Proc. Sixth Int. Symp. Polar. Phenom. in Nucl. Phys., Osaka, 1985
J. Phys. Soc. Jpn. 55 (1986) Suppl. p. 1136–1137

8.44 A method to polarize antiproton through antihydrogen formation

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The great success of the antiproton accumulation at CERN opened new field for both high energy and nuclear physics. It is quite important to investigate the methods to polarize an antiproton beam. A possible method is described in this report. The several types of the polarized proton source have been extensively developed for more than two decades. In all cases, large magnetic moment of an electron and coupling between the electron and a proton play a key role to polarize protons. The straight forward way to apply the technique of those polarized ion sources to polarize antiproton is to make an antihydrogen as the first step.

In the electron cooling of protons, because of the very low relative velocity between electrons and protons, spontaneous capture of electron can occur. Experimentally, hydrogen formation was observed in the cooling ring experiments and the measured capture rate was consistent with theoretical calculation. If the positron "cooling" is applied for the stored antiproton beam, antihydrogen beam is produced in the same manner. The capture rate depends on the temperature and density of the positron beam. To obtain the reasonable intensity antihydrogen, the positron beam must be stored in the ring and cooled by electrons. The antihydrogen can be extracted easily from the ring. In order to polarize the beam, the optical pumping by a circular polarized light (Laser) can be employed. With sufficient intensity of the light and sufficient time, both the orbital positron and the antiproton are fully polarized. If the energy of antihydrogen is more than 200 MeV, because of the doppler shift, a dye laser can be used for this transition. Recently Zelenskiy et al.1) proposed this method to polarize relativistic hydrogen (from H^-) beam and showed the necessary laser power and flight path length of atom to polarize nearly 100% is not unrealistic. The antihydrogen can be easily stripped to antiproton either by a foil or a laser beam. A conceptual view of the proposed method is shown in Fig. 1.

The hydrogen formation in the proton storage ring cooled by electrons and the possiblity of the antihydrogen formation are extensively discussed by R. Neumann et al. 2) The capture rate is given for spontaneous and induced capture in their paper. In the cooling ring, the rate of hydrogen formation depends on various parameters as,

$$R \propto n_e \cdot N_p \cdot \eta / \sqrt{T_e} \cdot \gamma^2$$

where η is a fraction of the ring used for the cooling, N_p; the number of proton in the ring, γ ; a Lorentz factor, n_e ; the electron density, T_e ; the electron temperature. The calculated capture rate was in the remarkable agreement with the experiment done at Nobosibirsk and ICE ring. In the ICE experiment, 750 H/sec/10^8 protons was obtained. In the case of antihydrogen, 5 10^{11} $\bar{p}$ can be stored in the ring but what about the positron density? An electron gun can provide high intensity and low temperature electron beam. But positrons are usualy produced by an electron linac. To obtain the low temperature and high density positron beam it should be stored in the ring and cooled by electrons. In this case, what limits the positron density? The positron density is primarily limited by the space charge as,

$$N_{sp} = (\pi \varepsilon_v \beta^2 \gamma^3 \Delta Q) r_e^{-1} (1 + \sqrt{\varepsilon_h / \varepsilon_v})$$

where N_{sp} is the number of positrons at the space charge limit, ΔQ; the tune shift, r_e ; the classical electron radius, $\varepsilon_{v,h}$ vertical and horizontal emittance and β, γ are the velocity and Lorentz factor of the positrons. $n_e^+ = 2\times10^6/cm^3$ is obtained, when

$\Delta Q = 0.2$, $\varepsilon_h = \varepsilon_v = 3$ mm mrad , $E_{e+} = 77$ KeV ($P_p = 500$ MeV/c) and ring circumference is 10 m.

If $\eta = 5\%$ and positron temperature is 0.2 eV, one can obtain 10^5 $\bar{H}$/sec. The capture rate to specific atomic states is also given in Ref. 2.
The ground and 2p state are dominant and the most states decay to the ground state

quickly. The 2s state is metastable and can not be polarized in the following polarization scheme. But the ratio of the 2s state is fairly small and can be quenched by a strong electro-static field.

The optical pumping by circular polarized photon is an established technique to polarize alkali atom and nuclei. But for the hydrogen, the wave lenghth of the radiation from 2p to 1s state is 121.6 nm and the optical pumping method has not been applied for hydrogen because such a short wave length laser has not been available.

Thanks to the doppler shift, a dye laser can be used for the optical pumping. The wave length of the laser in the lab system is a function of the velocity of the relativistic atom as, $\lambda = \lambda_0 \sqrt{(1+\beta)/(1-\beta)}$
With a photon of left-handed-helicity, $\Delta m = +1$ transition is selectively made, then the excited states (2p) decay to s-state by the selection rule. ($\Delta L = \pm 1$, $\Delta m = \pm 1, 0$). And eventnally, F = 2, m = +2 in 2p and F = 1, m = +1 in s-state are dominated depending upon the direction of the polarization of the photon.

The required light power for the saturation is defined as,

$$Q_s = h\nu_0/\sigma\tau, \ \sigma = (\lambda_0^2 A_{12} g_2)/(4\pi^2 \Delta\nu g_1)$$

where, $A_{12} = 1/\tau_0$ (τ_0 = 1.6 nsec) which is the life of 2p-1s spontaneous transition. $\Delta\nu = \nu_0 \beta \Delta p/p$ is a Doppler broadening. One can expect $\Delta p/p = 10^{-5}$ for the cooled antiproton, then the Q_s is 1 K W/cm^2. The time and the necessary power to polarize the antiproton can be estimated by using 2p-1s transition amplitudes. Zelenskiy et al. made a monte carlo calculation which was confirmed by Hiramatsu and Sato,3) by solving the rate equation. The results are shown in Fig. 2. As shown in the figure the antiproton can be polarized within 10 m flight path length with laser power of several hundred W/cm^2.

In summary, it is possible to polarize antiproton by using antihydrogen formation and optical pumping by a circular polarized laser beam in principle. The advantage of this method is to obtain the polarized antiproton almost without disturbing the circulating antiproton. The polarized antiproton of this scheme is fully compatible with other experiments with unpolarized antiproton beam, because the capture rate is very low that the stored antiproton beam can be hardly affected. It should be pointed out that the formation of antihydrogen itself is quite interesting for atomic physics and test of gravity on anti-matter.

References
1) A. N. Zelenskiy et al., Nucl. Instr. & Methods 227 (1984) 429
2) R. Neumann et al., Z. Physik. A313 (1983) 353
3) S. Hiramatsu and H. Sato, Private communication.

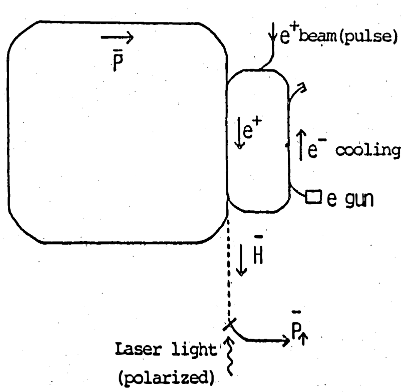

Fig. 1 Conceptnal view of the method to polarize antiproton

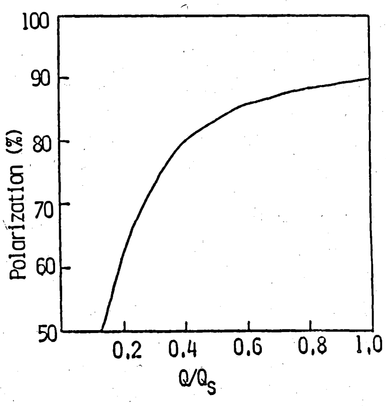

Fig. 2 Polarization vs radiation intensity with a 10 m flight distance. (Ref. 2)