CONF-860126--2

FEB 2 1986

BNL 37519

A METHOD OF GENERATING INTENSE NUCLEAR POLARIZED BEAMS BY
SELECTIVE PHOTODETACHMENT OF NEGATIVE IONS*

Ady Hershcovitch

BNL--37519

AGS Department, Brookhaven National Laboratory
Upton, New York 11973 U.S.A.

DE86 005815

ABSTRACT

A novel method for production of nuclear polarized negative hydrogen ions by selective neutralization with a laser of negative hydrogen ions in a magnetic field is described. This selectivity is possible since a final state of the neutralized atom, and hence the neutralization energy, depends on its nuclear polarization. The main advantages of this scheme are the availability of multi-ampere negative ion sources and the possibility of neutralizing negative ions with very high efficiency. An assessment of the required laser power indicates that this method is in principle feasible with today's technology.

I. Introduction

There has been demand [1] for spin polarized protons for high energy research, and there may be need [2] for intense "high" energy neutral deuterium beams with polarized nuclei for fusion reactors. Methods [3] presently being pursued have two major drawbacks: 1) the difficulty in producing a proper polarized atomic beam, which has both high density and high velocity (to avoid space charge effects and collisional destruction) and 2) the difficulty in producing "open ended" polarized atomic gas targets. In addition, the efficiency of converting polarized H^0 to polarized H^- (or even H^+) is not high.

This novel approach to the production of polarized protons with H^- ions utilizes selective neutralizations, by laser, of only one proton spin state of an H^- beam in a magnetic field, resulting in an H^- beam and an atomic hydrogen beam with polarized protons. The two beams can then be easily spatially separated in a magnetic field, yielding an H^- beam in which the protons are polarized. Figure 1a shows a possible schematic arrangement which can be used with high power lasers to selectively neutralize a beam in a single pass. Low to moderate power lasers, which are readily available, can be used by passing the H^- ions many times through the laser beam. A possible configuration is shown in Figure 1b. The advantage of this novel method is that multiamperes of H^- beams have been produced both pulsed [4] and in steady state. [5] Also, laser neutralization of H^- beams can be done with 100% efficiency. [6] Although the discussion throughout this paper refers to H^- ions, this scheme applies also to T^- and, in principle to D^- (although the problem will have to be completely reworked for deuterium due to the different hyperfine structure).

*Work performed under the auspices of the U.S. Department of Energy.

MASTER

REPRODUCTION OF THIS DOCUMENT IS UNLIMITED

gaw

Figure 1 - Schematic arrangements of selective neutralization systems: (a) "single shot", (b) multiple-pass.

II. Selective Neutralization

The concept is based on the following principle: when H^- ions are subjected to a uniform magnetic field, one of the electrons in each ion will have its spin aligned in the direction of the magnetic field, while the other electron will have its spin in the opposite direction. The proton spin of each of the H^- ions will be aligned either with or opposite to the magnetic field, i.e., $m_I = +1/2$ or $m_I = -1/2$. Since for magnetic fields below 10^8 Gauss, the H^- ion is a $1s^2$ $^1S_0$ configuration and it is the only bound state, [7][8] there will be only two spin states of H^- ions between which the sole difference is the orientation of the proton spin. The idea is to selectively neutralize one spin state of H^- ions resulting in a population of H^- ions who have proton spin down ($m_I = -1/2$) and a population of H^+ atoms with proton spin up.

Although extensive quantitative data about photodetachment of H^- ions exists, [9][10][11][12] the effects of an external magnetic field were never incorporated as in the work which was done for the photodetachment of S^- in the presence of a magnetic field. [13] The main difference between photodetachment in the presence and absence of a magnetic field is the quantization of the energy of the free electron in a magnetic field (into Landau levels). But, due to the electron dipole magnetic moment μ and the external magnetic field B , there will be an energy shift from each Landau level of $\mu \cdot B$. Thus, the total energy of the free electron is

$$E_f = (n + \frac{1}{2}) \hbar \omega_c + A X m_s + \frac{K_z^2}{2m_e}, \quad (1)$$

where A is the hyperfine structure interval factor which in the case of atomic hydrogen equal 9.375×10^{-18} erg (corresponds to 1420 MHz). K_z is the momentum parallel to the field (not quantized), m_s is the magnetic quantum number of the free electron, $X = 2\mu B/A$; ω_c is the cyclotron frequency and B is the magnetic field. To determine the final state of a detached H^- ion, the energies of the free electron and the H^0 atom must be added. In the region of intermediate magnetic field (1-1000 Gauss), the energy levels of the atomic hydrogen are given by the Breit-Rabi formula [14]

$$W = -\frac{A}{4} + m_F \mu_n B \pm \frac{A}{2} \sqrt{1 + 2m_F X + X^2}, \quad (2)$$

where μ_n is the nuclear magnetic dipole moment and m_F is the total magnetic quantum number. In this range of B fields two of the H^0 ground states, with $m_F = 0$, are mixed (spin wise). Hence an electron detached from an H^- ion, which results in a H^0 atom with $m_F = 0$, has finite probabilities of having either spin. Therefore, there are six possibilities: four resulting in $m_F = 0$ H^0 , one with $m_F = +1$ H^0 and one with $m_F = -1$ H^0 . The combined energy $E = E_f + W$ can be obtained by the addition of equations (1) and (2). At $X = 1$ these six states are shown in Figure 2, in which numerical values are written next to each level. In this figure α and β represent H^0 states with electron spin up and down respectively. The first subscript denotes proton spin while the second subscript represents the spin of the free electron: (+) means up and (-) means down. Figure 2 shows these levels for $n=0$. For $n \neq 0$, states are shifted by multiples of $\hbar \omega_c$, at 507 Gauss ($X=1$), $\omega_c \approx 1420$ MHz; $\hbar \omega_c = A$. The lowest state is $\beta_{+,-}$; $n=0$, while the first state of opposite nuclear spin is $\alpha_{-,-}$; $n=0$ at 1.42 A above it. Consequently, the maximum photon energy which can be used is (in frequency units) 2GHz above threshold. An examination of the asymptotic behavior of equations (1) and (2) for $\alpha_{-,-}$, $\beta_{+,-}$, and $\beta_{+,+}$ indicates that the optimum magnetic field for this scheme is close to $X = 1$.

Figure 2 - Energy levels of the stripped electron and the H^+ atom at 507 Gauss.

III. Resolution

Qualitatively, in view of the above discussion and if levels can be resolved, the possibility of selectively detaching electrons from H^- ions with proton spin up exists. At 507 Gauss most detached H^- ions will end up in the $\beta_{+,+}$ state and the rest in the $\beta_{+,-}$ state. Since the photon energy must be above $\beta_{+,+}$ and below $\alpha_{+,-}$ between which the difference is about 600 MHz, a resolution of 150 MHz should be sufficient. Since the laser line can be made arbitrarily narrow (for cw or "long pulse"), the effective Doppler broadening of the laser line as seen by H^- ions due to their thermal spread becomes the limiting factor. In the absence of any acceleration, the Doppler width $\Delta\nu(0)$ of a beam from a conventional H^- source is much larger than any hyperfine separation or splitting obtainable, e.g., at 1 eV the Doppler width is about 8.5×10^9 Hz. However, if the beam is accelerated, a phenomenon known as kinematic compression occurs. In simpler words, there is a reduction in Doppler width due to Doppler shift, which can be easily compensated for by adjusting the laser frequency. The factor [15] by which longitudinal Doppler width is reduced is given by

$$R = 0.5(kT/eU)^{1/2}, \quad (3)$$

where T is the beam temperature and U is the accelerating potential. In the case of a typical BNL H^- source with an H^- beam, whose thermal spread is about 4 eV, extracted at 20 kV, $\Delta\nu \sim 120$ MHz. This Doppler broadening is already acceptable and it can easily be further reduced. Spectroscopists have for some time employed this effect to resolve hyperfine structure with an accuracy which exceeds theoretical calculations. [16]

IV. Polarization and Laser Energy Needs

For this scheme to be of interest, a significant portion of H^- ions with $m_l = +1/2$ must be neutralized in order to achieve a high degree of polarization. When the spin up component of the H^- beam undergoes photodetachment, its current reduces as

$$I_+ = 0.5 I \exp(-\sigma_+ \Gamma \tau) \quad (4)$$

Where σ is the photodetachment cross section, τ is the interaction time, Γ (photons/cm²-sec) is the photon flux, I is the total beam current ($=I_+ + I_-$) and (+) and (-) refer to proton spin orientation for both I and σ . The polarization is given by the following expression

$$\text{polarization} = (I_+ - I_-)/(I_+ + I_-) \quad (5)$$

and the remaining fraction of the H^- beam F is

$$F = (I_- + I_+)/I \quad (6)$$

According to Broad and Reinhardt¹⁰ (Fig. 3 of that reference) the photodetachment cross section near threshold is given by

$$\sigma(\text{cm}^2) = 1.3 \times 10^{-27} f^{3/2} (\text{MHz}),$$

Where f is the photon energy above threshold in frequency units. Since the photon energy above threshold could be as high as 2 GHz, the photodetachment cross section for $M_l = +1/2$ ions is $\sigma_+ = 1.2 \times 10^{-22} \text{ cm}^2$. The resolution determines σ_- which for 150 MHz is $\sigma_- = 2.3 \times 10^{-24} \text{ cm}^2$. But first, the polarization is determined. A reasonable polarization of 76% can be obtained when $\sigma_+ \Gamma \tau = \lambda = 2$. Rewriting this equation as $\Gamma \tau = \lambda/\sigma_+$ and multiplying both sides of the equation by the energy per photon ($\sim 0.75 \text{ eV}$ for a 1.6 micron laser) result in an expression for the laser energy E_L that an H^- ion needs to be exposed to for selective stripping,

$$E_L = 0.75 \cdot \Gamma \tau = 2 \times 10^3 \text{ joules/cm}^2 = 2 \text{ KJ/cm}^2. \quad (7)$$

With this value of $\Gamma \tau$, using equations (4) and (6), the remaining fraction of the H^- current is determined to be 55% of the original current. By doubling the laser energy to 4 KJ, using equations (5) - (7) and repeating the above calculation yields a polarization of 96% at a beam current which is 47% of the original H^- current.

V. Possible Applications

Given the energy with which the H^- ions need to interact, the needed laser power can be determined from the interaction time. There are two basic approaches: 1) the laser energy is delivered in a single short pulse, and 2) the H^- ions make multiple passes through the beam of a moderate power long pulse laser. In the first case, an interaction length of a few meters is possible, e.g., an interaction region

of about 4 meters of a 1 KeV H^- beam results in $\tau \sim 10^{-5}$ sec. Therefore, a laser power of 2×10^8 watt is needed. There are no 1.6 micron lasers which can produce these power levels. However, Nd-glass YAG 1.06 micron laser can deliver power of more than 3×10^{12} watt. Thus, in principle, a configuration similar to Fig. 1a, in which the laser light is red-shifted, could be used. Red-shifting 1.06 micron laser light to 1.6 micron can be computed from the Doppler shift formula which yields $\beta = 0.39$ which corresponds to an energy of 80.8 MeV. This H^- energy can be achieved in one of the stages of the BNL linac.

A more practical approach is to subject the H^- ions to a moderate power laser for a longer period of time, i.e., extend the interaction time by having the H^- ions make multiple passes through the laser beam. This can be accomplished by using a storage ring. In storage rings, particles can have high energies. Therefore, the H^- energy can be chosen such that the Doppler shifted wavelength of an available powerful efficient laser corresponds to 1.6 microns.

One possibility is to store a 80.8 MeV beam to red shift a Nd glass YAG laser to 1.6 microns. A good example of such a device is LEAR [17] at CERN. It has four straight sections, 9 meters each, and in this machine 80.3 MeV H^- beams can be stored for over 7 seconds. The laser power needed is P (kW) = E_L/τ , where τ is the time during which the stored H^- ions are exposed to the laser radiation. In a device like LEAR the stored H^- spend most of the time in the straight sections, therefore it is reasonable to assume that in such a device the H^- beam could be subjected to the laser radiation for 4 seconds during a 7 second storage time. Since to achieve a polarization of 96%, the laser energy needed is $E_L = 4$ KJ, the laser power can be computed to be 1 kW at 1.06 microns. This power is available even cw. Another good example is the proposed AGS [18] booster at BNL. This device will have 12 straight sections, 3 meters each, which comprise about 18% of the total circumference. Uniform solenoidal magnetic field coils can be inserted in the straight sections. To prevent loss of spin [19] as the polarized H^- ions process in the guide fields, additional transverse field must be added to create magnetic field configurations known as "snakes". But, the energy in this device will be above 200 MeV. Therefore, a different laser must be chosen to match the Doppler shifted radiation as seen by the stored H^- ions to the 1.6 microns.

The closest (in wavelength) powerful and efficient laser is the CO laser. Its wavelength is 5 micron and its efficiency is 40%. Using the Doppler shift formula, the H^- kinetic energy required to blue-shift the 5 micron radiation to 1.6 micron is 679.15 MeV. The AGS booster could be used to store this H^- beam and a CO laser whose beam is reflected by mirrors through the straight sections could be pulsed for a period during which the 679.15 MeV H^- ions are stored in the ring. Figure 1b is a schematic representation of such an arrangement. In order to obtain a polarization of 96%, $E_L = 4$ KJ in a 10 sec storage period, the laser over needed is 2.2 kW. Thus, in the proposed AGS booster, this scheme can be used to achieve a nuclear polarized H^- beam with 96% polarization at 47% of the original H^- beam by using a pulsed 2.2 kW laser for a 10 second pulse duration.

Although not commercially sold, multi-kW CO lasers are available with bandwidths below 100 MHz. Many technical issues remain to be addressed, some of which, e.g., incorporation of "snakes" in storage rings, [19] are not straightforward. Nevertheless this scheme is in principle feasible.

VI. Table-Top Experimental Verification?

The main difficulty of this scheme is the need for operation near threshold where the photodetachment cross section is very small. This leads to the requirements of powerful lasers and long confinement times of intense high energy H^- beams. Both requirements are costly. Cheaper experiments would involve low power lasers and low H^- currents at modest energies, like the use of a gated electrostatic trap to confine the ions, and a 1.6 micron laser (to avoid the need of high energies for Doppler shifting).

An analysis of using a gated electrostatic trap [20] with a state-of-the art 1.6 micron laser, [21] showed that pulses of 4.4 nA of spin polarized H^- can be produced with a duty factor of 5×10^{-8} . Thus, at best spin polarized H^- can be produced at a rate of 1.4×10^6 per second. Since a polarimeter like the 760 keV at the end of the RFQ at BNL requires 2×10^{11} particles per measurement, each point will take about 40 hours. The problem now is that prolonged periods of data taking requires extensive computerization which increases the cost of such an experiment.

A more extensive discussion can be found in a paper which is due to be published in Nuclear Instruments and Methods in Physics Research after this workshop.

VII. References

- [1] C. Bournely, E. Leader and J. Soffer. Physics Reports 59, 96 (1980).
- [2] R.M. Kulsrud, H.P. Furth, E.J. Valeo and M. Goldhaber. Phys. Rev. Lett. 49, 1248 (1982).
- [3] W. Haeberli's review article in the proceedings of the 3rd International Symposium on Production and Neutralization of Negative Ions and Beams, K. Prelec, Editor, Brookhaven National Lab., p. 685, (1983). AIP Conference Proceedings No. 111.
- [4] Yu.I. Bel'chenko, V.G. Dudnikov. Proceedings XVth International Conference on Phenomena in Ionized Gases (ICPIG), Minsk, USSR, July 1981.
- [5] K.N. Leung and K.W. Ehlers, Rev. Sci. Inst. 53, 803 (1982).
- [6] H.H. Fink and A.M. Frank. Lawrence Livermore Laboratory Report UCRL-16844 (1975).
- [7] H. Bethe and E. Salpeter. Quantum Mechanics of One- and Two-Electron Atoms, Academic Press, N.Y. 1975, p. 154.
- [8] R. Henry, R. O'Connell, E. Smith, G. Chamugam, and K. Rajagopal, Phys. Rev. D9, 329 (1974).
- [9] M. Nascimento and W. Goddard III. Phys. Rev. A16, 1559 (1977).
- [10] J. Broad and W. Reinhardt. Phys. Rev. A1, 2159 (1976).
- [11] D. Feldmann, Z. Naturforsch 25A, 621 (1970).

- [12] H. Bryant, B. Dieterle, J. Donahue, H. Sharifian, H. Tootoonchi, D. Wolfe, P. Gram, and M. Yates-Williams, Phys. Rev. Lett. 38, 228 (1977); H. Bryant et al., Atomic Physics 7, 29, D. Kleppner and F. Pipkin Ed. Plenum Press, N.Y. (1981).
- [13] W. Blumberg, W. Iano, and D. Larson. Physical Review D19, 139 (1979).
- [14] G. Breit and I.I. Rabi, Phys. Rev. 38, 20822 (1931); H. Taub and P. Kusch, Phys. Rev. 75, 1481 (1949).
- [15] S.L. Kaufman. Optics Communications 17, 309 (1976).
- [16] W. Wing, G. Ruff, W. Lamb, and S. Spezeski. Phys. Rev. Lett. 36, 1488 (1976).
- [17] M. Chanel, P. Lefevre, D. Muhl, and D.J. Simon "LEAR Machine and Experimental Areas" CERN/PS 84-26(LEA) Oct. 1984.
- [18] Accumulator/Booster Proposal for the AGS. BNL report #32949-R. May 1984.
- [19] Ya. S. Derbenev and A.M. Kondratenko in AIP Conference Proceedings No. 51, titled "High Energy Physics with Polarized Beams and Polarized Targets." G.H. Thomas editor, Particles and Fields subseries No. 17, p. 292 (1979).
- [20] A. Hershcovitch, P. Politzer, Phys. Rev. Lett. 36, 1365 (1976); A. Hershcovitch, P. Politzer. Phys. Fluids 22, 249 (1979); W. White, J. Malmberg, C. Driscoll. Phys. Rev. Lett. 49, 1822 (1982); C. Driscoll, J. Malmberg. Phys. Rev. Lett. 50, 167 (1983).
- [21] L. Mollenauer, N. Vieira, and L. Szeto. Optics Lett. 7, 414 (1982).

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.