POLARIZED NEGATIVE IONS

W. Haeberli
University of Wisconsin, Madison, Wisconsin 53706

Summary

This paper presents a survey of methods, commonly in use or under development, to produce beams of polarized negative ions for injection into accelerators. A short summary recalls how the hyperfine interaction is used to obtain nuclear polarization in beams of atoms (Sect. 2). Atomic-beam sources for light ions are discussed first (Sect. 3). Important recent improvements in the design of the atomic beam source itself and in the ionization methods has led to beam intensities of $\vec{H}^+$ and $\vec{D}^+$ in excess of 100 μA and to intensities of $\vec{H}^-$ and $\vec{D}^-$ of up to 3 μA, with beam polarization of typically P ≈ 0.85. If the best presently known techniques are incorporated in all stages of the source, $\vec{H}^-$ and $\vec{D}^-$ beams in excess of 10 μA can probably be achieved. Production of polarized ions from fast (keV) beams of polarized atoms is treated separately for atoms in the H(2S) excited state (Lamb-Shift source) and atoms in the H(1S) ground state (Sect. 4). The negative ion beam from Lamb-Shift sources has reached a plateau just above 1 μA, but this beam current is adequate for many applications and the somewhat lower beam current is compensated by other desirable characteristics. Sources using fast polarized ground state atoms are in a stage of intense development. They use pickup of polarized electrons in optically pumped Na vapor by a beam of protons. No operating source exists, but difficulties are anticipated in reaching large intensities and high beam polarization at the same time. It is suggested to replace the polarized Na vapor by polarized atomic hydrogen. The next sections summarize production of polarized heavy ions by the atomic beam method, which is well established, and by optical pumping, which has recently been demonstrated to yield very large nuclear polarization (Sect. 5). A short discussion of proposed ion sources for polarized $^3\vec{He}^-$ ions (Sect. 6) is followed by some concluding remarks (Sect. 7).

1. Introduction

I have been asked to review the current status of negative polarized ion sources for hydrogen isotopes as well as for heavier ions. To present a concise but intelligible review is rather difficult because by now the development of polarized ion sources includes a number of quite diverse methods. Here we will limit ourselves to schemes which have practical importance and to schemes which promise to become important in the next few years. Even with this limitation, we are faced with the need to understand a rather specialized part of atomic physics and to deal with a vocabulary that is hardly self-explanatory even for the nuclear physicist who is versed in atomic physics. Since I can safely assume that most of you are not designers of polarized ion sources, I propose to remind you first of the underlying principles (Sect. 2), but must ask your tolerance because by necessity the explanations will need to be very brief. More details on the physics of polarized ion sources can be found in several review papers.[1-6]

As a second task I was asked to provide an assessment of how the technology of these sources will develop in the next three to five years. Of course all I can hope to do is to point to opportunities for further developments and I will do so throughout the text when we consider the advances that have been made during the last two or three years.

Readers who are interested in more details than can be presented here are referred to the proceedings of two recent conferences which treated the subject in some detail, namely the Fifth International Symposium on Polarization Phenomena in Nuclear Physics[7] (Santa Fe, August, 1980), and the International Symposium on High Energy Physics with Polarized Beams and Targets[8] (Lausanne, October 1980). For sources for polarized heavy ions a very thorough up-to-date review has recently been presented by Steffens.[9]

2. Principles and Classification of Polarized Ion Sources

A sufficient number of different types of polarized ion sources has been built or proposed to make a short review and classification of primary design principles useful.

Our discussion will concern primarily ions of the hydrogen isotopes, and ions of heavier alkali atoms (Li, Na). Except for ^{3}He ions, which will be mentione briefly, these are the only ion sources that have been developed. Possible application of the same principles to other heavy ions has been discussed elsewhere,[10] and will not be treated in any detail here.

The nuclear magnetic moment is some three orders of magnitude smaller than the electronic moment. In all sources of polarized ions one first produces (or selects) neutral atoms which are polarized in *electron spin*. In one form or another one employs the *hyperfine interaction* to obtain *nuclear* polarization. Finally the polarized atoms are ionized. For application to tandem accelerators we are interested in *negative ions*. In some sources, negative ions are obtained directly from polarized neutral atoms, in others one produces positive ions first and converts them to negative ions later by charge exchange collisions.

Sources of polarized ions can be divided into two groups, depending on whether the atomic beam is slow (thermal atoms) or fast (keV). This is a natural division because the methods which can be used to polarize and ionize the atoms are quite different in the two cases. In ion sources based on slow atoms, the atomic beam originates in a vessel with a small hole through which atoms emerge into an evacuated region. The emerging atoms are collimated by one or more apertures to form a directed beam. In the so-called atomic-beam polarized-ion source, polarization of the atoms is achieved by spatial separation in a strong, inhomogenous magnetic field (Stern-Gerlach separation). The six-pole magnets, which are commonly used for this purpose, provide an axially symmetric attractive harmonic oscillator potential for atoms with electron spin projection $m_j = +1/2$, and a corresponding repulsive potential for atoms with $m_j = -1/2$. To a good approximation, the beam at the exit-end of the spin-separation magnet is completely polarized in electron spin, the $m_j = -1/2$ atoms having been deflected away (Fig. 1a). However, since the magnetic moment of the atoms is very nearly the same for all hyperfine components, the 2I+1 possible nuclear spin projections m_I are all equally occupied. The desired nuclear polarization (vector polarization, or tensor polarization) is usually obtained by exposing the atomic beam to one or more RF transition units which induce transitions between hyperfine states after the atoms leave the spin-separation magnet. For example, the transition indicated in Fig. 1a will lead from an initial equal mixture of states 1 and 2 to an equal mixture of states 4 and 2. If these atoms are subsequently ionized in a strong magnetic field ($\chi \gg 1$) one obtains

DISCLAIMER

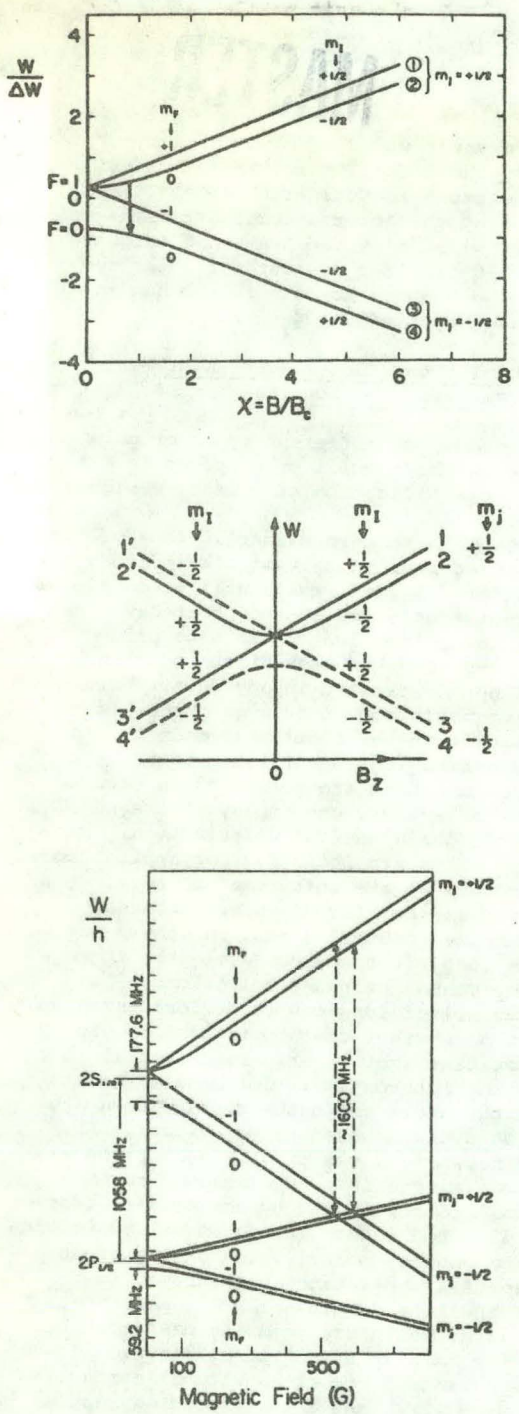

Fig. 1. Different methods are used to exploit the hyperfine interaction to obtain nuclear polarization. The above illustration applies to hydrogen atoms. Top: for a beam of slow (thermal) atoms, RF transitions between states 2 and 4 (arrow) produce proton polarization P = +1, while transitions between states 1 and 3 (not shown) yield P = -1 for ionization in a strong field, B >> B_c = 507 G. Center: for a fast (keV) beam of atoms, sudden field reversal is used, which turns population of states 1 and 2 into states 2' and 3'. Bottom: for atoms in the metastable H(2S) state, nuclear polarization can be obtained by the "spin filter", in which all but one of the upper two hyperfine components is quenched by mixing of 2S and 2P states by a 1600 MHz RF field.

complete proton polarization parallel to the magnetic field: P = +1. Similarly, a transition between states 1 and 3 leads to P = -1. The atomic-beam method has been applied to the production of polarized proton and deuteron beams, as well as to polarized ^{6}Li, ^{7}Li and ^{23}Na.

For alkali atoms, there is a second method to produce a polarized thermal beam, namely optical pumping. The atoms leaving the oven aperture are exposed to circularly polarized light. With modern lasers, sufficient photon flux can be produced for each atom to absorb and re-emit a photon several times during the time it travels a few cm. The optical-pumping method promises higher beam polarization than the conventional atomic-beam method if one succeeds to pump all the atoms into the hyperfine component of maximum $|m_I|$. In addition, one expects higher intensity, because the atomic beam is not limited to the small acceptance angle of the six-pole magnet.

The methods used to ionize the beam of thermal polarized atoms depends on the ionization potential. Alkali atoms are readily ionized by surface ionization. In some cases, nearly 100% of the atoms have been converted to positive ions. For hydrogen atoms, the ionization potential is too large for surface ionization, and the conventional ionization method is to produce positive ions by electron bombardment of the $\vec{H}^0$ or $\vec{D}^0$ atomic beam. For both types of ionizers, if *negative* ions are required, they are produced by accelerating the positive beam to a few keV and passing the beam through a charge exchange vapor. A magnetic field is applied over the charge exchange region to avoid depolarization. Recently, a new method has been developed to produce $\vec{H}^-$ from a thermal $\vec{H}^0$ beam without going through $\vec{H}^+$ as in intermediate steps. In this so-called colliding-beam method a beam of fast (~ 40 keV) Cs^0 atoms is used to bombard the atomic beam, making use of the rather large cross section for charge exchange reaction $H^0 + Cs^0 \rightarrow H^- + Cs^+$.

Sources based on *fast* (keV) beams of polarized atoms are of interest only for beams of the hydrogen isotopes (and possibly ^{3}He), but not for heavier ions. The only operating source of this type is the Lamb-Shift source, which makes use of atoms in the metastable H(2S) state. The H(2S) atoms are produced by charge exchange of a ~ 500 eV H^+ beam in Cs vapor. In contrast to the atomic-beam method, where polarization of the atoms is achieved by removing the atoms with m_j = -1/2, polarization in the Lamb-Shift source is achieved by making the unwanted states (e.g. the m_j = -1/2 states) decay to the ground state (selective quenching of H(2S) atoms). Quenching is achieved by mixing the wave function of atoms originally in the H(2S) state with the H(2P) state by bringing the atoms into a magnetic field of 575 G (Fig. 1c). It follows that the ionization process also must be selective, i.e. only the remaining H(2S) atoms should be ionized, but not the atoms which have decayed to the ground state. This is accomplished by charge exchange in argon. The good selectivity for ionization of H(2S) as opposed to H(1S) atoms arises from the fact that the electron pickup H(2S) + Ar → H^- + Ar^+ is nearly resonant (see Ref. 1), while for H(1S) the energy mismatch is large, namely equal to the H(2S) excitation energy of 10.2 eV.

No sources are in operation at the moment which use a beam of *fast* atoms in the *ground* state, but there is intense interest in such sources since new methods have recently been proposed which possibly may lead to large beam intensities. The basic idea is to produce an intense H^+ or D^+ ion beam of a few keV energy, and to permit the ions to pick up polarized electrons in a cell containing polarized alkali vapor, e.g. Na. The electron polarization of the alkali vapor is produced by optical pumping.

For *fast* (keV) beams of atoms polarized in electron spin, it is not possible to produce the desired nuclear polarization by RF transitions of the type mentioned above. Rather, one uses so-called sudden field reversal, or Sona transitions.[11] As illustrated in Fig. 1b, sudden reversal of the magnetic field [fast compared to a Larmor period] changes states 1 and 2 of hydrogen into states 3 and 2. The method is simple, requiring only suitable static magnetic fields, but not nearly as effective as RF transitions if tensor polarized deuterons are required. For the Lamb-Shift source (but not for *fast* ground-state sources), some flexibility is recovered by the possibility to quench selectively once more after the sudden transitions. Furthermore, for Lamb-Shift sources a very powerful device ("spin filter") has been developed[12] which permits the selection of one particular hyperfine state by quenching all the other hyperfine components (Fig. 1c).

3. Atomic-Beam Sources for H^- and D^-

Just about all sources of polarized ions make use of an atomic beam (i.e. beam of slow or fast neutral atoms), but by tradition only sources which use *magnetic separation* of spin states in a beam of *thermal* atoms are referred to as atomic-beam sources. Before discussing some of the recent improvements, let us recall that sources of this type typically produce about 2×10^{16} polarized atoms/sec. The average velocity of the atoms (typically $\sim 3 \times 10^5$ cm/sec) depends on the temperature of the gas in the dissociator, where H_2 (or D_2) is dissociated in an RF discharge. Until recently, the efficiency of ionization of the atomic beam by electron bombardment was about 3×10^{-3}, yielding an H^+ beam of some 10 μA. Acceleration of the H^+ to ~ 5 keV and charge exchange in Na vapor then typically yielded about 0.3 μA H^- or D^-. In this section, we will summarize recent improvements in this method.

3.1 Atomic-Beam Temperature

Lowering the average velocity of the atomic beam has a beneficial effect in two ways. In the first place the acceptance solid angle of the six-pole separation magnet for atoms emerging from the dissociator aperture increases with decreasing average velocity, because a fast atom will be deflected less by the magnetic field gradient in the six-pole magnet. Thus a fast atom entering the six-pole magnet must be directed more nearly parallel to the symmetry axis of the six-pole field if it is to pass through the magnet without hitting the magnet pole piece. For the same source flux, the number of atoms passing through the magnet is expected to increase in proportion to the acceptance solid angle $\Delta\Omega = 2.09\ \mu B_o/kT$ (Ref. 1) where μ is the magnetic moment of the atom, B_o is the field at the pole tip, and T the temperature of the atoms in the beam. In the second place, a lower velocity of the atoms in the ionizer increases the ionization efficiency simply because the probability of ionization increases in proportion to the time the atom spends in the ionizer. Averaged over the velocity spectrum, this second effect introduces an expected $T^{-1/2}$ dependence in the beam intensity. These simple arguments lead one to expect an overall increase in beam intensity proportional to $T^{-3/2}$. However, we should also take into account the fact that if we cool the gas in the dissociator, keeping the same density of atoms in the dissociator and the exit nozzle (i.e. same attenuation by scattering), the flux from the source decreases proportional to T simply because the atoms move more slowly. These simple considerations then lead to an expected beam intensity proportional to $T^{-1/2}$.

Cooling of the dissociator has been applied successfully in a number of cases.[13-15] The present tendency is to cool only the exit nozzle rather than the entire discharge tube. In a design developed at Bonn,[14] good heat transfer is obtained by using a copper nozzle cooled to 77K. Several coatings of the copper canal were studied for recombination. Best results were obtained for H_3PO_4 treatment [degree of dissociation (82±2)%]. The most probably velocity of the beam was found to be ~ 1500 m/sec, about the same as that observed for the beam from a microwave dissociator developed at CERN.[16] The velocity distribution measured at CERN is shown in Fig. 2. The width

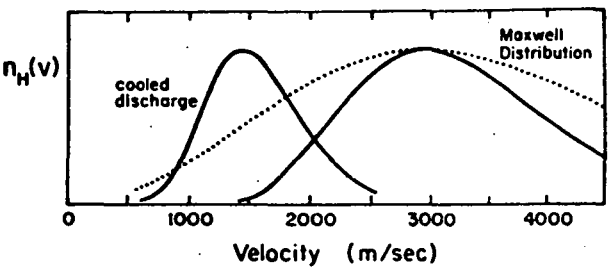

Fig. 2. Velocity distribution of the beam from an atomic-beam source, illustrating the effect of a cooled dissociator.

of the velocity distribution indicates that the beam is slightly supersonic. Reduced velocity spread is desirable because it reduces chromatic aberrations in the six-pole deflection and thus improves the beam transport into the ionizer (see below). For the beam developed at Bonn the Mach number is reported as 2.0±0.3.

Studies[15] at ANL (using a pulsed dissociator) showed that the increase in ion beam intensity is nearly proportional to $T^{-1/2}$ down to the lowest temperature measured (28 K). Others have reported an increase of roughly a factor two from cooling to liquid nitrogen temperature.[13] It appears that cooling of the dissociator nozzle offers a relatively simple means to increase the beam current from atomic-beam polarized ion sources.

3.2 Transport of the Atomic Beam

Of the polarized atoms emerging from the spin separation magnet only those are useful which are transported into the ionization region (Fig. 3). The wide variation of velocity in the beam prevents an effective waist-to-waist beam transport from the dissociator aperture to the ionizer. The very large chromatic aberration can be reduced by proper design of the field configuration in the separation magnet. For many years, the only measure taken was to introduce a slight taper in the aperture of the six-pole magnet, the aperture being largest near the ionizer. Later, calculations by Glavish[17] showed that a significant improvement can be obtained by use of a separate, second six-pole magnet ("compressor magnet") to form a more nearly achromatic system. This proposal has been applied successfully to a number of sources. The effect of the compressor magnet is illustrated in Fig. 3, which shows trajectories of $m_j = +1/2$ atoms with different velocities in the magnet system at Bonn.

The atomic beam apparatus developed at Bonn[14] is shown in Fig. 4. A turbomolecular pump and two cryopumps replace the more commonly used diffusion pumps. Measurements of the beam intensity and velocity distributions suggest an average H^0 density of

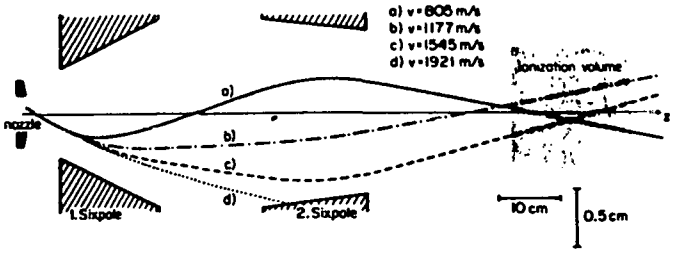

Fig. 3. Beam transport from the dissociator to the ionization region in the Bonn atomic-beam source. Note that the vertical scale is expanded.

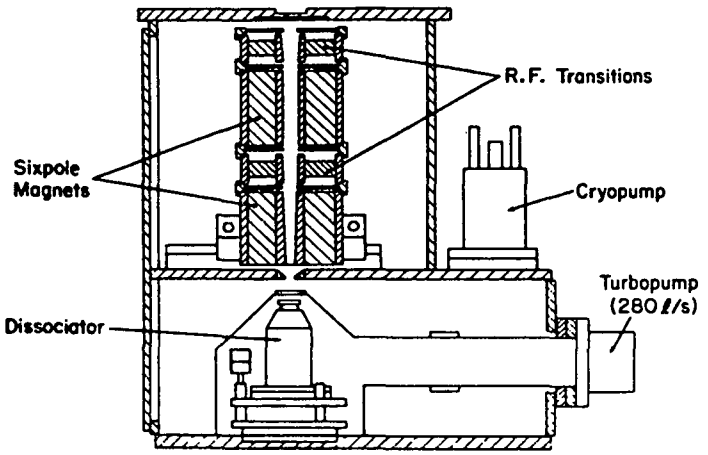

Fig. 4. The atomic-beam source developed at Bonn. The cryopump for the magnet compartment is not shown. The dissociator nozzle is cooled and adjustable in position. The sixpole magnets are each 10 cm long.

2.5×10^{11} cm^{-3} in an ionization volume of 1 cm diameter and 20 cm length. This indicates that a factor four increase can be obtained by using a cooled dissociator and a magnet system specifically designed to match the velocity distribution of the beam. Further work toward cooled, supersonic beams and optimum beam transport would seem worthwhile. In the design of the magnet, a further degree of freedom is provided by the possibility to combine four-pole and six-pole magnets.[18] An interesting departure from the conventional design is the atomic-beam source built at Dubna,[19] which uses a superconducting spin-separation magnet.

3.3 Ionization by Electron Bombardment

In the conventional atomic-beam method, production of $\vec{H}^-$ involves two steps: ionization of $\vec{H}^0$ to form $\vec{H}^+$, and charge exchange of the accelerated (~ 5 keV) $\vec{H}^+$ beam in an alkali vapor to form $\vec{H}^-$.

A gain in polarized-beam intensity from atomic-beam sources of a factor ten has been achieved during the last five years. This remarkable gain is the result of improved electron-bombardment ionizers. The initial development[16] was carried out jointly between CERN and ANAC. Figure 5 shows a cross section through this new type of ionizer, sometimes called the "super-ionizer". It operates by confining a plasma discharge in a magnetic field of modest strength (~ 0.15T).

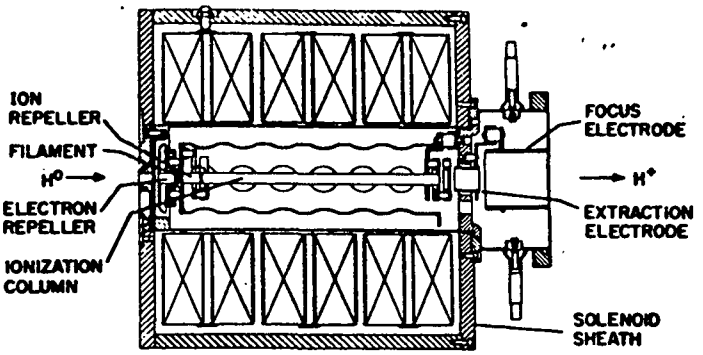

Fig. 5. The second-generation electron bombardment ionizer developed by the ANAC-CERN collaboration.

The discharge is supported by electrons from a filament. The solenoid is wound as a number of separate pancakes, so that the field along the axis can be contoured. An $\vec{H}^+$ current of 80 μA was obtained at the ANAC plant during a routine test of an ionizer prior to shipment.[20] The highest beam current yet[21] was reported by ETH, where a similar ionizer produced an $\vec{H}^+$ beam in excess of 100 μA. This current corresponds to an ionization efficiency of a few percent.

At ETH, the $\vec{H}^+$ beam is accelerated to 5 keV and passed through a Na-vapor charge exchange cell to produce negative ions for injection into a tandem accelerator. Beam currents of 3 μA $\vec{H}^-$ and $\vec{D}^-$ have been achieved.[21] The measured proton polarization after acceleration is P = 0.83. The emittance of the beam from the new high-efficiency ionizer has not been measured, but it must be very good since as much as 1.6 μA beam has been observed after the tandem. It should be pointed out that these results were reached without taking advantage of a cooled dissociator. It is likely that $\vec{H}^-$ and $\vec{D}^-$ beam intensities of 10 μA can be achieved by optimizing the atomic beam stage and the charge exchange cell.

3.4 Ionization by Colliding Beams

The colliding beam principle developed at Wisconsin has the unique feature of converting polarized thermal $\vec{H}^0$ atoms directly into $\vec{H}^-$ without going through positive ions or an intermediate step. The idea[22] is to bombard the H^0 atomic beam with a beam of fast atoms or ions which act as the donor of electrons. Of the two reactions which have been proposed:

$$\vec{H}^0 + Cs^0 \rightarrow \vec{H}^- + Cs^+ \qquad (1)$$

and

$$\vec{H}^0 + D^- \rightarrow \vec{H}^- + D^0 \qquad (2)$$

the first is used in the source installed on the Wisconsin tandem accelerator.[23] The ionizer of this source is shown in Fig. 6. The atomic beam enters from the left. Ions created in the collision region are extracted towards the right and are deflected by an electrostatic spherical deflector. The Cs^0 beam is collinear with the H^0 atomic beam. The Cs^+ gun and electrode system is gimbel-mounted such that the Cs beam can be aimed along the atomic beam axis. The 40 keV Cs^+ beam is neutralized in Cs vapor. The source, which is described in more detail in Ref. 24, has been used for nuclear physics experiments for more than a year. Beam currents up to 3.3 μA have been observed. The proton beam polarization is very high [P = 0.91±0.01 measured after acceleration, for ionization

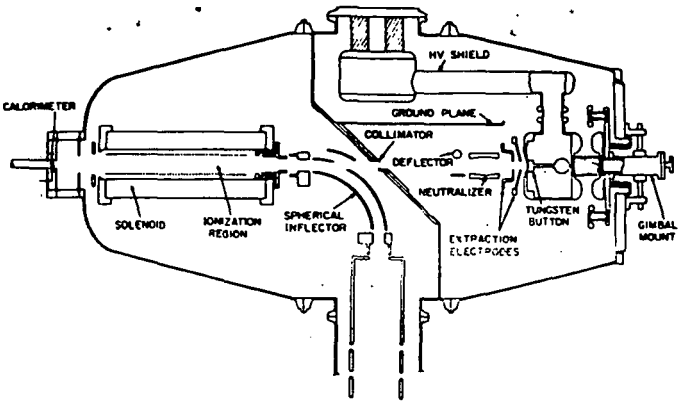

Fig. 6. Colliding-beams source for polarized negative ions. The atomic beam enters from the left. The exit port of the polarized negative ions is on the bottom of the drawing. The atomic-beam source is not shown. For normal operation, the calorimeter, which serves only to adjust the Cs-gun, swings out of the way.

in a 0.1 T field], because the cross section for production of H^- by collision of Cs^o with H_2 and hydrocarbon molecules is much smaller than for H^o.

It is interesting to note that the observed beam intensity is in quantitative agreement with a calculation based on the known charge exchange cross section, and the known atomic beam density and Cs^o current density. The observed beam current used to be somewhat higher than expected[23] but this is explained by newer cross section measurements[25] which give larger values than earlier ones. If we assume a cross section of 6×10^{-16} cm^2 for reaction (1), the expected beam current is

$$I = 1.5\ \mu A\ \overset{+}{H}^-\ \text{per mA/cm}^2\ Cs^o, \qquad (3)$$

in good agreement with experiment. The above number refers to a conventional atomic-beam source, and do not include the potential gain from a cooled dissociator.

Substantial gains in beam intensity can be expected in the future since, compared to other sources, little development work has been done. The present limitation to 3 μA is related to the poor focus of the Cs beam, which causes excessive loading of some of the ionizer power supplies. To study this problem, a separate test setup for the Cs gun was constructed. The results are encouraging, in that 8 mA of 55 keV Cs^o were observed in the calorimeter (1 cm diameter aperture), compared to 2-3 mA in the present source, with only a 50% increase in total Cs^+ output of the source. With an improved atomic beam source and the new Cs gun, beam currents in excess of 10 μA can be expected.

It would be very interesting also to develop a source based on D^- instead of Cs^o as the electron donor. The charge exchange cross section in this case is resonant and increases like 1/v. For a D^- energy of 2 keV and a standard atomic beam source [no cooling of dissociator etc.] one expects

$$I = 5\ \mu A\ \overset{+}{H}^-\ \text{per mA/cm}^2\ D^- \qquad (4)$$

Very intense sources of D^- have been developed for the CTR program. They have sufficiently good emittance to permit deceleration to 2 keV. A serious problem with this type of reaction is the loss of the newly-formed $\overset{+}{H}^-$ by the space charge of the D^- beam, but several methods to overcome the problem have been proposed.[6,16]

3.5 Surface Ionization

It may be of interest to mention surface ionization as a possible method to produce H^- ions directly from thermal H^o atoms. *Negative* ions will be formed when an atom strikes a surface whose work function is comparable to the electron affinity of the atom. Since the electron affinity of hydrogen atoms is 0.75 eV, a surface of very low work function is required to obtain appreciable H^- by surface ionization. A number of tests have been reported.[26,27] As far as I know the highest value of F_- observed so far ($F_- = 10^{-5}$) was obtained with a tantalum foil coated with a barium/strontium oxide mixture[27] (surface temperature 1200 K). An efficiency $F_- \approx 10^{-3}$ is required to produce 3 μA H^- by ionization of H^o atoms from an atomic beam source.

4. Negative Polarized Ions from Fast Polarized Atoms

The attraction of this method lies in the ease with which a fast (keV) polarized H^o beam can be ionized. The ionizer in this case simply consists of a suitable gas or vapor cell that converts H^o to $\overset{+}{H}^-$ by charge exchange. The H^- ion has no excited states. Thus the electron pickup leads directly to the (singlet) ground state and the proton polarization in H^- will be the same as in the original H^o atom.

As mentioned in Sect. 2, sources based on fast polarized atoms can be divided into two groups: those which use atoms in the metastable H(2S) state (Lamb-Shift sources), and those which prepare fast polarized hydrogen atoms in the ground state H(1S).

4.1 Lamb Shift Sources

This is by far the most common source of polarized H^- and D^- ions. It is in use not only at a large number of tandem accelerators, but also on a cyclotron and at the LAMPF and TRIUMF meson facilities. This type of source has been the subject of highly competent development programs at several laboratories for a number of years. The beam intensity seems to have reached a plateau of roughly 1 μA, with a proton polarization of P = 0.75-0.80. A beam current as large as 1.6 μA has been reported (Ref. 28) but at the expense of the degree of polarization (P = 0.65). The limitation in beam intensity seems to be associated with quenching of the metastable atoms, either by space charge of the remaining H^+ beam or by collisions with Cs ions and atoms in the Cs vapor cell where H(2S) is formed.

For the Lamb-Shift source the important developments took place several years ago. Thus I will not review them here. It should be emphasized, however, that this type of source still has much to recommend itself, even if it is not likely to keep up with other schemes as far as beam intensity is concerned. In the first place, for many applications the intensity provided by this type of source is adequate. In addition, it is at present the only source to produce a polarized triton beam. Another advantage is the availability of the so-called spin filter[12] developed at Los Alamos, which permits the selection of a single hyperfine component and thus maximum deuteron tensor polarization. Selection of a single hyperfine component is possible also with a thermal atomic-beam source, but requires RF transitions between two separation magnets as shown in Fig. 4. Other recent advances in the use of Lamb-Shift sources is the relatively simple and very effective pulsing and

bunching of the beam. The group at TUNL has compressed some 70% of the DC beam into bunches 1.5 nsec long.[29] Finally, a recent review paper by McKibben[30] describes in detail the methods which have been developed for rapid spin reversal in the Lamb-Shift source.

4.2 Sources Based on Fast H^0 Atoms in the Ground State

None of the sources now in use employ fast polarized hydrogen atoms in the *ground* state, but the development of such sources is currently an area of intense interest. Some see this as a relatively simple way to produce very intense beams of $\vec{H}^-$ ions. A recent review paper[31] projects an $\vec{H}^-$ beam current of 2 mA! In this section I will review the method and summarize the problems as far as they are presently understood.

This type of source is based on the production of fast polarized atoms by pickup of polarized electrons: $\vec{H}^+ + \vec{e} \rightarrow \vec{H}^0$. The basic idea is old. In 1957, Zavoiskii[32] proposed the production of fast $\vec{H}^0$ by passing protons through a magnetized ferromagnetic foil. The beam of fast H^0 is subsequently ionized by charge exchange in a second foil or in a vapor. Later I proposed[33] to replace the foil by a cell containing a polarized paramagnetic gas. In particular, I suggested the use of an optically pumped alkali vapor or of a $\vec{H}^0$ atomic beam in combination with a storage cell. The first of these ideas has recently met serious interest primarily because of a paper by Anderson[34] which points out that relatively dense spin-polarized alkali vapor targets can be produced by optical pumping with commercially available CW dye lasers. Also, Witteveen[35] recently constructed a prototype polarized H^- source in which an atomic beam apparatus produced the polarized Na atoms.

To discuss this type of source, we use the schematic diagram from Anderson's paper (Fig. 7). The protons of a few keV energy first pass through a

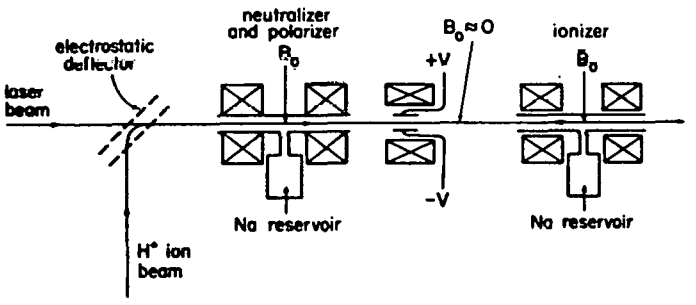

Fig. 7. Production of $\vec{H}^-$, using optically-pumped Na vapor. The Na vapor in the cell on the left is polarized by circularly-polarized light from a laser. Protons of a few keV energy pick up polarized electrons to form $\vec{H}^0$, which then undergoes charge exchange to $\vec{H}^-$ in the cell on the right. Sudden field reversal (see Sect. 2) at the point marked $B_0 \approx 0$ is used to obtain nuclear polarization.

polarized alkali vapor where some of them pick up a polarized electron. The remaining H^+ beam is removed by deflection plates. The polarized H^0 beam is converted to H^- in a second (unpolarized) alkali vapor cell. Both vapor cells are in a magnetic field along the beam axis. If electron capture in the first cell leads directly to the *ground state* of H^0, the resulting beam is completely polarized in electron spin (provided the field is "strong", B >> 507 G). Nuclear polarization is produced by sudden field reversal (Sect. 2). The application of this method to an $\vec{H}^0$ beam of several keV energy should present no problem. In Fig. 7, the sudden field reversal takes place at the point labeled $B \approx 0$ in the region between the two vapor cells.

The current interest in optical pumping arises from the following simple consideration taken from Ref. 34. A 1 W laser yields about 3×10^{18} circularly polarized photons/sec. If half of them are absorbed, one can polarize ~ 10^{18} Na atoms/sec. If the Na is contained in a tube of 1 cm^2 cross sectional area, the average time between collisions with the wall (Na vapor temperature 600 K) is about 10^{-5} sec. If the Na atoms lose their polarization in the collision with the wall, then each atom in the vessel needs to be polarized 10^5 times per second, which means that the tube should contain no more than ~ 10^{13} atoms. Some polarized atoms will be lost through the ends of the tube, but this is a minor perturbation. A proton passing through a 20 cm long tube will see a target thickness of 10^{13} Na atoms/cm^2. The cross section for $H^+ + Na \rightarrow H^0 + Na^+$ at 5 keV (near the optimum energy) is 6×10^{-15} cm^2, so that some 6% of the $\vec{H}^+$ beam will emerge from the optically pumped cell as $\vec{H}^0$. If we assume that 7% of this $\vec{H}^0$ beam can be converted to $\vec{H}^-$ in the second charge exchange cell, one expects an overall conversion efficiency from H^+ to $\vec{H}^-$ of 4×10^{-3}, i.e. 4 μA $\vec{H}^-$ per mA H^+ at 5 keV. The paper by Anderson mentions a current of 120 μA, assuming 10 mA H^+, a target thickness of $3 \times 10^{13}/cm^2$ and 10% conversion to negative ions.

There still is not enough information to allow a reliable assessment of proposed scheme, but attention should be called to some of the difficulties. There is no doubt that alkali vapors can be polarized by optical pumping. The important questions are what degree of polarization and what target thickness can be obtained for a given laser power, and whether useful polarizations can be obtained with multi-mode lasers. Some of these questions were investigated recently at KEK,[36] where Na vapor in a tube of 2 cm diameter and 10 cm length was illuminated with circularly polarized light from a 1W dye laser tuned to the Na D_1 line. The band width of the laser was sufficiently wide (40 GHz) to cover the absorption profile of the entire D_1 line, including the various Doppler broadened components. The electronic polarization of the Na atoms near the center of the tube was measured by allowing atoms from the center of the Na vapor target to pass through a six-pole magnet (Fig. 8). The electronic polarization of the Na vapor was deduced from the change in the number of atoms passing through the magnet when the circular polarization of the light was reversed, thus reversing the electron polarization from $m_j = +1/2$ to $m_j = -1/2$. An electron polarization $P_e = 0.75$ could be obtained with a target thickness of ~3×10^{12} atoms/cm^{-2}. This is in good agreement with the values predicted by Anderson. The results as a function of Na vapor thickness is shown on the right hand side of Fig. 8. Presumably, higher polarization and larger target density can be obtained by increasing the laser power. An upper limit (~3×10^{12} cm^{-3}) is set to the target density by imprisonment of radiation. Anderson estimates that for a 20 cm long charge exchange tube, a target thickness of 3×10^{13} cm^{-2} can be reached by six 1W dye lasers, pumped by two 20W argon ion lasers. Possible problems arising in the use of broad band lasers are mentioned in Sect. 5.2.

A fundamental difficulty in this type of source arises from the fact that the capture of the polarized electron by the proton in the first alkali cell does not lead directly to the ground state $H^0(1S)$. If the

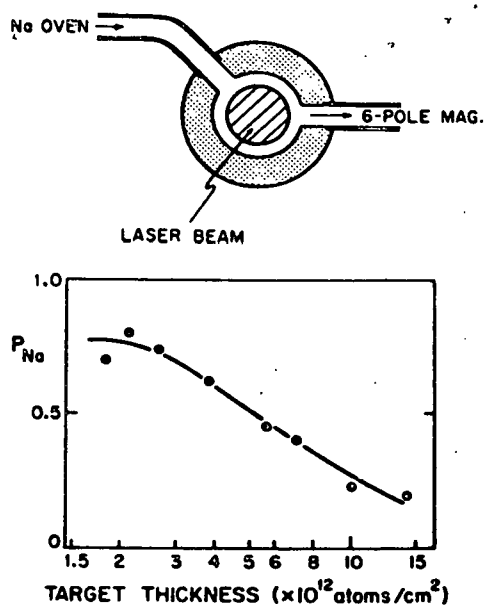

Fig. 8. Measurement of the electron spin polarization of optically-pumped Na (from Ref. 38).

polarization will be lost in the subsequent radiative transition to the ground state. There is no data on the relative population of the various states in H^0 produced by $H^+ + Na \rightarrow H^0$, but it is safe to assume that a majority of the H^0 is in excited states since the energy defect is much larger for formation of the ground state than for any of the excited states. Anderson has calculated that pickup of completely polarized electrons into the 2p state of H^0 leads to an electron polarization of 11/27 = 41% after decay to the ground state. Capture into the 2S state presumably leads to a similar result since this (metastable) state decays primarily by mixing with p-states. Capture into the n = 3 state or higher states leads to lower polarization yet. The beam polarization from this type of source has not yet been measured but in a recent experiment Witteveen[35] has measured the nuclear polarization resulting from the same type of source in which the optically pumped alkali vapor was replaced by sodium atoms polarized by the atomic beam method. The observed polarization was (28±8)% of the value expected if no loss of polarization occurs. However, this loss was attributed to unpolarized background vapor rather than to capture into excited states of $\vec{H}^0$.

The above discussion of the expected beam polarization assumed ionization in a magnetic field strong enough to decouple the electron angular momentum J from the nuclear spin I in the Na ground state, i.e. typically about 1.5 kG since the critical field is 0.63 kG. It has been suggested[34] that the problem of depolarization from capture into excited states of $\vec{H}^0$ can be avoided by applying a magnetic field strong enough to decouple L and S in H^0. For the n = 2 state, the critical field is 3.5 kG. The polarization of the hydrogen atoms as a function of magnetic field for completely polarized Na vapor is shown in Fig. 9 (Ref. 37). A field of 10 kG is required to reduce the loss in polarization to 20%. This field can readily be provided by placing a solenoid over the Na vapor cell but to deal with the ion optic effects of this strong a field on the 5 keV H^+ beam presents problems.

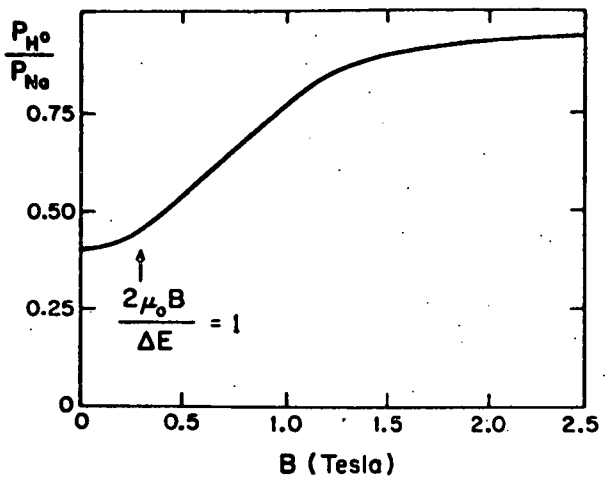

Fig. 9. Electron spin polarization of $\vec{H}^0$, obtained by pickup of electrons in polarized Na vapor, as a function of magnetic field applied to the Na cell. The calculations[37] assume that the hydrogen atoms are originally formed in the 2p-state.

The scheme described above is being studied in a number of laboratories, where the most advanced tests are those at KEK, where an intensity of 4 μA has been obtained.[38] Unfortunately the beam polarization has not been measured yet, but from the above considerations it is expected to be no more than 0.3. Already a magnetic field of 5 kG reduces the beam intensity to 1 μA, but possibly some of the loss can be avoided by placing the entire H^+ source inside the field.

It may be timely to repeat here the second of my suggested variations on Zavoiskii's theme, namely the use of $\vec{H}^0$ (or $\vec{D}^0$) atoms as the donor of polarized electrons for the H^+ beam, rather than Na. The advantage in this case is that the reaction $H^+ + \vec{D}^0 \rightarrow \vec{H}^0$ certainly leads to the ground state of the fast $\vec{H}^0$, and not to excited states. The charge exchange is resonant, with a cross section that increases at low energies as 1/v. As was mentioned in Sect. 3.3, a modern atomic beam source yields about 2.5×10^{11} atoms/cm^3. For an H^+ energy of 5 keV, the reaction $H^+ + \vec{D}^0 \rightarrow \vec{H}^0$ has a cross section[39] of 1.5×10^{-15} cm^2, so that an interaction region of 1 cm diameter and 20 cm length will yield 5 μA $\vec{H}^0$ (5 keV) per mA H^+. This is considerably less than what one expects from a Na target of 10^{13} atoms/cm^2, but the severe ion optics problems are eliminated. In addition, storage of $\vec{H}^0$ from an atomic beam source may be used to improve the target density.[40]

The capability of the methods discussed in this section cannot be assessed until a measurement of the polarization as a function of magnetic field in the first Na charge exchange cell is made. The method holds promise, but is not nearly as simple or inexpensive as first assumed. It should also be pointed out that this method is not suitable to provide tensor polarized deuterons, because the sudden field reversal will yield at best $P_{zz} = 1/3$. Note that this limitation does *not* apply to the Lamb-shift source, where sudden field reversal for deuterons has often been used, because in this case one can use selective quenching (i.e. spin selection) once more *after* the sudden transition region.

5. Sources of Polarized Heavy Ions

This section will be quite abbreviated because only a few months ago an excellent review devoted entirely to this subject was published by Steffens.[9]

5.1 Atomic-Beam Method

The only operating source of polarized heavy ions is the atomic-beam source at Heidelberg, which has provided $^6\vec{Li}^-$ and $^7\vec{Li}^-$ ions for a number of years and recently has been developed also for $^{23}\vec{Na}^-$ ions. The principle is the same as in the atomic beam source for the hydrogen isotopes, except that the dissociator is replaced by an oven. A system of heated and cooled collimators is used to form a directed beam.

After the six-pole separation magnet, the atomic beam is exposed to RF transitions to produce nuclear vector or tensor polarization. For ^{6}Li (nuclear spin I = 1), pure vector polarization of (ideally) P_z = 2/3 can be obtained and the sign can be reversed by switching RF transitions. Also, a tensor polarization P_{zz} of +1 or -1 can be produced. For ^{7}Li and ^{23}Na (I = 3/2) there are eight rather than six hyperfine components. In these cases, the tensor polarization reaches only 50% of the upper limit. To reach $P_{zz} = \pm 1$ one would need to induce π-transitions with $\Delta m_I = 2$, but so far it has not been possible to obtain high transition probabilities. The problem becomes the more acute the higher the nuclear spin. The situation can be improved by use of two separate separation magnets with RF transition units between as well as after the magnets, as shown in Fig. 4. A very effective solution to the problem can be achieved by use of optical pumping (see Section 5.4).

5.2 Ionization

Polarized neutral alkali atoms can be ionized by permitting the atomic beam to hit a hot surface of sufficiently high work function ϕ. Ionization to positive ions takes place with very high efficiency of $\phi - \varepsilon >> kT$, where ε is the ionization energy of the atoms. At Heidelberg, atomic beams of ^{6,7}Li and ^{23}Na are ionized with nearly 100% efficiency using oxydized W surfaces at a temperature of some 1700 K. Under these conditions there is no detectable depolarization,[41] while at lower temperatures the polarization is found to decrease because of the increasing dwell time of the atoms on the surface (interaction of the nuclear moments with fluctuating fields on the surface). The positive ions are subsequently accelerated and charge-exchanged to negative ions in Cs or K vapor. Beam currents of 150 nA Li^- and 200 nA Na^- are available at Heidelberg for injection into the tandem accelerator. The beam polarization is about 80% of the theoretical maximum. An increase in beam current could probably be achieved, since the Li atomic beam source developed for the SLAC polarized electron source, yields substantially more beam (10^{16} atoms/sec) than the Heidelberg source. It is not known what maximum current density can be obtained from a surface ionizer without depolarization, but at some point the interaction of neutral atoms on the surface will become a problem. Detailed studies of depolarization in surface ionization have recently been started.[43]

The colliding-beam source described in Sect. 3.4 in principle is suitable also for the production of heavy negative ions. For example, the reaction $\vec{Li}^O + Cs^O \rightarrow \vec{Li}^- + Cs^+$ has a cross section[44] of 3×10^{-16} cm^2 for a Cs^O energy of 65 keV. If we assume a Li atomic beam of roughly 2×10^{15} sec^{-1} as used at Heidelberg, and an average atomic beam velocity of about v = 2×10^5 cm/sec, one expects 0.3 μA Li^- for a Cs^O current density of 3 particle-mA/cm^2 and an interaction length of 30 cm. Since for H^- and D^- the measured beam intensity from the colliding-beam source closely corresponds to the calculated intensity, there is reason to believe that this would be the case here also. Ionization by Cs^O bombardment is probably more elaborate than the ionization method developed at Heidelberg, but could be used to advantage if a colliding-beam source is already available at the laboratory to produce light ions.

5.3 Depolarization

Experience has shown that polarized hydrogen ions can be injected and accelerated in tamdem accelerators without loss of polarization. A difficulty was encountered in the very first attempt[45] to accelerate a polarized beam in a tandem accelerator some 20 years ago, but it was recognized immediately that the observed depolarization could be avoided by replacing the gas stripper by a foil stripper. Depolarization is negligible if the transition from a negative ion to a fully stripped ion occurs in a sufficiently short time. In a gas stripper, the stripping, e.g. from H^- to H^+ takes place in two steps. In the intermediate H^O system the polarized nucleus is exposed to an unpaired and unpolarized electron and thus the nucleus depolarizes by the hyperfine interaction in a characteristic time which is given by the Larmor period.

For heavy ions, the depolarization effects have been studied extensively by the group at Heidelberg.[9] If the negative ion is stripped to a fully ionized positive ion by a foil in the high-voltage electrode of the tandem accelerator, no depolarization is expected. Indeed there is good evidence that the depolarization for the ^{6}Li and ^{7}Li beams at Heidelberg is small. Attempts to accelerate polarized *incompletely* stripped ions were made with the ^{23}Na beam. Because of the limited terminal voltage of the tandem (6 MV), the most probably charge state is Na^{6+}, whereas the two-electron state Na^{9+} is very improbably ($\sim 10^{-3}$). No significant nuclear polarization could be detected in the Na^{6+} and Na^{7+} beam after acceleration, even though it could be demonstrated by beam-foil spectroscopy that the Na^- beam was really polarized. Polarization after the tandem could only be detected[46] after a new polarization monitor was developed which had sufficient efficiency to be used with the weak Na^{9+} component in the beam. The tensor polarization of the Na^{9+} beam was between 30% and 60% of the initial polarization. Later, a polarization could also be detected for the Na^{7+} beam by employing post-stripping to Na^{9+}. Because of the requirement to strip at least down to the K-shell, acceleration of heavier polarized ions like ^{39}K would require rather high terminal potential ($\sim$ 30 MV).

A second important source of depolarization arises in magnetic beam-handling components. The problem is that already a small magnetic deflection α of the beam can lead to large spin precession angles δ, since for some ions the ratio δ/α is large, e.g. 17 for ^{23}Na. Here we are assuming a singly charged ion and electron spins which couple to zero. If the ion has a net electronic magnetic moment ($J \neq 0$) the effects of course become bigger by some three orders of magnitude. Thus a beam with $J \neq 0$ would be completely depolarized in a magnetic lens. For polarized ions where complete stripping can not be obtained, one thus wants to work exclusively with ions whose ground state has J = 0. In addition, ions in long lived (metastable) excited states should be avoided. At Heidelberg, the above mentioned increase of the ^{23}Na beam polarization by post-stripping is explained by the removal of metastable Na^{7+} ions prior to magnetic beam handling elements. The depolarization prior to injection can be avoided by using only electrostatic elements.

5.4 Polarized Heavy Ions by Optical Pumping

The basic process by which a directed beam of alkali atoms emerging from an oven aperture can be polarized by optical pumping is illustrated in Fig. 10

for the case of an alkali atom whose nuclear spin is I = 3/2 (e.g. ^{23}Na). If the $^2S_{1/2}$ atoms in various states (F, m_F) absorb right-hand circularly polarized resonance radiation (heavy solid lines in Fig. 10). $\Delta m_F = -1$, and thus the atom gains angular momentum. Consequently, even after the decay (light solid lines, Fig. 10) back to the ground state ($\Delta m_F = 0, \pm 1$) the occupation distribution has shifted toward states with

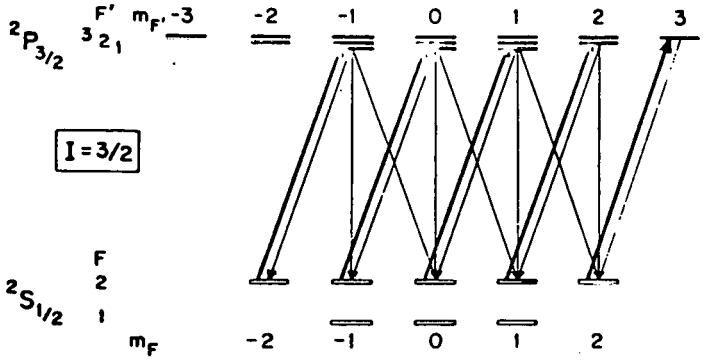

Fig. 10. Optical pumping of alkali atoms with nuclear spin I = 3/2. For the case of Na, the separation between the ground state atoms with F = 1 and F = 2 is 1.77 G Hz. Right circularly polarized light is absorbed (heavy arrows), and the excited atoms decay back to the ground state. After several cycles, most of the atoms are in the state with $m_F = +2$, leading to complete nuclear polarization, $m_I = 3/2$. To simplify the figure, all transitions from and to the ground state hyperfine component with F = 1 are omitted (see text).

larger m_F. If the light intensity is sufficient for many such pumping cycles to occur while the atom passes through the light beam, almost all atoms will be pumped into the hyperfine component with the largest spin projection, i.e. the $^2S_{1/2}$ state with $m_F = 2$. This is a state of maximum possible nuclear polarization $m_I = +3/2$. In Fig. 10, for simplicity, pumping of only the F = 2 ground state atoms is indicated. Atoms with F = 1 can be pumped into the F = 2, $m_F = 2$ state in the same way.

Production of a Li polarized ion beam by optical pumping has been discussed by Anderson,[47] while the development of a ^{23}Na beam has been progressing at Marburg for some time.[48] In principle, ion sources based on optical pumping may produce larger beam currents than atomic-beam sources which have a limited acceptance angle for atoms from the oven, but it is not clear how much of an increase could in fact be utilized. Possibly a more important factor than the intensity is the possibility to obtain large polarization with relative ease. For the atomic-beam method, the polarization is limited, at least for nuclear spin I > 1, unless a more complicated design of the magnets and transitions is used.[10] Large beam polarization from the ion source is important, in particular, for ions of large mass number, because a substantial fraction of the polarization may be lost in the accelerator.

In practice, the optical pumping of a beam of alkali atoms is complicated by the splitting between the hyperfine components in the ground state [e.g. 1.77 GHz for ^{23}Na] which is large compared to the ~ 1 MHz width of a mode of a dye laser. One solution which has been proposed[47] is to use a broad band dye laser, since the bandwidth from such a laser (~ 10 GHz) easily overlaps the transitions from both ground state hyperfine levels. However, it is by no means trivial to excite all atoms, because the frequency spectrum from such a laser consists of a set of discrete frequencies (modes), separated by a few hundred MHz. Even though the absorption profile for each transition is broadened by power broadening and Doppler broadening, this is not sufficient to insure that each atom will be exposed to resonance radiation most of the time, particularly since at any one time only some of the possible modes of the laser are in fact lasing. This problem would be reduced considerably if the different modes flickered on and off rapidly compared to the transit time of the atoms through the beam, but this does not seem to be the case.[37] Anderson sees this as the reason why in a recent experiment to pump a Li atomic beam, they obtained an electron polarization of only some 50%, in contrast to the nearly complete polarization anticipated in Ref. 47, and suggested that the simultaneous use of a number of different lasers may solve the problem since in this case some power is available over most of the bandwidth at all times.

The most striking demonstration that an ion beam of large nuclear polarization can be obtained by optical pumps was recently reported by the group at Marburg.[49] Their solution to the large splitting of the ground state is to use two separate single-mode dye lasers, one tuned to pump the F = 1 states, the other tuned to pump the F = 2 states. The hyperfine structure of the $^2P_{3/2}$ excited state is not resolved, because of Doppler-and power-broadening. The atomic beam was ionized by surface ionization. The nuclear vector polarization of the resulting 15 keV $^{23}Na^+$ beam, measured by beam-foil spectroscopy, was found to be $P_z = 0.86 \pm 0.05$. This means that more than 90% of the atoms are in the desired F = 2, $m_F = 2$ state.

The use of two single-mode dye lasers is very effective, but for application to an accelerator environment one would prefer simpler and less expensive methods. One possibility[49] is to depopulate the F = 1 levels by RF transitions between the F = 2 and F = 1 state (1.77 GHz). For ^{6}Li, where the ground state splitting is only 228 MHz, an elegant method has been developed at Bielefeld[50], where simultaneous pumping of both hyperfine states was achieved with a single laser by frequency-splitting the laser light with an acousto-optic modulator. Also, in earlier experiments at Marburg,[48] large polarization was observed in a ^{23}Na beam using one laser only to pump the F = 2 ground state atoms, by rejecting the F = 1 atoms in a six-pole separation magnet.

6. Production of Polarized $^3He^-$ Ions

A review of methods to produce $^3\vec{He}^+$ was presented by Slobodrian.[51] A Lamb-Shift ion source producing a beam of $^3\vec{He}^+$ has been in use at Birmingham for a number of years. Also, a beam of $^3\vec{He}^+$ has been extracted from a discharge in optically pumped ^{3}He gas. No sources exist for the production of negative ^{3}He ions, but a possible method has been discussed by Anderson[34] recently. The proposed method involves pick-up of polarized electrons by a He^+ beam in an optically pumped Na vapor target. The $^3He^-$ ion has a (1s)(2s)(2p) configuration with all electron spins parallel: $^4P_{5/2,3/2,1/2}$. Formation of He^- from He^+ by charge exchange, e.g. in Na, proceeds through the 2^3S_1 state of $^3He^o$. This is the ground state of ortho-helium, which has the very long life time of some 4 sec. Nuclear polarization is produced by the hyperfine interaction in $^3He^o(2^3S_1)$. For pickup of completely polarized electrons by $^3He^+$, the nuclear polarization in $^3He^o$ is calculated[14] to be 37%, provided the pickup proceeds only and directly to the 2^3S_1 state of $^3He^o$. Anderson proposes that the charge exchange to $^3\vec{He}^-$ should be carried out within the same polarized Na cell, but this should be reexamined since

his arguments neglect the coherent time dependence of the states formed. Charge exchange from $^3He(2^3S_1)$ to $^3He^-$ in a separate, unpolarized vapor may in fact be preferable.

Slobodrian[51] has discussed the possibility to produce a beam of relatively slow $^3He(2^3S_1)$ atoms and to polarize the atoms by Stern-Gerlach separation. He proposed to produce the $^3He(2^3S_1)$ atoms by neutralization of a $^3He^+$ beam originating from an RF ion source or a duoplasmatron in a charge exchange cell. The beam would have to be slowed to $\leq$ 10 eV prior to neutralization. The intensity estimates in Ref. 51 should be viewed with caution as they do not take into account the emittance of the $^3He(2^3S_1)$ beam at 10 eV in relation to the acceptance of the sixpole magnet. The direct production of the metastable helium atoms by an RF discharge in ^3He gas would seem the more promising method. After the separation magnet, the nuclear polarization of the ^3He atoms can be enhanced by suitable RF transitions between hyperfine states. Slobodrian proposed ionization to $^3He^+$ by electron bombardment. Direct conversion of the $^3He(2^3S_1)$ to $^3He^-$ by Cs^0 bombardment (colliding beams method) should be considered if negative ions are required.

7. Conclusions

Not so many years ago, experimenters had to suffer a big loss in intensity if they wanted to use polarized beams. As this review shows, striking progress has been made during the last five years in the development of sources for polarized ions. This progress is exemplified by the production of highly polarized beams of positive hydrogen ions in excess of 100 μA, and of negative hydrogen ions of 3 μA. While many experiments (e.g. polarization transfer experiments, production of highly polarized neutrons, injection of polarized beams into high energy accelerators) justify continued work on further increases in intensity, other considerations, such as reliability and ease in maintenance, must be kept in mind as well. Other characteristics of ion sources which have not been emphasized in this review, but which have great importance in some applications are the flexibility of choice in beam polarization (e.g. pure tensor polarization for deuterons), the ease with which the polarization can be changed without associated changes in beam intensity or beam position, the uniformity in polarization-magnitude and direction across the beam profile, or the efficiency with which the beam can be pulsed or bunched.

The present review reflects the great variety of stimulating new ideas that are under discussion by the small group of scholars who are interested in the development of polarized ion sources. Progress at present is not limited by a lack of good ideas, but by the relatively small effort in this field worldwide. Nevertheless, there is good hope that existing methods will be perfected to yield even larger beam intensities with high reliability, and that new applications of low temperature techniques, storage of polarized atoms or ions, and of optical pumping, will lead to successful new methods for the production of polarized ions.

Finally I should like to thank the many colleagues who have contributed to this review by providing me with their results and ideas.

References

1. W. Haeberli, Ann. Rev. Nucl. Sci. 17, 373 (1967).
2. D. Fick, "Einführung in die Kernphysik mit Polarimeten Teilchen", Bibliographisches Institut, Mannheim. Hochschulskripten 755/755a.
3. W. Haeberli, in "Nuclear Spectroscopy and Reactions" (J. Cerny, Ed.), Academic Press (N.Y. 1974), Part A, p. 152.
4. H.F. Glavish, Proc. Third Int. Symp. on Polarization Phenomena in Nuclear Reactions (Univ. Wisconsin Press, 1971), p. 267.
5. B.L. Donnally, Proc. Third Int. Symp. on Polarization Phenomena in Nuclear Reactions (Univ. Wisconsin Press, 1971), p. 295.
6. W. Haeberli, High Energy Physics with Polarized Beams and Polarized Targets, Argonne, 1978. AIP Conf. Proc. No. 51, p. 269.
7. Polarization Phenomena in Nuclear Physics, 1980. AIP Conf. Proc. No. 69, American Institute of Physics (New York, 1981).
8. High Energy Physics with Polarized Beams and Polarized Targets, Lausanne 1980 (to be published).
9. E. Steffens, Fifth Tandem Conference, Catania, 1980. Nucl. Instr. Meth., to be published.
10. E. Steffens, Int. Conf. on Heavy Ion Sources, Gatlinburg, 1975. IEEE Trans. Nucl. Sci. 23, 1145 (1976).
11. P.G. Sona, Energ. Nucl. 14, 295 (1967); see also T.B. Clegg, G.R. Plattner and W. Haeberli, Nucl. Instr. Meth. 62, 343 (1968).
12. J.L. McKibben, G.P. Lawrence and G.G. Ohlsen, Phys. Rev. Lett. 20, 1180 (1968).
13. Y. Wakuta, Y. Koga, H. Hasuyama and H. Yamamato, Nucl. Instr. Meth. 147, 461 (1977).
14. H.G. Mathews, Ph.D. thesis, University of Bonn (1979).
15. P.F. Schultz, E.F. Parker and J.J. Madsen, AIP Conf. Proc. No. 69, p. 909.
16. H.F. Glavish, Higher Energy Polarized Proton Beams (Ann Arbor, 1977), AIP Conf. Proc. No. 42, p. 47; W. Kubischka, CERN, private communication.
17. H.F. Glavish, Proc. Fourth Int. Symp. on Polarization Phenomena in Nuclear Reactions (W. Grüebler and V. König, eds.) Birkhäuser (Basel) 1976, p. 844.
18. G.J. Witteveen, Nucl. Instr. Meth. 141, 515 (1977).
19. A.A. Belushkina, V.P. Ershov, V.V. Fumishkin, G.I. Gaj, L.S. Kotova, Yu. K. Pilipenko, V.V. Smelyansky, A. Sulik, G.P. Tsvinevs and A.I. Valevish, High Energy Physics with Polarized Beams and Polarized Targets, Lausanne 1980 (to be published).
20. H.F. Glavish, ANAC, Inc., 3067 Olcutt Street, Santa Clara, California 95050 (private communication).
21. P.A. Schmelzbach, W. Grüebler, V. König and B. Jenny, Nucl. Instr. Meth. (to be published).
22. W. Haeberli, Nucl. Instr. Meth. 62, 355 (1968).
23. D. Hennies, R.S. Raymond, L.W. Anderson, W. Haeberli and H.F. Glavish, Phys. Rev. Lett. 40, 1234 (1978); W. Haeberli, M.D. Barker, G. Caskey, C.A. Gossett, D.G. Mavis, P.A. Quin, J. Sowinski and T. Wise, AIP Conf. Proc. No. 69, p. 877.
24. W. Haeberli et al., Nucl. Instr. Meth. (to be published).
25. A.S. Schlachter, K.R. Stalder and J.W. Stearns, Phys. Rev. A (to be published).
26. W.G. Graham, Bull. Am. Phys. Soc. 23, 409 (1977); R.S. Raymond, W. Haeberli and P.A. Quin, Nucl. Phys. Progress Report (1978), (unpublished).
27. R. Goldstein and J.E. Graf, JPL Invention Report 30-3834/NPO-14113, Cal. Tech., Pasadena, California.
28. W. Arnold, H. Berg and G. Clausnitzer, AIP Conf. Proc. No. 69, p. 882; and G. Clausnitzer, private communication.
29. S.A. Wender, C.E. Floyd, T.B. Clegg and W.R. Wylie, Nucl. Instr. Meth. 174, 341 (1980).
30. J.L. McKibben, AIP Conf. Proc. No. 69, p. 830.
31. E.F. Parker, IEEE Trans. Nucl. Sci., June 1981 (to be published).
32. E.K. Zavoiskii, Soviet Physics JETP 5, 338 (1957).
33. W. Haeberli, Proc. Second Int. Symp. on Polarization Phenomena in Nuclear Reactions (P. Huber and

H. Schopper, eds.) Birkhäuser (Basel) 1966, p. 64.
34. L.W. Anderson, Nucl. Instr. Meth. 167, 363 (1979).
35. G.J. Witteveen, Nucl. Instr. Meth. 158, 57 (1979).
36. Y. Mori, K. Ito, A. Takagi and S. Fukumoto, High Energy Physics with Polarized Beams and Polarized Targets, Lausanne 1980 (to be published.
37. L.W. Anderson, private communication.
38. Y. Mori, K. Ito and S. Fukumoto, IEEE Trans. Nucl. Sci. June 1981 (to be published).
39. W.L. Fite, R.F. Stebbings, D.G. Hummer and R.J. Brackmann, Phys. Rev. 119, 663 (1960).
40. W. Haeberli, Nucl. Instr. Meth (to be published).
41. R. Böttger et al., AIP Conf. Proc. No. 69, p. 979.
42. M.J. Alguard et al., Nucl. Instr. Meth. 163, 29 (1979).
43. R. Böttger, P. Egelhof, K.-H. Möbius, D. Presinger, E. Steffens, W. Dreves, B. Horn, I. Koenig and D. Fick, Z. Phys. A299 (to be published).
44. F. Wittchow and H. Neuert, Annual Report 1. Institut für Experimentalphysik, 1978/79, p. 54.
45. W. Haeberli, W. Grüebler, P. Extermann and P. Schwandt, Phys. Rev. Lett. 15, 267 (1965).
46. P. Egelhof et al., AIP Conf. Proc. No. 69, p. 916.
47. L.W. Anderson and G.A. Nimmo, Phys. Rev. Lett. 42, 1520 (1979).
48. W. Dreves, W. Broermann, M. Elbel, W. Kamke, D. Fick and E. Steffens, AIP Conf. Proc. No. 69, p. 925.
49. W. Dreves, W. Kamke, W. Broerman and D. Fick, preprint (1981).
50. G. Baum, C.D. Caldwell and W. Schröder, Appl. Phys. 21, 121 (1980).
51. R.J. Slobodrian, AIP Conf. Proc. No. 69, p. 797; R.J. Slobodrian, Nucl. Instr. Meth. (to be published).