Recent Developments in Intense Polarized Hydrogen and Deuterium Ion Sources

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Abstract

The technology of producing intense beams of polarized H and D ions continues to improve. The variety of techniques available demands careful consideration of experimental program needs before a particular ion source design is chosen for construction. The performance of modern polarized sources will be compared and criteria for selection will be discussed. Present technical limits to source performance will be outlined.

I. INTRODUCTION

Long part of the fabric of low and medium-energy accelerator laboratories, polarized ion sources for H and D ions are often considered crucial. As their use becomes accepted and widespread, their variety and capabilities grow to match the needs of experiments and the requirements of accelerators where they are installed.

In this brief review, I outline recent advances for the two major types of H and D polarized sources being used today: optically pumped sources and atomic beam sources. A third type, the Lamb-shift source, is still used but is no longer competitive. Since development and use of any polarized source ultimately must rely on acquiring accurate knowledge of the emerging beam's polarization, I also briefly discuss low-energy polarimetry techniques which have proven most successful as diagnostics.

Further details about these developments are included in reviews[1,2] and in conference and workshop proceedings.[3-8] Each of these contains extensive references to the original literature.

II. OPTICALLY PUMPED SOURCES

A. Basic Technique

First proposed over a decade ago[9], this type of source requires that a beam of protons become neutralized by picking up polarized electrons from an optically pumped and polarized alkali vapor. It is essential that the optically pumped vapor reside in a strong magnetic field (>12kG) because a significant fraction of the H_0 atoms produced there are formed initially in an excited state. Without the strong magnetic field to decouple L and S, substantial loss of polarization would result during their dexcitation[10]. Thus polarized in electron spin, the H_0 beam then traverses a spatial region where the axial magnetic field reverses quickly compared with the Larmour precession rate of the atoms in that field. This causes a "sudden" or diabatic transition in which the atom's electron polarization is tranferred to the proton. Subsequently, further charge-exchange occurs either in He to produce $\vec{H}^+$ or in Na to produce $\vec{H}^-$ output beams.

The development of these sources has been pushed in laboratories at KEK[11], INR-Moscow[12], LANL[13], and TRIUMF[14]. The first two of these sources operate only in pulsed mode. The last operates d.c. The LANL source provides pulsed beams, but utilizes a laser system which operates continuously. Reports on the latter two sources appear in the proceedings of this conference[15-17]. This type of polarized source is not competitive for deuterium which has a nuclear spin of 1ħ. Attaching a single polarized electron does not introduce enough angular momentum into the system to provide interestingly high values of deuteron vector and tensor polarization[18].

B. Proton ion sources

This strong magnetic field over the vapor cell restricts the type of ion source used to provide the initial proton beam. Were this beam to originate outside the magnetic field and enter it while charged, severe emittance growth would result from the charge-exchange inside that field[19].

Two approaches are used to overcome this difficulty. In the most common solution[11,15,17] the proton beam is produced by an electron-cyclotron-resonance (ECR) ion source operating *inside* the magnetic field. It is important for obtaining optimum output beam polarization that the H_2 gas flow from the ECR source be limited and that beam focussing and pumping in the region between the source and the vapor canal be optimized. This reduces the chance of unpolarized electron pickup by the H_0 beam from background H_2 gas in the neighborhood of the optically-pumped vapor.

The second, much more surprising solution, places the proton source *outside* the magnetic field. The proton beam is intentionally neutralized in H_2 gas before entering the strong B-field, thus avoiding beam emittance growth. Once inside, the H_0 beam enters a He cell where it is stripped to become H^+ again before entering the optically pumped vapor. This latter solution is astonishing because of its success, utilizing as it does a total of four charge-exchange media to produce the final 4 mA $\vec{H}^+$ beam[12].

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B. Optically-pumped vapor systems

The polarized alkali vapor of choice originally was sodium. The circularly polarized, 589 nm Na(D1) light needed for optical pumping was readily available from dye lasers, with ~2W and 170W, respectively, available in continuous and pulsed operation. Especially in the former case, it is found that the density of the vapor which can be polarized, and the percentage of vapor polarization achieved, increase with laser power. At high densities the vapor atom polarization is limited by radiation trapping, the absorption of photons emitted by decaying atoms[20].

Considerable effort has been expended in trying to identify coatings for the vapor cell to inhibit the usual complete loss of alkali vapor polarization upon collisions with the cell walls. This could substantially reduce the need for increased laser power. Coatings successful in static cells operating at the required temperature degrade immediately when they are used on cells with beam passing through[21].

Rapid development in solid state laser technology makes it now more favorable to optically pump potassium or rubidium vapor. For both K (770 nm) and Rb (795 nm), up to 3 W of effective light can now be obtained from a single Ti-sapphire laser. These longer wavelengths imply that more photons per watt of laser power are available for the optical pumping than with Na. In addition, K and Rb are heavier than Na and require lower temperature for the same vapor density. Both facts imply that K and Rb atoms move more slowly than Na under operating conditions inside these sources. Thus, these atoms remain longer in the laser beam and are easier to polarize. The LANL source now operates with K vapor[15]; the TRIUMF source is presently being modified to use Rb[17].

An additional practical advantage of solid-state over dye lasers is their stability of operation. While monitoring of the alkali vapor polarization using the Faraday rotation of probe laser beams has been used, it is found at LANL that continuous monitoring and optimization of the vapor absorption of primary laser power offers the best measure of optical pumping stability and performance[22].

The strong magnetic field over the alkali vapor cell removes the degeneracy of the sodium ground state $3S_{1/2}$ and excited $3P_{1/2}$ levels involved in the optical pumping. This means the laser frequencies for the left and right circularly polarized photons are different, and are a function of the applied field. Separately pumped lasers at the two frequencies are often provided to facilitate switching the polarization of the optically pumped vapor quickly.

The necessity of providing maximum pumping power, especially for systems operating continuously, has recently driven LANL's utilization of all available lasers simultaneously to pump any given transition. Changing handedness of the pumping light to flip the vapor's polarization then requires adjusting the optics of all laser systems and can require ~10 sec. It is found also that use of multiple laser beams offers more flexibility for spatial and bandwidth coverage of the vapor, yielding further polarization improvement[16].

III. ATOMIC BEAM SOURCES

A. Basic Technique

Atomic beam polarized sources were among the first used. Their underlying physics has remained little changed for nearly two decades[23], but details of their technical design have been dramatically improved. In these sources, H_2 (or D_2) gas is dissociated in a radio-frequency discharge and formed into an H_o (or D_o) beam via a nozzle which is often cooled[24]. The emerging, highly directed atomic beam passes down the axis of a sextupole magnet system where, via Stern-Gerlach separation, atoms having electron spin parallel to B are focussed toward the axis while atoms of opposite electron spin direction are defocussed. Subsequently, the electron-spin-polarized atomic beam passes through radio-frequency transition regions where the electron polarization is converted to nuclear polarization.

B. *Atomic Beam Systems*

The best polarized atomic beams are now being developed to feed $\vec{H}_o$ or $\vec{D}_o$ internal targets for scattering experiments at storage rings. Most notable of these are systems under development at Heidelberg[25] and in Novosibirsk[26]. The Heidelberg source has produced output $\vec{H}_o$ fluxes of 3.8×10^{16} atoms/sec into a compression tube 1.0 cm in diameter and 10 cm long[27]. This has been achieved by very careful attention to design of the permanent magnet sextupole system for which the pole-tip fields reach 1.4 Tesla and by working to minimize surface recombination at the cooled atomic beam forming nozzle and scattering in the axial region from the nozzle through the first sextupole.

While performance of the best systems is impressive, major advances in atomic beam flux have been difficult to obtain over the last five years. It is technically possible now with high-speed computers to model accurately the axial and radial field distributions of permanent magnet sextupole systems and to combine these results with Monte Carlo codes to determine their focussing characteristics for the polarized atomic beam. While computerized optimization of these focussing systems is thus now possible, it still is very difficult to model the effects of unwanted atomic beam scattering from background gas in the axial region immediately following the beam forming nozzle.

C. Ionizer Systems

Four types of ionizer systems, three of them distinctly different, are used with atomic beam sources. The two most prevalent depend on $\vec{H}_o + e \rightarrow \vec{H}^+ + 2e$ electron impact ionization of the polarized, neutral atomic beam. In the oldest method, an intense electron beam arising from a hot filament is confined on the axis of a solenoidal B-field with the focussed polarized atomic beam[28]. The best of these ionizers is now

operating at Saclay where ~400 μA of pulsed $\vec{H}^+$ beam is routinely available[29]. Others operate at Osaka and Indiana. The principle difficulty with this ionizer is the presence of a large radial space-charge electric field associated with the electron beam. This causes an inherent energy spread of the extracted $\vec{H}^+$ beam which has been measured at Saclay to be ≥ 1 keV[29]. This spread makes beams from these sources difficult to bunch efficiently into the phase-space acceptance of cyclic accelerators.

In a different implementation of this basic technique, ionizing electrons are provided in an electron-cyclotron-resonance-heated plasma[30]. Such plasmas have the virtue that their ion temperature is typically < 5eV. The emerging $\vec{H}^+$ beam thus has much reduced energy spread. It has been shown at PSI to be capable of being bunched, before injection into the cyclotron, 3 to 6 times more efficiently than beams from their previous electron bombardment ionizer[31]. Collective experience at PSI, Bonn, and TUNL shows that there is a small (~5%) reduction of beam polarization when ionizing in these ECR plasmas. This probably arises because some polarized ions and atoms reach surfaces in the ionizer or extraction regions and neutralize or recombine there to become unpolarized. They then can migrate back into the active plasma to be ionized as an unpolarized background beam. Increased ionizer pumping and minimized obstruction of the polarized beam within the ionizer and beam extraction region minimize this problem.

Both ionizers discussed above have been coupled with subsequent alkali vapor charge-exchange systems to provide outgoing negative polarized beams. At TUNL electron pickup in cesium vapor converts up to 10% of our $\vec{H}^+$ (or $\vec{D}^+$) beam to $\vec{H}^-$ (or $\vec{D}^-$).

Both electron impact ionizers offer a diagnostic opportunity to optimize the efficiency of the radio-frequency transitions providing the nuclear polarization of the entering atomic beam. As discussed above, when the transitions are off the atomic beam is polarized in electron spin; when on, the nuclear polarization is increased and the electronic polarization decreased. Since these ionizers rely on electron impact ionization, since this ionization cross section is spin dependent, and since operating conditions are possible so ionizing electrons come largely from previously ionized polarized atoms, then a small (~0.08%) modulation in output polarized ion current occurs as the transitions are switched on and off. Observation of this modulation with a lock-in amplifier facilitates rapid optimization of transition unit parameters[32].

Another ionizing technique being actively used to produce $\vec{H}^-$ beam was first implemented at Wisconsin[33]. In this scheme, a counterflowing neutral, 50 keV cesium beam encounters the polarized atomic beam inside a solenoid where $\vec{H}_0 + Cs \rightarrow \vec{H}^- + Cs^+$ ionization occurs. The process also works for deuterium. The ionizer's very high selectivity for polarized atomic beam over unpolarized molecular background gas means that the output ion beam is highly polarized. The emerging beam's emittance is also extremely good. Such ionizers are being successfully used at Wisconsin[34], Seattle[35], and Brookhaven[36]. The latter is the most capable of reliable, high intensity operation because it is pulsed. In this case the general contamination and sputtering caused by the cesium beam is substantially reduced. The method has also been chosen for the new pulsed source under construction for COSY at Jülich[37].

The final ionizer type developed in Moscow requires a deuterium plasma[38]. In this device the thermal, polarized atomic beam enters a solenoid which confines the plasma of deuterium ions fed from a high intensity arc source. Inside the solenoid the highly favored charge-exchange reaction $\vec{H}_0 + D^+ \rightarrow \vec{H}^+ + D_0$ occurs. The resulting, extracted $\vec{H}^+$ beam pulses are very intense; up to 6 mA has been achieved in ~30 msec pulses at 1 Hz. The intensity drops for longer, more frequent pulses, because of scattering in background gas both at the nozzle of the atomic beam source and in the region of the ionizer. Operation of this and other ionizers with a D^- plasma to produce negative ions via $\vec{H}_0 + D^- \rightarrow \vec{H}^- + D_0$ has been discussed and is being tested[36].

IV. Performance Comparisons

The table on the next page collects data for presently operating polarized ion sources where I have been able to identify typical conditions. The upper section of the table describes the performance of operating optically-pumped sources. The lower section is devoted to atomic beam sources, with four separate sub-sections indicating the performance of sources equipped with the four different styles of ionizers.

The reader is cautioned that performance figures tabulated are extremely difficult to compare. Output currents, polarizations, and emittance values should really be compared only with a full understanding of the conditions under which they were measured. Nevertheless, perusal of the table entries allows several interesting general conclusions.

First, as stated before, the optically-pumped sources are satisfactory only for hydrogen beams; atomic beam sources can also provide deuterium. Second, sources producing positive beams are capable of approximately ten times higher output current than sources producing negative beams. Third, there is nearly always a higher current for sources operating in a pulsed mode than for sources operating d.c. Part of this advantage results from the improved vacuum conditions in sources where the input gas can be pulsed.

For pulsed optically-pumped sources, this higher current and the accompanying higher polarization clearly also result from the higher photon flux of pulsed lasers. In general, d.c. optically pumped sources provide the choice of higher beam intensities with lower polarizations (up to 35μA of $\vec{H}^-$ with P≈52% at TRIUMF)[39], or vice versa. In no case, for either pulsed or d.c. sources, is the polarization obtained yet as high as that from atomic beam sources.

For atomic beam sources, there has recently been a trend to construct ECR ionizers rather than electron-beam ionizers. The former are simpler to operate and provide beams with much improved longitudinal phase space emittance, which facilitates efficient beam bunching for pulsed accelerators. The latter provide slightly higher polarization. Cesium-beam ionizers

OPERATING POLARIZED SOURCE PERFORMANCES AND FEATURES

Laboratory [ref.]	Ions Available	Intensity μA	P_H %	P_D % of Maximum	Rep. Rate Hz	Pulse μs	Normalized Emittance* mm-mrad	Ionizer
Optically-Pumped Sources								
KEK-Tsukuba [11]	H^-	120	65	-	20	-	-	Na
INR-Moscow)	H^+	4000	65	-	1	30	1π	He
INR-Moscow) [12]	H^-	400	65	-	1	30	-	Na
TRIUMF [17,39]	H^-	20-35	61-52	-	d.c.	-	< 0.7π	Na
LAMPF [15]	H^-	15-20	62-60	-	120	1000	-	Na
Atomic-Beam-Type Sources								
ETH-Zürich)	H^+,D^+	400	-	85	d.c.	-	-	e-beam
ETH-Zürich) [28]	H^-,D^-	16	79	85	d.c.	-	-	e-beam + Na
Saturne/Saclay [29]	H^+,D^+	580	90	~ 90	1	1000	4π	e-beam
TUNL)	H^+,D^+	~ 60	-	80-85	d.c.	-	-	ECR
TUNL)	H^-,D^-	~ 6	75	80-85	d.c.	-	-	ECR + Cs
PSI [30]	H^+,D^+	150	79	~ 85	d.c.	-	< 1.2π	ECR
Bonn [42]	H^+,D^+	-	> 80	> 80	d.c.	-	< 0.83π	ECR
Wisconsin [34]	H^-,D^-	3	> 95	> 95	d.c.	-	0.35π	Cs-beam
Seattle [35]	H^-,D^-	1	> 93	> 85	d.c.	-	-	Cs-beam
Brookhaven [36]	H^-	40	75-80	-	0.5	500	-	Cs-beam
INR-Moscow [40]	H^+	6000	76	-	1	30	2π	D + - plasma

*For comparison, measured emittance limits were converted if necessary to the normalized units $\varepsilon_n = \pi x x' \beta\gamma$, where $\beta\gamma = mv/m_oc$ with $m_o = m_{proton}$.

provide negative beams only, but these have the highest output polarization and the best overall beam emittance of beams from any of the sources described, albeit at the expense of significantly lower current and more frequent maintenance in d.c. operation than for sources equipped with electron bombardment ionizers.

Finally, one must marvel at the very high output currents achieved from the two sources operating in Moscow. Their performance continues a twenty-five-year trend in which polarized source improvements have doubled output beam intensities roughly every two years.

V. LOW-ENERGY POLARIMETRY

Low-energy (<300 keV) polarimetry is essential for evaluating a new source, for tuning it up later whenever it is operated, and for monitoring its continued performance. Each laboratory develops techniques which best suit its needs. Lack of attention to low-energy polarimetry can cost valuable experimental time while the beam is accelerated to energies where polarimetry is more routine. Low-energy polarimeters are usually of two types: those which rely on the polarization sensitivity of a particular nuclear reaction and those which employ atomic physics techniques.

Among the former, the reaction of choice for H beams is $^6Li(p,^3He)^4He$, with analyzing powers of 0.19, 0.21, and 0.48 at 200, 300, and 750 keV, respectively[17]. For D, the T(d,n) ^4He reaction has long been used for energies near 100 keV and has large and well-defined sensitivity to tensor polarization of the deuteron beam. A reaction with sizeable but not-yet-calibrated tensor *and* vector polarization sensitivity is D(d,p)T.

Successful atomic polarimeters for H and D rely on unique properties of the H_o or D_o atom in the n=2 excited states. The $H_o(2S)$ atom is metastable; it is created by charge exchange of the polarized ion beam before it enters the polarimeter. By proper application of electric and magnetic fields, it can be caused to decay to the $H_o(1S)$ ground state with different rates for different hyperfine states. The simplest such polarimeters are sensitive only to the atomic electron's spin in the 2S state, allowing one to infer the nuclear polarization of the beam[40]. The most elegant such suggested polarimeter allows measurement of the relative population of individual hyperfine states[41].

VI. CONCLUSION

In this brief summary it is clear that improvement in polarized source performance and technology continues unabated. The community of polarized source builders is still active and productive, using a variety of technical schemes well-suited to the individual accelerators where the sources are needed. It still is often true that experimenters lack enough polarized beam to suit their needs, so further source developments will continue. These will draw skills and knowledge from other areas of physics, in particular, atomic physics and surface physics. This cross-disciplinary fertilization is both impressive and essential.

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