

OPTICALLY PUMPED POLARIZED ION SOURCES

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TRIUMF

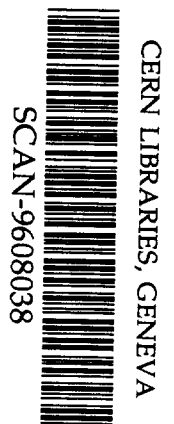
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Polarization transfer collisions between protons, atomic hydrogen, or deuterium and optically pumped alkali-metal vapour are implemented in the high current optically pumped polarized ion source (OPPIS) and the laser driven source (LDS) of nuclear polarized atoms for target applications. The OPPIS technique overcomes the limitations on intensity of the conventional atomic beam source technique and meets the requirements of the new generation of polarization experiments at multi-GeV accelerators and colliders.

1 Introduction

There are a number of proposals for polarization phenomena studies at high energy proton accelerators and colliders. According to the SPIN collaboration proposal, polarized beam at the FNAL Tevatron-Collider would allow unique studies of spin phenomena at the highest available energy including: cleaner searches for new particles, direct and unambiguous tests of perturbative QCD and measurements of the transverse spin structure of hadrons /1/. An experimental program at RHIC will address proton spin structure studies and test perturbative QCD /2/. Two major innovations -the "Siberian Snake" technique for polarization preservation during acceleration and high current polarized H⁻ ion sources- have made these studies feasible. Today, experiments with polarized beams having the same intensities as unpolarized are being considered. We believe that the understanding that polarization can be obtained as an extra beam quality without sacrificing intensity, will make a difference to future experimental programs at the highest energy accelerators and colliders.

A 1.6 mA DC polarized H⁻ ion current was recently obtained at the TRIUMF OPPIS with a promise of further increases to the 5 mA range /3/. A pulsed H⁻ ion current of 1.5 mA is required to produce a polarized proton-antiproton collision luminosity of 10³² /cm²s, equal to the projected unpolarized value at FNAL /1/. The TRIUMF OPPIS has already met the above requirements and potentially may satisfy all requirements of polarized injectors for high energy accelerators.



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2 Polarization Techniques

The general polarization scheme is basically the same for any kind of polarized ion source. In the first step, electron-spin polarized atoms are produced; in the second, electron polarization is transferred to nuclei by means of hyperfine interactions, and in the last step atoms are ionized (see Fig. 1).

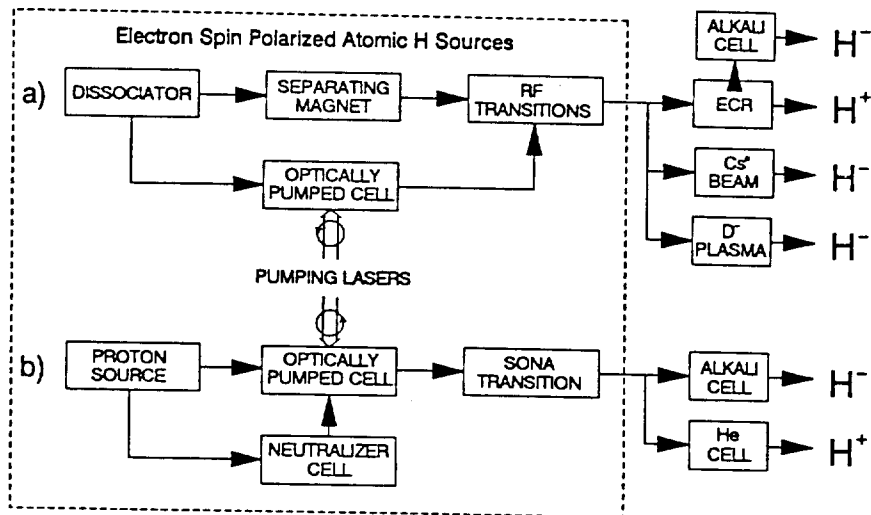


Fig. 1. General layout of the polarized ion sources. a) ABS, low velocity $V \leq 10^5$ cm/sec; b) OPPIS, fast H beam $V \geq 3 \times 10^7$ cm/sec. The option of spin exchange polarization is included.

An essential parameter for comparative analysis of different types of sources is the velocity (energy) of the atomic H beams.

No doubt, a low velocity ($\sim 10^5$ cm/s) beam should be used for polarized targets. For polarized ion source applications, however, fast ($\sim 10^8$ cm/s) atomic H beams are preferable due to the higher intensity of the fast polarized atomic H beams. Another major advantage of the fast beam is the ease of conversion to a negative H^- ion beam in an alkali vapour cell or to positive ions in a gaseous He ionizer cell (70-80% ionization efficiency in the latter case). In sodium vapour the equilibrium yield of H^- ions is about 9% at 2-4 keV beam energies. At 1 keV the yield is 16% in Rb vapour. That compares favourably with 0.5% ionization efficiency with a Cs colliding beam technique at the AGS operational source/4/, or 2.0% with a D^+ plasma ionizer at the test bench at INR, Moscow/5/. In both latter cases the duty factor is less than 0.1% and difficult to increase without losing efficiency.

In the atomic beam source the separation sextupole magnets select hydrogen

atoms in one particular electron spin state. Intrabeam scattering limits the polarized atom intensity. It appears that atomic beam source parameters have been well-optimized and 10^{17} atoms/s within the ionizer acceptance cannot be substantially improved. Scattering is an inevitable limit only for conventional atomic beam sources with separation magnets. However, thermal hydrogen atoms can be polarized by spin-exchange collisions with optically-pumped alkali-metal vapour in a cell. A polarized atomic H beam intensity in excess of 10^{18} atoms/s has been obtained by the use of K-H spin-exchange collisions /6/. At the moment the laser-driven source for target applications is limited by the high (20-30%) molecular hydrogen component and the admixture of potassium vapour. These problems could perhaps be solved with a proper choice of cell wall materials, temperature regime and cell geometry. The selective ionization of atomic hydrogen by the colliding beam technique can be used to obtain a high polarization for ion source applications. In spite of low ionization efficiencies, with a 10^{18} atoms/s atomic H intensity, a polarized H⁺ ion current up to 3 mA could perhaps be produced.

A fast (beam energy of 3.5 keV) polarized H beam intensity of 10^{17} atoms/s within the ionizer acceptance was obtained at the TRIUMF OPPIS in dc operation resulting in 1.6 mA polarized H⁺ ion current /3/. In a pulsed mode of operation, much higher beam intensity (up to 3×10^{18} atoms/s) can be produced within the same ionizer acceptance by using the BINP(Novosibirsk)-type atomic H injector /7/. Due to low divergence and high brightness of this beam the current density in the optically pumped cell will be practically the same as for the dc OPPIS where high polarization was obtained.

Electron polarization of a fast atomic beam is produced by spin-transfer collisions. This can be done by polarized electron capture from a ferromagnetic foil, as originally proposed by Zavoiski /8/, or electron capture from polarized hydrogen or alkali metal atoms polarized by separation magnets. However, the two most efficient processes are polarized electron pick-up by a primary proton beam traversing optically pumped alkali-metal vapour (charge-exchange polarization) /9/, or spin-exchange polarization in collisions of hydrogen atoms with the optically pumped alkali metal vapour /10/. The neutralization cross-section for H-Rb collisions is high at 3-4 keV H beam energy (about 7×10^{-15} cm²), so a Rb vapour thickness of about 10^{14} atoms/cm² is sufficient for charge-exchange polarization. A higher thickness of about $(5-10) \times 10^{14}$ atoms/cm² is required for spin-exchange polarization. All present operational OPPIS's are based on charge-exchange polarization. It is possible to polarize up to 10^{15} atoms/cm² in a 100 cm long cell using a high power pulsed laser. Therefore spin-exchange polarization or a combination of charge-exchange and spin-exchange polarization are promising for future polarized H⁺ ion current increases to the 10-30 mA range. Direct optical pumping of hydrogen is limited at present by the shortage of laser power at the transition wavelength 121.6 nm, but in the future progress in free electron laser technology could make feasible direct optical pumping of a fast atomic H beam and hence 100 mA polarized H⁺ ion current. There exists the

possibility of direct optical pumping of a relativistic atomic H beam. The Doppler effect shifts the transition wavelength to a value accessible to a pulsed tunable laser. For example, 121.6 nm will be shifted to 357 nm for a 600 MeV atomic H beam counterpropagating with the laser beam. A relativistic atomic beam could be obtained by stripping of an accelerated H^+ ion beam. That could be interesting for experiments requiring a high current short pulse polarized proton beam [11].

An elegant technique of polarized D^+ ion production in an OPPIS with optical pumping of both Rb neutralizing and Rb ionizing cells was developed at KEK. A D^+ current of 360 μA was obtained at a vector polarization of 70% [12].

2.1 Optical Pumping in the Presence of a Proton Beam

Although optical pumping of alkali metal vapour is well studied, predictions of the polarization in OPPIS are limited by ambiguous results of polarization relaxation measurements and the absence of realistic calculations of radiation trapping in the "thick" vapour cell. The presence of proton or atomic H beams strongly affects polarization processes.

First, it makes a dry-film coating useless. It is known that a dry-film coating deteriorates quickly in the charge-exchange OPPIS, perhaps after exposure to the high flux of UV radiation which is produced in decays of the 2S, 2P excited states. There was a hope that in a spin-exchange source, where this flux is much smaller, the coating would survive longer. However, experimentally we have found that the polarization relaxation time is reduced from more than 1 ms to 0.1 ms after a few minutes exposure to a DC atomic H beam. At present, the processes of dry-film deterioration or conditioning are unknown and we cannot rely on their use in operational sources. The relaxation time measurements should be repeated for different materials in the presence of atomic and ion beams. The understanding of the beam action could help to select the materials with better resistance. The dry-film coating produces a minimal depolarization but has a short lifetime in the presence of the beam. Perhaps some materials will have better resistance and a reasonable relaxation time. Any durable increase of the relaxation time to more than one bounce is very important for OPPIS applications and also for laser-driven sources. We hope new research on polarization relaxation times will be done in the near future.

Secondly, electron capture by a proton is effectively a Rb atom polarization loss and should be considered in terms of relaxation time reduction. Consider a proton beam of 2 cm diameter and a proton current density of 100 mA/cm², typical for present OPPIS's. About 50% of Rb atoms passing through this beam will be ionized. Higher current densities up to 500 mA/cm² are available in a pulsed mode from the BINP-type source. Therefore optical pumping dynamics in the presence of such a beam are very different from the usual case of optical pumping of alkali vapour. In the presence of a proton beam polarized electron capture, not wall collisions, could be the dominant process of Rb polarization loss. The Rb vapour

density will become inhomogeneous in radial and longitudinal directions (due to proton beam neutralization). At present, these processes are not completely understood. Probably, the short Rb atom mean free path in the presence of a high current proton beam is a positive effect since it increases the polarization transfer efficiency and reduces the probability of radiation trapping by reducing the effective Rb density. Electron capture from excited states also reduces radiation trapping.

To use spin-exchange polarization, a vapour thickness of at least 5×10^{14} atoms/cm² is required. The experimental limit on polarized Rb vapour density (90% polarization with pulsed laser pumping) is about 10^{13} atoms/cm³ for a relaxation time of 50 μ s. Optical pumping of a high vapour thickness in a long cell near the radiation trapping limit is complicated by strong laser power absorption along the cell. Although we cannot rely on a longer relaxation time to avoid the radiation trapping limit, there is the possibility of relaxing these limitations a bit by varying the magnetic field in the cell. If the magnetic field varies linearly from 30 kG to 25 kG along a Rb cell length, the laser power absorption will be spread homogeneously along the cell due to the Zeeman shift of the absorption frequency, which is about 9 GHz for a 5 kG field change. The effective absorption width including Doppler broadening will be about 12 GHz which fits well to the typical multimode pulsed laser emission profile. The Zeeman shift of the resonant frequency will also reduce the photon absorption cross-section, for a photon emitted along the cell, and therefore the radiation trapping density limit will be increased.

The use of an alkali vapour mixture with spin-exchange polarization of the higher density component [13] does not look so attractive under the condition of a short relaxation time, but there is still a possibility of optical pumping of both species near the radiation trapping limit and hence doubling of the effective vapour thickness. Therefore, we conclude that a highly polarized alkali vapour thickness up to 10^{15} atoms/cm² is feasible, at least in a cell longer than 50 cm.

2.2 Charge-exchange Polarization

A 1.6 mA polarized H⁺ ion current was recently obtained at the TRIUMF OPPIS as a result of the ECR primary proton source optimization. The full proton current was as high as 170 mA and the corresponding proton current density in the optically pumped cell was 120 mA/cm². Only 20% of the polarized H beam intensity (about 10^{17} atoms/s) was within the ionizer acceptance because of the high primary proton beam divergence. In the INR-type OPPIS, a high brightness atomic H beam is initially produced outside the magnetic field and then injected into the solenoid where primary protons are produced in a gaseous He ionizer cell. Replacing the ECR proton source with the Novosibirsk atomic H injector, having similar current density but much smaller divergence than the ECR proton source, should increase polarized H⁺ ion current to at least 5 mA. The atomic H injector

is capable of producing up to 500 mA of equivalent atomic H beam, which would allow 20-30 mA of polarized H⁺ current to be obtained. However, it is expected that space-charge of the proton and Rb ions produced in the charge-exchange polarization process will increase beam divergence and reduce the current at some point. Experiments at BINP Novosibirsk are now in progress to study the limits on the OPPIS pulsed current production.

2.3 Spin-exchange Polarization and Combined Technique

The advantage of the spin-exchange polarization technique is that neutral beam intensities are not space-charge limited. The experiments at INR, Moscow /13/ and TRIUMF /14/ demonstrated the feasibility of spin-exchange sources. But the higher optically pumped Rb thickness required for the spin-exchange source can be obtained only in a long cell (as discussed above, the dry-film coating doesn't work in the presence of the beam) and spin-exchange cross-sections are lower than theoretical predictions at 1-2 keV atomic H beam energies /10/. Both factors reduce the expected current from the spin-exchange OPPIS, but still this possibility should be closely examined, especially if new coatings more durable in the presence of beam are found.

In the INR OPPIS both injected and outgoing beams are neutral and space-charge is compensated. The equilibrium fraction of neutral H beam after the He ionizer is 30% and without separation the unpolarized atoms will reduce the final proton polarization. A bias voltage applied to the He ionizer cell gives the polarized and unpolarized beam energy separation - as a result high proton polarization of 65% was obtained at a 12 kG solenoid magnetic field /15/- but partially destroys the space-charge compensation giving rise to about 40% beam current losses.

To avoid the limitations of charge-exchange and spin-exchange polarization techniques we propose a combined scheme where charge-exchange collisions are used for protons produced in the unbiased He ionizer cell and spin-exchange collisions in the high thickness optically pumped Rb cell enhances polarization to over 90%. Practically, it could be done in a single Rb cell about 100 cm long with pulsed He injection at the upstream end. In a pulsed operation with a 100-200 μ s pulse duration, He gas will fill up only 20-30 cm of the cell length. The high 25-30 kG magnetic field is required as usual to prevent depolarization during the charge-exchange polarization process. The high field also eases the optical pumping of high density vapour.

In calculations we considered the combined charge-exchange and spin-exchange polarization of the two component proton and atomic H beam. We used experimental spin-exchange cross-sections /12,13,16/ which are about 30% lower than theoretical values in a 1-5 keV energy range. All possible charge-exchange processes were included. The results of polarization energy dependence are presented in Fig.2.

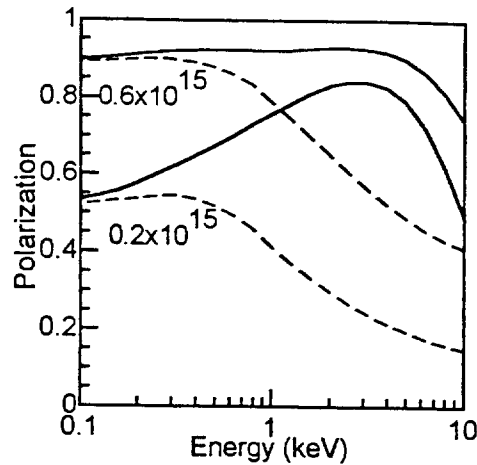


Fig. 2. The hydrogen electron polarization in the combined technique as a function of the incident atomic H beam energy (solid lines). Gaseous He cell thickness - 3×10^{16} atoms/cm². Dashed line - the spin-exchange polarization alone. The Rb vapour thicknesses are 0.2×10^{15} atoms/cm² and 0.6×10^{15} atoms/cm².

The most interesting result is the existence of the optimal beam energy of 3-4 keV, where the combined action of the charge-exchange and spin-exchange collisions give rise to 90% hydrogen electron polarization even at comparatively moderate Rb vapour thicknesses of about $4-6 \times 10^{14}$ atoms/cm². The optimal energy is determined by the more efficient charge-exchange polarization process. The H⁺ ion yield is highest (about 70% at 3×10^{16} atoms/cm² He cell thickness) at 3-4 keV beam energy and polarization is also rising quickly especially at 2×10^{14} atoms/cm² Rb thickness, where charge-exchange polarization is dominant. The residual hydrogen atoms are polarized in spin-exchange collisions which are essential for obtaining practically useful polarization. A high thickness optically pumped Rb vapour cell is still required (see Fig.3), however, not as high as for pure spin-exchange polarization. At a 6×10^{14} atoms/cm² Rb vapour thickness the hydrogen electron polarization will be about 90% and as discussed above this vapour thickness can be optically pumped in a long cell by a high power pulsed laser.

In the INR OPPIS only 20% of the primary atomic H beam entering in the He ionizer cell was converted to polarized H beam, because of 70% ionization efficiency in the He cell, 50% neutralization efficiency in the Na optically-pumped vapour and 40% losses at energy separation. In the proposed combined polarization technique, assuming space-charge effects do not cause beam losses, the only losses will be multiple elastic scattering. At 3-4 keV beam energy these losses will not exceed a few percent and the use of a long cell is acceptable.

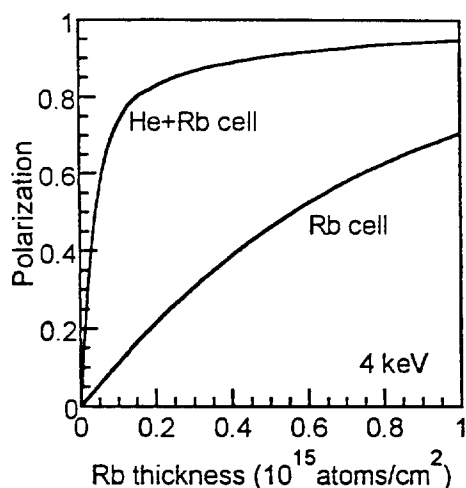


Fig. 3. Hydrogen electron polarization in the combined technique as a function of the Rb vapour thickness (top line). Bottom line - spin-exchange polarization only. The incident atomic H energy is 4 keV.

Experiments on high current production using the geometry which is required for a combined OPPIS were done at the BINP Novosibirsk. Equivalent atomic H beam intensity of 360 mA was obtained through an ionizer cell two centimeters in diameter at a distance 200 cm from the source. About 9% of this beam can be ionized in a sodium vapour ionizer producing about 30 mA of H⁺ ion current. Polarization measurements of charge-exchange polarization and the combined technique using the BINP-type atomic H injector are planned to be carried out at the TRIUMF OPPIS setup.

3 Conclusions

The optically pumped polarized ion source technique has surpassed the long awaited milestone of 1 mA polarized H⁺ ion current. The operating experience with OPPIS at TRIUMF, KEK and LAMPF has been highly reliable. The OPPIS beam quality meets the extremely demanding requirements of the parity violation studies in pp scattering at TRIUMF. The TRIUMF OPPIS is capable of delivering sufficient intensity of polarized H⁺ ion beam to the cyclotron for production of a 100 uA accelerated beam for future experiments with a polarized neutron beam, now under consideration. The experiments at KEK have proven the possibility of deuteron vector polarization in a scheme with double optical pumping. It is expected that tensor polarization can be obtained by using an RF transition unit /17/.

In a pulsed mode suitable for new proposed high energy polarization facilities

at RHIC, FNAL and LISS, the INR OPPIS technique or the combined charge-exchange and spin-exchange technique proposed in this paper will meet the requirements of the polarized beam injector with the polarized H^- ion beam current close to the unpolarized current value.

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