First Observation of Magnetic Moment Precession of Channeled Particles in Bent Crystals

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Spin precession of channeled particles in bent crystals has been observed for the first time. Polarized Σ^+ were channeled using bent Si crystals. These crystals provided an effective magnetic field of 45 T which resulted in a measured spin precession of $60° \pm 17°$. This agrees with the prediction of $62° \pm 2°$ using the world average of Σ^+ magnetic moment measurements. This new technique gives a Σ^+ magnetic moment of $(2.40 \pm 0.46 \pm 0.40)\mu_N$, where the quoted uncertainties are statistical and systematic, respectively. We see no evidence of depolarization in the channeling process.

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Channeling of high-energy particles in bent crystals has been observed in the momentum range [1-5] of 1.7-800 GeV/c. This technique has already found applications [3-5] in the deflection of high-energy beams. Another possibly important application of channeling is the precession of the spin of a polarized particle. This may allow the measurement of magnetic moments in distances of only a few cm. The lifetimes [6] of baryons containing charm quarks are so short that they travel only a few centimeters even at the highest available accelerator energies. Because of these short lifetimes, classical spin precession techniques using conventional magnets would produce negligibly small spin precession angles.

It was pointed out by Baryshevskii [7] and Pondrom [8] that the magnetic moments of particles should precess if they were channeled in a bent crystal. The detailed precession theory has been developed by Lyuboshits [9] and Kim [10]. In a curved crystal the 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 [9]

$$\varphi = \gamma\omega(g-2)/2 \text{ for } \gamma \gg 1\,, \qquad (1)$$

where γ is the Lorentz factor, g is the gyromagnetic ratio, and ω is the deflection angle of the channeled particle. From a measurement of φ and ω of the channeled particle, we can determine g and hence the particle's magnetic moment,

$$\bar{\mu} = (ge/2mc)\bar{S}\,, \qquad (2)$$

where e, m, and $\bar{S}$ are the charge, mass, and spin of the particle, respectively. We expect [11] that channeling could be preserved for equivalent magnetic fields up to ≈ 1000 T, thus offering the potential of significant precession angles even when the length of the bent crystal is as small as 1 cm.

Modern hyperon beams [12] provide a tool for testing this concept [13]. Using a beam of polarized Σ^+ hyperons, we measured their spin precession in bent Si single crystals. With this result we determine the Σ^+ magnetic moment. The measurements [14] were performed as part of Fermilab experiment E761 which was designed to measure the asymmetry parameter [15] in the decay of polarized $\Sigma^+ \to p\gamma$. Figure 1(a) shows the relevant parts of the E761 apparatus [14,15] used in these measurements. The same components were used as in the asymmetry-parameter measurement [15] but some of the relative spacings were changed. The apparatus consists of a hyperon spectrometer (one dipole magnet and three

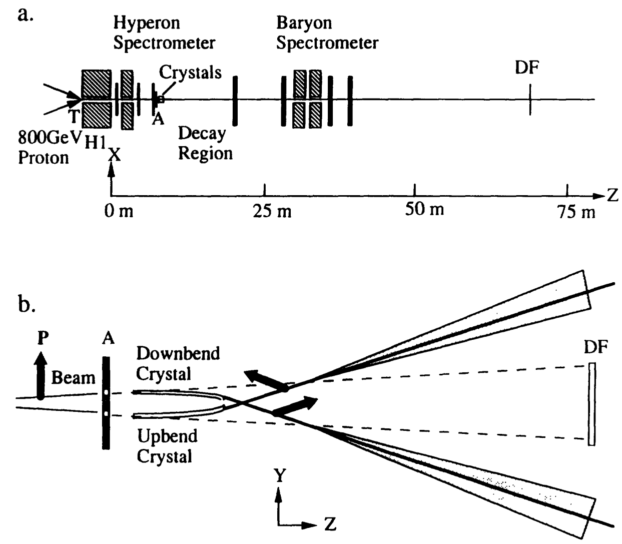

FIG. 1. (a) Plan view of the incident proton beam and spectrometer system. The horizontal scale (z) correctly illustrates the length of the apparatus, the vertical scale (x) is schematic only. (b) Elevation view of the channeling apparatus (not to scale). The arrows illustrate the spin precession in the crystals. Shaded areas depict the Σ^+ decay cone. The scintillation counters A and DF are part of the trigger and are described in the text.

clusters of silicon strip detectors) and a baryon spectrometer (two dipole magnets and four clusters of multiwire proportional chambers).

Two bent Si crystals were installed downstream of the hyperon spectrometer at the beginning of the decay region. The major faces of the crystals were cut along their (111) planes, which were oriented in the x-z plane [Fig. 1(b)]. Each crystal was $2.50\times0.04\times4.50$ cm^3 and was bent using a multipoint bending jig. The beam was incident on the 2.50×0.04-cm^2 face. The upper crystal deflected the beam down and the lower crystal deflected the beam up. The deflections were approximately the same. The crystal curvature produced an equivalent magnetic field B_x which precessed the spins of the channeled particles in the y-z plane. The bending of the two crystals was such that each crystal precessed the channeled particle's spin in opposite directions [Fig. 1(b)]. Energy loss detectors were implanted along the beam path in each crystal. These measured the energy loss of particles traversing the crystals and helped distinguish channeled particles, which have less energy loss, from nonchanneled ones.

As illustrated in Fig. 1, a vertically polarized Σ^+ beam [14] was produced by directing the Fermilab Proton Center extracted 800-GeV/c proton beam onto a Cu target (T). The resulting Σ^+ were produced alternately at a +3.7- or −3.7-mrad horizontal targeting angle relative to the incident proton beam direction. This allowed the polarization direction to be periodically reversed. The mean Σ^+ beam momentum was determined by the hyperon channel geometry (H1) and magnetic field to be 375 GeV/c with a full momentum spread of $\Delta p/p = 7\%$. We measured the polarization to be $(12\pm1)\%$. At 10 m from the target the beam composition was $\approx 1\%$ Σ^+, the rest being mostly pions and protons. The vertical beam size (FWHM) at the z position of the crystals was 1.8 cm with a vertical divergence of 1.4 mrad.

Individual beam particles were measured by the hyperon spectrometer to a precision (σ) of 15 μm, 12 μrad, and 7 μrad in position, horizontal angle, and vertical angle, respectively, at the crystals. Individual track momenta were measured to $\Delta p/p = 0.7\%$. In our case only a small fraction, 2.5×10^{-4}, of the beam particles were channeled. This was mainly determined by the ratio of the active area of the crystals to the beam area at the crystals and the probability of the incident particles to be within the Lindhard critical angle [16] (≈ 10 μrad). The channeling fraction was consistent with expectations [2].

The total beam flux in the hyperon spectrometer averaged 100 kHz. The small fraction that channeled was enhanced using a scintillation counter trigger. This trigger, whose major components are shown in Fig. 1(b), included beam defining counters in the hyperon spectrometer (not shown), a counter (A) which rejected beam tracks that missed the crystals, and a counter (DF) which rejected undeflected beam tracks. The trigger also required an energy loss signal from a crystal in coincidence with the beam. The trigger rate averaged 200 Hz. The data were collected over a period of 74 h.

The baryon spectrometer (Fig. 1) measured the downstream track with resolutions (σ) of 0.6%, 20 μrad and 13 μrad in momentum, horizontal angle, and vertical angle, respectively. For each event tracks were reconstructed in the spectrometers and the angle between them was computed. Channeled particles were identified by their deflection angle ω and by their lower relative energy loss ΔE in the crystals. Figure 2(a) illustrates the characteristic energy loss spectrum for beam particles which satisfied the trigger requirements. Here ΔE has been normalized to the most probable random energy loss. The lower peak is due to channeled particles. Figure 2(b) shows the overall distribution of deflection angles after a channeling energy loss requirement of $0.50 < \Delta E < 0.85$ was imposed. The alignment of the crystal's angle relative to the x-z plane was done using a remotely controlled goniometer with a least count 1.8 μrad. Changes were made so as to maximize the fraction of particles in the low-energy portion of the ΔE plot of Fig. 2(a). The beam deflection by the crystals [Fig. 2(b)] was also monitored.

The deflection of the channeled particles was measured to be $\omega = 1.649\pm0.043$ and -1.649 ± 0.030 mrad for the up- and down-bending crystals, respectively. For 375-GeV/c Σ^+ this corresponds to an effective magnetic field of $B_x \approx 45$ T in the crystals. The magnetic moment [6] of the Σ^+ should precess by $\varphi \approx 1$ rad in such a field.

The Σ^+ was identified by measuring the vector momen-

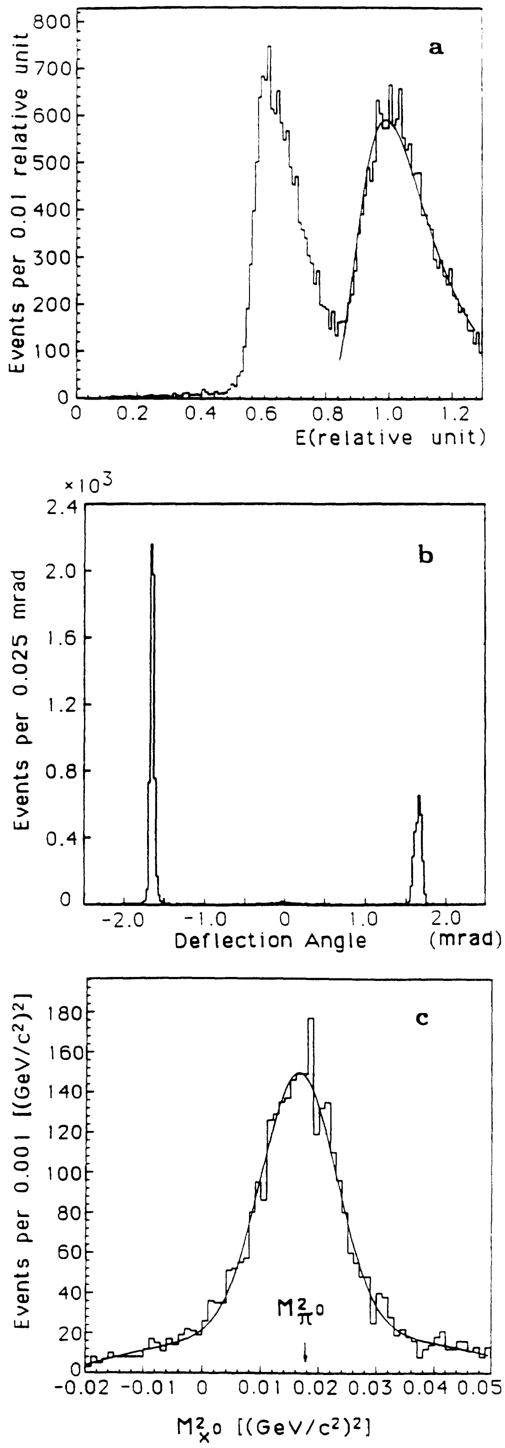

FIG. 2. Data selection criteria. (a) Energy loss distribution for triggered events in the down-bending crystal. The peak at lower energy loss values is due to channeled particles. The solid line through the nonchanneled portion is a theoretical Landau distribution. (b) The distribution of deflection angles for particles which satisfied the channeling energy loss requirement for both crystals. (c) Event distribution from both crystals of the mass squared of the missing neutral particle (X^0) for the hypothesis $\Sigma^+ \to pX^0$. Note the expected peak at the π^0 mass squared. Illustrated is a fit by a Gaussian plus a second-order polynomial.

ta of the Σ^+ in the hyperon spectrometer and the proton in the baryon spectrometer for the mode responsible for 52% of the decays [6], $\Sigma^+ \to p\pi^0$. Events were reconstructed assuming the Σ^+ were channeled and deflected by the full crystal deflection angle ω measured for nondecaying particles [Fig. 2(b)]. With this assumption the decay position z_v of the Σ^+ as well as Θ, the proton laboratory decay angle relative to the Σ^+ direction, were determined. The precision of the decay position measurement in the 10-m decay region averaged 50 cm. The kinematic variables Θ and R (the ratio of baryon to hyperon momentum) were important in isolating our signal. Long-lived channeled beam particles and Σ^+ decays through its other major decay mode, $\Sigma^+ \to n\pi^+$, were eliminated by accepting events only in the regions $0.60 < R < 0.96$ and $0.20 < \Theta < 0.80$ mrad. The geometrical acceptance is almost 100% for decays in the decay region. Nonchanneled Σ^+ are eliminated by these cuts. The crystals were at $z = 7.6$ m (see Fig. 1). Interactions in the crystals were suppressed by selecting events with fitted vertices in the decay region $8.9 < z_v < 18.9$ m. Figure 2(c) shows a mass squared distribution of the missing neutral particle (X^0) for the hypothesis $\Sigma^+ \to pX^0$ after the above R, Θ, and z_v requirements were imposed. The center and width of the π^0 peak are in agreement with the expected resolution. Only events within 2σ of the π^0 peak were retained. These selection criteria left 2167 ± 47 events in the final sample. The background fraction under the π^0 peak in Fig. 2(c) is 17%.

The $\Sigma^+ \to p\pi^0$ decay mode [6] has a large asymmetry parameter, $\alpha = -0.98$, making it a sensitive analyzer of Σ^+ polarization. In order to control systematic uncertainties [15] in the calculation of polarizations it is necessary to compensate for the differences in acceptance caused by changes in the beam phase space when the targeting angles are reversed. This is done by dividing the data into bins and beam-angle space in the x direction, calculating the polarization components for each region, and averaging the polarizations for the final result. In the rest frame of the channeled Σ^+, the angular distribution of the decay protons for the spin-up case in bin j is given by

$$dN_j^+/(N_{0i}^+ d\cos\theta_j) = \tfrac{1}{2} A_{ij}(1 + \alpha P_i^+ \cos\theta_i)\,, \qquad (3)$$

where $i = x$, y, and z, α is the asymmetry parameter, P_i is the Σ^+ polarization component, N_{0j}^+ is the total number of events, $\cos\theta_{ij}$ is the direction cosine of the proton momentum in the Σ^+ rest frame, and A_{ij} is the accep-

TABLE I. Σ^+ polarization components as measured with the two crystals.

	Down-bending crystal	Up-bending crystal
P_x	-0.014 ± 0.054	0.038 ± 0.054
P_y	0.085 ± 0.055	0.032 ± 0.049
P_z	0.106 ± 0.054	-0.100 ± 0.046

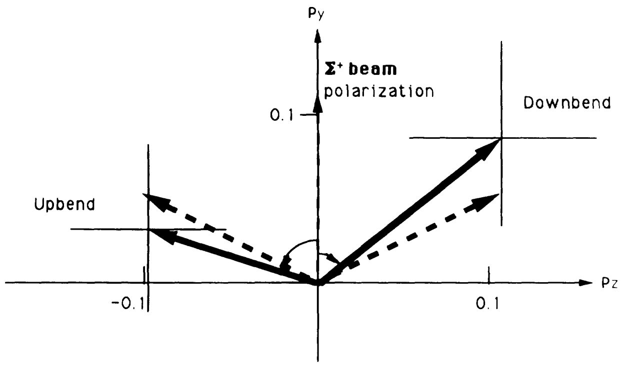

FIG. 3. Measured polarizations and uncertainties (1σ statistical errors) after spins have been processed by the two crystals. The dashed arrows show the expected precessions.

tance which is a function of the apparatus, beam, trigger, and analysis. A similar distribution was obtained for the spin-down case.

We extract the polarization P_i by averaging the difference over the sum of the above equation for spin-up and spin-down data. The measured polarizations are listed in Table I. 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 [14] without the Σ^+ precession by the crystals.

These polarizations are plotted in Fig. 3. The predicted precessions of the Σ^+ magnetic moments based on previous measurements [6] are also shown. The measured precession angles for the down-bending and up-bending crystals are $+51° \pm 23°$ and $-72° \pm 26°$, respectively. The average of the magnitude of the experimental value of $60° \pm 17°$ is consistent with the predicted value of $62° \pm 2°$. As anticipated, the spins in the two crystals precess in opposite directions. The Σ^+ spin precesses around the x axis; hence, P_x should be zero. This is in agreement with our measurements (Table I). Since the magnitude of the polarization after precession is consistent with the undeflected measurement, there is no evidence of depolarization during channeling. The Σ^+ magnetic moments and their statistical errors derived from the down-bending and up-bending crystals are $(2.15 \pm 0.61)\mu_N$ and $(2.74 \pm 0.71)\mu_N$, respectively. Their average of $\mu=(2.40\pm 0.46)\mu_N$ is consistent with the experimental world average [6] of $(2.42\pm 0.05)\mu_N$.

Systematic uncertainties in the crystals' bend angles and in the incident hyperon momentum contribute $0.03\mu_N$ and $0.01\mu_N$ to the uncertainty in our measurement. The major contribution of $0.40\mu_N$ comes from studies of the stability of our result to reasonable changes in data selection variables (R, Θ, ΔE, missing mass, and z_v).

This experiment has confirmed spin precession for particles channeled in bent crystals. This phenomenon may open the way for magnetic moment measurements of short-lived particles such as charm baryons. A candidate might be the Λ_C which current experiments [6] have already shown has a large asymmetry parameter and may be produced with significant polarization [17].

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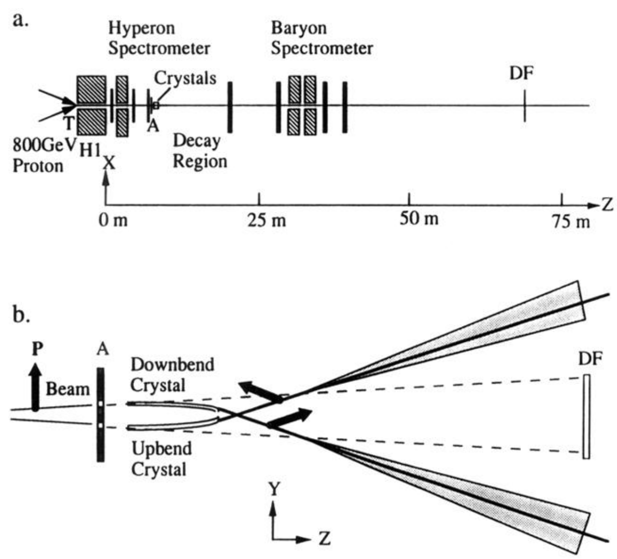

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