Antiproton beam polarizer using a dense polarized target

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Abstract. We describe considerations regarding the spin filtering method for an antiproton beam. The proposed investigation of the double polarization cross section for antiproton to nucleon interaction is outlined. It will use a single path of an antiproton beam through a dense polarized target, e.g. $^3$He or CH$_2$, followed by a polarimeter.

1. Introduction

Since the discovery of the antiproton and especially after the creation of an intense antiproton beam at CERN and FNAL, there have been many attempts to develop a method to polarization antiprotons, see the review [1]. These attempts were motivated by a possible physics program with polarized antiprotons ($\bar{p}$), which is very exciting, especially in the case of double polarization experiments [2]. Experiments with transversely polarized $\bar{p}$ will address the most intriguing questions of present hadron physics, such as transverse spin nucleon structure and transverse momentum distributions [3].

In spite of decades of research, there is at present only one proven method of $\bar{p}$ polarizing, which is the filtering method, first proposed for the proton storage ring 40 years ago [4]. This filtering method is based on the circulation of antiprotons in the storage ring with some mechanism of beam cooling and a polarized target. It exploits the dependence of the scattering cross section on the relative orientation of the target and projectile spins. A number of targets have been investigated, ranging from atomic hydrogen [5], to the electron [6], and the bremsstrahlung photon [7].

2. Filtering through the nuclear target

The polarization build-up is the result of the difference between life-times for two parts of the beam which have opposite polarizations. As shown, see e.g. in Ref. [8], the cross section could be presented as a sum ($\sigma_0 + P_{b,t}P_{t,t}\sigma_1 + P_{b,l}P_{t,l}\sigma_2$), where $P_{b,t}$ is a product of the transverse polarizations of beam and target, $P_{b,l}$ is the same for the longitudinal polarizations, $\sigma_0$ is the total cross section, which is between 50-200 nb [9], and $\sigma_{1,2}$ is a spin-dependent part, which is expected to be between 10-50 nb, depending on beam momentum and models [10, 11, 12].

The spin filtering requires passage of the beam through very thick polarized matter, which varies with the beam energy, but is always of the order of a nuclear interaction length (about 50 g/cm$^2$ for hydrogen). The technology of the polarized jet target provides an ideal filter, but
it has an extremely low thickness (∼10^{14} \text{ atoms/cm}^2). As a result, the beam should circulate in the ring for many hours, the number of turns should be on the order of 10^{11}. The interaction of the beam with the target leads to the growth of the beam emittance. Such an effect is especially important at low beam momenta. The target induced growth of beam emittance needs to be compensated for, e.g. by electron cooling [15]. Without beam cooling after passage through 50 g/cm^2 of hydrogen, the beam transverse momentum spread, \( p_\perp \), is of 10 MeV/c, which is close to acceptable for the 8 GeV/c \( \bar{p} \) ring at FNAL. However, at such a large energy, the value of \( \sigma_2 \) is unknown.

The practical application of the method has only one difficulty: the very long time required for polarization build-up. A full scheme of the antiproton beam preparation includes several steps (the production in high energy proton-nuclei interaction, the accumulation at several GeV momentum, the cooling of the phase-space distribution), all of which take a relatively short time, on the order of 1000 seconds. After that, the spin filtering can be done. It is desirable that the preparation of a highly polarized \( \bar{p} \) beam be completed on the same time scale and that the next cycle of \( \bar{p} \) accumulation starts.

Currently, the theory of polarization build-up in the filtering method is well developed, see Refs. [11, 10]. However, the uncertainty in such calculations is largely due to a lack of double polarization experimental data. There are two double polarization terms of the \( \bar{p}N \) interaction cross section which could be used in the spin filtering process. They correspond to the observable \( A_{TT} (\sigma_1/\sigma_0) \) and the observable \( A_{LL} (\sigma_2/\sigma_0) \) [11]. The longitudinal polarization correlation parameter \( A_{LL} \) is relatively large (∼0.1) even at a beam energy of 800 MeV, see Ref. [12]. If the \( A_{LL} \) stays at this level for several GeV of beam energy, the optimum beam energy for the antiproton polarizer ring should be in that range because the storage ring acceptance is larger and the beam operation is simpler for higher beam momenta.

2.1. The dense polarized target

The number of polarized nucleons per cm^2, spin thickness, of a \(^3\)He target could be 10^9 times higher than that achieved with the best hydrogen atomic beam source. At such a large thickness, the beam polarizing requires just 500 turns in the ring even with lower effective polarization of the nucleons in the \(^3\)He target. Here we present considerations of how some of enormous density of polarized target could be used in spite of the mismatch between the beam cooling time achievable with electron cooling and fast growth of the beam emittance due to its interaction with the high density target.

2.1.1. An open cell with \(^3\)He gas

One easy way to reduce the target thickness is to open the windows. In such a case, the achievable thickness is limited by the pumping speed of the vacuum system for He gas. The same time \(^3\)He has very small depolarization compared with atomic hydrogen, so the storage cell length is limited only by the accelerator size. The \(^3\)He target in the storage ring has been used extensively, see Ref. [13, 14]. For example, with a cell as long as 20 m and a diameter of 5 cm, the thickness of 10^{16} atom/cm^2 requires a leak rate of He at a rate of 0.2 \( \mu \)g/s. This leak rate will require a differential pumping system to maintain the accelerator vacuum on the level of 10^{-8} Torr.

2.1.2. A very thin window

A \(^3\)He target with 10^{18} atom/cm^2 with solid windows will have an acceptable dilution factor if the window has less than 10^{17} nucleon/cm^2 or a thickness of 0.1 – 1 \( \mu \)m. Because the target cell could be 20 m long, the pressure inside the cell is as low as 5 mTorr (at 100^\circ K), so the window could hold the pressure in spite of its minimal thickness. Such a window doesn’t need to be completely hermetic. For example, a hole of 100 \( \mu \)m will lead to a leak of only 0.01 \( \mu \)g/s of \(^3\)He. It is so small that an additional flow of the polarized gas through the cell should be arranged to maintain high polarization in the cell.
2.1.3. One turn beam bypass  The effective thickness of the target could be varied by using pulse magnets to direct the beam to the bypass line where the target is located. Such beam gymnastics are not simple, because it should be done with a very low beam loss (∼0.1%). However, it allows us to use a full thickness polarized target and minimum dilution. Using \(^3\)He as an example, we estimated the following. When the beam passes through the target one time per \(2 \times 10^6\) turns, the polarizing process stretches to 1000 seconds (assuming 1 \(\mu\)s per turn). Between the passes through the target, the spread of the beam transverse momenta will be of 0.5-1 MeV/c, which is sufficiently small for usual acceptance of a storage ring. In this configuration it is especially interesting to use a so-called HD polarized target [16] because of its reduced dilution factor.

3. The measurement of the \(A_{LL}\) parameter

In the 1988 experiment [17] at LEAR, a polarized \(\bar{p}\) beam was produced in the extracted beam line. This double scattering experiment was successful. The measurement provided unique information about the analyzing power \(a_H\) in \(\bar{p}H\) scattering at beam momenta of 800 and 1100 MeV/c. The value of \(a_H \sim 0.83\) (GeV/c\(^{-1}\)) is comparable to one for the proton-proton case, but limited to small scattering angles, where the elastic channel dominates. Using the result for \(a_H\) we plan a measurement of the double polarization parameters which are essential for the optimization of the antiproton polarizing system.

There is also a plan to investigate the polarization of the stored antiproton beam interacting with a polarized hydrogen target [18]. We propose a measurement of the \(A_{LL}\) parameter using a single path of the beam through a dense polarized target. It resembles closely the proposal of a preliminary experiment [4]. A number of targets could be used. For example, the polarized \(^3\)He target developed at UVa for the TJNAF experiments has 17 mg/cm\(^2\) of polarized neutrons with a 65% degree of polarization [19]. Two dilution factors need to be taken into account: The first one is about 3, due to unpolarized protons in \(^3\)He, and the second of 3.6 is due to the glass windows of the target cell. For the beam filtering application, up to ten cells could be combined into one which will provide 170 mg/cm\(^2\) of polarized neutrons. At the same time, such a long cell has a dilution factor of 1.3, much smaller than that of a short cell. Using the nuclei interaction length (65 g/cm\(^2\)) and the \(A_{LL}\) value at 800 MeV/c from the \(\bar{p}p\) calculation [12] as an estimate, one can find that the beam polarization will be about \(1.3 \times 10^{-4}\) after one path through the target. The typical polarized \(\text{NH}_3\) target has a thickness of 5000 mg/cm\(^2\), a high proton polarization of 75%, and a dilution factor of 6. It will provide beam polarization of \(7 \times 10^{-4}\). A very interesting polarized target for such a measurement is the polarized scintillator [20], which allows detection of the interaction of the beam particle.

![Diagram](image)

**Figure 1.** The layout of experiment with extracted antiproton beam to measure the polarization transfer parameter \(A_{LL}\).

The layout of the proposed measurement is shown in figure 1. The beam from the antiproton source is directed via the beam line to the polarized target. After the beam passes through the target it is directed to a polarimeter, which is comprised of a dipole magnet, a liquid H\(_2\)
analyzer, and the counters. The GEM trackers provide event-by-event tracks of the incident and scattered \( \bar{p} \). The dipole should deflect the beam and rotate the spin of the antiproton by an angle close to 90°. The scattering in the analyzer is sensitive to transverse polarization. The antiprotons scattered from the analyzer will be detected by a set of scintillator counters. The difference in rates between the left and right counting systems allows us to measure the beam polarization (using the value of the analyzing power from Ref. [17]). The flip of the target polarization will be used to cancel the systematics of the polarimeter. Alternatively, the scattering from unpolarized material could be used to measure instrumental asymmetries.

We can estimate the statistics required for the measurement. The statistics of \( 10^{10} \) incident antiprotons on the polarizing target and 20 cm long liquid hydrogen analyzer will lead to \( 3 \times 10^8 \) recorded counts with average analyzing power of 0.10 (at 800 MeV/c beam momentum). So, the beam polarization will be detected at the level of one sigma. Therefore, with a NH\(_3\) polarized target and \( 10^{13} \) recorded counts, the relative accuracy for beam polarization (statistical) will be 3%. The achieved intensity of accumulated antiprotons at FNAL [21] is about \( 3 \times 10^{11} \) per hour, which allows us to accomplish the measurement in 30 hours of data taking.

3.1. The road map to the measurement of \( A_{LL} \) for \( \bar{p}N \)

The measurement of \( A_{LL} \) in the \( \bar{p}N \) interaction should be performed in several steps which include apparatus development:

- Experimental proof and optimization of the concept using a polarized and an unpolarized proton beam at different momenta.
- Extraction of the antiproton beam of required energy at CERN or FNAL to the experimental area.
- Measurement of \( A_{LL} \) with different polarized targets (NH\(_3\), \(^3\)He, CH\(_2\), and HD).

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