THE OPTICALLY PUMPED POLARIZED H⁻ SOURCE AT TRIUMF

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ABSTRACT

An optically pumped ion source capable of producing more than 10 μ A continuous polarized H⁻ suitable for injection into the cyclotron is being constructed. Preliminary measurements of sodium target polarization are reported. Broadband laser pumping is shown to be effective, and increases in polarization with magnetic field and with bi-directional pumping are observed and explained.

INTRODUCTION

An optically pumped polarized H⁻ ion source, which should eventually increase the available polarized current by at least a factor of ten over the present Lamb-shift source, is being developed at TRIUMF. By early 1985 TRIUMF expects to achieve 1 μ A of 75% polarized H⁻ current from a test stand presently under construction. If successful, the system will be upgraded to higher current and connected to the TRIUMF cyclotron. This paper briefly describes the optical pumping technique, as proposed by Anderson,¹ and summarizes TRIUMF results and present work.

OUTLINE OF OPTICALLY PUMPED POLARIZED ION SOURCE

The main feature of this source is the production of electron spin polarization in an optically thick ($1-5 \times 10^{13}$ atoms cm⁻³) sodium vapour target by optical pumping with circularly polarized laser light tuned to the D₁ resonance in sodium at 5896 Å. A beam of 5 keV protons, generated by an electron cyclotron resonance (ECR) source, passes through the sodium vapour. Polarized electrons are picked up by charge exchange, forming a beam of neutral electron spin polarized hydrogen atoms. The ECR source and sodium cell are within the same axial magnetic field, thus keeping small the emittance of the beam. The magnetic field following the sodium vapour is reversed to form a Sona-type zero crossing.² This diabatic field reversal technique, well proven in current Lamb-shift sources, transforms the electron spin polarized atomic beam into one that is proton spin polarized. Charge exchange in a potassium vapour cell within the reversed field yields a proton spin polarized H⁻ beam. The estimated current, neglecting aperture restrictions, is 4 μ A of H⁻ for each mA of protons. Attractive features of the source are: (1) efficiency - polarization of the atomic beam is produced directly and does not rely on quenching or throwing out of undesired substates, (2) high intensity mainly limited by laser power, (3) the polarization of the H⁻ beam

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can be reversed with no change in energy, current or emittance simply by reversing the laser polarization, (4) the H⁻ current from the sodium cell gives a convenient low energy measure of the electron polarization of the neutral hydrogen beam,³ since H⁻ can only be formed by the double charge exchange of oppositely polarized electrons.

Mori at KEK has built and tested an optically pumped polarized ion source in a pulsed mode. He reports 30 μ A of H⁻ with a polarization of 46±8%, and higher polarization at lower current.⁴ He used single frequency laser pumping, i.e. a narrow band laser with a bandwidth of ~10 MHz. His ECR proton source operated at 16.5 GHz in 200 μ s pulses at 20 Hz repetition rate.

OPTICAL PUMPING THEORY

Figure 1 shows the energy levels relevant to the D₁ ($2S_{1/2} \rightarrow 2P_{1/2}$) transition in sodium. At high magnetic fields (>1 kG) total electron angular momentum $\underline{J}$ and nuclear spin $\underline{I}$ become decoupled and thus m_J and m_I become good quantum numbers. Each level splits into two $m_J = \pm 1/2$ substates, each consisting of closely spaced hyperfine levels, giving a total Doppler broadened bandwidth of approximately 3 GHz for each m_J substate. If left-hand circularly polarized (σ^+) light is tuned to the D₁ wavelength only the transition obeying $\Delta m_J = +1$ is allowed, as shown. The excited state rapidly ($\tau = 16$ ns) decays to the ground state, with relative probabilities η shown. Because pumping is only out of the $m_J = -1/2$ substate, it is eventually emptied in the absence of mixing between the two ground state substates, leaving all atoms in the $m_J = +1/2$ substate and 100% spin

Fig. 1. Energy level scheme of sodium atoms at high magnetic field. Optical pumping with left circularly polarized light (σ^+) produces a depletion of population in the $2S_{1/2}$, $m_J = -1/2$ level and a positive polarization of the sodium vapour.

polarized. In the present case, wall collisions is the dominant depolarizing mechanism, occurring every 10^{-5} s.

The broadband laser used to pump the sodium has a bandwidth of approximately 30 GHz. The frequency separation of the two $2S_{1/2}$ substates increases by 4 GHz kG⁻¹, and is an order of magnitude smaller in the $2P_{1/2}$ state. Therefore, at fields above 8 kG the substate separation is more than the laser bandwidth and optical pumping is possible with linearly polarized light by tuning to the exact frequency of the $\Delta m_J = +1$ transition, albeit not as efficiently as with circularly polarized light.

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Fig. 2. Layout of TRIUMF optically pumped ion source. The calculated axial magnetic field is also shown.

TRIUMF OPTICALLY PUMPED ION SOURCE

Figure 2 shows the layout of the source now under construction. The proton beam is produced by an ECR proton source operating at 28 GHz, corresponding to resonance at 10 kg, with a microwave supply (Varian Extended Interaction Oscillator, Model VKO-2CH5F) capable of up to 1 kW cw power. The high power is fed in radially to avoid interfering with the laser optics. The power consumed producing the magnetic field plotted in Fig. 2 is approximately 70 kW. The extraction electrode and sodium target fit into the 12 kg field in order to minimize emittance increases and minimize radiative depolarization of the neutral hydrogen beam as it cascades to the ground state.⁵ The latter occurs if the field is not strong enough to decouple the orbital and spin angular momenta $\vec{L}$ and $\vec{s}$. Deflection electrodes placed in the low field Soma zero crossing region remove charged particles exiting the sodium target. A second charge exchange alkali vapour cell is located in the reversed 2 kg field, which preserves nuclear polarization. Potassium is used because it does not interact with the laser beam. Laser windows at both ends of the source allow laser diagnostics to be made and pumping from both directions.

RESULTS AT TRIUMF

Preliminary tests on a 10 GHz ECR source have shown that extracted currents of 120 mA cm⁻² through a 4 mm diameter aperture are achievable, with a proton fraction of 0.9 in the extracted beam.

Figure 3 shows the experimental apparatus used to produce and measure sodium polarisation. Optical pumping is performed by a broad-band Coherent CR-590 dye laser operating at 5896 Å. Splitting the

Fig. 3. Schematic of experimental apparatus to produce and measure polarization in a sodium vapour target. Broadband pumping is by circularly polarized counter-propagating beams. A weaker probe beam centred between the sodium D lines measures polarization and thickness. The etalon monitors the probe stability.

laser beam into two and pumping the sodium from both directions increases the polarization and polarization uniformity. At any instant the laser is operating on several modes, each much narrower than the Doppler width, averaging in time to a 30 GHz total bandwidth. Each narrow mode interacts with a population of sodium atoms having velocity v say. By pumping from the other direction, a particular mode will also interact with atoms having velocity $-v$, thus increasing polarization efficiency.

The polarization is measured using an optical rotation technique similar to a method used by Cornelius.⁶ The rotation of the plane of polarization of a linearly polarized probe laser tuned midway between the sodium D lines is directly proportional to both target thickness and polarization. The effects can be distinguished by measuring both with and without optical pumping. Figures 4, 5 and 6 show some results. Figure 4 plots sodium polarization against target thickness. Figure 5 plots polarization against magnetic field for different pump powers, and Fig. 6 plots polarization against field for single- and bi-directional pumping. Polarization increases with laser power, target thickness and for bi-directional pumping. It also increases with B, because inhomogeneities in B increase to a maximum of ± 0.4 kG, thus

Fig. 4. Polarization of sodium vs. target thickness, for broadband single beam pumping on D_1 line. Pump power into target is 680 mW, magnetic field is 8.7 kG.

Fig. 5. Polarization of sodium vapour target vs. magnetic field for different pump powers. Pumping was broadband on the D_1 line from one direction. Target thickness was $1.7 \times 10^{13} \text{ cm}^{-2}$.

Fig. 6. Polarization of sodium target vs. magnetic field at 800 mW. a) sodium thickness = $1.2 \times 10^{13} \text{ cm}^{-2}$, counter-propagating beams, b) as a) except single beam, c) as a) except thickness = $1.9 \times 10^{13} \text{ cm}^{-2}$.

increasing the effective transition bandwidth and improving its match with the laser bandwidth. That makes broadband pumping effective at high field strengths and gives results comparable to single frequency pumping. Because it is cheaper and more reliable, broadband pumping is preferred.

FUTURE PLANS

In collaboration with Dr. Y. Mori of KEK the source will be tested and optimized during 1984. As soon as the source provides cw current of approximately 10 μA with reasonable polarization and emittance, it will be placed on the accelerator. A new high voltage terminal will be ready by late 1985, thus making possible initial operation of the intense polarized ion source by early 1986.

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