction of protons hitting the crystal. Note that this method allows to tune the beam to an angular spread of a few microradians, beyond the accuracy reached with standard beam instrumentation. In ref. [6] the same beam line was used but the beam turned out to be more divergent than in the present measurements. Fig. 3b shows the intensity of low energy loss particles (channeled) as a function of angle to the (111) plane. The FWHM is around $17 \mu\text{rad}$, to be compared with $2\psi_p = 18 \mu\text{rad}$. The very steep sides of the distribution show that the horizontal beam divergence is less than about $3 \mu\text{rad}$, as in ref. [5].

4. Bending Results and Discussion

Measurements were performed at different deflection angles, i.e. different bending of the silicon crystals. A typical horizontal beam profile as measured in DC2 is shown in Fig. 4a for a 2.4 mrad deflection angle, with no condition on the energy loss spectrum. The intensity of the deflected beam is almost 50% of the total beam hitting the crystal, with about 35% of protons undeflected and 15% being lost due to dechanneling in the bent crystal. Fig. 4b shows the example of 8.1 mrad deflection angle. A vertical expansion of Fig. 4b is shown in Fig. 4c to demonstrate some details of the beam profile: the region between straight and bent beam is populated with tracks from protons initially channeled and then lost due to dechanneling. For comparison, the solid line in Fig. 4c shows the beam profile for an equal number of events incident on a non-aligned crystal (random orientation), i.e. all particles are in the straight beam peak. A characteristic feature of a 3-point bender is clearly visible in Fig. 4c: The dechanneling losses occur in the first half of the bent crystal, i.e. in the part with increasing curvature. Protons which are not dechanneled in this first part will be deflected by the full angle, i.e. end up in the bent beam peak as mentioned above. This can be well understood in the transverse energy description: the outer side of the channeling potential well (cf. Fig. 1) is lowest where the curvature is maximum, i.e. in the centre point of a 3-point bender.

For 3.7 mrad deflection a horizontal beam profile in DC2 is shown in Fig. 5a. Clearly there is strong dechanneling (the middle peak) at the point where the central pin pushes against the crystal. This middle peak is seen in almost all bending experiments using a 3-point bender. The strong dechanneling at this point is due to lattice distortion from the pressure of the pin. The distortion is greatest near the contact point of the pin and decreases gradually to zero on the opposite side of this point. In order to investigate this hypothesis, 0.2 mm wide slabs of the crystal were selected in DC1. In Fig. 5b is shown the dechanneling in the pin area for different slabs. Clearly for the central slab the middle peak disappears almost completely, so all data shown below are taken from the central region of the crystal (this also avoids effects of crystal miscut and surface quality). Note that the most pronounced

middle peak is found for the smaller bending angles which allow also the particles with higher transverse energy to follow the bend.

By integrating the particles between the random peak and the middle point, it is possible to estimate the bending dechanneling as a function of bend angle. Fig. 6 shows expanded views of the measured dechanneling rates ranging from the undeflected peak to the middle peak for 8.1 mrad deflection. In Fig. 7 is shown the measured rate of dechanneling (obtained from data as shown in Fig. 6) as a function of bend angle. The results are shown for bend angles 1.4, 2.4, 3.7, 4.7, 6.3, 8.1, 8.9 and 9.8 mrad. Dechanneling results have been obtained for the wide (111) planes only. The measured rate of dechanneling in the first half of the crystal is given as a function of $p \cdot \kappa_{\text{average}}$ and $p \cdot 2\kappa_{\text{average}}$. We assume a linearly increasing curvature (0 to $2\kappa_{\text{average}}$) for the first half of the crystal in an ideal 3-point bender. The curvature $2\kappa_{\text{average}}$ corresponds to the lowest value of the potential $Y(x)$ (Fig. 1). In Fig. 7 the experimental results are compared to a curve calculated by Ellison with charge smearing over the planes [11]. The agreement with the data shown as a function of $p \cdot \kappa_{\text{average}}$ is better, indicating the uncertainty on the curvature for our 3-point bender.

The deflection efficiency obtained from channeling in the narrow (111) planes has been investigated. A cut on the region of energy loss for random incidence, which contains also the particles channeled in the narrow (111) planes (see below), was applied. The number of bent particles found under these conditions corresponds to a contribution to the beam deflection of about 5% relative to the wide (111) planes. This holds only for the small bend angles; above 4 mrad, particles channeled in the narrow (111) undergo strong bending dechanneling.

The results of the present beam deflection experiment are shown in Fig. 8. Measured deflection efficiencies for various deflection angle from 1 to 11 mrad show values up to 50 %. The error bars indicate statistical errors only. Systematic errors due to mechanical or other instabilities may be deduced from the scattering of the data points - note that the experiment is sensitive to angular changes in the order of a microradian!

In Fig. 8 the experimental results are compared to the expected efficiency for an ideally bent crystal (uniform curvature) - practice has shown that this is difficult to achieve and it was not attempted in the present experiment. The theoretical estimate involves the following contributions: (a) The surface transmission was calculated for a perfectly parallel 450 GeV/c beam incident on a (111) silicon crystal and found to be 0.75. This is the ultimate efficiency possible for bending the 450 GeV/c beam in a (111) silicon crystal (it would be 0.82 for (110) silicon), independent of the length of the crystal or the perfection of the bending device, (b) the multiple scattering dechanneling in the straight parts of the crystal was included - this is an effect off a few percent at very high energies, and (c) bending dechanneling and multiple scattering dechanneling were considered in the bent part of the crystal - these effects determine the reduced efficiencies at the larger deflection angles.

In the present experiment, we used a 3-point bender, chosen for its simplicity (Fig. 2b). Estimates of the expected deflection efficiency for an "ideal" 3-point bender (maximum curvature in the centre equal to twice the average curvature) are also

shown in Fig. 8. The calculation includes the same terms as described above for uniform curvature, with the change of the bending dechanneling term due to the increase of the maximum curvature which was assumed to be twice the average curvature. The experimental results fall in between the two extreme models.

5. Energy Loss and Straggling using a Bent Crystal

As mentioned above, a bent crystal equipped with a detector can be used to obtain detailed information on energy loss distributions. In the present experiment, the detector (4 mm wide in beam direction) on the straight part of the crystal was used for dE/dx and straggling measurements. The spectrum for random orientation of the crystal is shown in Fig. 9a, where a curve representing a Landau function superimposed on a smooth background has been fitted to the data. In Fig. 9b we show the aligned energy loss spectrum with a residual random contribution due to surface transmission and dechanneling. In the energy loss peak for random incidence there is also a contribution from channeling in the narrow (111) planes. These planes should give aligned energy loss 10% above random (see ref. [17]). The squares correspond to protons bent 8.9 mrad. Here, the energy loss peak for random incidence has disappeared. Moreover the straggling is strongly reduced because the number of close collisions is reduced, particles having suffered violent close encounters having been dechanneled during the passage through the bent crystal. For comparison to earlier measurements, the energy loss spectra for random incidence and for channeling in (111) planar direction obtained with a divergent beam [17] are inserted in Fig. 9a. In these spectra strong limits on angle were imposed both on the incident and the exit side of the crystal, in order to reduce the contribution from random particles. Nevertheless, the energy loss peak from random incidence is substantially larger than in the present experiment.

In Fig. 9c we compare energy loss spectra for particles bent 1.4 mrad and 8.9 mrad. From these curves (Fig. 9c) it is clear that the steep energy loss side is essentially independent of bend angle whereas straggling is reduced by nearly 50% for the stronger bending. For increasing bend angle the outer potential barrier decreases, with the effect that only particles with progressively lower transverse energy will be able to follow the bend. Thus the steep low-energy-loss side corresponds to the particles channeled at the bottom of the potential well (i.e. deeply channeled with low $E_{\perp}$) - an interpretation that had been questioned in some earlier investigations [17]. A good parameter to characterise energy loss for the best channeled particles is found to be $\Delta E_{1/2}$. On the other hand Figs. 9b and 9c show that the most probable energy loss ΔE_p is somewhat dependent on $E_{\perp}$. For a deflection angle of 8.9 mrad (Fig. 9c), 10% of the originally channeled particles are deflected (Fig. 8). The energy loss for these particles corresponds to that for the deeply channeled ones. With reference to the most probable energy loss for particles at random incidence, ΔE_p (bent) is found to be 0.55 times ΔE_p (random). This is more than 10% lower than the result obtained in ref. [16]. On the other hand the results with an aligned crystal in ref. [16] are most likely diluted by random particles especially in the case of the silicon data (the critical angle is small). The energy loss distribution for particles deflected through 8.9 mrad (Fig. 9c) is almost Gaussian - indicating that nearly all close encounters (leading to the typical tail of a Landau distribution) with electrons in the channel have been excluded. A comparison with calculated distributions

could give values for the electron densities "seen" by the channeled particles. Such an analysis requires, however, high statistics dE/dx spectra for different bend angles and will be attempted in future investigations.

As mentioned above, the energy loss of the narrow (111) planes was calculated in ref. [17] to be around 10% higher than the random value using $\Delta E_{1/2}$. In the measurements of ref. [17] it was not possible to measure the energy loss distribution for these narrow planes because of contamination from random particles (see insert of Fig. 9a). Using bent crystals, it is now possible to remove the random contribution simply by considering the deflected particles only. In Fig. 10a is shown the energy loss spectrum for particles bent 2.4 mrad. Fig. 10b shows an expanded view of the spectrum where an exponential background is subtracted. Clearly there are two distributions - one from the wide (111) planes and one from the narrow ones. The experimental values are decomposed into the two distributions - the higher dE/dx corresponding to the narrow planes.

From these results $\Delta E_{1/2}$ for wide and narrow planes can be deduced. The ratio $\Delta E_{1/2}(\text{wide}) / \Delta E_{1/2}(\text{narrow})$ equals 0.52. This is in good agreement with the theoretical value of 0.54 calculated in ref. [17] and 10% higher than the random value, as can also be seen from the calculated energy loss curve inserted in Fig. 10a. In a recent Monte Carlo simulation, Biryukov calculated energy loss spectra in good agreement with the ones measured in this experiment [18]. Clearly, the straggling for the narrow planes is much broader than for the wide ones because the average electron density is high - leading to a large contribution from close collisions. Note that the energy loss distribution at higher dE/dx could be distorted by particles "fed in" to channeling conditions during passage of the detector. However, "feed in" could occur at any place in the detector, therefore such particles would give a uniform energy loss distribution and not a peaked one.

The present results open the way for new interesting energy loss measurements for channeled GeV particles. Esbensen and Golovchenko [19] calculated the path dependent energy loss for channeled GeV particles taking into account the density effect. In the case of random incidence, a Landau distribution is constructed to give the right mean energy loss whereas the shape of the distribution is determined by close collisions. In the same manner an energy loss distribution was constructed for the most-deeply channeled particles from the local electron density [18]. Due to experimental difficulties - contamination from particles with random incidence - a comparison with experimental data could not be made in the past [17]. In an experiment like the present one, using a bent crystal and the condition of deflected particles in the analysis of the energy loss spectrum, it is possible to exclude random contributions. Moreover, with detectors positioned also on the bent part of the crystal, one could measure dE/dx and straggling for increasing electron density simply by changing the bend angle of the crystal.

6. Summary

The present experiment has shown that it is possible to bend up to 50% of a 450 GeV/c proton beam - in agreement with theoretical predictions. The results are promising for the projects using bent crystals to extract protons from high energy

accelerators, where about 10% extraction efficiency has recently been obtained [20]. Moreover, bent crystals supplied with intrinsic solid state detectors are a unique tool to measure energy loss and straggling of channeled particles without any contribution from randomly oriented particles. The present experiment shows that a good parameter to characterise energy loss for the most-deeply channeled particles is the energy loss at half maximum on the low-energy-loss side, and that the most probable energy loss ΔE_p depends on transverse energy. Bent crystals with intrinsic detectors also on the bent part open new possibilities to measure path-dependent energy loss and straggling for channeled GeV particles. By increasing the bend angle the deflected particles "see" smaller and smaller electron densities in the crystal. For the first time, it has been possible to measure energy loss through the narrow (111) planes for GeV particles.

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Figure Captions:

- Fig. 1 Effective planar potential between two (110) planes in Si, spaced 1.92 Å apart. The full-drawn curve represents the potential in a straight crystal, the dot-and-dash curve the potential in a crystal with radius of curvature 400 cm, and the dotted curve the potential for a radius of curvature 100 cm at 120 GeV. The potential is measured in units of the maximum potential from a single plane.
- Fig. 2 a) Schematic view of the experimental arrangement. The bent silicon crystal is mounted on a goniometer turntable with 1.7 μ rad stepsize. Two driftchambers (DC, resolution 0.1 mm r.m.s.) are used to track the beam particles. Three scintillation counters (SC1,2,3) in coincidence serve as trigger counters. A large scintillator (SC4, 30*30 cm²) is placed off axis in order to veto particles interacting in the crystal.
b) Details of the bending device used to curve the crystal to variable radii. Two bars at 30 mm distance support the crystal, while pressing on the central part with a bar provides the curvature of the crystal. Also indicated is the energy loss detector at the entrance side of the crystal.
- Fig. 3 a) Energy loss spectrum in the front detector for aligned incidence of 450 GeV/c protons. The arrows indicate the energy loss window used during the scans to align the crystal with the beam (cf. Fig. 3b).
b) Intensity of low energy loss particles as a function of angle to the (111) plane.
- Fig. 4 a) Horizontal beam profile as seen in the downstream driftchamber DC2 for a deflection angle of 2.4 mrad. Undelected (in Ch 320) and deflected beams are clearly visible, the latter containing about 50% of all protons hitting the crystal. The region between the two peaks is populated by protons initially channeled and lost due to dechanneling during the passage along the bent crystal.
b) The same as Fig. 4a, for a beam deflection angle for 8.1 mrad.
c) Vertical expansion of Fig. 4b, showing the distribution of dechanneled protons between the straight and the deflected beam. The solid line indicates the same spectrum for a non-aligned crystal, where all protons are in the straight beam. For further details, see text.
- Fig. 5 a) Horizontal beam profile in DC2 for a deflection angle of 3.7 mrad, showing the straight beam (at Ch. 340) and the deflected beam (Ch. 490). The profile shows protons hitting the central 200 μ m of the crystal.
b) Expanded view of the area around the middle pin in Fig 5a. The dotted curve corresponds to the pin side, whereas the full drawn curve represents the central slab of the crystal and the dashed curve the side opposite of the pin.

- Fig. 6 Typical measurement of the fraction of dechanneled protons for a deflection angle of 8.1 mrad. The horizontal beam profile in DC2 shown here contains only protons which gave signal in the low energy loss peak (cf. Fig. 3a). The protons in the straight beam peak (0 mrad) stem from noise signals in the energy loss detector. The insert shows the identical profile with a vertically expanded scale.
- Fig. 7 Particles dechanneled in the first part of the bent crystal as a function of $p \cdot \kappa_{\text{average}}$ and $2p \cdot \kappa_{\text{average}}$. The theoretical curve is taken from Ellison [11]. Data points are obtained from beam profiles as shown in Fig. 6.
- Fig. 8 Comparison of experimental results (dots with bars indicating the statistical errors) with theoretical estimates for uniform curvature and an ideal 3-point bender. Details are explained in the text.
- Fig. 9 a) Energy loss spectrum as seen by the detector at the entrance of the silicon crystal, for random orientation of the crystal, showing the usual Landau distribution. Inserted is the result of an earlier measurement in a straight silicon crystal [17].
 b) The same as Fig. 9a, for an aligned crystal (open dots). The ratio of channeled (i.e. low energy loss) protons to unchanneled ones is about 3 to 1, indicating a surface transmission of about 75%. The black squares show the energy loss spectrum for protons which were deflected by 8.9 mrad through the bent crystal. Note that the energy loss distribution is narrower for these particles (see text).
 c) Comparison of energy loss distributions of protons deflected by 1.4 and 8.9 mrad, respectively.
- Fig. 10a) Energy loss distribution for particles bent by 2.4 mrad. Inserted is the theoretical $\Delta E_{1/2}$ as function of distance to the (111) planes (taken from ref. [17]). The left hand side of this figure corresponds to particles in the middle of the wide planar channel, whereas the right hand side corresponds to particles in the middle of the narrow (111) channel. Such particles should therefore experience an energy loss slightly above random.
- b) Expanded view of Fig. 10a, where a curve fitted to the data is shown. The fit includes two Landau functions and an exponential background. The distribution at larger energy loss corresponds to protons channeled between the narrow (111) planes experiencing an energy loss slightly above the one for random incidence (see text).

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10