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A REVIEW OF OPTICALLY PUMPED POLARIZED ION SOURCES

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ABSTRACT

The status of optically pumped polarized H^- ion sources is reviewed. Three sources are currently being tested and a fourth is funded. Recent results from the three operating sources are summarized. The INR source in Moscow has already achieved 60 μA of H^-. Aspects requiring further research and development, before the source is capable of producing 1 mA, are outlined.

I INTRODUCTION

In the two and one-half years since the Vancouver workshop a number of significant developments have demonstrated that an optically pumped polarized ion source, based on the scheme of Zavoiskii [1], Haeberli [2] and Anderson [3] is feasible. The first such source, built by Mori, has already been used to provide polarized beam for the KEK accelerators. At the INR in Moscow, Zelenskii and his coworkers have built and tested an intense pulsed H^- source intended for use with the Moscow Meson Factory. At TRIUMF, where a dc H^- source has been built and tested, plans are underway which should result in the source being attached to the cyclotron in 1987. A fourth source has been funded at LAMPF and is well into the design and manufacture stage. Other schemes are also being examined. Anderson et al have examined the possibility of achieving nuclear polarization through multiple spin-dependent charge transfer from an optically pumped alkali to atomic beams of H, D or T [4,5]. They have called the process "collisional pumping" and postulate that it should be possible to make polarized D^- beams in the ampere range. Alternatively, spin-spin exchange from a polarized alkali to an atomic species has been proposed by Happer as a promising technique for producing intense polarized beams for accelerators [6].

The original technique, as proposed by Anderson, involves polarizing the electron spin of sodium atoms in an optically dense sodium vapour ($n\ell > 10^{13}$ atoms/cm^2) by optically pumping with a dye laser tuned to the sodium D1 absorption wavelength. Protons, at an energy of approximately 5 keV, pick up 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 an applied axial magnetic field: the loss mechanism being radiative depolarization occurring when hydrogen atoms formed 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 in direction to create a Sona-type zero crossing. This diabatic field reversal technique transforms the electron-spin aligned atomic beam into a proton-spin aligned atomic beam. Charge exchange in a second (unpolarized) alkali vapour within the reversed magnetic field yields a proton polarized H^- beam. A block diagram of a source based on this design is shown schematically in Fig. 1. The estimated current, neglecting aperture restrictions, was about 4 μA of H- for each mA

of protons at a sodium target thickness of 10^{13} atoms/cm^2.

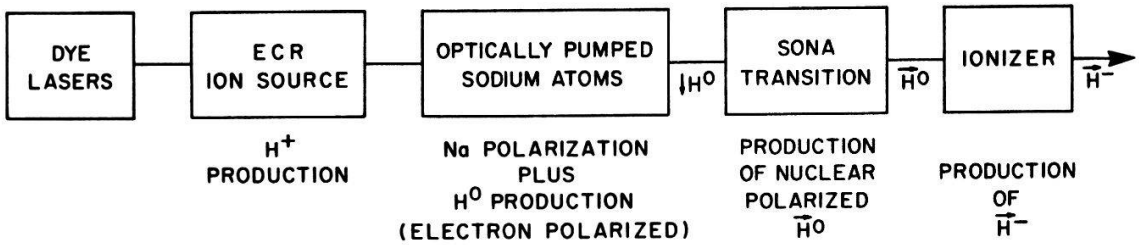

Fig. 1. A block diagram of an optically pumped polarized ion source based on the proposal by Anderson.

II PRESENT STATUS

The KEK source was described by Mori at the Vancouver workshop [7]. That source uses a 16.5 GHz electron-cyclotron-resonance proton ion source (ECRIS) operating with 0.15 ms long pulses at a 20 Hz repetition rate. The magnetic field at the sodium vapour target is 9 kG although tests have been carried out at higher fields. Two single frequency dye lasers were used to polarize the sodium vapour and a combination of broadband and single frequency dye lasers are currently being used. Recent progress has been on developments to meet the operational demands of stable beam over long periods.

At the Institute for Nuclear Research (Moscow), a duoplasmatron and neutralizing gas replaces the ECR proton source shown in Fig. 1. Neutral hydrogen atoms at 5 keV are then brought into the magnetic field surrounding the sodium target where they are first reionized in a helium gas target prior to picking up polarized electrons from the sodium. A flash-lamp pumped dye laser is used for optical pumping. A pulsed solenoid can be operated at fields up to 16 kG. The beam pulse width is 30 μs with a repetition rate of 1 Hz. The source has been tested both as an H^+ and as an H^- polarized source. 1 mA of polarized protons have been reported with a polarization of 65±3% [8]. As a polarized H^- source 60 μA have been obtained. The normalized emittance is less than 0.1 π cm-mrad.

An optically pumped polarized ion source has been built at TRIUMF in order to test the feasibility of producing intense polarized dc H^- beams. Protons are produced in a dc mode with an ECRIS operating cw at 28 GHz and at powers up to 1 kW. The extraction electrodes and sodium vapour target are located in a 12 kG uniform axial magnetic field. A single broadband dye laser is used to optically pump the sodium vapour. Initial measurements on the polarized atomic beam have observed about 10% of the expected neutral beam intensity in a normalized beam emittance of 0.007 π cm-mrad. By comparison, Mori has measured at KEK a normalized emittance of 0.011 π cm-mrad after accelerating 50% of the beam to 750 keV. A scattering chamber was set up beside the TRIUMF source in order to measure the angular asymmetry of scattered neutrons from the reaction $^3H(d,n)^4He$ at 55 keV. This measurement set a lower limit of 0.62±0.09 to the polarization transfer efficiency during charge exchange from sodium atoms to 5 keV deuterons in a 12.6 kG magnetic field.

At LAMPF, an 18 GHz ECRIS with superconducting coils capable of

providing up to 18 kG over the alkali vapour target is being assembled. It is planned to use three broadband dye lasers for optical pumping. This source is scheduled to be ready for initial operation with the linac by the spring of 1988.

Collisional pumping requires alkali vapour targets with a thickness 10^{15} to 10^{16} atoms/cm^2 in a low magnetic field. Tests are required to determine if optical pumping yields high target polarizations under these conditions. The group at Berkeley has outlined in a proposal the critical steps on the path towards demonstrating the feasibility of a source using collisional pumping. The details of this scheme are described in a contribution by Kaplan to this workshop.

III OPTIMIZATION AND FUTURE DEVELOPMENTS

It is very evident that there are still many areas that require research before operation of the optically pumped source is near optimal. The following paragraphs of this section contain a personal list of several of the key processes which can significantly influence the source's performance. In my opinion, these topics should be addressed in the working sessions of this workshop.

Sodium Polarization - In order to ensure long term stability of both polarization and current from the source it is necessary to monitor online both the sodium polarization and the sodium target thickness. Two techniques are currently being used but neither are satisfactory. The polarization and thickness can be estimated by measuring the absorption differences for right and left circularly polarized light at the D1 absorption line [9]. Alternatively, the Faraday rotation of linearly polarized light at a wavelength centered between the two D lines yields similar information [10]. The absorption technique is suitable for measuring polarization directly only at very low thicknesses ($\lesssim 10^{12}$ atoms/cm^2). The Faraday rotation technique is expensive in terms of equipment and source construction. At TRIUMF, the H^- beam is deflected off axis so that the Faraday rotation can continuously be monitored. At KEK, the laser frequencies are kept stable with a feedback loop and the target thickness is assumed to be adequately known from the oven temperature. Fig. 2 summarizes polarization results for cw optical pumping from three laboratories. Broadband pumping, matched to the Doppler absorption width is more efficient (and considerably more economical) than single frequency saturation pumping. Multiple lasers detuned with respect to each other are more efficient, in the single frequency case, than a single laser of equal power. A wall liner, such as Viton, increases the spin relaxation time and clearly increases the pumping efficiency. Nevertheless, even with Viton it is more efficient to use multiple dye lasers in order to achieve an acceptable polarization at a reasonable thickness, since the polarization does not scale linearly with laser power. Wall liners are important because they not only increase the pumping efficiency but also improve the spatial uniformity of the sodium polarization. Anderson has found a number of promising new materials with longer spin relaxation times [11]. These materials need to be tested with beam in a source. Viton, for example, fails to work unless it is placed well off axis from the primary beam. The sodium polarization can also be enhanced with the use of buffer gases [12]. The effect of these buffer materials on the resulting beam polarization should be examined. At TRIUMF,

bi-directional pumping with a single laser has been shown to increase the pumping efficiency. In addition a magnetic field gradient over the alkali vapour was used to achieve a better overlap between the D1 absorption linewidth and the bandwidth of the broadband laser. Finally, will radiation trapping set a limit to the ultimate performance of the source? Theoretical fits to the data of Fig. 2 indicate that even at thicknesses of 10^{14} atoms/cm^2 radiation trapping is negligible. This would imply that currents ten times Anderson's original estimate are attainable. In summary, there are two basic questions with regard to achieving high sodium polarization. First, what is the best technique to monitor the sodium polarization? Second, what is the most efficient, economical and reliable method of polarizing the sodium target?

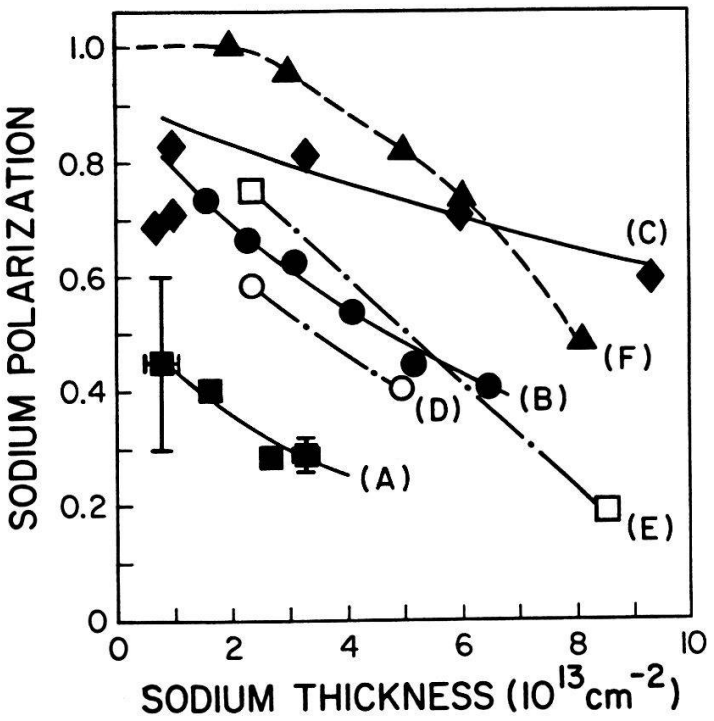

Fig. 2 Polarization data for a sodium vapour target vs. target thickness for optical pumping at the D1 absorption line.

A)- 0.45W, 30GHz δf, metal wall, 1 laser, 12kG, Faraday rotation, TRIUMF
B)- 0.55W, 30GHz δf, Viton wall, 1 laser, 12kG, Faraday rotation, TRIUMF
C)- 0.55W, 6GHz δf, Viton wall, 1 laser, 12kG, Faraday rotation, TRIUMF
D)- 1.0 W, 1MHz δf, metal wall, 1 laser, 9kG, Faraday rotation, KEK [7]
E)- 1.0 W, 1MHz δf, metal wall, 2 lasers separated by 0.05 cm^{-1}, KEK [7]
F)- 0.40W, 2.1GHz δf, metal wall, 1 laser, 0.75kG, absorption, Heidelberg, [9]

Proton polarization - An efficient, reliable, low-energy polarimeter is needed to optimize the polarization. Several techniques have been tried to date in order to measure the polarization that is transferred to the protons. The asymmetry in H^- production from the neutralizing alkali, between sodium polarized and unpolarized, was suggested by Cornelius as a method for measuring polarization [13]. This technique has been tried at KEK

and TRIUMF, but in practice it requires a relatively large analyzing magnet placed between the two alkali canals; a region which is already crowded! The group at Moscow has developed a technique in which the polarized protons are neutralized in a sodium vapour. The metastable atoms, in one of the four hyperfine 2S states, which pass through a spin filter are detected by their Lyman α radiation. The relative intensity of hyperfine states 1 and 3 is proportional to the number of polarized protons in each of the two respective states. Mori has used the nuclear reaction $^{6}Li(\vec{p},^{4}He)\ ^{3}He$ with 355 keV protons to measure the proton polarization. At TRIUMF, the $^{3}H(d,n)\ ^{4}He$ reaction was used at 55 keV to infer the proton polarization. The results from these measurements are summarized in Fig. 3 where the fraction of sodium polarization transferred to the protons is shown as a function of magnetic field. The published INR data has been multiplied by 1.17 in order to account for the 90% sodium polarization and the 95% alignment expected from the 1.5kG field at the ionizer. Also shown in Fig. 3 are the original calculations of Hinds et al [14] for the three cases; a) all charge transfer is into the $m_\ell = 0$ (T=1), b) all m_ℓ states are equally populated (T=0) and c) only $m_\ell = \pm 1$ are populated (T=−1). The same data have been plotted both for P_{Na}=+1 and P_{Na}=−1. Is the data now sufficiently accurate to conclude that higher magnetic fields and superconducting coils are necessary?

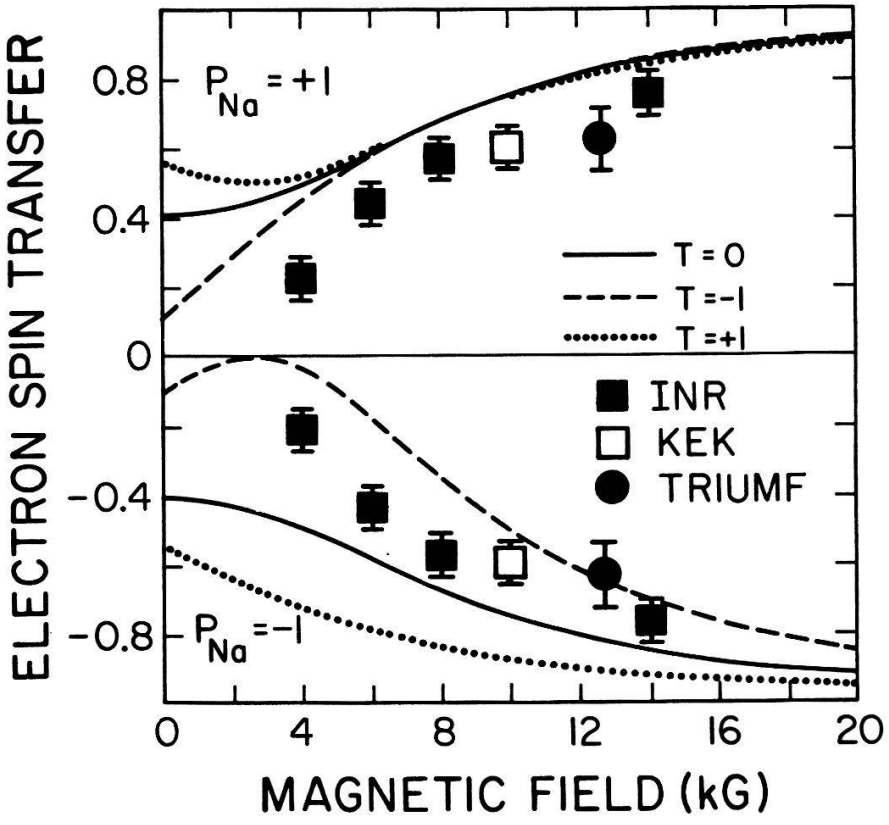

Fig. 3 Polarization transfer efficiency for polarized sodium to protons vs. applied magnetic field. The data points are from INR, KEK and TRIUMF. The smooth curves are from Hinds et al [14].

Beam Optics - In order to optimize the current from an optically

pumped polarized ion source careful attention must be given to the beam optics. R. Stevens Jr., using particle tracing techniques at LAMPF, has re-examined for the TRIUMF source the emittance growth which occurs when the atomic beam is ionized in a magnetic field [15]. He concludes that the emittance growth in the ionizer is relatively small compared to the effect of the fringe field and that the previous result of Ohlsen et al [16] is correct although incomplete. Ohlsen's paper does not take into account the defocussing of the fringe field which can lead to a significant beam divergence downstream of the solenoid. The beam emittance (ε) growth after the ionizer is given by $\pi.r_2 r'_{max}(r_2)$, where r_2 is the radius of the ionizer assuming that the beam fills the aperture and $r'_{max}(r_2)$ is the maximum angular divergence at radius r_2 due to the fringe field. From the results of Ohlsen

$$r'_{max}(r_2) = (q.B.r_2)/(2.m.v_z) = r_2/(2.\rho),$$

and the emittance growth is given by

$$\Delta\varepsilon = (\pi.r_2^2)/(2.\rho).$$

For most practical geometries the emittance growth dominates and essentially determines the final emittance (i.e., $\varepsilon \approx \Delta\varepsilon$). Since the source emittance need not be larger than the accelerator acceptance, the appropriate ionizer radius, r_2 is defined by the accelerator.

It is instructive to use the TRANSPORT [17] beam formalism in order to demonstrate how certain key parameters, if unoptimized, may limit the total current. The equation of a four dimensional ellipsoid in matrix form is

$$X^T \sigma^{-1} X = 1$$

where X^T is the transpose of the coordinate vector X and σ_i is a beam matrix with diagonal elements

(σ_{11}) = maximum half-width of the beam in the x-plane,
(σ_{22}) = maximum half-angular divergence of beam in the x-plane,
(σ_{33}) = maximum half-width of the beam in the y-plane,
and (σ_{44}) = maximum half-angular divergence of beam in the y-plane.

The beam matrix, σ_i, after undergoing a matrix transformation R is given by $\sigma = R\sigma_i R^T$. For simplicity an initial upright ellipse ($\sigma_{21} = 0$) is assumed with azimuthal symmetry (i.e., $\sigma_{11} = \sigma_{33}$ and $\sigma_{22} = \sigma_{44}$) inside of the solenoid. Using a solenoidal transfer matrix [18], the beam radius after travelling a distance ℓ in the solenoid is given by

$$r_{max} = \{\sigma_{11} + 2\sigma_{22}.\rho^2.(1-C)\}^{1/2}$$

where $C = \cos(\theta)$,
$\theta = \ell/\rho$,
$\rho = (mv_z)/(Bq)$,
m = mass of the proton,

v_z = axial velocity of the proton beam,
B = axial magnetic field,
and q = charge of the proton.

Thus the beam size oscillates in size, as one would expect, due to the initial beam divergence. Now, if in addition, the matrix transformation for a drift distance L is included to simulate the neutral beam optics from the first alkali neutralizer to the second alkali ionizer the maximum beam radius at the ionizer is

$$r_{max} = \{\sigma_{11} + \sigma_{22}\ [2\rho^2.(1-C) + 2\rho SL + L^2]\}^{1/2}$$

where $S = \sin(\theta)$. It is possible to minimize the beam size at the alkali ionizer by locating the neutralizer such that $\tan(\theta) = -L/\rho$. Unfortunately, for most practical values of B, ρ, σ_{11} and σ_{22} the change which can be made to the beam size is quite small. It is, however, worth noting that if $r_1 = (\sigma_{11})^{1/2} < 0.5$ cm, $r'_1 = (\sigma_{22})^{1/2} > 0.02$ rad and $L > 40$ cm then the beam size at the ionizer is basically determined by $L.(\sigma_{22})^{1/2}$; i.e., essentially independent of the beam size at the neutralizer. Thus for maximum current, the extraction and initial alkali target canal apertures should be larger than the ionizer canal aperture ($r_1 \gtrsim r_2 + L.r'_1$). It is assumed that the maximum angular divergence does not increase as the beam radius (r_1) is increased. This assumption is valid provided multi-aperture extraction is used. If the current density distribution is uniform across the beam, then the H^- current from the ionizer is proportional to $\{r_1.r_2/(L.r'_1)\}^2$.

It is also possible to examine the effect of introducting a field bump δB at the neutralizer in an attempt to undo the σ_{22} introduced by the source. The beam size at the ionizer is then given by

$$r_2 = \{\sigma_{11}\ (1+\alpha 2L^2) + \sigma_{22}[2\rho^2\ (1-C) + 2L\rho S + L^2.(1-2\alpha\rho(1-C)(1-\alpha\rho))]\}^{1/2}$$

where $\alpha = \delta B/(2\rho B)$ and is minimized when $\alpha = \sigma_{22}\rho(1-C)/[\sigma_{11} + 2\sigma_{22}\rho^2\ (1-C)]$. It is now possible to devise reasonable parameters which lead to a significantly reduced beam size. Numerical paticle tracking needs to be used to determine if the angular impulse approximation implicit in the matrix formalism adequately describes the 5 keV proton beam.

Miscellaneous Considerations - There are a number of effects which remain to be experimentally investigated. Both at KEK and at TRIUMF, it has been observed that the polarized neutrals resulting from H^+_2 can under certain circumstances be higher polarized than those from H^+. Is this theoretically to be expected? Should one optimize an H^+_2 source rather than emphasizing high proton fractions?

All three sources exhibit a significant unpolarized neutral beam which is not due to the neutralizing alkali target. The origins of this beam have not been fully established. The INR source rejects this unpolarized component of the beam by applying a retarding voltage to the sodium vapour canal. This technique can be used in the second alkali canal, as well, in order to select only H^- particles that underwent the appropriate charge

exchange reaction in both of the alkali vapour targets.

The design of an alkali vapour target requires refinement. Several of the parameters which put limits on the radial dimensions are being established. These factors include beam optics, accelerator acceptance, an acceptable diabatic field reversal and wall liners. However, what are the factors which determine the ideal canal length?

To date little attention has been given to user concerns. What is the best technique for achieving rapid spin reversal? Is the polarization uniform across the beam? What are the differences between the two spin states? Can the polarization and current be maintained reliably over long periods of time?

IV CONCLUSIONS

It has been a tradition, which I shall maintain, to not only present the status of existing sources at these workshops, but also to estimate the polarized H^- current that might eventually be obtainable. For the case of the optically pumped ion source using an ECRIS, I believe that the H^- current is given by the expression

$$I(H^-) = (J^+)(\pi\ r^2{}_1)(T)(F_{+0})(r^2{}_2/[r^2{}_1+L^2\ r'^2{}_1])(F_{0-})$$

where $J^+ = 300$ mA/cm^2 = ECRIS proton current density observed at TRIUMF with a 2 mm diameter exraction hole,

$r_1 = 0.85$ cm = the extraction hole radius,

$r'_1 = 20$ mrad = the neutral beam divergence ($E_x = 2$ eV),

$T = 0.75$ = transparency of multi aperture extractor,

$F_{+0} = 0.45$ at $n\ell = 10^{14}$ atoms/cm^2 = fraction of protons neutralized,

$r_2 = 0.25$ cm = radial aperture of the ionizer for a normalized emittance of 0.02 π cm-mrad with a 2 kG ionizing field,

$L = 30$ cm = the minimum separation between the two alkali targets,

$r^2{}_2/[r^2{}_1+ L^2 r'^2{}_1]$ = fraction of neutral beam within the acceptance of the ionizer

and $F_{0-} = 0.07$ = the fraction of neutral beam negatively ionized.

Substituting these values into the above equation implies an H^- current of ~0.9 mA within a normalized emittance of 0.02π cm-mrad (0.4π cm-rad eV$^{1/2}$) is possible. In this approximation the current scales with emittance. Although the maximum polarization has not yet been established, it certainly will exceed 60%. Reaching polarized currents of 1 mA still requires a great deal of research and development and it is the challenge for the working sessions at this workshop to minimize this effort.

Secretary's report, Session (A), J. Alessi:

Following the review by P. Schmor on optical pumping sources, the point was made that the beam emittance as a function of axial field in the charge exchange region is often not as bad as predicted by Ohlsen, et al. (In Lamb-shift sources, for example, the emittance may decrease as the magnetic field increases). The result of Ohlsen, et al., is for a parallel beam.

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