PROSPECTS FOR PRODUCING POLARIZED ANTIPROTONS

E. Steffens

Max-Planck-Institut für Kernphysik

D-69 Heidelberg, Fed. Rep. of Germany

Introduction

The availability of a polarized antiproton beam would greatly improve the study of low energy antiproton-proton collisions. In conjunction with a polarized proton target, such a beam allows not only to measure cross section $d\sigma/d\Omega$ and polarization $P(\theta)$, but also the spin correlation in the entrance channel, described by quantities $A_{ij}(\theta)$ (ij = nn, ss, kk, sk). In high energy $\bar{p}p$ collisions, polarized beams would enable to measure the spin correlation in W and Z production, thus enabling to look at right-handed currents in weak interaction[1].

Antiprotons are produced by bombarding a thick production target with energetic protons. In the present scheme, antiprotons are collected within a sizable solid angle around zero degrees and are certainly not polarized. Asymmetric collection schemes would reduce the collection efficiency drastically. Therefore the only practical way seems to be to collect unpolarized $\bar{p}$s and to polarize them in a second step. In order to make efficient use of $\bar{p}$s and taking the low strength of the polarizing "forces" into account, this step should be performed in a $\bar{p}$ storage ring.

Several proposals were made to polarize antiprotons [2-7] and this question was also the subject of a recent workshop[8]. It is the aim of my talk to review the most promising ideas and to give my personal view how the prospects for performing experiments with polarized antiprotons are.

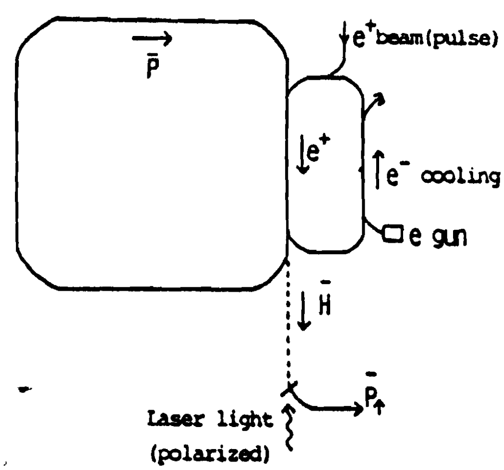
Methods Based on Antihydrogen

Polarized proton sources make use of the properties of the hydrogen atom, e.g. the strong coupling of the nuclear spin to external fields via the electron spin. If antihydrogen ($\bar{H}$) could be produced in large quantities, then it seems straightforward to polarize it using conventional schemes. In reality, $\bar{H}$ is likely to be formed in flight, which makes the task of polarizing $\bar{H}$ more difficult.

$\bar{H}$ formation

$\bar{H}$ atoms are formed by radiative capture of positrons by antiprotons at low relative velocity. Therefore overlapping cold beams of e^+ and $\bar{p}$s and are required.

Imai[5] proposes to use one $\bar{p}$ and one e^+ storage ring, both with electron cooling, with a common straight section, where the $\bar{H}$ formation occurs



Figur 1: Conceptional view of producing polarized $\bar{p}$s by optical pumping of antihydrogen[5].

(see fig. 1). With the two rings filled to the space charge limit, the author estimates a formation rate of 10^5 $\bar{H}$/s, but with more realistic numbers of stored particles this figure might go down by a factor of 100 or more.

A simpler scheme is proposed by a CERN-Heidelberg-Karlsruhe Collaboration[6] on the expense of formation rate. Instead of injection moderated e^+ from a radioactive source into a storage ring, only a single passage through the overlapping $\bar{p}$ beam is foreseen. With a 10 Ci source a spontaneous rate of about 1/3 $\bar{H}$/min is estimated.

Several possibilities to enhance the $\bar{H}$ formation rate are discussed in ref.6, employing laser induced capture into defined levels like n = 2 and considering pulsed moderated e^+ beams produced by an electron linac with a time structure matched to the laser pulse shape. Formation rates as high as 600/s (n = 2) and $2 \cdot 10^4$/s (n = 5 - levels) are predicted.

Polarizing $\bar{H}$ atoms in flight

In both proposals[5,6] optical pumping of $\bar{H}$ is considered, as it was discussed recently by A.N. Zelenskiy et al[9] for a relativistic H^0 beam. Tunable laser light is Doppler-shifted into the ultra-violet range ($\bar{H}$-energy 200 to 600 MeV) in order to match the hydrogen K_α-line. For an interaction length of 10m the required laser power of about 0.5 MW/cm^2 (ref.6) and 1 kW/cm^2(ref.5), respectively, is still high and depends critically on the assumption of the $\bar{p}$ beam momentum spread.

As an alternative scheme it is proposed[6] to do laser-induced capture into the n = 2 states, one third of which are in the metastable 2S state. One then could apply selective quenching of the two lower 2S levels by applying a longitudinal 570 Gauss field. After diabatic field reversal the remaining metastable atoms have to be ionized selectively, e.g. by selective excitation to n = 4 and field ionization. This scheme of polarizing metastable H-atoms is applied routinely in Lamb-shift type polarized ion sources[10]. Metastable atoms are formed at an energy of about 1 keV. The question remains open from the point of view of motional fields, adiabaticity conditions etc whether it can be applied to $\bar{H}$ beams of at least several MeV in energy.

Stern-Gerlach Separation of Circulating Ions

The proposed method[7] is based on the Stern-Gerlach effect, i.e. the spatial separation of a beam of particles having a magnetic moment by an inhomogeneous B-field. This method has been used extensively to separate the electron spin states of thermal neutral atomic beams of hydrogen[10]. In this case no Lorentz force is present and the only (weak) force is given by:

$$F_{SG} = \text{grad}\ (\vec{\mu}\cdot\vec{B}) \qquad (1)$$

It was shown by W. Pauli that SG separation of electrons, i.e. charged particles, is inhibited in the presence of the Lorentz force by the uncertainty principle[11]. To which extent these arguments are invalidated in the case of heavy particles like antiprotons circulating in a storage ring has to be investigated.

Spin separation in a quadrupole field

As elements with strong inhomogeneous B-fields quadrupole lenses are proposed, which could be lattice quadrupoles or special elements. The quadrupole field is described by:

$$B_x = Gy \qquad (2)$$

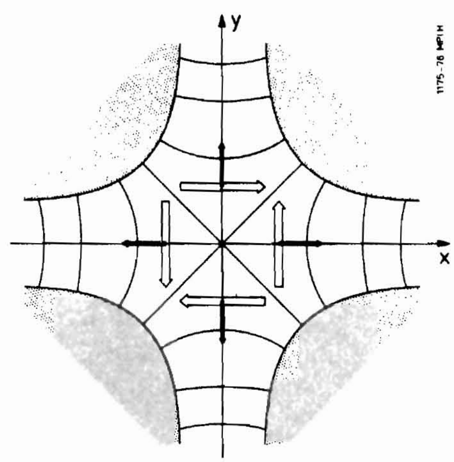
$$B_y = Gx$$

We assume, in contrast to the atomic beam case, a non-adiabatic passage of the quadrupole field, i.e. the spin direction stays fixed. The force is then:

$$\vec{F}_{SG} = G \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right) (\mu_x y + \mu_y x) \qquad (3)$$

$$= G (\mu_y, \mu_x, 0)$$

Here x, y and z are taken in the radial, vertical and longitudinal direction. As indicated in fig. 2, a vertical spin is deflected horizontally and vice versa. It also follows from (3) that a combination of two quadrupoles with opposite gradient, i.e. a focussing and a defocussing quadrupole, produces no net effect, unless the spin component considered for separation is inverted in between. In the original proposal 180° spin precession by the lattice dipole magnets was assumed.



Figur 2: Force on a magnetic moment in a quadrupole field.

<u>"Spin-Splitter" proposed for LEAR</u>

A new proposal[12] for the LEAR ring is based on the so-called Spin-Splitter, a combination of two (F and D) skew quadrupoles and a solenoid in between which rotates the transverse spin component by 180°. This combination causes weak coupling between the horizontal and vertical plane only. A few additional weak correction elements are required for stable operation of the storage ring. On the other hand, by the use of skew quads the horizontal and vertical kick is reduced by a factor $1/\sqrt{2}$.

Resonance condition. The separation of the horizontal spin components is performed by spin-dependent excitation of betatron oscillations. In order to achieve a build-up of separation over many revolutions, spin tune Q_s, i.e. the number of spin rotations in the horizontal plane, and vertical betatron tune Q_v has to be identical (mod. 2π):

$$Q_s = Q_v \pm n \qquad (4)$$

The spin-splitter represents a "Siberian snake"[13] with a spin tune of Q_s = 1/2. From equ.(4) it follows that the machine has to be operated at or close to a half-integer resonance.

In the proposal some arguments are given about the effect of tune spread ΔQ_v and how one might maintain coherence between spin and betatron motion. Cooling would of course reduce or cancel the spin separation and cannot be applied. Therefore the question of emittance growth near resonance has to be studied. Also the question of coherence of betatron motions of different particles is important to obtain an overall polarization of the stored particles

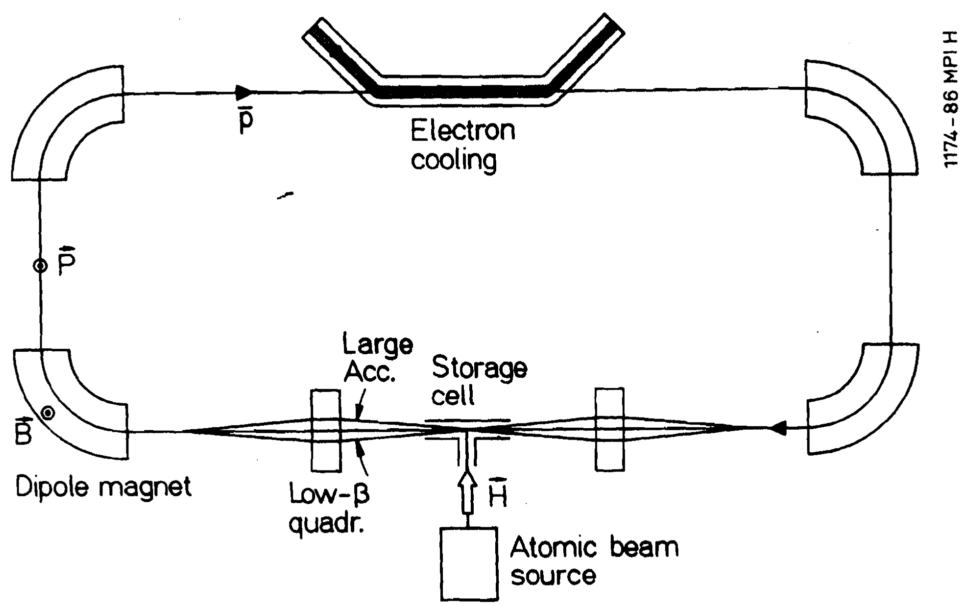
The separation estimated for the spin splitter is in the order of mm/h. By an asymmetric scraper at a distance of $(m/2 + 1/4)\ \lambda_v$ behind the spin-splitter one spin state is selectively attenuated. If the remaining problems of beam dynamics could be solved by tracking calculations and machine tests e.g. with protons, this method might turn out to be a universal method to polarize fairly large numbers of stored ions.

Filter Method

This method[2] is based on a possible difference in the $\bar{p}p$ total cross section for the two spins parallel compared to antiparallel. The beam of antiprotons circulating in a storage ring interacts many times with an internal hydrogen target with constant vertical polarization (see fig. 3).

Particles with one magnetic quantum number with respect to the vertical direction will eventually scatter more frequently than the other. This will result, besides a continuous beam loss due to strong interaction, in a build-up of polarization of the particles left over in the storage ring. The arrangement of target and storage ring components is sketched in fig. 3.

Heating of the beam by the target is compensated by means of electron cooling. Low-β quadrupoles at the target are employed to have a small beam size and to make the angular acceptance of the ring large. In this way losses by small-angle Coulomb scattering are minimized[14]. As a general rule, losses which are not spin-dependent, as from Coulomb scattering (target, residual



Figur 3: Arrangement of polarized internal target and storage ring to polarize $\bar{p}$s by the "Filter Method".

gas) or from resonant excitation, have to be small compared to those due to strong interaction in the target.

Experiment proposed for LEAR

It has been proposed recently[4] to polarize the $\bar{p}$s circulating in LEAR by an internal $\vec{H}$ target and to measure the spin correlation in various channels using the same target surrounded by detectors.

Polarization build-up[4]. The total $\bar{p}p$ strong interaction cross section for the interaction of $\bar{p}$s ($m = \pm 1/2$) with a proton target (vertical polarization $P_T = 1$) can be written as:

$$\sigma_\pm = \sigma_0 \pm \sigma_1 \qquad (5)$$

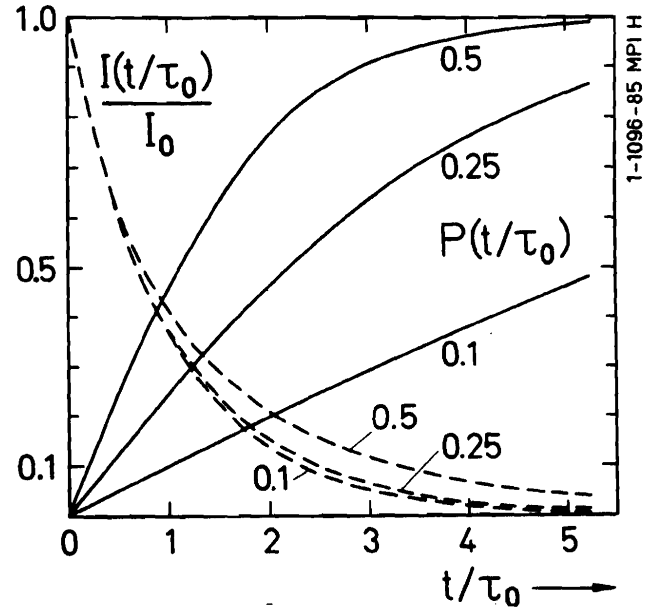
Here σ_0 is the spin-independent and σ_1 the spin-dependant part. In the absence of depolarization the time-dependence of intensity and polarization is given by:

$$I(t) = I_0 e^{-t/\tau_0} \cosh(\sigma_1/\sigma_0 \cdot t/\tau_0) \qquad (6)$$

$$P(t) = \tanh t/\tau_1 = \tanh(\sigma_1/\sigma_0 \cdot t/\tau_0)$$

with $\tau_0 = (n\ f\ \sigma_0)^{-1}$ and $\tau_1 = (n\ f\ \sigma_1)^{-1}$. Here n is the target density (atoms/cm^2), f the revolution frequency, τ_0 is the beam life time for strong interaction and τ_1 the polarization build-up time. P(t) and I(t) are shown in fig. 4 for different degrees of "spin dependence" σ_1/σ_0.

Internal polarized hydrogen target. The required target density has been determined in a somewhat arbitrary manner by demanding a beam life time τ_0 of at most 10 hours ($f \simeq 1$ MHz, $\sigma_0 = 0.3$b):



Figur 4: Intensity and polarization (equ. 6) of circulating ions as function of time in units of the beam life time τ_0.

$$n_{target} \geq (1\text{MHz} \cdot 3 \cdot 10^{-25}\text{cm}^2 \cdot 10\text{h})^{-1}$$
$$n_{target} \geq 10^{14} \text{ atoms/cm}^2 \tag{7}$$

The target has to be thin and window-less in order to match the limited cooling strength of existing devices. Presently available $\vec{H}$ atomic beams range only to about $10^{12}/cm^2$ in density[15]. But injecting an intense $\vec{H}$ beam into a storage cell[16] may lead to a target which has the required density.

The T-shaped target cell has one entrance tube for injecting the atomic beam and two openings for the circulating beam, as indicated in fig. 3. The size and shape have to be optimized for low gas conductance, i.e. high target density, which means small openings. On the other hand the full machine acceptance is required in order to minimize spin-independent losses. In addition, wall material with low depolarization at low temperatures is required. Estimates have led to a target cell geometry with a conductance of 12 l/s at liquid nitrogen temperature[4]. In this case about 10^{17} hydrogen atoms per second have to be injected in order to obtain the required target density.

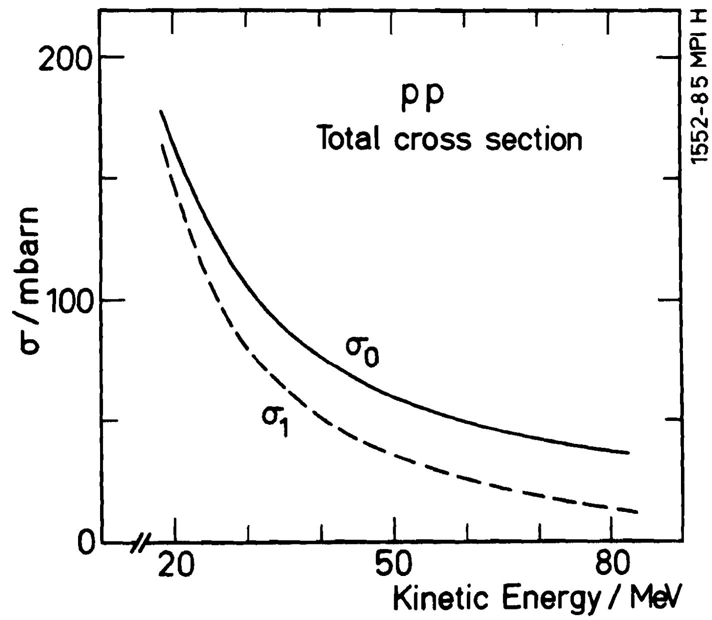
Proton tests at the Heidelberg TSR ring. The feasibility of the LEAR experiment depends critically on several open questions of storage ring physics which could be tested with protons in a ring similar to LEAR. Questions of this kind are the polarization life time for stored particles with simultaneous heating and cooling of the beam, the effective machine acceptance under realistic conditions and the resulting storage times, which have to be of the order of many hours.

Therefore, it is intended to do a proton test experiment using the Heidelberg "Test Storage Ring" TSR, which is presently under construction at the Max-Planck-Institut für Kernphysik[17]. The basic parameters of the TSR relevant for the proton tests are listed in tab. 1. For multiturn injection into the TSR the existing tandem-linac combination will be employed. The ring will comprise laminated magnets, an acceleration cavity and electron cooling.

Maximum magn. rigidity	:	$(B\rho)_{max} = 1.5$ Tm
Maximum proton energy	:	$(T_p)_{max} = 100$ MeV
Circumference	:	$C = 55$ m
Long straight sections	:	$4 \times (L = 5$ m$)$
Vacuum design pressure	:	$p < 10^{-11}$ Torr

Table 1: TSR basic parameters.

Although even for the pp-system it is difficult to measure the spin-dependence of σ_{tot} directly, it can be calculated rather precisely from the phase shift which have been obtained by analyzing the various pp scattering data. The result[4] is shown in fig. 5. Due to the Pauli principle σ_1/σ_0 exceeds 0.5 at energies below 60MeV. At 30MeV from equ.(6) a polarizing time constant τ_1 of about 40h follows. After 5h a polarization of 0.1 is expected which can



Figur 5: Calculated total cross sections σ_0 and σ_1 for the pp system as function of proton lab. energy[4].

be easily detected using proton-carbon scattering.

For the proton test experiment the following steps are required:

1) Exploration of the optimum design of a target cell using a storage cell test facility[16].

2) Development of the complete target with high intensity atomic beam source, differential pumping system and charged particle detectors.

3) Installation of low-β quadrupoles in the experimental straight section of TSR.

4) Installation of the target and test experiment.

If a sufficient polarization build-up is observed, the polarization life time would be explored under various conditions. This is essential for the LEAR experiment in order to deduce from the measured polarization build-up a spin-dependent cross section σ_1 or to place an upper limit on it.

Conclusion

After the first round of antiproton experiments at LEAR now several attempts are made to polarize antiprotons.

The first method is based on optical pumping of $\bar{H}^0$ or selective quenching of metastable $\bar{H}^0$ (2S). It would greatly profit from good $\bar{H}^0$ formation rates. The fact that no single $\bar{H}^0$ atom has been produced yet shows the need for experiments, in particular on schemes which enhance the spontaneous formation rate. These tests could be done also with protons.

The other two methods aim at polarizing $\bar{p}$s circulating in a storage ring which seems important in view of the economic use of $\bar{p}$s in an internal target experiment.

Stern-Gerlach separation of stored antiprotons is attractive because of its potential of polarizing $\bar{p}$s to a high degree without too much losses. It seems that the theory of SG separation of stored ions is still not fully explored and computer simulations are required before one can judge on the final potential of this method. It is intended to perform a test experiment with protons, preferentially in LEAR during the ACOL shutdown[12].

The filter method requires the development of a very dense internal $\vec{H}^0$ target. With such a target proton tests at Heidelberg will be performed, from which all the storage ring physics questions can be answered. The final aim of polarizing $\bar{p}$s then requires a sufficient spin-dependence of the total $\bar{p}p$ cross section which will be the first result of the proposed LEAR experiment. It should be mentioned that even a low value or an upper bound for σ_1 would be a very important restriction for the present models on $\bar{p}p$ interaction.

In conclusion, I would like to say that the prospects for obtaining useful quantities of polarized antiprotons are good, although the experiments are difficult and go to the limit of present technology. On the other hand, polarized antiprotons are an indispensable tool for a satisfactory understanding of $\bar{p}p$ interaction at low energies.

References

1 J. Lindfors, in "High Energy Spin Physics-82", Brookhaven, AIP Conf. Proc. 95, p. 259.

2 P.L. Csonka, Nucl. Instr. Meth. 63(1968)247.

K. Kilian and D. Möhl, Proc. Workshop on "Physics at LEAR with Low Energy Cooled Antiprotons", Erice 1982, V. Gastaldi and R. Klapisch (Ed), Plenum Press, p. 701.

3 E. Klempt, ibid, p. 709.

4 W. Brückner et al, Proc. Workshop "Physics with Antiprotons at LEAR in the ACOL Era", Tignes 1985, V. Gastaldi et al (Ed), éditions frontières, p. 245.

H. Döbbeling et al: Measurement of Spin-Dependence in $\bar{p}p$ Interaction at Low Momenta, CERN Proposal, PSCC/P92 (Nov. 1985).

5 K. Imai, in Proc. Symp. on Pol. Phenomena, Osaka 1985, p. 1136.

6 H. Poth: Feasibility Study for Antihydrogen Production at LEAR, Add. to Proposal PSCC/P86 (March 1986).

7 T.O. Niinikoski and R. Rossmanith: Self-Polarization of Protons in Storage Rings, CERN-EP/85-46 (April 1985).

8 Workshop on Polarized Antiprotons, Bodega Bay, April 1985.

9 A.N. Zelenskiy et al, Nucl. Instr. Meth 227(1984)429.

10 W. Haeberli, Ann. Rev. Nucl. Sci. 17(1967)373.

11 W. Pauli, Helv. Phys. Acta 5(1932)179.
W. Pauli: Das magnetische Elektron, Rapport du conseil-Solvay 1930

12 Y. Onel, A. Penzo and R. Rossmanith: Polarized Antiprotons, Memorandum PSCC/M258 (March 1986).

13 Ya.S. Derbenev et al, Part, Acc. 8(1978)115.

14 K. Kilian and D. Möhl, LEAR note 81-1 (1981).

15 W. Haeberli: Review of Operating Atomic Beam Sources, Proc. Workshop on Pol. Sources and Targets, Montana 1986.

16 W. Haeberli, in Proc. Workshop Nucl. Phys. with Stored Cooled Beams, Indiana 1984, AIP Conf. Proc. 128, p. 251.

W. Haeberli: Storage Cells as Polarized Gas Targets, Proc. Workshop on Pol. Sources and Targets, Montana 1986.

17 Experimente mit Gespeicherten Schwerionen, Memorandum, Max-Planck-Institut für Kernphysik, Febr. 1985.