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GENERATION OF INTENSE POLARIZED BEAMS BY
SELECTIVE NEUTRALIZATION OF NEGATIVE IONS*

A.I. Hershcovitch

Brookhaven National Laboratory, Upton, NY 11973

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E.A. Hinds

Yale University, Dept. of Physics, New Haven, CT 06520

DE84 007377

ABSTRACT

A novel scheme is proposed. This method is based on selective neutralization by laser of negative hydrogen ions in a magnetic field. This selectivity is based on the fact that the final state of the neutralized atom depends on nuclear polarization in the magnetic field. A two-scenario approach is to be followed: one in which the resulting neutral atom is in the ground state, and in the other the neutral atom is in the $n = 2$ level. Limiting factors are discussed. The main advantages of this scheme are the availability of multi-ampere negative ion sources and the possibility to neutralize negative ions with very high efficiency.

INTRODUCTION

There has been demand¹ for spin polarized protons for high energy research, and there may be need² for intense "high" energy neutral deuterium beams with polarized nuclei for fusion reactors.

All methods³ presently being pursued start by either polarizing the electron of the hydrogen atom or by producing nuclear and electron spin polarized atomic gas. The next step is either to polarize the nuclear spin in one case or to eject a particular spin state from a gas in the other case. Finally, this nuclear polarized atomic beam has to be converted to either a positive or negative ion beam before it enters an accelerator. The major drawbacks of all present methods is 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). In addition, the efficiency of converting polarized H to polarized H⁻ (or even H⁺) is rather poor.

This novel approach to the production of H⁻ ions with polarized protons utilizes selective neutralization, 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 separated in a section with curved magnetic field. Figure 1 shows possible schematic arrangements which can be used. The advantages of this one-step

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Figure 1. Schematic arrangements of selective neutralization systems. To minimize laser power optimization of interaction length (a), and/or cavity (b) can be done.

method are obvious: multiampères of H^- beams have been produced both pulsed⁴ and steady state.⁵ Also, laser neutralization of H^- beams can be done with 100% efficiency.⁶

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SELECTIVE NEUTRALIZATION

The concept is based on the following principle: when H^- ions are subjected to a uniform solenoidal 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. Since for magnetic fields below 10^8 Gauss, the H^- ion has only one bound state,^{7,8} there will be two populations of H^- ions between which the sole difference is the orientation of the proton spin. The idea is to selectively neutralize only one population of H^- ions resulting in a population of H^- ions who have spin down and a population of H atoms with proton spin up. The negative ions can then be separated from the neutrals with curvature in the magnetic field.

Selective neutralization can work if there are proton spin dependent states which are preferentially formed, i.e. selective neutralization of H^- ions will be the result of selective formation of H atoms. There are two possibilities which we would like to explore: formation of H atoms in the ground state and formation of excited hydrogen atoms (in the $n = 2$ level). The advantage of operating near the threshold (H atoms in the ground state) is the availability of lasers; however, the photodetachment cross section is low.⁹ While the cross section for the formation of excited hydrogen atoms is eleven orders of magnitude higher,¹⁰ lasers at that wavelength of 1135 Å have short pulses.

Since more data exists for photodetachment of H^- ions which result in ground state H^0 atoms, including experimental verification,¹¹ this case will be used in this paper to demonstrate how the scheme works. Although extensive quantitative data about photodetachment of H^- ions exists,^{9,11} the effects of an external magnetic field were never incorporated like the work which was done for the photodetachment of S^- in the presence of a magnetic field.¹² The main difference between photodetachment in 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 $\mu \cdot B$. Therefore, in each shifted level, there could be either an electron spin up from one Landau level, or an electron spin down from the Landau level above it, i.e. $\mu \cdot B$ is added to or subtracted from each Landau level. Since the lowest energy level in the ground state hydrogen atom is electron spin down and proton spin up, the lowest energy state of a detached H^- ion is an H atom with electron spin down, proton spin up, and a free electron spin up. Figure 2 shows combined energy levels of a stripped H^- ion in a magnetic field of a few hundreds Gauss, i.e., the added energy levels of the free electron and the H atom in the ground state. The Landau levels refer to the energy levels of a free electron in a magnetic field. These levels are

Figure 2. Energy levels of the stripped electron and H^0 atom for magnetic fields below (a) or above (b) the critical field.

quantized¹² perpendicular to the field. Please note that by degenerate levels it is meant that the levels are either truly degenerate or very closely spaced.

RESOLUTION

Qualitatively, in view of the above discussion, the possibility of selectively detaching the spin up electron from H^- ions with proton spin up exists. In frequency units, the energy difference between hydrogen atoms with proton spin down and proton spin up (with the electron spin down) is over 400 MHz for magnetic fields of a few hundred Gauss to about 1 KG. Therefore, a resolution of about 100 MHz should be sufficient. Present day commercial lasers have resolutions much better than 100 MHz.

Stark broadening would not be important for this scheme due to low density and thermal spread of the H^- beam. Since the laser line can be made arbitrarily narrow (for cw or "long pulses"), 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 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 by which Doppler width is reduced¹³ $R = 1/2(kT/eU)^{1/2}$, where T is the beam temperature and U is the accelerating potential. Thus, the reduced Doppler width becomes $\Delta\nu = \Delta\nu(0) R$. 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 been employing this effect to resolve hyperfine structure with an accuracy which exceeds theoretical calculations.¹⁴ We plan to use a Penning source whose thermal spread is about 1 eV. The selective neutralization can then be done at beam energy of about 1 KeV.

LASER POWER NEEDED

For this scheme to be of interest, one proton spin orientation of H^- ions must be fully neutralized in order to achieve a very high degree of polarization. Therefore, the probability of photodetachment $p \gg 1$ is required. The photon flux Γ (photons/cm²-sec) needed can be estimated from

$$p \approx \sigma \Gamma \tau \quad (1)$$

Where, σ the photodetachment cross section and τ is the interaction time. At 1 KeV for an interaction region of about 4m, $\tau \sim 10^{-5}$ sec. At threshold, the photodetachment cross section when extrapolated from experimental¹¹ and theoretical results is only 10^{-24} cm². Solution of equation (1) yield $\Gamma \sim 10^{29}$ photons/cm²-sec. Assume a beam cross section $A \approx 0.1$ cm², the required power P for 0.75 eV photons is

$$P = A\Gamma h\nu \approx 10^{11} \text{ watt.} \quad (2)$$

There is no hope in achieving this power level in the foreseen future. The problem in this case of a single photon absorption stems from low cross section near threshold while it peaks at about 1.5 eV photons. By contrast, the double photon absorption cross section, which requires the use of 3.2 micron laser, peaks at threshold. Since the H^- ion has a very high degree of dynamic polarizability, the cross section for double photon absorption must be high at threshold. It is presently being estimated.

An alternative option is to use 10.93 eV photons (i.e. 1135 Å laser), whose photodetachment products are a free electron and an H atom excited in the $n = 2$ level. At this photon energy, the cross section has a very sharp resonance whose magnitude is 1.4×10^{-15} cm². Using this value of cross section in equation 1 and $h\nu$ of 10.93 eV in equation 2 the needed power becomes

$$P = 12.5 \text{ watt} \quad (3)$$

Lyman Alpha lasers have achieved power levels of 100 watt,¹⁵ for 10's of nsec. Utilization of such a laser in the configuration of Fig. 1b should work.

CONCLUSION

The scheme described in this paper is in principle feasible. Multiampere of negative ions have been produced and kinematic compression can be used to resolve hyperfine structure with an accuracy which exceeds theoretical calculations. For future work, a two scenario approach is to be followed: use a commercial 3200 Å laser if double photon absorption has the large cross section expected, i.e. leave the H^+ in the $n = 1$ level. Or, use an available 1135 Å laser (with the resulting H^+ in the $n = 2$ level). The latter would limit future uses of this scheme to short pulses, unless free electron lasers become a reality in which case the sky is the limit.

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