STATUS OF THE TRIUMF INTENSE POLARIZED H^- SOURCE

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Summary

An optically pumped ion source capable of producing in a dc mode 30 to 50 μA of polarized H^- suitable for injection into the cyclotron is being constructed at TRIUMF. The source incorporates an electron cyclotron resonance (ECR) proton source operating with a 12 kG maximum magnetic field and a 1 kW oscillator at 28 GHz. Electronic polarization of an atomic H beam is achieved by charge exchange from an optically pumped alkali vapour with a 5 keV proton beam from the ECR source. Nuclear polarization of the atomic beam is obtained through a diabatic field reversal technique. Charge exchange in a second alkali vapour produces polarized H^-. Results from broadband optical pumping at TRIUMF are compared to single frequency pumping. The polarization is enhanced by having the magnetic field vary slightly over the sodium vapour and by pumping with two counter-propagating beams.

Introduction

The initial plans and motivation for an improved polarized H^- ion source at TRIUMF were outlined at the previous conference.[1] Since then, modifications to the operating Lamb-shift type polarized source have considerably improved its performance. The polarized current routinely delivered on target has increased from 200 to 400 nA with a peak of 600 nA having been demonstrated. As a result, priority has shifted to the second phase, namely the development of an optically pumped polarized source which should increase the available current by at least a factor of 10. This development has been divided into two stages. The first stage is to demonstrate prior to April 1985 the feasibility of the source by producing at least 1 μA of polarized H^- in a dc mode. If successful, the source will then in the second stage be upgraded for higher currents and connected to the accelerator.

Calculations and experimental studies on various aspects of an optically pumped source at LAMPF, KEK and TRIUMF have led to modifications of our original concept. The design has now been finalized and source assembly has begun. It is anticipated that the source will be operating on a test stand in the laboratory by the fall of 1984. This paper summarizes the TRIUMF results and outlines the distinctive features of the TRIUMF source.

Optically Pumped Polarized Ion Source

The technique, as proposed by Anderson,[2] involves aligning the electron spin of sodium atoms in an optically dense sodium vapour ($n\ell \simeq 10^{13}$ atoms/cm^2) in a magnetic field by optical pumping. The beam from a dye laser is tuned to the sodium D1 absorption wavelength and directed into the sodium vapour parallel to an applied magnetic field. With circularly polarized radiation, one-half of the ground states with a given spin alignment are depopulated giving rise to an electron-spin aligned polarized sodium target. Protons, at an energy of approximately 5 keV, pick up by charge exchange with relatively large probability a polarized electron from the sodium to form an electron-spin polarized atomic hydrogen beam. The polarization transfer efficiency from the sodium atoms to the atomic beam increases with the strength of the magnetic field,[3] the loss mechanism being radiative depolarization as hydrogen atoms created in an excited state cascade to the ground state. The magnetic field along the source axis in the region following the sodium vapour is reversed to form a Sona-type zero crossing.[4] This diabatic field reversal technique, which is used in Lamb-shift type polarized sources to enhance the polarization, transforms the electron-spin aligned atomic beam into a proton-spin aligned atomic beam. Charge exchange in a second alkali vapour within the reversed magnetic field yields a polarized H^- beam. The estimated current, neglecting aperture restrictions, is about 4 μA of H^- for each mA of protons. The proton polarization is determined by how effectively the sodium can be polarized, the polarization transfer efficiency and the quality of the Sona zero crossing. The first process has been studied at TRIUMF.

Mori at KEK has built and tested an optically pumped polarized ion source in a pulsed mode.[5] He reports 25 μA of H^- with a polarization of 39±21%. The polarization increases at lower currents (lower sodium densities) and is believed to be limited by laser power. The source uses a 16.5 GHz electron-cyclotron-resonance ion source (ECRIS) operating with 1 ms long pulses at a 20 Hz repetition rate. The peak magnetic field within the sodium vapour is 9 kG.

TRIUMF Optically Pumped Ion Source

The source being built at TRIUMF incorporates several innovations which should improve both the efficiency of the optical pumping and the polarization transfer to the proton beam. A general source layout is given in Fig. 1. Protons will be produced with an ECRIS operating in a dc mode. The extraction electrodes and sodium vapour target have been designed to fit into the 12 kG axial magnetic field in order to minimize radiative depolarization of the atomic beam. (Radiative depolarization can occur if the magnetic field is not strong enough to fully decouple the orbital and spin angular momenta such that $\vec{\ell}$ and $\vec{s}$ are good quantum numbers.) Optical pumping of the sodium is accomplished by two counter-propagating beams through the vapour. Provision has been made for a third low intensity probe beam to monitor the sodium polarization. Deflection electrodes, located after the sodium vapour in a region of relatively low magnetic field, remove the charged (unpolarized) particles exiting the sodium target along with the atomic beam. A second alkali target, located in a 2 kG magnetic field to define the spin direction, produces H^-. Potassium is used here rather than sodium because it does not interact with the pumping beam and has the added advantage of requiring lower temperatures to achieve adequate vapour densities. The energy dependence and charge exchange cross sections for the two alkalis are comparable. The potassium oven can be biased to reduce the angular divergence of the H^- beam leaving the magnetic field.

ECRIS

The ECR proton ion source will operate at 28 GHz corresponding to resonance at 10 kG. A Varian Extended Interaction Oscillator (Model VKQ-2H35F) capable of providing 1 kW cw power at 28 GHz has been purchased. Unlike KEK, TRIUMF requires a dc beam. The much higher average power implied by 1 kW cw has imposed constraints on the design. The microwave power will be fed in radially rather than axially (preferred) because of the difficulty in manufacturing a 28 GHz vacuum

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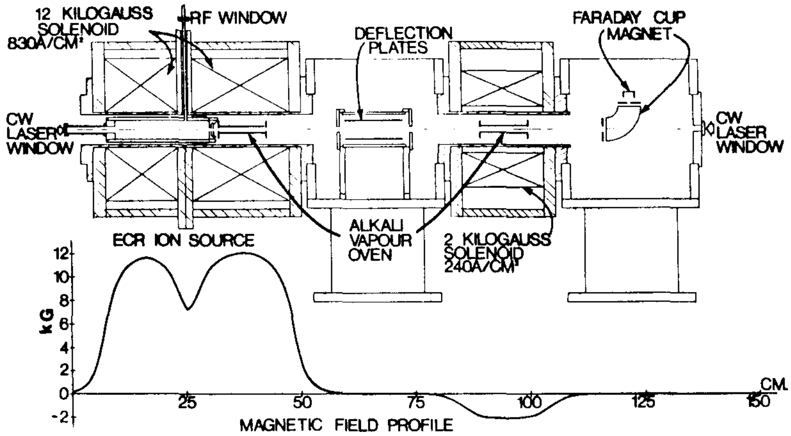

Fig. 1. Layout of TRIUMF optically pumped ion source. The calculated axial magnetic field is also shown.

microwave window for this power that is also transparent at 5896 Å. The magnetic field profile is a mirror configuration with a peak of 12 kG, a saddle at 8 kG; the mirror ratio is 1.5. The power consumption for the field plotted in Fig. 1 is approximately 70 kW. Preliminary tests with a 10 GHz ECR source have shown that plasma densities of the order of 10^{12} atoms/cm^3 can be achieved in a multimode plasma chamber. Proton fractions $\left(H^+/(CH^+ + H_2^+ + H_3^+)\right)$ in the extracted beam of the order of 90% were also achieved, both in a multimode chamber and a waveguide plasma chamber. In the waveguide the plasma had to be isolated from the walls of the chamber by a dc dielectric in order to reduce the H_2^+ and H_3^+ contributions. Design of the extraction electrode is being optimized with the computer code SNOW.[6] Design goals are extracted currents of 120 mA/cm^2 through a 4 mm diameter hole.

Optical Pumping - Theory

An optically pumped polarized ion source relies on optical pumping of a charge exchange vapour target to produce electronic polarization in that target. In the present case, sodium vapour is used. Figure 2 is a schematic of the ground state and first excited state of sodium, at magnetic fields (> 1 kG) high enough to decouple nuclear spin I and electronic total angular momentum J, i.e., at fields where M_J and M_I become good quantum numbers. In the example shown, left circularly polarized light, which carries angular momentum + ħ per photon, induces a transition from the m_J = -1/2 level in the $^2S_{1/2}$ ground state to the m_J = +1/2 level in the excited state $^2P_{1/2}$. The transition from m_J = +1/2 in the ground state to m_J - -1/2 or +1/2 in the upper state is forbidden. The excited state rapidly (τ = 16 ns) decays to the ground state, with relative probabilities η shown. Since pumping only induces transitions out of one ground state level, while decay is to either, the m_J = -1/2 level is eventually emptied, leaving the population of atoms all in the m_J = +1/2 state, i.e. all with electron spin +1/2 and the target is 100% polarized in the absence of depolarizing mechanisms. With right circular pumping, the process is the same except for a change in sign. On average, 1.5 photons are required to polarize each sodium atom. At the densities used in this application, wall collisions are the most important depolarizing mechanism.

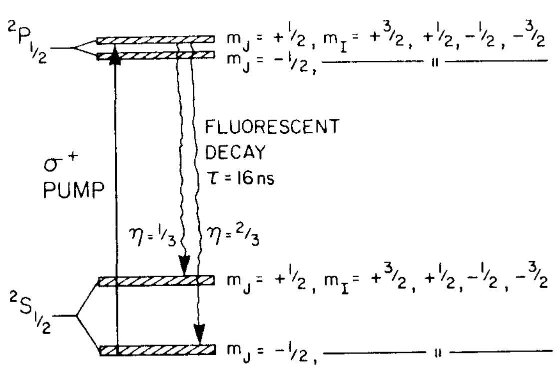

Fig. 2. Energy level scheme of sodium atoms at high magnetic field. Optical pumping with left circularly polarized light (σ^+) produces a depletion of population in the $^2S_{1/2}$, m_J = -1/2 level and a positive polarization of the sodium vapour.

The broadband laser used to pump the sodium atoms has a bandwidth of approximately 30 GHz. The Doppler broadened bandwidth of the m_J sublevels is a few GHz and the transition frequency changes by approximately ±2 GHz per kG for $\sigma^\pm$ pumping. At the magnetic fields attained, up to 9 kG, the σ^+ and σ^- transition frequencies are separated by more than the laser bandwidth, and it is possible to achieve sodium polarization even with linearly polarized light, albeit not as efficiently as with circularly polarized light.

At any given instant, the laser is operating on several modes, each of which is much narrower than the Doppler width of the sodium transitions. Therefore, the light only interacts with a velocity sub-group in the population distribution at any moment.

Optical Pumping - Results

Initial measurements of polarization in sodium vapour were made using a single Coherent CR-590 broadband laser to both pump the vapour and probe it. The beam was split, and the pump and weak probe were made to pass through the vapour at a small angle to each other, in both co-propagating and counter-propagating configurations. Pumping light was left circularly polarized, and the probe was either left or right circularly polarized. A qualitative measure of sodium polarization was found by scanning the laser frequency across the D_1 line, and comparing the relative absorption of the probe depending on whether it was left or right circularly polarized. Figure 3 summarizes the results. It was found that the measured sodium polarization increased with applied magnetic field, and was greater for co-propagating beams. That is because a co-propagating probe samples the same sub-population of atoms that is being directly pumped, whereas a counter-propagating beam probes a different sub-population. If polarization is lost between velocity changing collisions such an effect is expected. The average polarization lies somewhere between these two measurements.

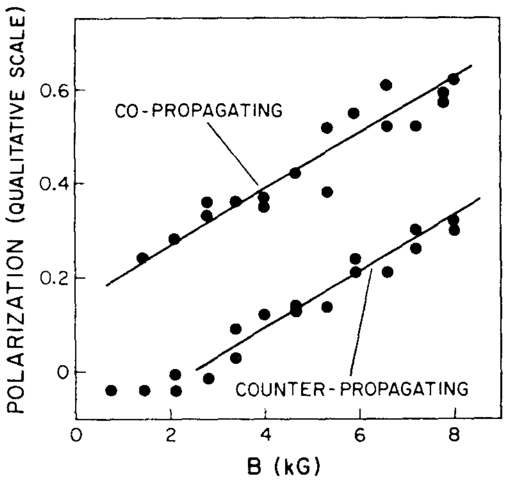

Fig. 3. Polarization of sodium target vs. magnetic field, using a single broadband laser tuned to D_1 line. The laser beam was split into a pump and probe beam. As shown, the measured polarization was higher when pump and probe were co-propagating through the sodium vapour rather than counter-propagating.

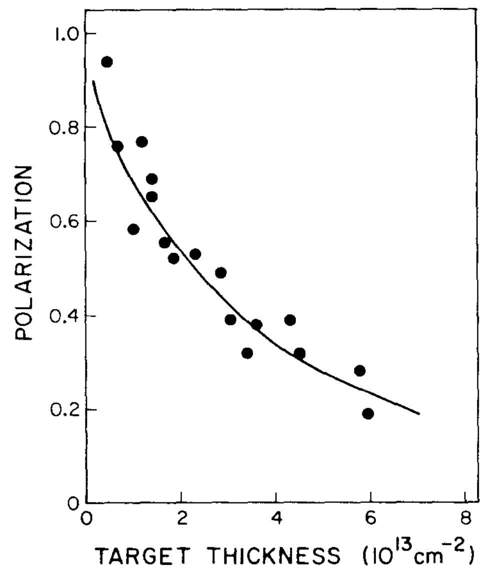

Fig. 5. Polarization of sodium target vs. target thickness, for broadband single beam pumping on D_1 line. Pump power into target is 680 mW, magnetic field is 8.7 kG.

Accurate measurements were made using two lasers and an optical rotation method. Figure 4 is a schematic of the experimental set-up used to pump the vapour both parallel and anti-parallel to the applied magnetic field, with the broadband laser. An unstabilized Coherent CR-699 ring laser probe was used to measure the polarization of the sodium vapour, similar to a method used by Cornelius.[7] The probe wavelength was set between the two D lines. With no magnetic field and no pump beam, the polarizer was set to give a minimum signal from the detector, set at the probe wavelength. Application of the field B caused a small rotation of the plane of polarization of the linearly polarized probe (Faraday rotation). Resetting the polarizer to give a new minimum gave a direct reading of the rotation angle, and hence the sodium density. Directing the pump laser into the sodium produced polarization and a further rotation of the plane of polarization of the probe beam, again measured directly after setting the minimum. Figures 5, 6 and 7 summarize the most interesting results, plotting polarization against B magnetic field, target thickness, pump power and pump direction.

Even though the laser bandwidth is an order of magnitude greater than the transition bandwidth, the optical pumping is surprisingly efficient. It is thought that the main reason for the increase of polarization with magnetic field results from inhomogeneities in the field which lead to an increase in the effective transition bandwidth. The field variation is ±0.4 kG at the highest field strengths. Since the vapour is optically thick, all transition frequencies are strongly absorbed.

Because different velocity sub-groups are sampled, it is advantageous to pump with two opposing beams from one laser, as shown in the schematic, Fig. 4. The improvement over single beam pumping is shown in

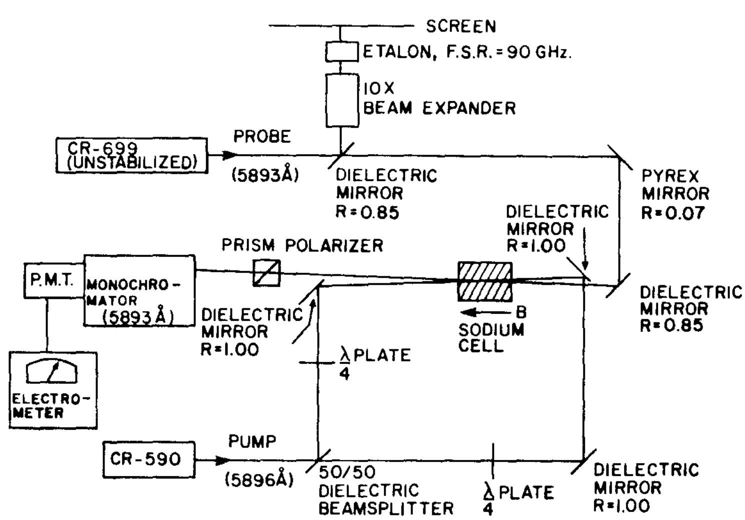

Fig. 4. Schematic of experimental apparatus to produce and measure polarization in a sodium vapour target. Broadband pumping is by circularly polarized counter-propagating beams. A weaker probe beam centred between the sodium D lines measures polarization and thickness. The etalon monitors the probe stability.

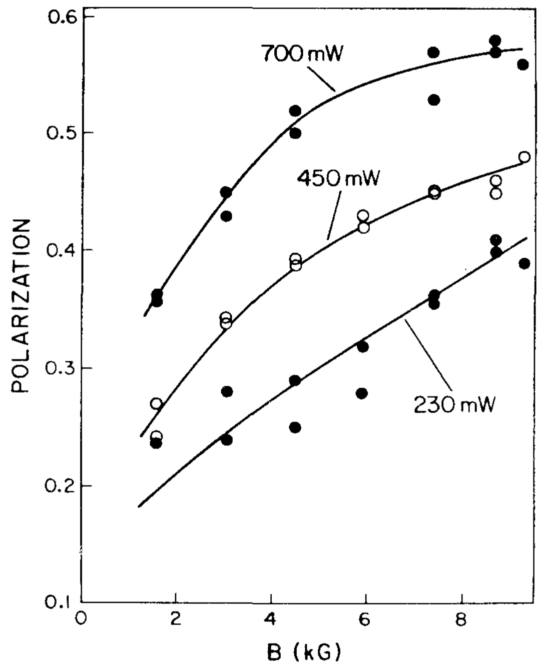

Fig. 6. Polarization of sodium vapour target vs. magnetic field for different pump powers. Pumping was broadband on the D_1 line from one direction. Target thickness was 1.7×10^{13} cm^{-2}.

Fig. 7. Furthermore, the uniformity of polarization should be much better.

As shown in Fig. 7, a sodium polarization of 75% has been achieved for a target density of 1.2×10^{13} atoms/cm^2 and 55% for 1.9×10^{13} atoms/cm^2 at a broadband power of 800 mW. This compares favourably with the results of Mori.[5] He reports at a density of 2.2×10^{13} atoms/cm^2 polarizations of 60%, 45%, 30% for single frequency pump powers of 1000, 750, 300 mW, respectively. Thus the polarization obtained by the two approaches does not favour one method over the other. The cost and operating characteristics, however, make broadband pumping the preferred approach.

Future Plans

In collaboration with Dr. Mori of KEK the source will be tested and optimized during the summer and fall of 1984. As the ECR source works equally well with deuterium, the polarization will be measured in the laboratory using deuterons and a tritium target. This will permit the polarization transfer efficiency (from the sodium to the deuterons) to be measured independently of the effects of the Sona zero crossing. As soon as the source provides a dc current substantially larger than the Lamb-shift source, with reasonable

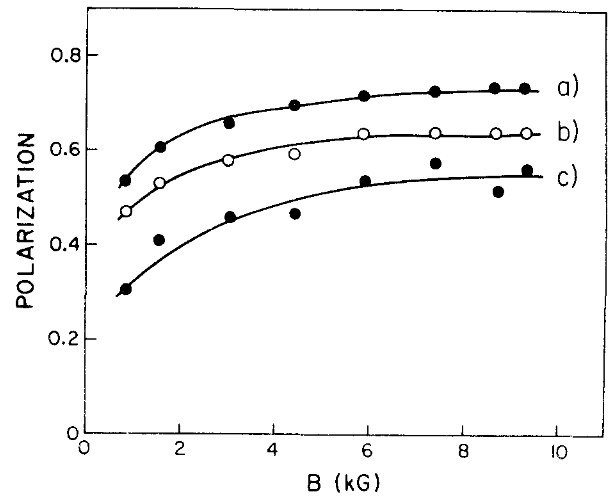

Fig. 7. Polarization of sodium target vs. magnetic field at 800 mW. a) sodium thickness = 1.2×10^{13} cm^{-2}, counter-propagating beams, b) as a) except single beam, c) as a) except thickness = 1.9×10^{13} cm^{-2}.

polarization and emittance, it will be placed on the accelerator. A third high voltage ion source terminal which could house this source is under construction. This terminal should be ready for commissioning by the fall of 1985. Thus it would be possible by early 1986 to begin initial operation with the intense polarized ion source.

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