IONIZATION OF POLARIZED HYDROGEN ATOMS*

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ABSTRACT

Methods are discussed for the production of polarized H^- ions from polarized atoms produced in ground state atomic beam sources. Present day sources use ionizers of two basic types--electron ionizers for H^+ production followed by double charge exchange in a vapor, or direct H^- production by charge exchange of H^0 with Cs^0 . Both methods have ionization efficiencies of less than 0.5%. Ionization efficiencies in excess of 10% may be obtained in the future by the use of a plasma ionizer plus charge exchange in Cs or Sr vapor, or ionization by resonant charge exchange with a self-extracted D^- beam from a ring magnetron or HCD source.

I. INTRODUCTION

Presently, all polarized ion sources produce at some stage in the process polarized H^0 atoms, which must then be ionized to produce polarized H^+ or H^- . In some sources these polarized atoms are at high energies (550 eV in Lamb shift, 5 keV in optical pumping). Other "ground state" sources produce the polarized atoms at thermal energies ($< .03$ eV). In the ionization of the fast atoms in Lamb shift sources one is very restricted. One wants a "selective" ionization process, where metastable atoms are ionized with a much larger probability than the ionization of ground state hydrogen atoms. This is best accomplished for polarized H^- production by passing the beam through an argon gas cell, with an efficiency of $H^0 \rightarrow H^-$ of $\sim 7\%$. In optical pumping, where one also has fast H^0 atoms, the ionization is done by passing the beam through a vapor target (sodium). The ionization of thermal polarized atoms can be done in a variety of ways, and the ionization techniques continue to be improved. Only the application of various ionization techniques to these ground state atomic beam sources will be discussed in this paper. Other recent reviews of ground state ionizers have been given by Haeberli¹ and Gruebler².

The following section will give some general requirements of ionizers for ground state polarized ion sources, covering some things you can and cannot do when working with a polarized atomic beam. Then, in Section III, the first part of a two step process for H^- production, that being the formation of H^+ , will be discussed. This will include electron ionizers and "plasma" ionizers. Section IV will then cover the conversion of H^+ to H^- by charge exchange in vapors and surface conversion. The direct conversion of H^0 to H^- by charge exchange with a Cs^0 beam or D^- , will be discussed in Section V. Finally, Section VI will briefly summarize the existing methods and the possible future improvements.

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II. GENERAL CONSIDERATIONS

Before discussing particular ionization techniques presently used on polarized ion sources, some basic information will be presented which might be of interest when considering whether an ionization scheme might or might not work. What are some considerations in determining the feasibility of an approach?

When one looks at the flux of polarized atoms produced by present ground state sources (a few $\times 10^{16}$ atoms/sec) and considering both future improvements due to cooling of the atomic beam and $\bar{H}$ -intensities desired in the future (25 mA for the AGS, for example) one sees the need for as high an ionization efficiency as possible (at least until one has an ultracold atom source³). In addition, because the thermal atomic beam is achromatic and one cannot form a parallel beam, the ionizer should be as close as possible to the atomic beam section. Polarized atoms can be transported some distance by confining them with surfaces having a low recombination rate for hydrogen. For example, in one experiment, polarized atomic hydrogen from an atomic beam source traveled through a 10 cm long, 1 cm diameter teflon coated tube, into a teflon coated target vessel, where each atom experienced an estimated 900 wall collisions, and no depolarization was measured.⁴

The direction of polarization of the atoms will follow changing magnetic fields as long as the field changes are adiabatic, i.e., changes in the field have to be slow compared to the Larmor precession time of the magnetic moment in that magnetic field. Because the beam has thermal velocities, this condition is nearly always automatically satisfied. It is only when the field gets very close to zero, and the Larmor precession time in this field becomes long, that one may run into problems. One frequently encounters depolarization when the atomic beam travels in a region where a magnetic field passes through zero.

Depending on how the polarized atoms are prepared, ionization can occur in either a strong magnetic field (> 1.5 kG) or a weak "guide field" (a few gauss) which merely serves to keep the direction of polarization well defined. In strong field ionizers, the maximum final polarization depends on the strength of this field ($P = 90, 95$, and 97% at $1.0, 1.5$, and 2.0 kG, respectively). To get $P > 50\%$ in a weak field ionizer, one must have a state selection magnet after an rf transition unit⁵.

Once the ionization occurs, the polarized ions maintain the polarization direction they had at the point of ionization (i.e., the direction of B at the point of ionization). Therefore, the ionization must be done in a region of uniform field. After ionization, electric fields, and magnetic field parallel to the polarization direction will not change the direction of polarization of the atom, even though the direction of motion of the atom may change. Magnetic fields transverse to the direction of polarization will cause the polarization direction to precess by a well defined amount, and causes no basic problem unless different parts of the beam see different transverse B , causing variations in the polarization direction across the beam. This can occur, for example, in the fringing magnetic field at the exit of a strong field ionizer.

Loss of nuclear polarization during ionization or charge exchange is not a problem unless the process takes you through a stage where you have $\vec{H}^0$ without a strong magnetic field for a time comparable to the Larmor precession time. In experiments originally done to see if one could accelerate a $\vec{D}^-$ beam in a Tandem Van deGraaff, it was demonstrated that one could go from $\vec{D}^+$ to $\vec{D}^-$ and also from $\vec{D}^-$ to $\vec{D}^+$ without loss of polarization by passing the respective beams through thin carbon foils^{6,7}. In both cases, there was no external magnetic field, but the transit times through the foil were short compared to the Larmor precession frequency. However, in the same experiments, there was a loss of polarization in going from $\vec{D}^-$ to $\vec{D}^+$ in a gas stripper, with no applied magnetic fields, because during the intermediate step the D^0 was depolarized. A gas stripper in a strong magnetic field ($B > 1.5$ kG) causes negligible depolarization.

Another consideration when discussing ionizers is a reduction in polarization of the extracted beam due to ionization and extraction of unpolarized hydrogen coming from background gas (molecular hydrogen coming from the atomic beam stage, water vapor, hydrocarbons). Typical atomic beam densities are only a few $\times 10^{11}$ cm⁻³ in the ionizer, so a background H_2 pressure in the 10^{-6} Torr range is not negligible. In addition, the ionization of background gas is aggravated if the volume over which one is ionizing is much larger than the extent of the atomic beam. Even in cases where the method of ionization does not readily produce H^+ from H_2 , one has to worry about dissociation of H_2 on hot surfaces (filaments) and subsequent ionization of H. Problems will also occur in ionizers where there is recycling of gas between a discharge and metal walls. Therefore, one tries to make the ionizer as "open" a structure as possible.

A final point concerning "strong field" ionizers is an increase in the beam emittance due to the ionization in and subsequent extraction from the magnetic field. This growth in normalized emittance is⁸:

$$\Delta \epsilon_N = \frac{e}{2mc} B R^2 \pi \text{ m-rad} \quad (1)$$

where m is the mass of the particle, B the field in the ionizer, and R the radius of the beam, all in mks units. This is often a major contribution to the final beam emittance.

III. PRODUCTION OF POSITIVE IONS FROM POLARIZED ATOMS ($\vec{H}^0 \rightarrow \vec{H}^+$)

The efficiency of an electron ionizer, η , can be expressed as

$$\eta = \frac{I(\vec{H}^+)}{I(\vec{H}^0)} = 1 - e^{-(J_{e-} \sigma l / e v_{\vec{H}^0})} \quad (2)$$

where J_{e-} is the electron current density, l is the ionizer length,

σ is the ionization cross section, and v_{H^0} is the velocity of the polarized atoms. The cross section for ionization by electron impact has a maximum of 7×10^{-17} at ~ 60 v, and falls off approximately as $1/V$ at higher energies. However, since the space charge limited current of the electron beam increases as $V^{3/2}$, the ionization efficiency typically improves as the electron energy is increased.

Early ionizers used an electron beam in a weak magnetic field, and had poor efficiencies ($\sim 10^{-4}$). Subsequently, by doing the ionization in a magnetic field of 1-2 kG, a higher ionization efficiency was obtained (a few $\times 10^{-3}$). The field confines electrons, increases their effective path length in the ionizer, and along with suitably biased electrodes, allows multiple passes of the electrons through the ionizer. Further improvements in the design of these ionizers (contouring the magnetic field, improving the electrode configuration) has now raised the efficiency to about 5%. Figure 1 shows a schematic of an ANAC, Inc. "super ionizer"⁹, and a

Fig. 1. The ANAC, Inc. "super ionizer."

similar ionizer in use at ETH, Zurich is described in another paper in these proceedings^{10,11}. The electron current density in the ETH ionizer is several A/cm², the ionization length is 35 cm, and 120 μ A of H^+ has been extracted.

All the above mentioned ionizers use a hot cathode to supply electrons. At Bonn University, a Penning ionizer is used¹², in which the ionization is done in a superconducting solenoid with magnetic fields of up to 75 kG. A self sustaining discharge occurs at pressures of 10^{-7} to 10^{-6} torr. While an ionization efficiency of approximately 6% is obtained, the strong magnetic field causes the beam emittance to be very large.

It may be possible in some cases to improve the ionization by adding a "buffer" gas. While it is sometimes observed that as the background pressure in an electron ionizer increases the extracted current drops, this trend may reverse as one continues to

increase the pressure. Recently, experiments were described in which the effect of buffer gases was studied.¹³ Extracted hydrogen current was measured for a fixed background hydrogen pressure (2.2×10^{-4} Torr). Adding argon increased the extracted hydrogen by a factor of 40 due to ionization by plasma electrons, and gave an ionization efficiency of 8.3%. It is not clear, however, what one would actually gain over existing ionizers, since the ratio of extracted current to background gas density is similar to the ratio of extracted H^+ to H^0 density presently obtained in the ETH ionizer.

It has recently been suggested that H^0 ionization using a hollow cathode discharge (HCD) plasma may be very effective¹⁴. Attractive features of the HCD are that it can operate in magnetic fields from a few hundred gauss to several kilogauss, it can produce a plasma of 1-2 cm^2 cross section and 10 cm to $\rightarrow$ 1 meter length, and with differential pumping it can operate at pressures down to $\sim 10^{-5}$ Torr. One can easily get an electron current density of 10 A/cm^2 , and the electron energy is under 100 volts. In addition, plasma densities from 10^{12} - 10^{14} cm^{-3} can be obtained, depending on the background pressure. One could imagine feeding an HCD-produced plasma (argon, for example), into a configuration similar to an electron ionizer ($l = 35 \text{ cm}$), and with a similar extraction geometry. Due to the increased ionization cross section at the operating energy, and the increased electron current density, the ionization efficiency calculated from equation 2 is greater than 50%. If the HCD were operated with deuterium, symmetric charge exchange between the polarized hydrogen atoms and the plasma D^+ ions would lead to a significantly higher ionization efficiency, while the extracted D^+ current would be no greater than the H^+ current, and could be magnetically separated. Configurations using an HCD ionizer are presently being studied at BNL, and it is likely that a very high ionization efficiency can be obtained in a plasma of only 10 to 20 cm length. A possible difficulty is efficient ionization of H_2 coming from the atomic beam, resulting in a large unpolarized component in the beam.

The use of an rf discharge ion source to ionize polarized atoms has been tried in the past. In one case¹⁵, polarized deuterium was injected into a pyrex system (coated with silane to reduce recombination). D^+ ions extracted from the rf discharge (with a helium buffer gas) were not polarized, and it appeared that most of these ions came from ionization of gas coming from the walls of the vessel. In another attempt¹⁶, D^0 was injected into a pyrex vessel, again with a helium buffer gas. The extracted beam was partially polarized when operated in a magnetic field of 350 gauss. More recently, it has been suggested that an electron cyclotron resonance (ECR) ion source¹⁷ may be an efficient ionizer for polarized atoms. This source has a high electron density (10^{12} cm^{-3}), and electron energy of several keV. The ionization efficiency of this source is high, and as with the HCD, by operating with deuterium one could benefit from symmetric charge exchange. A concern with an ionizer of this type is that the similarity of the electron cyclotron resonance conditions to the conditions for inducing transitions between hyperfine levels in the hydrogen atom, could lead to strong depolarization². It has been pointed out, however, that the conditions

are close to those needed for $2 \rightarrow 4$ transitions in the Rabi diagram, and hence depolarization might be avoided by injecting a polarized atomic beam in a pure 1 state¹⁸. If depolarization in the ECR discharge is not a problem, a configuration as is used to produce H^-/D^- for fusion¹⁹--i.e., the H^+ extraction and charge exchange to H^- in Cs vapor, all immersed in a magnetic field--is essentially what would be required for a polarized H^- source.

Finally, ionization using a fast proton beam by the reaction $H^+ + H^0 \rightarrow H^0 + H^+$ has been tried²⁰, but the efficiency was only 0.1%. This was done using a 10 keV proton beam, decelerated to 4.7 keV in the interaction region, and with a 75 kG superconducting solenoid magnet to cause a spiraling of the proton beam and also to act as a mirror to reflect the beam.

IV. PRODUCTION OF NEGATIVE IONS FROM POLARIZED PROTONS ($H^+ \rightarrow H^-$)

In order to obtain the efficiency of producing H^- from H^0 , one must multiply the ionization efficiencies discussed in the previous section by the efficiency for subsequent conversion of H^+ to H^- . This double charge exchange is typically done by passing the beam through a vapor target. As mentioned in section II, this charge exchange must occur in a strong magnetic field to prevent depolarization.

Equilibrium negative ion yields have been measured for H or D in a variety of vapor targets^{21,22}. One sees from these measurements, for example, that one could get ~ 7% H^- conversion efficiency at 5 keV in Na, ~ 20% at 1 keV in Rb, ~ 30% at 500 eV in Cs or Sr, and almost 50% ionization in Sr at 250 eV. The difficulty as one goes down in beam energy is that the H^+ current entering the vapor target decreases due to beam optics considerations. Na is often used as the charge exchange vapor, at a beam energy of ~ 5 keV. The Na charge exchange cell used at ETH is shown in figure 2²³. They obtain a conversion efficiency of H^+ to H^- of 6%, and are limited by their H^+ beam optics. Of course, one would like to gain a factor of ~ 5 by going to lower energies and using Sr or Cs vapor. A beam optical system such as that developed at Grenoble for neutral beam heating¹⁹ might be applicable. By having a strong magnetic field all the way from the source to beyond the neutralizer, they improve the confinement and space charge neutralization of the positive ion beam. In this way, they have been able to get a conversion efficiency of 22% of 1 keV D^+ to D^- . On the other hand, if one can substantially increase the H^+ current by improvements in both the atomic beam and in the $H^0 \rightarrow H^+$ ionizer, it will become even more difficult to decrease the beam energy to gain in $H^+ \rightarrow H^-$ conversion. At higher currents, where the H^+ current through the vapor cell would be proportional to $v^{3/2}$, the product of the conversion efficiency (values given above) times H^+ current into the cell ($\propto v^{3/2}$) would increase with increasing beam energy.

It was mentioned in section II that due to the short transit time during charge exchange, a thin foil could be used with no external magnetic field. The conversion efficiency of a 40 keV H^+ beam to H^- in a 5 $\mu\text{g}/\text{cm}^2$ carbon foil was ~ 1%²⁴.

Fig. 2. The ETH Na charge exchange cell.

Another possibility may be surface conversion of $\vec{H}^+$ to $\vec{H}^-$. This process is often used in high current, unpolarized negative ion sources. At FOM, measurements of the conversion of H^+ to H^- in grazing incidence ($\theta > 80^\circ$ with respect to normal) on cesiated monocrystalline W(110) surfaces have shown total conversion efficiencies of up to 37% at 200 eV²⁵. At 1 keV, the conversion efficiency was 21%. The conversion efficiency in grazing incidence on polycrystalline W was 12% at 400 eV and 10% at 1 keV²⁶. One essentially has specular reflection of the particles from the surface. The interaction time here is very short, and it seems likely that the polarization of an incident $\vec{H}^+$ beam would be preserved in this type of interaction. Some experiments which may be relevant in this regard have to do with the production of polarized Li^+ (and Na^+) by surface ionization of polarized atoms on a hot W-O surface. In one case the surface ionization occurred in a "strong" magnetic field, and only a slight depolarization was observed even though the hold-up times of the particles on the surface were many orders of magnitude larger than the Larmor period²⁷. Polarization was lost when the magnetic field was turned off. In another experiment the polarization after surface ionization of polarized Li and Na was measured, again with an external magnetic field²⁸. Here, however, depolarization was observed as the surface residence time increased (lower surface temperatures). While $\vec{H}^-$ surface production does not offer any higher efficiency at a given energy than what can be achieved with a vapor target, there may be some source configurations where surface conversion would be more suitable.

One might consider the combination of a plasma ionizer and surface conversion for producing polarized H^- ions in some "traditional" surface plasma source. However, it seems less likely that polarization would be preserved in normal incidence conversion occurring in surface-plasma sources, where desorption is an important process. In addition, one would need an open geometry to reduce recycling of gas from walls. Even if some such scheme were to work, it is unlikely that one would end up with a higher overall $\text{H}^0 \rightarrow \text{H}^-$ ionization efficiency than with some of the other configurations discussed in this paper.

V. PRODUCTION OF NEGATIVE IONS FROM POLARIZED ATOMS ($\text{H}^0 \rightarrow \text{H}^-$)

The reaction $\text{X}^0 + \text{H}^0 \rightarrow \text{X}^+ + \text{H}^-$ was suggested by Haerberli²⁹ as a way of directly producing H^- from H^0 . Subsequently, a polarized source based on this ionization scheme was built at the University of Wisconsin³⁰, and more recently a source with this same type ionizer has become operational at BNL³¹. These sources use Cs^0 as the ionizing beam. A schematic of the configuration is shown in figure 3. Cs^+ ions are produced by surface ionization on a porous tungsten

Fig. 3. The BNL Cs beam ionizer arrangement.

ionizer (1.9 cm diameter), and accelerated to 40-55 kV. The Cs beam is then neutralized in a Cs vapor neutralizer and travels into the interaction region, where it is collinear with the H^0 beam. The interaction region is ~ 35 cm long, and has an axial magnetic field of 1.5-2 kG. H^- ions formed by charge transfer are accelerated by a weak axial electric field (< 1.5 v/cm) toward the extraction end, where the ions are accelerated to 20 keV, focused, and electrostatically deflected by 90° . A nice feature of this technique is that one has two neutral beams, and therefore no problems with space charge forces. The efficiency of this type ionizer is given by

$$\eta \approx \frac{J_{\text{Cs}} \sigma_{\text{I}} / e v_{\text{H}^0}}{\quad} \quad (3)$$

where J_{Cs} is the Cs^0 current density in the ionization region, l is the ionizer length, and v_{H^0} is the atomic beam velocity.

The $\vec{H}^-$ current is proportional to the intensity of the Cs^0 beam overlapping the atomic beam in the interaction region. The atomic beam has a diameter of ~ 1 cm in this ionization region. With the neutralizer, electrostatic mirror, and H^- extraction electrodes in between, the distance from the exit of the Cs source to the far end of the interaction region turns out to be ~ 90 cm in the Wisconsin source and ~ 120 cm in the BNL source. One is left with fairly stringent optical requirements for the Cs beam ($\sim 1/2^\circ$ convergence). At Wisconsin, where the source operates dc, they obtain 2.5 mA of neutral Cs within 1 cm diameter at the far end of the interaction region, and with an improved source, 10 mA Cs^0 in 1 cm diameter at an equivalent distance on a test stand. At BNL, on a test stand we typically measured 8-10 mA of Cs^+ on a 1.6 cm diameter Faraday Cup located 1.2 meters from the source. Since only a pulsed H^- beam is required for the AGS, the Cs beam from the porous emitter is pulsed. It has been found that when operating in this mode, the Cs intensity is limited by pulse width requirements³³.

From present day performance, $J_{Cs} \approx 5-10$ mA/cm². The maximum cross section for the charge exchange reaction with Cs^0 is $\sim 8 \times 10^{-16}$ cm²³². Therefore, from eq. 3 one could expect an ionization efficiency of 0.5-1.0%. At Wisconsin, with their less intense Cs source and an uncooled atomic beam, the efficiency is about .1%, and at BNL, with the Cs neutralizer performance still unsatisfactory, the efficiency is roughly estimated to be $\sim .3\%$ (the atomic beam flux is uncertain). Unpolarized H^- coming from ionization of background H_2 hydrocarbons, water vapor, etc. is small, due to the small cross sections involved. At Wisconsin, the extracted H^- with the dissociator turned off is only 0.3% of the polarized current. At BNL, a somewhat larger H^- background is observed which seems to come from Cs beam hitting metal surfaces around the ionization region.

Improved ionization efficiency due to an increased Cs beam intensity should be possible. The Cs beam energy could be increased to improve the extractor optics (the charge transfer cross section drops fairly slowly). Focusing elements could be added between the Cs source and neutralizer (plasma lens or electrostatic quadrupoles). Also, one could increase the optical acceptance of the interaction region by decreasing the distance between the source and interaction region.

Use of the resonant charge exchange reaction $D^- + \vec{H}^0 \rightarrow D^0 + \vec{H}^-$ was originally suggested by Haeberli²⁹ as an attractive ionization technique due to its large cross section, and the availability of intense D^- sources. D^- rather than H^- is chosen as the ionizing beam because it allows one to later mass analyze and separate the $\vec{H}^-$ from the unpolarized D^- ions. The difficulty encountered in this approach is that space charge forces from the intense ionizing beam could cause the blowup of the H^- ions, which have thermal velocities. One solution which has been suggested is to confine the ions with a very strong magnetic field, but in this case the $\vec{H}^-$ emittance would become very large. Other possibilities for compensating the space charge are to inject (heavy) positive ions into the ionization region along

with the D^- , or merely to use properly biased electrodes at the ends of the ionization region to trap positive ions formed in the ionizer³⁴. While no ionizer using the above reaction as yet exists, an experiment is presently beginning at BNL to test an ionizer based on a pulsed D^- magnetron source. The basic idea³⁵ is shown in figure 4.

Fig. 4. The ring-magnetron ionizer under development at BNL.

One has a ring shaped magnetron source, with the anode on the inside, operating in a magnetic field of ~ 1.5 kG. D^- ions produced on the cathode emerge through slits in the anode, directed toward the center of the ring. They have an energy of ~ 200 eV (where the cross section for the charge exchange is 6×10^{-15} cm²). The polarized atoms pass through the center of this source, where they are ionized by charge exchange with D^- . After extraction, the H^- and D^- ions will be magnetically separated. Because there is no extraction field inside the ring of the magnetron, plasma D^+ ions can diffuse from the magnetron discharge and contribute to the space charge compensation of the D^- ions and any H^- ions formed. The pulsed magnetron source is designed to deliver 0.5 A of D^- ions to the center of the ring. In estimating the efficiency of this ionizer³⁵, destruction of H^- by collisions with D^+ , D^0 , charge exchange with fast D^0 , etc. were included. The overall ionization efficiency is estimated to be 8%, although scattering of H^- and H^0 in the high pressure outside the magnetron could reduce the effective efficiency to $\sim 1\%$. Based on present estimates, the conversion efficiency in an optimized magnetron design could be as high as 16% (neglecting gas scattering). An advantage of this ionizer is the short ionization length (1-2 cm). Because the polarized atomic beam is very achromatic, one should be able to get more atoms through this ionizer than what one can get through the much longer Cs beam or electron ionizers.

An alternative ionizer, which could operate steady state and at much lower pressures, would use an HCD D^- source³⁶ operating inside a solenoidal magnetic field. The H^0 beam would then travel along the source slit and again charge exchange with 100-200 eV self-extracted D^- ions. If necessary, a gas such as krypton could be added to aid the space charge neutralization of the beam. By allowing the D^- ions to travel a short distance from the source before interacting with the H^0 beam, and relying on Kr^+ rather than D^+ to provide space charge neutralization, the ionization efficiency would be improved because an important destruction process (mutual neutralization of H^- and D^+) would be reduced.

VI. SUMMARY

The two methods presently producing the highest intensity H^- beams from ground state sources, an electron ionizer with Na double charge exchange, or charge exchange with a Cs beam, both have ionization efficiencies less than 0.5%. Neglecting improvements coming from reducing the velocity of the atomic beam, the efficiencies of both techniques can still be improved by careful development. However, somewhat radical variations of these two basic methods seem to offer more dramatic improvements. For example, an HCD plasma ionizer could improve the $H^0 \rightarrow H^+$ ionization efficiency by an order of magnitude. The use of Cs or Sr for H^+ to H^- conversion in a system similar to that developed at Grenoble could give an additional improvement of at least a factor of 4. The combined effect would be an $H^0 \rightarrow H^-$ conversion efficiency of ~ 20%. Resonant charge exchange with a D^- beam in a ring magnetron type configuration could give efficiencies of 1-10%. With a D^- beam produced from an HCD based source, the efficiency could be greater than 20%, and in principle, offers the highest conversion efficiency of the techniques considered here. Thus, one can be optimistic about the prospects for improving ionizers for polarized H^- sources. However, much development and attention to details has gone into existing ionizers, and one must not underestimate the work involved in making a practical ionizer based on a new approach. In addition, improvements must be made in the atomic beam intensity in order to get > 10 mA of polarized H^- .

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