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INFORMAL WORKSHOP ON INTENSE POLARIZED ION SOURCES: A Summary

O'Hare Hilton Hotel

O'Hare International Airport

Chicago, Illinois

March 6, 1980

ARGONNE NATIONAL LABORATORY

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Organized and Edited by:

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Accelerator Research Facilities Division

PREFACE

The Accelerator Research Facilities Division of Argonne National Laboratory sponsored an Informal Workshop on Intense Polarized Ion Sources on March 6, 1980. For the convenience of those attending, the Workshop was held at the O'Hare Hilton Hotel at O'Hare International Airport, Chicago, Illinois. Eighteen people from twelve institutions attended.

The main topic was the concept of utilizing optically-pumped alkali vapor described by L. W. Anderson of the University of Wisconsin [Nucl. Instrum. Methods 167, 369 (1979)] and the questions he raised in that paper. The workshop started with a talk by Professor Anderson in which he further described the concepts of his paper and suggested some topics which he felt needed further investigation. The discussion following Professor Anderson's talk centered on the questions he had raised and the possible means of investigating them. Later on in the day, the discussion switched to other possible high-intensity polarized sources, in particular the H/Cs charge exchange source similar to the system operating at the University of Wisconsin.

The following pages are a summary of Professor Anderson's talk and the discussions following it. I am grateful to D. G. Crabb and R. C. Fernow for providing the notes on which this report is based.

P. F. Schultz
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INFORMAL WORKSHOP ON INTENSE POLARIZED ION SOURCES: A SUMMARY

by

Peter F. Schultz

ABSTRACT

An Informal Workshop on Intense Polarized Ion Sources was held on March 6, 1980, at the O'Hare Hilton Hotel, Chicago, Illinois. The purpose of the Workshop was to discuss problems in developing higher-intensity polarized proton sources, particularly the optically-pumped source recently proposed by L. W. Anderson of the University of Wisconsin. A summary of the discussions is reported.

OPTICALLY-PUMPED ION SOURCE*

L. W. Anderson

The proposed source of polarized H^- ions (Fig. 1) uses a 1 W dye laser to polarize a Na vapor target by optically pumping the Na atoms in a magnetic field. The reason for interest in an optically-pumped polarized ion source can be understood from the following simple calculations. A 1 W dye laser has a photon flux of 3×10^{18} photon/sec. Calculations indicate that it will take 1.5 photons to polarize a Na atom in the magnetic field if the field strength $B >> B_c$. Thus, for 50% absorption, one can polarize about 10^{18} Na atoms per second.

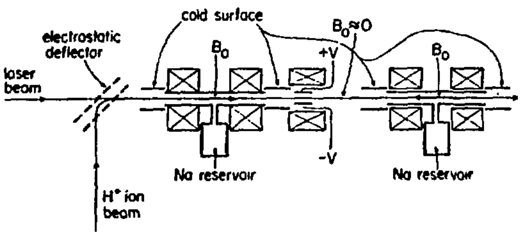


Fig. 1. Schematic Diagram of Proposed Optically-Pumped Polarized Ion Source

If the Na vapor target is 1 cm in diameter, then the average time between wall collisions is about 10^{-5} sec for a 600^{o}K temperature. Thus, one can produce a target with about $\pi = 10^{13}$ Na atoms/cm^2, even if every wall collision depolarizes the Na atoms. Loss by effusion from the target ends is small compared to wall loss of polarization.

The total cross-section, σ_{+o}, for the charge transfer reaction

$$H^+ + Na \rightarrow H^o + Na^+$$

at 5 keV energy is 6×10^{-15} cm^2. Thus, 6% of the H^+ emerges neutral from the first target (for $\pi = 10^{13}$ atoms/cm^2). The equilibrium fraction of H^- ions $F^{\infty} = (7.3 \pm 0.7)$% in the second target. Thus, one can get 4 μA H^- per μA H^+ incident on the first target.

The possible polarization of the H^- depends on the level the H^o is produced in. The energy defect is smaller for n = 2 than for n = 1 or higher n's. Production will be in n = 2 predominantly. Radiation from the n = 2 to n = 1 transition will carry away angular momentum, and the polarization of the ground level will be less than the Na atom polarization. If 100% polarized

*This text is based largely on the viewgraphs presented by Proffesor Anderson and on notes taken by D.G. Crabb, R.C. Fernow, and P.F. Schultz and is not intended to be the equivalent of a scientific journal publication.

electrons from Na are captured in the 2p level, then after radiative decay $P_e = 11/27 \approx 41\%$ in the ground 1S level of H^o. Capture into 2S or n = 3 levels also leads to loss of polarization.

The actual level populations are not known from either experiment or theory. Therefore, experiments are needed to determine these populations.

The loss of polarization can be avoided if $\vec{L}$ and $\vec{S}$ are decoupled by a strong B field. A measure of the coupling of $\vec{L}$ and $\vec{S}$ is the splitting of the $2^2P_{3/2}$, $2^2P_{1/2}$ level in hydrogen.

$$\left[E(2^2P_{3/2}) - E(2^2P_{1/2})\right]/2\mu_o = 3500\ G$$

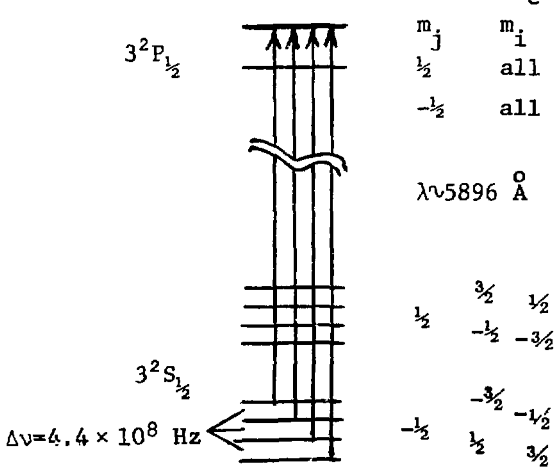
Thus, fields as large as 10^4 G may be needed. Experiments are needed to measure polarization of the H^- ions as a function of B.

Witteveen measured a nuclear polarization P = 14 ± 4% when ≈40% was expected. Witteveen assigned the difference to background gas, but it may be due to loss of polarization from radiation as H^o atoms decay to the n = 1 level.

The Sona transition between the two targets should present no problems. In fact, it should be easier here than in the Lamb shift sources, since the velocity is ∿3 times higher.

OPTICAL PUMPING OF TARGET

The Na energy levels for $B >> B_c$ are shown in Fig. 2.



$$E(3^2P_{\frac{1}{2}}) = E_o + \frac{2}{3}\mu_o B_o m_j$$

$$E(3^2S_{\frac{1}{2}}) = 2\mu_o B_o m_j + \frac{h\Delta\nu m_I m_j}{2}$$

$\Delta\nu$ = 1772 MHz for Na

Fig. 2. Optical Pumping Transitions for Left Circularly Polarized Light

The spread in frequency for any one line due to Doppler broadening is $\Delta\nu_D = 1.7 \times 10^9$ Hz at 600^0K.

Each line is broadened by $\Delta\nu_D$ (Fig. 3a). Thus, the total absorption looks like Fig. 3b.

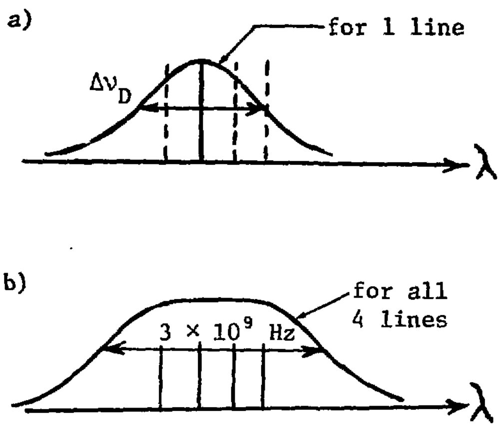


Fig. 3. Doppler Broadening

The laser must not be too narrow or some Doppler-shifted atoms will not be pumped. The laser should be about $2\Delta\nu_D + \frac{3}{4}\Delta\nu_{HFS} \approx 5 \times 10^9$ Hz in bandwidth.

The relative populations of the ground state sublevels are calculated similar to the method of Franzen and Emslie. The relative transition probabilities are shown in Fig. 4a for the $3^2S_{1/2} - 3^2P_{1/2}$ transitions. Figure 4b shows the transitions which are relevant to optically pumping the Na target.

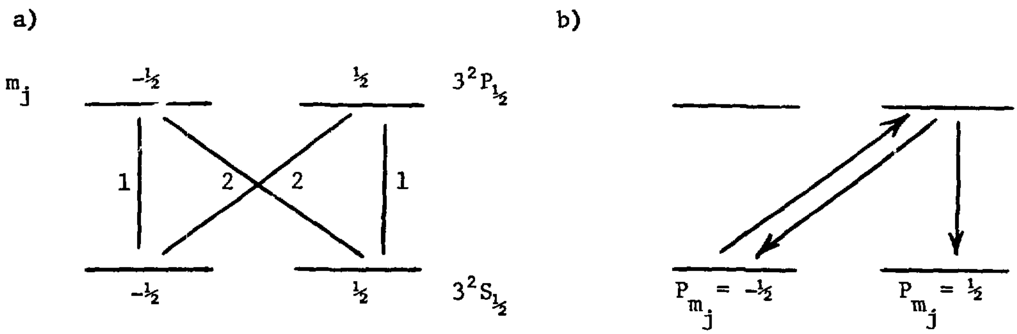


Fig. 4.

The relative populations are given by:

$$\frac{dP_{m_j=-1/2}}{dt} = \beta_o P_{m_j=-1/2} + \frac{2}{3}\beta_o P_{m_j=1/2} - \left(\frac{P_{m_j=-1/2}-1/2}{\tau}\right)$$

$$\frac{dP_{m_j=1/2}}{dt} = \frac{1}{3}\beta_o P_{m_j=-1/2} - \left(\frac{P_{m_j=1/2}-1/2}{\tau}\right)$$

where $\beta_o = \int I_\nu \sigma_\nu d\nu$ and τ = relaxation time. The solution to the differential equations is:

$$P_{m_j=-\frac{1}{2}} = \frac{1}{2(1 + \frac{2}{3}\beta_o \tau)}$$

where $\beta_o = \int_o^\infty I_\nu \sigma_\nu d\nu \simeq I_o \int_o^\infty \sigma_\nu d\nu$

$$= I_o \pi c r_o f = 4.4 \times 10^{-3} I_o$$

using f = 1/6 for the oscillator strength. If the laser bandwidth is 10^{10} Hz, then $\beta_o = 1.7 \times 10^6\ \mathrm{sec}^{-1}$. The polarization of the Na target is:

$$P_e = P_{m_j=\frac{1}{2}} - P_{m_j=-\frac{1}{2}} = 1 - \frac{1}{(1 + \frac{2}{3}\beta_o \tau)}$$

$$\simeq 88\%$$

assuming $\tau = 1.25 \times 10^{-5}$ sec.

If 3/4 of the photons are absorbed at the line center, then β_o decreases to $\beta_o = 2.1 \times 10^5\ \mathrm{sec}^{-1}$ at the end of the target and $P_e = 64\%$ at the end of the target. Thus, $\bar{P}_e = 75\%$ and one can produce a target with $\pi = 6 \times 10^{12}$ atoms/cm^2. This corresponds to about 2.2 μA of polarized H^- ions per mA of H^+ incident. Other bandwidths or changes in the B_o field can change this number somewhat, but not by a large fraction. More laser power per bandwidth can improve P_e and π significantly. Experiments should be done that test P_e and π for an optically-pumped target.

What is τ? Does Na depolarize at each wall collision? Can polyethylene or some other material prevent depolarization? A wall surface that permits bouncing without depolarization can lengthen τ and increase the value of P_e and π that can be obtained by a substantial fraction. Experiments are needed on wall properties of τ.

The target length π cannot become very large, as imprisonment of resonance radiation will limit it, probably by about $\pi = 5 \times 10^{13}$ atom/cm^2.

The mechanism for imprisonment of radiation is shown in Fig. 6.

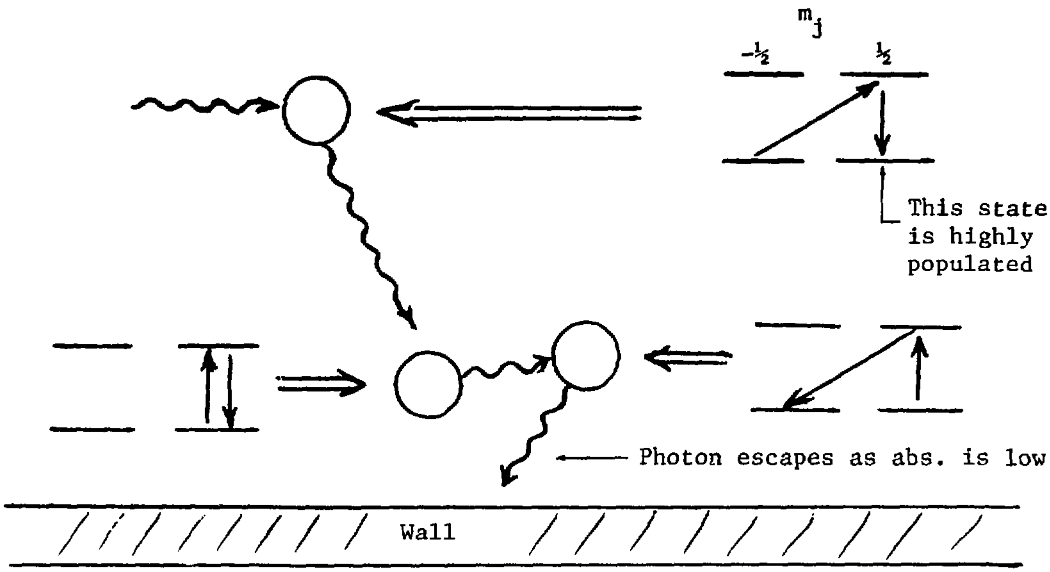


Fig. 6

Imprisonment of radiation limits the density at the center of the target to a density from which radiation can have a reasonable chance of escape without absorption for ℓ = 1/2 cm (the radius of the target). Experiments are needed to determine the exact density at which imprisonment limits π.

BEAM INTENSITY

In my paper, I assumed 10 mA of H^+ beam. With this beam, an output polarized H^- beam of about 22 μA is possible with a nuclear polarization of about 78%. But can one really put 10 mA of H^+ through a tube 20 cm long? The space charge limit for the current is:

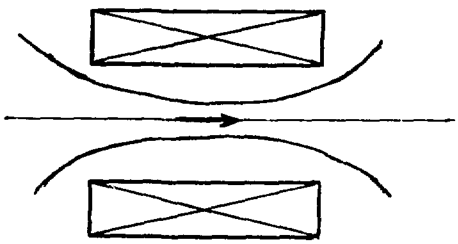
$$I = 38 \times 10^{-6} \left(\frac{d}{\ell}\right)^2 V^{3/2} \frac{1}{m^{1/2}} \text{ A}$$

$$= 0.8 \text{ mA}$$

Space charge neutralization will occur, of course, so the question is how much current can be put through a tube? Experiments are needed.

THE MAGNETIC FIELD PROBLEM

The fringe field of the solenoid (Fig. 7) will impart transverse velocity to the beam. The radial field is given by:



$B_o = B_z$ at center of solenoid

Fig. 7

$$\int 2\pi r B_r d\ell = \pi r^2 B_o$$

$$\int B_r d\ell = \frac{r}{2} B_o$$

The transverse force is:

$$F_t = ev_z B_r$$

so,

$$mv_z = \int F_t dt = \int ev_z B_r \frac{d\ell}{v_z}$$

$$= \int eB_r d\ell = \frac{eB_o r}{2}$$

So, $\frac{v_t}{v_z} = \frac{eB_o r}{2mv_z} = 0.25$ if $B_o = 10^4$ Gauss, $r = .5 \times 10^{-2}$ m, m = mass of proton, and $v_z = 10^6$ m/sec (5 keV); v_t/v_z of 0.25 is clearly unacceptable. Thus, B_o must be lower or the ion source must operate in the same B_o. Experiments are needed to show whether either of these is possible.

COMPARISON TO OTHER ION SOURCES AND SUMMARY

The colliding beam ($H^o + Cs^o$) polarized ion source at the University of Wisconsin has produced 3 μA of H^- with polarization near 1. The ion source runs well at 1 μA output, but there remain some problems of sparking, etc. All remaining problems seem soluble without great difficulty. With study, colliding beams (either $H^o + Cs^o$ or $H^o + H^-$) can no doubt be increased in intensity. The Cs^+ source, especially, should be worked on as the H^- beam is directly proportional to the Cs^o beam.

1. At the present time, the $Cs^o + H^o$ colliding beam source is the most promising polarized ion source.
2. The $H^- + H^o$ colliding beam ion source is also promising and should be pursued.
3. The optical-pumping ion source should be researched so that the questions raised in this talk are answered. Only then can a realistic assessment of the optical-pumping

ion source be given. The optical-pumping ion source may eventually be a good source.

4. For D^- ions, the optical-pumping source has no means for rf transitions, whereas the colliding beam sources do.

5. The optical-pumping source may be useful for T beams, whereas the colliding beam sources cannot be.

6. The colliding beam source can be run in near-zero B field, whereas optical-pumping sources cannot, so emittance may be better for colliding beam sources.

DISCUSSION

The discussion following Professor Anderson's talk covered many of the questions he had raised. The discussion is summarized in the following paragraphs.

ATOMIC PHYSICS

Los Alamos plans to investigate the relaxation time τ_R using a laser and a Na cell they have obtained. The method they propose to use is to irradiate the Na cell, located in a B = 3500 G field, with circularly polarized light and measure the transmitted intensity vs. the incident intensity (Fig. 8).

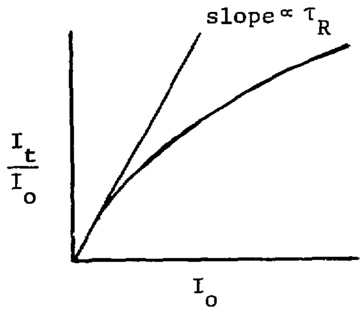


Fig. 8

As the laser intensity, I_o, is increased, the polarization of the target also increases, decreasing the number of atoms in the photon absorbing state. When the target is completely polarized, the transmission will be 100%. The initial slope of the curve depends on the relaxation time τ_R.

Their investigation will include studies of wall coatings and the cell design in order to optimize τ_R. The polarization of the Na target can be measured, using the Faraday effect.

Lasers with the required intensity and bandwidth are commercially available, so the discussion concerning them centered more on what specific requirements would be desired. In order to avoid inequalities in polarizations arising from polarization reversal, the bandwidth would have to completely overlap both $m_j = 1/2$ and $m_j = -1/2$ sets of transitions. Otherwise the laser frequency would have to change at the same time the polarization is reversed. In either case, the polarization can be easily reversed with a Pockels cell. The recommendation was made that lasers with higher power than actually needed be purchased, since the dye laser tube lifetime would be greatly increased. For instance, a 2- to 3 W laser should be purchased if 1 W of power is needed.

If nondepolarizing wall coatings can be used for the Na target in the environments envisioned, the laser power required would be less. It is known that some polymers such as polyethylene do not cause depolarization, so experiments should be done to investigate their survivability. The diameter of the Na target cell is not crucial, as long as the optically-pumped region completely overlaps the proton beam region. Therefore, the design of the target can be concerned mainly with physical and thermal properties. The density of Na in the target will be limited by radiation imprisonment and birefringence. The latter is expected to become important at densities of $\pi \gtrsim 10^{14}$ cm^{-2} which is above the densities currently anticipated.

BEAM OPTICS

The primary topic associated with beam optics concerned the effect of the 10 kg solenoidal field on the divergence of the H^{0} beam. A suggested alternative configuration shown in Fig. 9 places the H^{+} source in the same solenoidal field as the Na target.

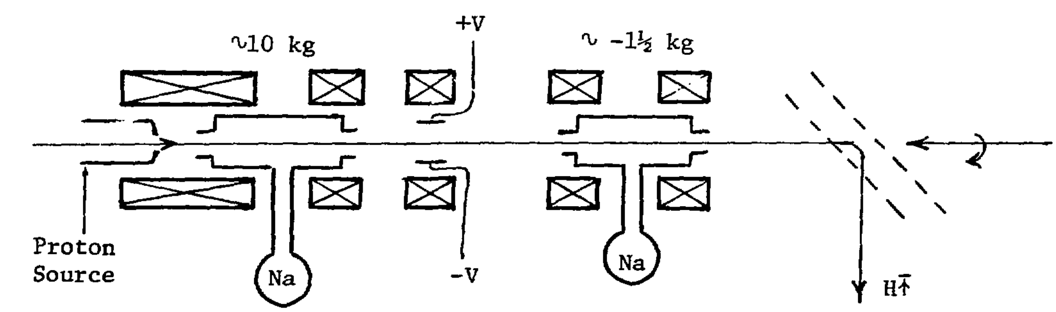


Fig. 9. Alternative Configuration for Optically-Pumped Polarized Ion Source

Some types of proton sources have ∿3 kg field and probably one could operate at ∿10 kg. To eliminate unpolarized background due to unwanted species (like H_2^+), some magnetic analysis would have to be done on the $H^{\mp}$ beam. The laser beam would have to be incident antiparallel to the H^+ beam direction. In this configuration, it might be necessary to use a different vapor than Na for ionization from H^0 to $H^{\mp}$. Another possible configuration that was suggested would be to simulate the type of injection into a cyclotron, but in the reverse direction (Fig. 10).

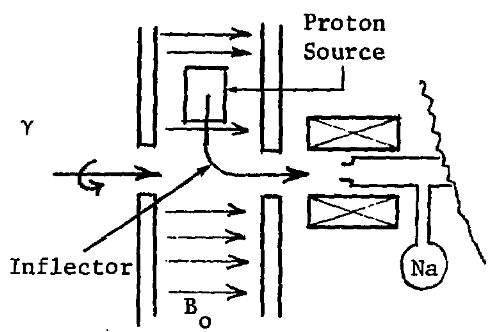


Fig. 10

DISCUSSION OF CHARGE EXCHANGE SOURCES
(COLLIDING BEAM SOURCES)

Wisconsin told of their experience with their $H^0 + Cs^0 \rightarrow H^- + Cs^+$ source. The Cs beam has several mA intensity. However, at ∿40 kV, it is a good sputter beam and causes some surface erosion. The surface ionization tungsten source has a lifetime of ∿150 hours before its performance becomes degraded by a factor of 2. To prevent electron backstreaming which erodes the W button, the extractor is run with a negative potential which overfocuses the Cs^+ beam, and the overlap of the Cs^0 and H^0 beams is not optimized. However, Wisconsin gets about 1 μA H^- per mA Cs^+.

The intensity of H^- in the Cs colliding beam source can most likely be increased. One could, for instance, use a Cs^+ source different from the surface ionizer -- for instance, a Penning source (similar to the one made by Hughes for the ANL Xe^+ beam for the ion beam fusion program). Also, the experience of ANL shows that cooling the dissociator nozzle of the atomic hydrogen beam source can result in ∿2½ times the intensity compared to no cooling. ANL plans to continue investigating the effect of cooling. For synchrotron applications, pulsing the dissociator can also increase the intensity by a factor of 2.

The other reaction suggested by Haeberli in 1968,

$$H_2^0 + D^- \rightarrow H_2^+ + D^0$$

should provide high intensity if the problems of space charge of the slow D^- are solved. The cross section is highest for small relative velocities, but for intense D^- currents such as are available now, ~50 to 100 mA, space charge forces are formidable.

CONCLUSIONS

The biggest question concerning the optically-pumped source involved the large divergences caused by performing charge exchange in a high solenoid field. If this problem could be solved (either by determining that a field much smaller than 10 kG could be used or by some different configuration), the optically-pumped source would have a good chance of succeeding in producing currents of 100 μA or more.

The charge exchange source of the H/Cs type has been shown to work quite well. With refinements, particularly with respect to the cesium beam, this type of source should be able to achieve many times more beam than currently obtained at the University of Wisconsin.

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