New Method to Polarize Protons in a Storage Ring and Implications to Polarize Antiprotons

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A feasibility test of a new method to polarize beams of strongly interacting charged particles circulating in a storage ring is described. The stored particles, here protons, pass through a polarized hydrogen gas target (thickness 6×10^{13} $\vec{\mathrm{H}}/\mathrm{cm}^2$) in the ring some 10^{10} times and become partially polarized because one spin state is attenuated faster than the other. The polarization buildup is clearly demonstrated in the present experiment.

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The study of current problems in nuclear and in elementary particle physics often requires the use of spin-polarized projectiles. Polarized protons and polarized neutrons were produced for the first time some 40 years ago in experiments in which an unpolarized target was bombarded with an unpolarized beam [1]. For a number of different reactions, the particles emitted at angles $\Theta \neq 0°$ were found to be partially polarized. The polarization of the particles was detected as a left-right asymmetry in a second scattering or reaction which served as the polarization analyzer (double scattering).

A major difficulty in this method to produce polarized particle beams is the large loss in intensity and the large spread in angle and energy introduced by nuclear scattering from a target. For beams of protons and deuterons, these problems have been overcome by the development of sources of polarized ions, i.e., the preparation of polarized atoms by atomic methods (e.g., Stern-Gerlach separation) and subsequent ionization of the atoms to produce polarized ions [2].

Here we report the first feasibility test of a new method to polarize beams of strongly interacting charged particles. The method is of particular interest for the production of polarized antiprotons, for which the construction of polarized ion sources is not feasible, and for which the large loss in intensity resulting from the double-scattering method has so far prevented experiments with beams of polarized antiprotons.

The method can be described as spin-selective attenuation of the particles circulating in a storage ring. The idea was first proposed by Csonka [3]: a polarized target—in our case a target of polarized hydrogen gas ($\uparrow$)—is inserted in a storage ring. The particles stored in the ring pass through the target for a sufficiently long time that a fraction of the particles is lost by nuclear scattering in the target. Since in general the total strong interaction cross section is different for beam and target spins parallel ($\uparrow\uparrow$) and antiparallel ($\uparrow\downarrow$), one spin direction of the circulating beam is depleted more than the other, so that the circulating beam becomes increasingly polarized, while the intensity of the beam decreases with time. The method has been referred to as a "spin filter" since the spin-selective attenuation amounts to a filter which is more transparent to one spin state of the beam than the other.

For simplicity, we assume that the target has polarization P_T in the vertical direction, i.e., normal to the orbit of the ions in the storage ring. The beam can be considered to consist of a fraction of particles with spin up and a fraction with spin down. The total strong interaction cross section of the beam with the target can be expressed as

$$\sigma_T = \sigma_0 \pm \sigma_1 P_T \ , \tag{1}$$

where the positive and negative sign applies, respectively, to the fraction of the beam whose spin is parallel ($\uparrow\uparrow$) and antiparallel ($\uparrow\downarrow$) to the spin of the target. Here, σ_0 is the spin-independent part and σ_1 is the spin-dependent part of the cross section. Note that for low-energy pp scattering σ_1 is negative. If we neglect mechanisms other than interaction with the target, the intensity of the spin-up and spin-down particles in the stored beam each decreases exponentially but with different time constants. The resulting polarization buildup of the beam as a func-

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tion of filter time t can be expressed in the absence of depolarization as [4]

$$P(t) = \tanh(t/\tau_1) \ . \tag{2}$$

The time constant τ_1, which characterizes the rate of polarization buildup, is

$$\tau_1 = 1/\sigma_1 P_T n f \ , \tag{3}$$

where n is the target thickness in atoms/cm^2 and f is the revolution frequency of the particles in the ring. The intensity of the stored beam decreases according to

$$I(t) = I_0 e^{-t/\tau_s} \cosh \frac{t}{\tau_1}, \tag{4}$$

where

$$\tau_s = 1/(\sigma_0 + \sigma_C) n f \tag{5}$$

depends on the spin-independent part of the nuclear total cross section σ_0. Here we have added to σ_0 a cross section σ_C to represent the loss of particles by small-angle Coulomb scattering either in the target or in the residual gas of the ring. While the total cross section for Coulomb scattering diverges if one neglects screening of the nuclear charge by the atomic electrons, σ_C is finite because particles scattered by sufficiently small angles are within the ring acceptance and thus are retained. The limiting angle that is still accepted, and thus σ_C, depends on the ion-optic properties of the ring (β function) at the position of the target.

In order to build up significant polarization, the beam has to pass through the target for times t of the order τ_1 [Eq. (3)]. At best, the magnitude of σ_1 is of the order of the total strong interaction cross section, or about 100 mb for pp scattering at 30 MeV [5]. For a revolution frequency of $f = 10^6$ s^{-1}, which is typical for low-energy proton and antiproton rings, and an assumed target thickness of $n = 10^{14}$ atoms/cm^2, Eq. (3) leads to $\tau_1 = 10^5$ s or about one day. Here we consider only relatively low energies of the circulating beam because with increasing energy the strong interaction cross section decreases, leading to even slower polarization buildup.

We now discuss the internal polarized gas target which is required for the spin filter method. In principle, a hydrogen polarized gas target can be produced by use of a jet of polarized atoms from an atomic-beam source (see, e.g., Ref. [6]). However, the target thickness provided by such a jet is only about 2×10^{11} $\vec{\mathrm{H}}$ atoms/cm^2. A test of the spin filter method thus requires an improvement in target thickness of the polarized H target by a factor of several hundred. For the present tests, this was accomplished by injecting the polarized atoms into a windowless T-shaped storage cell [7], through which the circulating beam passes. The polarized atoms make some hundred wall collisions before they exit from one of the ends of the tube. Depolarization of the atoms in wall collisions is suppressed by coating the cell walls with a suitable coating [8].

The principle of the experiment is illustrated schematically in Fig. 1. The polarized target is located in the center of a straight section of the Heidelberg Test Storage Ring [9]. The ion optics of the straight section (low-β section) was chosen to minimize loss of particles from Coulomb scattering in the target, since Coulomb scattering attenuates the beam but does not contribute to the polarization buildup. Electron cooling is applied continuously in order to compensate for the energy loss and the emittance growth caused by the target. The polarized hydrogen target was provided by atoms from an atomic-beam source [10], which were injected into a thin-walled 250 mm long aluminum tube of 11 mm inner diameter. The atomic beam entered through an entrance tube of 10 mm diameter and 100 mm length. The cell was cooled to 100 K in order to increase the target density. The target thickness, $n = (5.6 \pm 0.3) \times 10^{13}$ $\vec{\mathrm{H}}$/cm^2 for atoms in a single hyperfine state, was deduced from the measured pp count rate using the known circulating beam current, pp cross section and detector geometry. The target chamber is described in Ref. [11]. A powerful differential pumping system prevented the target gas from entering the other parts of the storage ring proper.

The target polarization was determined in separate measurements at the beginning and at the end of the experiment, in which a 27 MeV beam of α particles was stored in the ring instead of protons. The target polarization was deduced from the left-right asymmetry of recoil protons detected at $\Theta_{\mathrm{lab}} = 21°$. The analyzing power for p-α scattering at the relevant angle ($\Theta_{\mathrm{c.m.}} = 138°$) is large and known accurately from previous experiments [12]. The magnitude of the target polarization was found to be $P_T = 0.83 \pm 0.03$.

The experiment was carried out as follows. An (unpolarized) 23 MeV proton beam of up to 1 mA was stored in the ring, using multiturn stacking, while reducing the beam phase space by electron cooling. Subsequently the beam was left to circulate (coast) for periods between 30 and 90 min. After 90 min, the beam intensity had de-

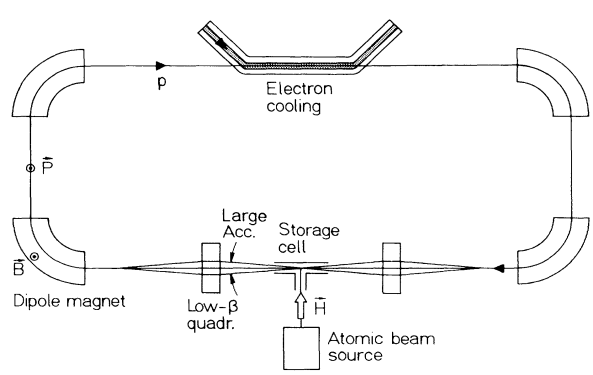

FIG. 1. Principle of the spin filter experiment with storage ring, low-β target section, storage cell, and electron cooler.

creased to 5% of the initial value, so that longer filter times could not be explored. The polarization of the remaining beam was subsequently detected by making use of the large difference in the *pp* elastic scattering cross section between parallel and antiparallel spins. For this purpose the direction of the 5 G guide field, which determines the direction of the target polarization (up or down), was reversed periodically and the *pp* elastic count rates for the two target orientations were compared.

Scattered protons were detected in scintillation counter telescopes (see Ref. [11]), located at $\Theta_{\rm lab} = 33.3°$ above and below the plane of the storage ring. Therefore the normal to the scattering plane (y) is in the horizontal direction. For target and beam polarization in the vertical direction (x), the cross section is

$$\sigma(\Theta) = \sigma_0(\Theta)\,[1 \pm A_{xx}(\Theta) P_B P_T] \ , \qquad (6)$$

where the positive sign applies when beam and target are polarized in the same direction, the negative sign when they are in opposite directions. The spin correlation coefficient $A_{xx} = -0.93$ was calculated from the *pp* phase shifts [5].

We denote the sum of the number of counts registered in the two detectors for target spin up and target spin down by $N_\uparrow$ and $N_\downarrow$, respectively, and define the count rate asymmetry ϵ as

$$\epsilon = (N_\uparrow - N_\downarrow)/(N_\uparrow + N_\downarrow) \ . \qquad (7)$$

Measurements of ϵ were continued for 10–30 min after the end of the polarization buildup. During the beam polarization measurement the target polarization is reversed many times, so that no further buildup of polarization occurred. Reversal of the target polarization was controlled by a beam current integrator, which integrated the intensity of the circulating beam until a predetermined amount of charge (760 μC) had passed through the target. The circulating beam was measured nondestructively with a dc current transformer.

The component of beam polarization in the up direction, P_B, is obtained from ϵ as

$$P_B = \epsilon / A_{xx} P_T \ , \qquad (8)$$

where P_T is the magnitude of the target polarization during the beam polarization measurement. The asymmetry ϵ, measured after filtering the stored beam for different lengths of time, is shown in Fig. 2. Each point shown is the weighted mean of a number of measurements with approximately the same filtering time. The solid dots refer to filtering with target polarization up, while the open circles refer to target polarization down during filtering. Measurements were also made for zero filtering time. As expected, the rate of polarization buildup is the same for both directions of the target spin during filtering. Instrumental effects on beams or detectors associated with reversal of the guide field could in principle cause $\epsilon \neq 0$ for filter time zero. The data indicate that such effects are small.

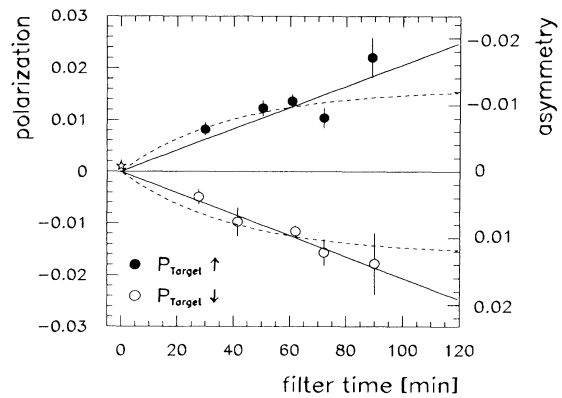

FIG. 2. Asymmetry (right-hand scale) and polarization (left-hand scale) measured after filtering the beam in the storage ring for different times t. The solid lines are based on an assumed rate of polarization buildup of 1.24×10^{-2} h^{-1}, which corresponds to $\tau_1 = 80$ h. The dashed lines are based on the expected buildup rate ($\tau_1 = 42$ h) and an assumed polarization lifetime of $\tau_p = 81$ min.

The straight lines in Fig. 2 show the best fit to the data, with a rate of polarization buildup of

$$\Delta P_B / \Delta t = \pm(1.24 \pm 0.06) \times 10^{-2}\ \mathrm{h}^{-1} \ , \qquad (9)$$

which, according to Eq. (2), implies $\tau_1 = 80$ h. The polarization which the beam acquires is in the same direction as the polarization of the target. This is in agreement with expectation, since the *pp* cross section is lower when the proton spins are parallel than when they are antiparallel.

It is interesting to compare the observed rate of polarization buildup [Eq. (9)] with the rate expected from Eqs. (2) and (3). Since $P_B \ll 1$, the rate of buildup is $1/\tau_1 = \sigma_1 P_T n f$. The spin-dependent part of the 23 MeV *pp* total cross section, calculated from the known *pp* phase shifts [5], is $\sigma_1 = 122$ mb. With $f = 1.177$ MHz, the expected initial rate of polarization buildup is

$$1/\tau_1 = \sigma_1 P_T n f = 2.4 \times 10^{-2}\ \mathrm{h}^{-1} \ , \qquad (10)$$

which is about twice the observed value.

A possible explanation for the discrepancy is that the circulating beam may have a finite polarization lifetime τ_p. If we assume the value of τ_1 given by Eq. (10), the best fit to the measurements is obtained with a polarization lifetime $\tau_p = 81 \pm 7$ min (dashed curves in Fig. 2). The quality of the data at present is not sufficient to tell whether the polarization buildup is slower than expected from Eq. (10) (straight lines in Fig. 2, χ^2/d.f. = 1.43) or whether the beam depolarizes during the buildup (χ^2/d.f. = 1.57).

In order to increase the usefulness of the spin filter

method, the following improvements should be considered.

(i) Optimum choice of beam energy: For the present experiment, the optimum beam energy is near 40 MeV [13], which, however, was not accessible because the energy of the injected beam was limited and equipment to accelerate the beam had not yet been installed. It should be noted that the choice of the optimum energy for filtering does not preclude the use of the beam at higher or lower energies because the stored beam can be accelerated or decelerated to the desired energy after filtering.

(ii) Increased polarization lifetime: The storage ring was operating very near a depolarizing resonance [14]. The effect of depolarizing resonances can be eliminated by the use of spin precessors ("Siberian Snakes"), which have been shown [15] to be strikingly successful in suppressing the effect of imperfection resonances as well as intrinsic resonances.

(iii) Increased beam lifetime: Further increase in beam polarization can be expected if the beam lifetime, which is presently 30 min, can be increased. For reasons which are not yet understood, the measured ring acceptance (4 mrad) is a factor 3 less than expected from the design value of the β function. With an acceptance of 12 mrad, beam loss by single scattering would be reduced by a factor 9, with corresponding increases in τ_s and in filtering time, provided single scattering is the primary loss mechanism.

It is not unreasonable to assume that improvements of the method may increase the figure of merit (P^2I) by an order of magnitude compared to the results of the first test reported here. Additional difficulties arise for applications to antiprotons, where the spin-dependent part of the total cross section is not known but is expected to be less than for pp scattering. On the other hand, the results in Fig. 2 indicate that with a luminosity of more than 10^{28} $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ after filtering and the capability of rapid spin reversal, small effects can be measured with good precision (Fig. 2). Therefore, interesting experiments on the spin dependence should be possible, even if the achievable polarization of the stored antiproton beam were only a few percent.

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