Development of a Spin-Exchange Polarized H^- Ion Source for High Energy Accelerators

A.N. Zelenski
INR Moscow, Russia
and
C.D.P. Levy, K. Jayamanna, P.W. Schmor, J. Welz, G.W. Wight
TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C., Canada V6T 2A3

Abstract

The H-Rb spin-exchange cross section energy dependence has been measured in the range 0.5–2.0 keV. The cross section and proton polarization increase as the beam energy decreases from 2.0 to 0.5 keV. Proton polarization as high as 48% has been measured at a beam energy of 0.6 keV and an optically pumped Rb thickness of 4×10^{14} at/cm^2. The polarization should be improved to 80% by use of high power pulsed lasers. These results are very promising for future development of high-intensity polarized H-ion sources.

1 INTRODUCTION

"Polarization phenomena in TeV-energy proton collisions are very sensitive to the manifestation of new physics beyond the standard model, and should help identify the nature of objects produced" [1,2]. Accelerator physicists must meet the demand for high luminosity and high polarization proton beams. It has been experimentally proven that the "Siberian Snake" technique prevents depolarization during acceleration. Another essential experimental component is a high current source of polarized H^- ions. At least 1 mA pulsed current is required to produce a reasonable polarized $p\bar{p}$ collision luminosity of about 10^{32} cm^{-2} sec^{-1}. Ideally, the polarized ion source should deliver polarized H current similar to unpolarized beam. The results presented in this paper give us hope that a pulsed, optically pumped polarized ion source (OPPIS) will meet the latter requirement.

All presently operating OPPIS are based on charge-exchange collisions. The TRIUMF OPPIS now produces 56 μA of dc H^- ion current with 85% polarization and up to 120 μA with 78% polarization with a normalized emittance of less than 1.0 pi mm mrad (90% level). The drop of polarization at higher current is due mainly to a shortage of laser power and could be improved in the pulsed mode. In the pulsed charge-exchange OPPIS at INR Moscow, based on a unique scheme using high intensity atomic hydrogen beam injection, 400 μA H^- current was obtained with the use of an optically pumped sodium vapour cell[3], and with a conservative estimate at least 1 mA pulsed H^- current in 1.5 π mm mrad emittance could be obtained from such a source with a Rb cell[4]. The maximum current of this source will be limited by space-charge in the charge-exchange cells. The experimental study of these limits has started at TRIUMF in collaboration with INR Moscow, KEK Japan, and the Budker Institute for Nuclear Physics in Novosibirsk.

Another method of polarization transfer is through spin-exchange collisions between H atoms and optically pumped alkali metal vapour[5]. Two possible schemes should be compared.

First, a source based on H-K spin-exchange collisions at thermal energies has produced up to 10^{18} electronically polarized H atoms per second[6]. Polarization transfer to protons could be done by means of rf transitions. A serious problem is the ≈30% molecular component of the flux. Selective ionization must be used to achieve H^- production from polarized atoms. A 30–50 keV Cs atomic beam or D^- ion beam or D^- enriched plasma could be used for this purpose. The experimentally achieved efficiency of such ionizers is about 0.3–0.5%. Hence with 10^{18} at/sec flux the maximum H^- current will be about 1.0 mA.

In the second scheme, polarization transfer occurs in spin-exchange collisions between an atomic H beam of keV energies and optically pumped alkali-metal vapour. A 1–2 keV proton beam is neutralized to form a fast atomic H beam, which then passes through an optically pumped polarized alkali vapour, where the H become electronically polarized by spin-exchange collisions with the alkali. The H atoms then undergo the same polarization processes as in the OPPIS based on charge-exchange collisions. The advantage with sources based on spin-exchange is that neutral beam intensities are not space charge limited. High brightness atomic H injectors which have been developed at BINP, Novosibirsk are capable of producing up to 0.5 A of equivalent atomic H intensity beam within the acceptance of a spin-exchange polarizer[7]. Another advantage of the fast atomic beam is the ease of conversion to negative H^- ions. In a sodium ionizer the equilibrium H^- yield is about 9% at 2–5 keV beam energies. Below 2 keV the yield in Rb is about 16%. Therefore, the use of the BINP atomic H injector should result in polarized H^- currents in excess of 10 mA. The critical factors determining the feasibility of this concept are: the upper limit on the alkali vapour density, how efficiently is the polarization transferred to the H beam, and how much atomic H beam can be transmitted through the alkali vapour cell. Previous experiments were rather successful and up to 50% proton polarization has been obtained from a spin-exchange source[8,9]. The goal of the present investigation is to measure spin-exchange cross sections and study the basic limitation on optical pumping of the high density Rb vapour.

2 EXPERIMENTAL STUDIES

The spin-exchange polarization experiments were done with the operational TRIUMF OPPIS setup[10], which was modified in the following way (see Fig. 1). A duoplasmatron followed by an unpolarized Rb cell was used as an injector of atomic H beam. The OPPIS ECR source was removed and the magnetic field in the solenoid was adjusted to a fairly flat shape. A longer 60 cm optically pumped Rb cell was installed (inner liner diameter 12 mm). The Sona transition, ionizer, and polarization diagnostics were exactly the same as for the well studied charge-exchange OPPIS, so that all polarization measurements could be compared with known reference points.

Initially, we studied optical pumping of high density Rb vapours in a 25 cm cell with a dryfilm coated copper liner. The magnetic field in the cell was 25 kG. Two Ti:sapphire lasers delivered 8 W power to the cell. A polarization relaxation time in excess of 1 ms was obtained with a fresh dryfilm coating. The results of polarization measurements are presented in Fig. 2. The Rb polarization of about 90% was obtained at a thickness of 2.5×10^{14} at/cm^2. This thickness is at least twice as high as without any coating. At higher densities radiation trapping causes a nonlinear growth of the absorbed power and finally limits the maximum density of highly polarized vapours even for infinite laser power[11]. The theoretical limit on density is about 10^{14} at/cm^3 and our experimental limit is only 10^{13} at/cm^3. Possibly some of the calculation assumptions are wrong, or polarization losses exist other than radiation trapping.

Spin-exchange in Rb-Cs vapour mixtures gives rise to Cs polarization when Rb only is optically pumped. Cs polarization of 60% was measured at a Rb density of 10^{13} at/cm^3 and a Rb polarization of 90%. The use of alkali vapour mixtures increases the radiation trapping limit on total density either by pumping of one species and spin-exchange polarization of another, or by pumping both near the radiation-trapping-limited density. Most promising is apparently a Rb-Cs mixture.

It is known that a dryfilm coating quickly deteriorates in the charge-exchange OPPIS, apparently after exposure to the high flux of VUV radiation which is produced in decays of the 2S, 2P excited states. There was hope that in the spin-exchange source, where this flux is much smaller, the dryfilm coating would survive longer. However, experimentally we have found that the polarization relaxation time is reduced from 1 ms to 0.1 ms after a few minutes of beam exposure. The experiments on spin-exchange polarization were done with an uncoated cell.

The proton polarization was measured at 300 keV in a polarimeter based on the $^6Li(p,{}^3He)^4He$ reaction. This polarimeter was calibrated by comparison with the reference 200 MeV polarimeters. In all experiments we used fast spin-reversal at a 40 sec^{-1} repetition rate and a synchronous detection technique for noise reduction. As a result, proton polarization measurement accuracy of about $\pm 1.5\%$ was routinely obtained in a 5 minute integration time. For Rb thickness and polarization measurements the well developed technique of Faraday rotation was used.

The results of spin-exchange polarization measurements are presented in Fig. 3. The H^- polarization grows quickly up to a thickness of 3×10^{14} at/cm^2. A wide plateau is the result of competition between spin-exchange collisions, which push the polarization up, and radiation trapping, which pulls Rb and hence proton polarization down. The maximum thickness of highly polarized Rb is limited by available laser power in the dc mode of operation. Nevertheless, the maximum 48% H^- polarization is very satisfactory for a dc source without any dryfilm coating. In the pulsed mode suitable for high energy accelerators the density and thickness could be at least doubled by using high power pulsed lasers[9]. The proton polarization would then increase to 80%.

The energy dependence of spin-exchange cross sections has been studied in the range 0.5–2.0 keV (see Fig. 4). The cross sections are close to calculated values but a substantial shift in the position of the maximum was observed.

A polarized H^- current of about 10 μA was obtained

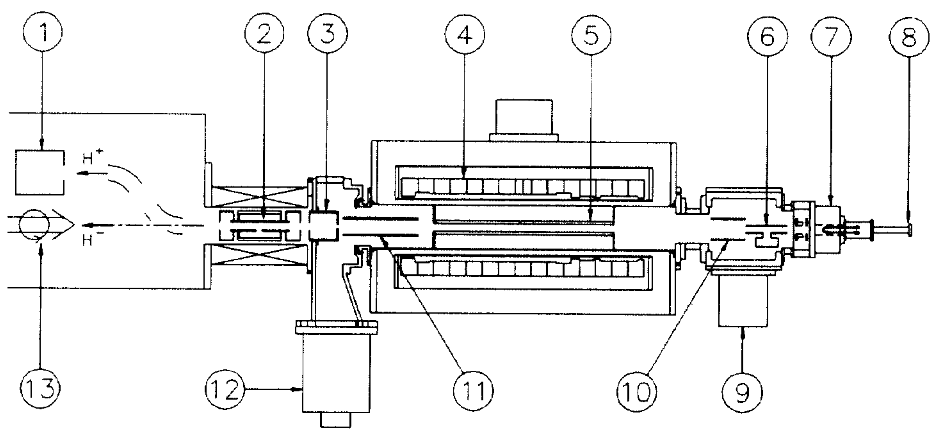

Fig. 1. Setup for spin-exchange polarization measurements. 1) Lyman-alpha polarimeter, 2) ionizer Rb cell, 3) Sona transition region, 4) 10 kG S.C. solenoid magnet, 5) 60 cm optically-pumped Rb cell, 6) neutralizer Rb cell, 7) duoplasmatron, 8) window for probe laser, 9) turbopump, 10–11) deflection plates, 12) cryopump, 13) pump laser light.

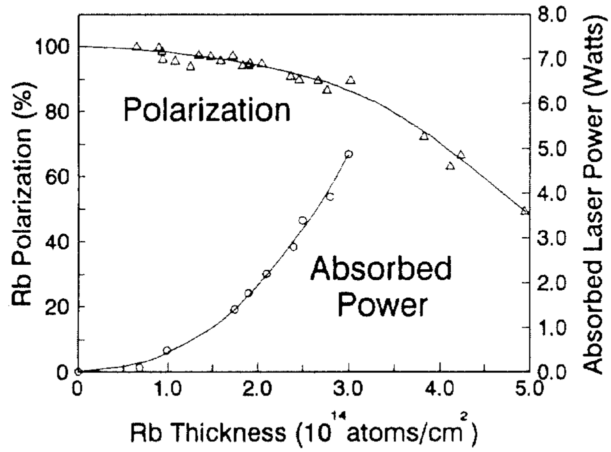

Fig. 2. Rb polarization and absorbed laser power dependence on Rb thickness, using a dryfilm-coated 25 cm long cell.

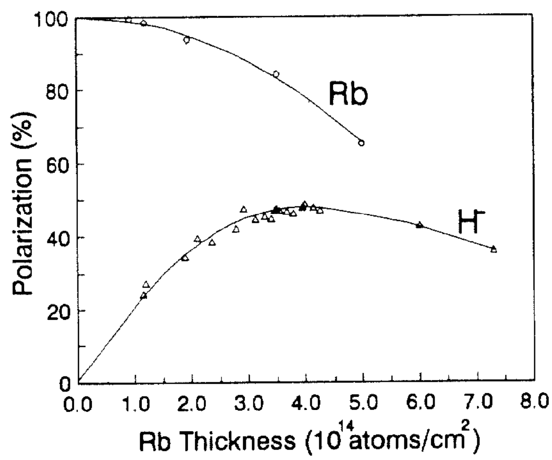

Fig. 3. Rb and H^- polarization dependence on Rb thickness, using an uncoated 60 cm long cell.

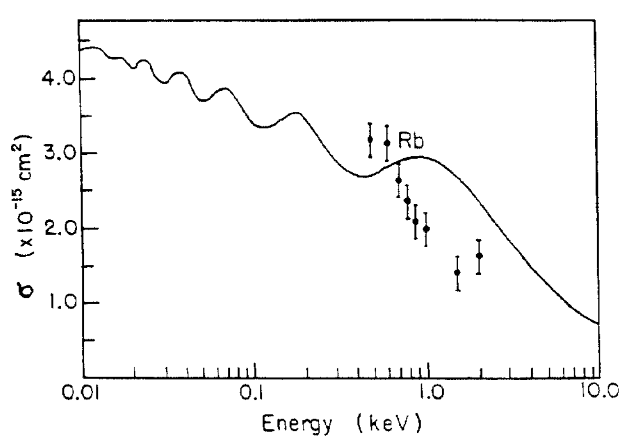

Fig. 4. H-Rb spin-exchange cross section dependence on atomic H beam energy. Data points, present work; solid line, calculated values[5].

with a duoplasmatron from the old TRIUMF Lamb-shift source without any special optimization. It is planned to develop a high brightness atomic hydrogen injector in collaboration with BINP Novosibirsk to replace the duoplasmatron.

3 CONCLUSIONS

At present the TRIUMF dc OPPIS produces a polarized H^- current of 120 μA. A pulsed INR-type OPPIS could produce at least 1 mA H^- current, and therefore a TRIUMF-INR-KEK-LANL-BINP team has proposed source development in the framework of the SPIN collaboration for experiments at FNAL. The results of the present work are very promising for the future development of a 10 mA pulsed spin-exchange OPPIS.

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