SOURCES OF POLARIZED NEGATIVE IONS: PROGRESS AND PROSPECTS

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1. INTRODUCTION

I have been asked to present a summary of recent progress in the art of producing beams of polarized ions. The special interest in *negative* ions arises from the great advantage which they have over positive ions for insertion into synchrotrons, since negative ions readily permit multiturn injection. My discussion will be limited to negative ions of *hydrogen* and *deuterium*, because I assume that heavier ions are of no current concern to high-energy physics. Deuterium ions *are* of interest for those high-energy accelerators in which depolarizing resonances prevent acceleration of protons. For deuterons, depolarization is less of a problem[1] because the deuteron has a much more favorable g-factor than the proton.

In all sources of polarized ions, one first produces (or selects) neutral atoms which are polarized in electron spin. Below, we will first discuss those types of sources which use a beam of *thermal* polarized hydrogen atoms. We will summarize progress made in the preparation of the atomic beam and the methods used to convert the neutral atoms to polarized ions. The second type of source to be discussed is based on *fast* (keV) polarized hydrogen atoms. Conversion to negative ions is very simple because one only needs to pass the fast atoms through a suitable charge exchange medium (gas or vapor). However, the production of the polarized atoms is more difficult in this case. We will particularly discuss the proposal to employ polarized alkali vapor to form a beam of polarized fast H atoms, where the polarized alkali atoms are produced either by an atomic beam apparatus or by optical pumping. Discussion of possibilities for future developments of either type of ion source seems particularly appropriate at this time, because no change in polarized H^- source output has been achieved since the last Symposium two years ago, yet a new generation of polarized H^- sources for high energy physics will be needed in the next few years.

Since space in the proceedings of this symposium is rather limited, I omit a detailed introduction about the basic principles of atomic beam sources and Lamb-shift sources, and refer the reader to my paper[2] in the proceedings of the preceding Symposium. Only in the case of the alkali charge-exchange sources will more detailed background be presented.

2. NEGATIVE POLARIZED IONS FROM THERMAL POLARIZED ATOMS

The system common to sources of this type is the atomic beam apparatus which produces the polarized beam of thermal atoms by separation of magnetic substates in an inhomogeneous magnetic field. After the separation magnet, two hyperfine states of the H atoms remain in the atomic beam: half of the atoms are in hyperfine state 1 with proton spin projection $m_I = + 1/2$, the other half in state 2, which, in a "strong" field ($B >> B_C = 50.7$ mT) has $M_I = - 1/2$ (see ref. 2). In order to obtain nuclear polarization +1 or -1, the atomic beam passes through RF transition units and then into a strong homogeneous magnetic field (typically 0.15 T or above). Ionization takes place inside this magnetic field, which is provided by a solenoid.

2.1. Atomic Beam Improvements

DISCLAIMER

No fundamentally new ideas have been introduced in the last two years but I should like to report on some of the recent work at Bonn[3] because it illustrates the type of systematic and quantitative work that is required to advance ion source development. Earlier work of the same nature was done by the CERN-ANAC collaboration[4] and the group at the ZGS[5]. The atomic-beam apparatus designed at Bonn is shown in fig. 1. The source is pumped entirely by cryopumps and one turbomolecular pump. Recombination of H-atoms on the surface of the cryopumps might be thought to lead to an intolerable thermal load of the pumps, but as soon as the cold surface is coated with a layer of H_2, the surface has a reflection coefficient ~ 1 for atomic hydrogen. The

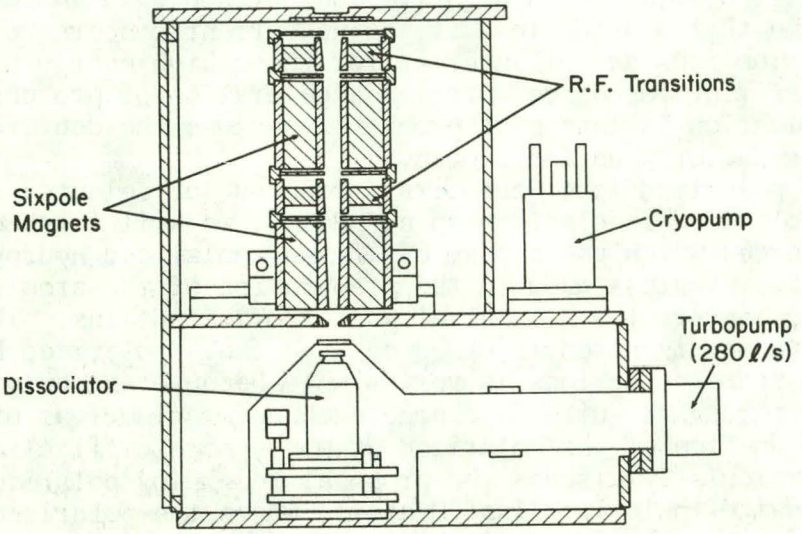

Fig. 1. The atomic-beam source used at Bonn (ref. 3). The position of the dissociator is adjustable. Two cryopumps of 9000 lbs. for H_2 are used to evacuate the second atomic-beam stage and the magnet chamber. The sixpole magnets are 16 cm long.

study of Mathews[3] concerned two areas: determine (1) how can one best produce an intense atomic beam of relatively low velocity and (2) how the separation magnet must be dimensioned to transport the beam most effectively into the rather small acceptance radius of their particular ionizer[6]. The atomic beam density at the center of the ionization volume was measured with a small electron bombardment ionizer, i.e. bombardment of the atomic beam by an electron beam of known current density. The resulting ions formed in a known interaction volume were extracted and passed through a mass analyzer. In this way the density of atomic and molecular hydrogen could be measured separately. The atomic beam was modulated with a chopper to eliminate the signal from background gas by lock-in methods and to permit time-of-flight measurements.

An atomic beam of low velocity is advantageous because the acceptance solid angle of the six pole magnet (spin separation magnet) increases with decreasing average velocity of the beam. In addition, a small velocity spread (supersonic flow) allows for more efficient transport of atoms into the ionization volume because of reduced chromatic aberration. There have been repeated reports that cooling the entire dissociator or cooling only the exit nozzle increases the output of polarized-ion sources (see e.g. ref. 7). The present trend is toward cooling the nozzle only. Two recent designs are shown in fig. 2. The Bonn design (left) uses a copper nozzle cooled to 77 K (ref. 3). Several coatings of the Cu canal were studied for recombination.

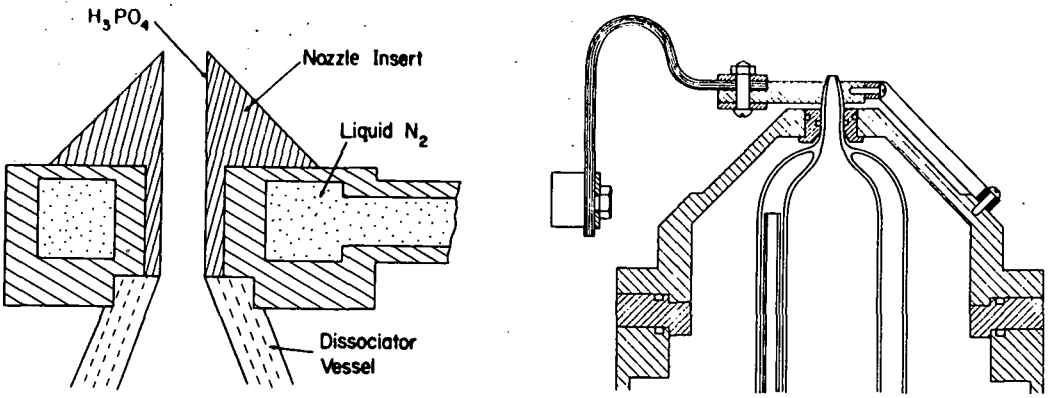

Fig. 2. Cooled dissociator nozzles. On the left the liquid N_2 cooled nozzle used for DC operation at Bonn (ref. 3). On the right, the nozzle used at ZGS for pulsed operation of the discharge. Cooling to 30 K is via a flexible copper strap (ref. 5).

Best results were obtained with H_3PO_4 treatment [degree of dissociation in beam of (80±2) %]. At the ZGS, for pulsed operation of the discharge, the glass nozzle of the dissociator is cooled by contact with a copper block which was cooled with a closed cycle He refrigerator (fig. 2, right). Cooling the copper block to 28 K increased the beam by a factor 2.5 (ref. 5). Earlier measurements[4] of the velocity distribution at CERN had shown that the atomic beam is slightly supersonic. The most probable velocity of the beam at Bonn[3] is about the same as for the cooled microwave dissociator at CERN (~ 1500 m/sec) but the Mach number is reported to be somewhat higher (2.0±0.3).

Measurements of the velocity distribution in the atomic beam are important in order to optimize the geometry of the separation magnet by ray tracing calculations. Most new sources use the magnet design proposed by Glavish[8]: a second sixpole magnet ("compressor magnet") is employed as an achromatic lens to increase the atomic-beam *density* in the ionization volume. Fig. 3 shows calculated trajectories[3] of atoms in the Bonn magnet system to illustrate the achromatic focussing of the beam into the ionization volume. A very flexible way to match the field configuration to the dissociator characteristics and to the ionizer acceptance is provided by a new commercial atomic beam source which employs four short separate sixpole magnets with separate power supplies (see fig. 1 of ref. 7). A further degree of freedom is provided by the possibility of combining four-pole and six-pole magnets.[9]

The measurements of ref. 3 suggest that with a cooled dissociator and a well-matched separation magnet one can obtain in D.C. operation an average $\vec{H}^0$ density of 2.5×10^{11} cm^{-3} in an ionization volume of 1 cm diameter and 20 cm length. For applications requiring a pulsed beam of low duty factor, further studies of pulsed and cooled dissociators would seem interesting. An interesting departure from the conventional design is the atomic-beam source built at Dubna[11] which uses a superconducting separation magnet. We also note that the recent achievement[12] of storing polarized atomic hydrogen gas of densities greater than 10^{16} cm^{-3} for periods of minutes may open new avenues to the production of polarized beams.

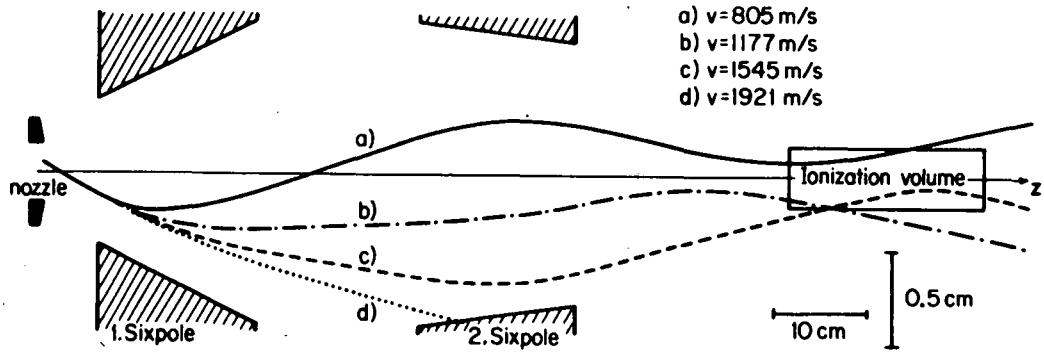

Fig. 3. Atomic beam apparatus with achromatic focussing. The curvature of the trajectories near the ionization volume arises because a very strong ionizer solenoid field (7.5 T) was assumed. The figure is from ref. 3.

2.2. Ionization by Electron Bombardment

The conventional way to ionize the thermal H^0 atoms is by electron bombardment: $\vec{H}^0 + e \rightarrow \vec{H}^+ + e + e$. Negative ions are subsequently produced by accelerating the H^+ beam a few keV and passing the beam through an alkali vapor (usually Na), where H^- is formed by sequential pickup of two electrons. To avoid depolarization of the proton by the hyperfine interaction the charge exchange takes place in a strong magnetic field ($B \gg 50.7$ mT).

At the preceding Symposium I mentioned two efficient new ionizers. The one developed at Bonn[6] is referred to as the Penning-Ionizer because it operates with a self-sustained discharge in a very strong magnetic field [7.5 T superconducting solenoid]. This ionizer has been tested further with the new Bonn atomic beam source and has produced H^+ beam currents as high as 160 μA, of which 35 μA are within the acceptance of the cyclotron (16 π mm mrad $MeV^{\frac{1}{2}}$). The relatively poor emittance is connected with the very large magnetic field which the ionizer requires. The other ionizer was developed jointly between CERN and ANAC and is sometimes referred to as the Super-Ionizer. It operates by confining a plasma discharge, supported by electrons from a filament, in a magnetic field of modest strength (0.15 T). The solenoid is wound as a number of separate pancakes so that the field along the solenoid axis can be contoured. A commercial ionizer of this type[13] has been in routine operation at the SIN injector cyclotron for more than a year. Also there is available operating experience at the ANAC plant, where a DC beam of 80 μA was observed. For a description of this ionizer, see ref. 15. In a contribution[14] to this symposium, Schmelzbach et al. from ETH-Zürich report a good-emittance beam in excess of 100 μA from a similar home-built ionizer. In none of the tests of the "super-ionizers" was the dissociator cooled. I conclude that these ionizers are superior to the Penning ionizer and that peak polarized H^+ currents of 200 μA (DC) and 400 μA (pulsed) are feasible if the best current techniques are combined. For pulsed beams the above estimate is supported by the measurements of ZGS where, with the old *short* ionizer, 100 μA (pulsed) are obtained.[5]

Experience at several nuclear physics laboratories indicates that in practice about 5% of the polarized H^+ beam can be converted to $\vec{H}^-$ by charge exchange in Na vapor at ~ 5 keV. At ETH-Zürich a $\vec{H}^-$ beam of up to 3 μA has been obtained, as described in a contribution to this symposium.[14] I es-

timate that 10 μA (DC) and 20 μA (pulsed) of polarized H^- can be obtained by application of the best current techniques.

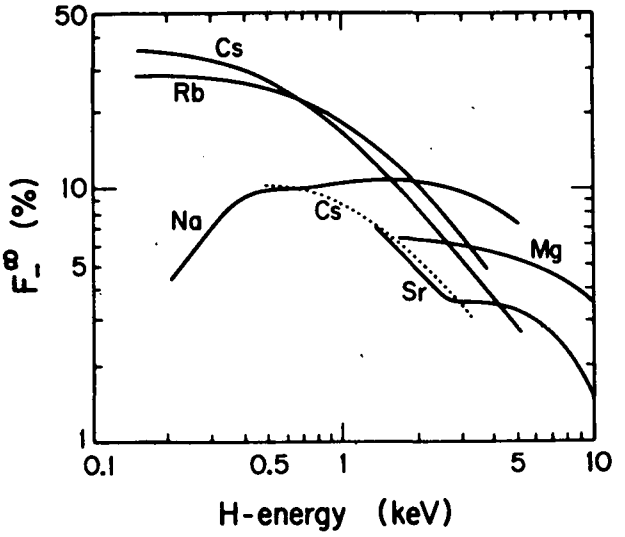

Fig. 4. Equilibrium negative ion yield in alkali vapors (from ref. 16). The dotted line for Cs is from ref. 17.

Whether the present charge exchange efficiency of 5% can be increased substantially is not clear. Fig. 4 shows a summary of equilibrium negative fractions F_-^∞ for different donors. The curves represent new measurements at the Berkeley Fusion Research Division[16]. Recent measurements still show large discrepancies, as illustrated in Fig. 4 by another measurement[17] for Cs. It should be pointed out that in practice the negative ion yields will be less than F_-^∞ because of beam loss by scattering, because it is not always practical to work with a very thick vapor cell, and because beams of very low energy are difficult to handle. Nevertheless it is conceivable that a factor two might be gained by redesigning charge-exchange cells and decel-accel systems.

2.3 Ionization by Colliding Beams

The colliding-beam principle[18] has the advantage of converting the polarized $\vec{H}^0$ atoms directly to $\vec{H}^-$ without going through positive ions as an intermediate step. The idea is to bombard the $\vec{H}^0$ atomic beam with a beam of fast atoms or ions such as Cs^0 or D^- (see refs. 2,18).

Two years ago I described a test set-up which produced 3 μA of polarized H^-, employing charge transfer from Cs^0 (40 keV) to H^0. Since the nuclear physics research program on our tandem accelerator required immediate replacement for our anemic Lamb-shift source, we constructed a better engineered version of the colliding beam source in collaboration with ANAC, without spending time on further improvements of the output current. The ionizer of the new source is shown in fig. 5. The Cs gun and electrode system is gimbel mounted such that the Cs beam can be aimed along the atomic-beam axis. The insulators are placed away from the Cs beam and are shielded to avoid discharges along insulator surfaces. The source, which is described in more detail in ref. 19, has been used for nuclear physics experiments for more than a year. Beam currents up to 3.3 μA have been observed, but most of our present experiments use about 1 μA. So far the demand for beam time has prevented a systematic program of source improvements. Contrary to statements made in a recent review paper[20] the beam polarization of the colliding-beam source is[21], and always has been[22], higher than for any other source of H^- or D^- ions [(91±1) % proton polarization, measured after acceleration, for ionization of atoms in a 0.1 T field]. 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. It is easy to extract and neutralize 12 mA of Cs beam, but of this current only 2-3 mA passes through the collimator

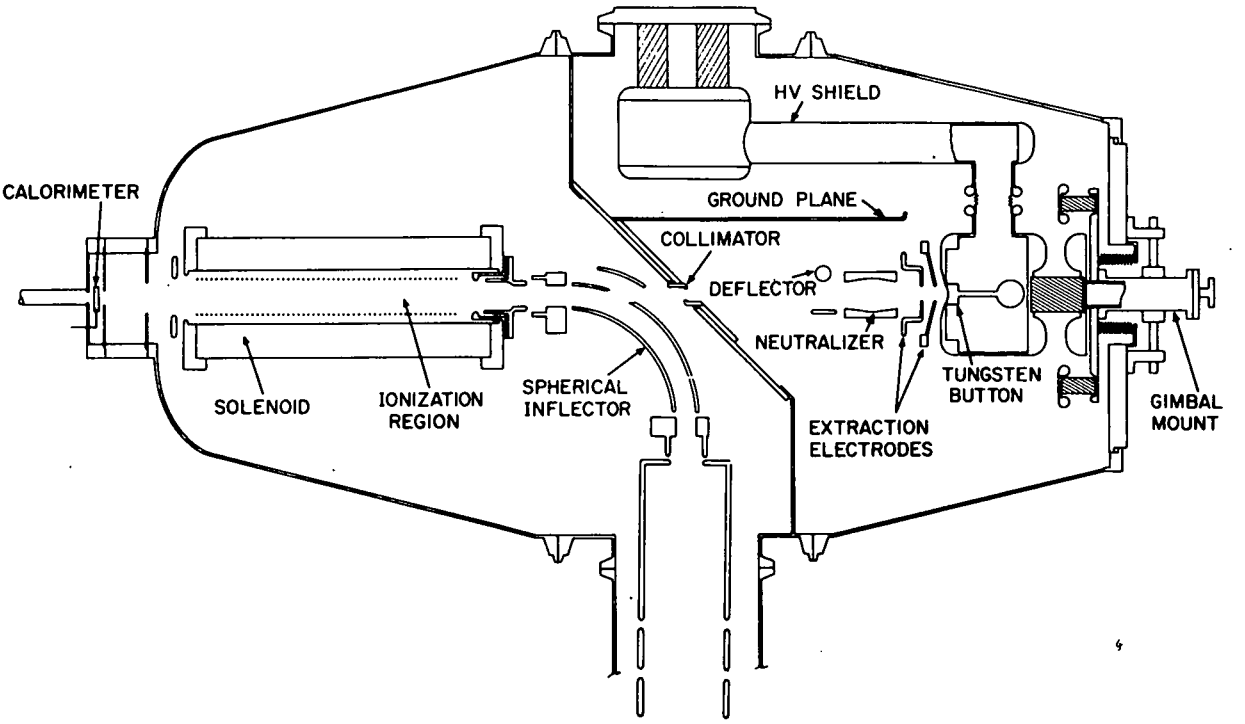

Fig. 5. Colliding-beam source for polarized negative ions. The atomic-beam enters from the left. The atomic beam source is not shown. From ref. 21.

and the 1 cm diameter calorimeter aperture.

It is disappointing that during the last two years no additional development work has been done on this promising method. Primarily we need a systematic development program for the Cs beam. It has been pointed out[23] that the problem here is similar to the production of well collimated intense beams for ion implantation, where magnetic focussing is used to transport space-charge neutralized positive ion beams of the order 20 mA/cm^2.

Experience indicates that the H^- output can be predicted reliably if the Cs current density and the atomic beam intensity and velocity are known. The measured H^- current used to be rather higher[2] than expected from the $H^0 + Cs^0$ charge exchange cross section, but newer measurements [see ref. 16] suggest that the cross section may be considerably larger than had been assumed in ref. 2. Taking into account the larger cross section and the increase in atomic beam density mentioned in sect. 2.1, one now can expect for a Cs^0 beam of ~ 40-100 keV a polarized H^- beam current (DC) of about

$$I = 5\ \mu A\ H^-\ \text{per}\ mA/cm^2\ Cs^0.$$

Since the two colliding beams are neutral, the H^- beam scales accurately with Cs^0 beam. Thus a well collimated 20 mA/cm^2 Cs beam will yield polarized H^- beams (DC) of about 100 μA. For pulsed operation, peak currents of 200 μA and conservative operation at 100 μA can be expected under these conditions. Thus, serious development work on a suitable Cs source promises to be very rewarding.

In spite of the fact that intense unpolarized D^- sources are being run

routinely for plasma beam heating experiments, no results are available on production of polarized H^- by $\vec{H}^0 + \vec{D}^- \rightarrow \vec{H}^- + D^0$. For a modern atomic beam source this reaction should yield a DC current of

$$I = 15\ \mu A\ H^-\ \text{per}\ mA/cm^2\ D^-$$

assuming a D^- energy of 2 keV. Pulsed D^- and H^- sources provide well above 100 mA beam with sufficiently good emittance to allow deceleration to 2 keV. Very intense polarized beams might be achieved by this method, but attention has to be paid to space charge problems (see ref. 2).

2.4 Surface Ionization

It is well known that intense polarized Li^+ beams can be produced by surface ionization of a polarized Li atomic beam on an oxidized hot W surface[24]. This ionization method has the advantage of great simplicity and very high efficiency. Similarly, *negative* ions may be formed when an atom strikes a surface, provided the work function of the surface 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[22]. As far as I know the highest value of F_- observed so far ($F_- \simeq 10^{-5}$) was obtained with a tantalum foil coated with a barium/strontium oxide mixture[23] (surface temperature 1200 K). An efficiency $F_- \simeq 10^{-2}$ is required to produce 30 μA H^- by ionization of H^0 atoms from an atomic beam source.

3. NEGATIVE POLARIZED IONS FROM FAST POLARIZED ATOMS

The attraction of this method lies in the ease with which a fast (keV) polarized H^0 beam can be ionized. The ionizer in this case simply consists of a suitable gas or vapor cell that converts $\vec{H}^0$ to $\vec{H}^-$ 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^0 atom.

One ion source of this type is the Lamb-shift source which operates with a 0.5 keV beam of H^- atoms in the 2S metastable state. Polarization is achieved by inducing decay to the ground state for some of the H(2S) hyperfine components but not for others. Ionization to $\vec{H}^-$ is achieved through charge exchange in Ar gas.

The other ion source of this type is based on the possibility to produce a fast polarized H^0 beam by pickup of polarized electrons: $H^+ + \vec{e} \rightarrow \vec{H}^0$. The basic idea is very old. In 1957, Zavoriskii[24] proposed to use a magnetized ferromagnetic foil as the polarized-electron donor. This method has been tried but has not lead to a practical source. In 1965 I proposed[28] that certain problems might be eliminated if the ferromagnetic foil were replaced, for instance, by an optically pumped alkali vapor. This idea has only recently met serious interest because intense DW dye lasers at wave lengths suitable for pumping Na or Rb are now commercially available.

3.1 Lamb-Shift Sources

This is by far the most common polarized H^- and D^- ion source. It is in use not only at a large number of low-energy nuclear physics installations,

but also at LAMPF and TRIUMF. Nevertheless I will not discuss this type of source because it will not be the high-intensity source of the future. Slight improvements in beam intensity are still being achieved, often at the expense of polarization. At Giessen[29] it was found that the beam current could be increased up to 1.6 μA (P = 0.65) by careful adjustment of the duoplasmatron emission aperture. The basic limitation of this type of source is thought to be quenching of the metastable beam by the electric field of the charged component in the beam, but the problem has not been studied quantitatively. Despite a number of excellent development programs, the best beam from this type of sourse has remained near 1 μA for some time.

3.2 Pick-up of Polarized Electrons in Polarized Alkali Vapor

Zavoiskii[24] proposed that a *fast* polarized beam of H^0 atoms can be produced by passing protons through a magnetized ferromagnetic foil, where they pick up polarized electrons. The beam of fast H^0 is subsequently ionized by charge exchange in a second foil or in a vapor. Later, I proposed 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. These ideas have recently met serious interest primarily because of a paper by Anderson[30] 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[31] recently constructed a prototype polarized H^- source in which an atomic beam apparatus produced the polarized Na atoms.

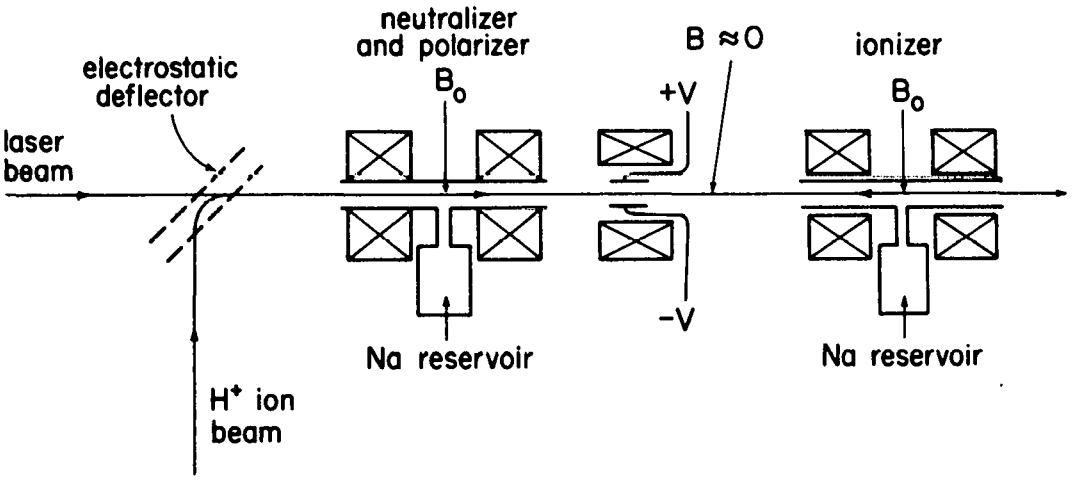

Fig. 6. Production of polarized negative ions by pickup of polarized electrons in optically pumped alkali vapor (from ref. 30).

To discuss this type of source, we use the schematic diagram from Anderson's paper (fig. 6). The protons of a few keV energy first pass through a 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 "strong" magnetic fields ($B_0 >> 50.7$ mT). 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 but has no nuclear polariza-

tion as long as the atoms are in a strong field (equal population of states 1 and 2). For *fast* H^0 atoms, the adiabatic RF transitions employed in thermal atomic beam sources can not be used, but instead a very simple configuration of *static* magnetic fields (sudden field reversal, also called Sona-transition, see ref. 2) can be used to obtain, ideally, complete proton polarization if ionization takes place in a "strong" magnetic field. This method is often used in Lamb-shift sources. The application to a $\vec{H}^0$ beam of several keV energy should present no problem. In fig. 6, the sudden field reversal takes place at the point labeled $B \approx 0$ in the region between the two vapor cells.

The alkali vapor in the first cell (fig. 6) can be polarized by absorption of circularly polarized photons (optical pumping). As an alternative to an optically pumped vapor, a polarized alkali beam from an atomic-beam apparatus can also be used. The second method was studied by Witteveen[31] who used a Na atomic beam apparatus. He obtained 0.02 μA H^- with a polarization of (14±4) %. Under the conditions of his experiment (no sudden transitions, 80% Na polarization) this amounts to (35±10)% of the expected value. An ion source based on the same principle has been constructed at Tsukuba[32] for the KEK synchrotron. A 3-4 mA, 5 keV H^+ beam was collinear with the $\vec{Na}$ beam and ions created along a 25 cm long region were extracted. A current of 3 μA was observed, but the beam polarization is estimated to be at best 30-40%, because of unpolarized background vapor.

There is reason to believe that a higher polarized-alkali target density can be achieved with optical pumping than with an atomic-beam apparatus. The current interest in optical pumping arises from the following simple consideration taken from ref. 30. A 1 W laser will yield about 3×10^{18} circularly polarized photons/sec. If half of them are absorbed, one can polarize $\sim 10^{18}$ Na atoms/sec. If the Na is contained in a circular 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 $\sim 10^{13}$ atoms. Some polarized atoms will be lost through the ends of the tube, but this is a minor perturbation. A proton passing through the tube will see a target thickness of 10^{13} Na atoms/cm^2. The corresponding number for a polarized Na atomic beam is $\sim 10^{12}$ atoms/cm^2 for an interaction region of 20 cm length[32]. 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 H^+ beam will emerge from the optically pumped cell as $\vec{H}^0$. If we assume that 5% of this $\vec{H}^0$ beam can be converted to H^- in the second charge exchange cell, one expects an overall conversion efficiency from $\vec{H}^+$ to $\vec{H}^-$ of 3×10^{-3}, i.e.

3 μA 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 is not enough information at present to make a reliable assessment of the proposed scheme. There is no doubt that alkali vapors can be polarized by optical pumping. A paper submitted to this conference[33] reports on a Na vapor target of thickness 3×10^{12} atoms/cm^2 polarized to 70% by light from a 1 W dye laser. The most serious uncertainty of the proposed scheme is the attainable degree of proton polarization. Even if the alkali atoms are completely polarized in electron spin, the resulting H^- beam will

not necessarily have very high nuclear polarization. The problem is that the capture $H^+ + \vec{Na} \rightarrow \vec{H}^O$ leads primarily to states in the H^O atom with principal quantum number n=2 and higher. When these atoms decay to the ground state, the radiation carries away angular momentum so that part of the polarization is lost. The final polarization is calculated to be[30] 11/27 or 40.7% of the initial electron polarization. For states with n>2 the polarization is expected to be less. It is interesting to note that the polarization measured in Witteveen's experiment[31] is entirely consistent with this depolarization mechanism, although he assigned the low polarization to other causes.

The preferential pickup into n>2 states arises from the general property of charge exchange reactions, that the cross section σ_{+o} is large if the energy defect, i.e. the Q-value, is small (near-resonant $^{+o}$ charge exchange). In fact, the cross section is large for electron pickup of H^+ in alkalis precisely *because* the energy defect is only ~ 1 eV for n=2, compared to nearly -10 eV for n=1. Of course $H^+ + H^O$ is resonant for n=1, but there are no lasers to pump H^O. The loss in polarization can presumably be avoided by applying to the vapor cell a magnetic field strong enough to decouple L and S (ref. 30). The critical field in this case is 0.35 T, so that a magnetic field of B ~ 1 T would have to be applied to the first vapor cell. The presence of this field creates obvious problems from emittance degradation when the low energy beam passes through the fringe field of the 1 T solenoid.

The required laser power depends on the thickness of the Na vapor target and on the magnetic field. If one needs to decouple L and S, the required laser band width is larger (~ 40 GHz) and so is the required power. A 2 W dye laser should yield a target thickness of $10^{13}/cm^2$ with 84% polarization, while 6 W of dye laser power should give 3×10^{13} cm^2 Na atoms of P_e = 97%. This might be accomplished by combining the light from six commercial 1 W dye lasers, which are pumped in turn by two 20W Ar ion lasers[30]. The required power is reduced, of course, if the atoms do not depolarize upon colliding with the wall. Suitable wall coatings can possibly be found. A natural limit to the target thickness is set by imprisonment of resonance radiation. Anderson estimates that this problem becomes serious for a target thickness above $5 \times 10^{13}/cm^2$, but measurements are needed to determine the operational limit.

There is no question that optically pumped alkali vapors can be used to produce a polarized H^- beam but the limitations on beam polarization and beam intensity are not clear. Neither the fundamental physics of the atomic processes which limit the beam polarization, nor the practical problem of running a number of advanced lasers and solving the ion-optic problems have been studied sufficiently to make reasonable predictions about source performance. It is safe to say, however, that the problems arising in this type of source are technically no less demanding than the problems in other high intensity sources of H^- ions.

4. CONCLUSIONS

In two laboratories, a 3 μA DC beam of highly-polarized H^- ions has been obtained. Both sources are based on ionization of a thermal atomic hydrogen beam. In one case, the colliding beam principle is used in which H^O is converted directly to H^- by bombardment of the H^O beam with fast Cs^O atoms, in the other case some 100 μA polarized H^+ is produced first by electron bombardment, followed by charge exchange of H^+ to H^- in Na vapor. Experience

at other laboratories shows that the beam from atomic beam sources gains a factor 1.5-2 from pulsing and a factor 2-3 from cooling of the nozzle. Some additional gain is expected from careful matching of the separation magnet to the observed velocity distribution of the beam and from minor ionizer improvements. I conclude that the combination of the best *currently established* techniques will allow pulsed H^- currents of 20 μA from either type of source and that reliable long-term operation in an accelerator environment at the 10 μA level can be achieved.

What developments should be pursued to increase the beam intensity by another order of magnitude beyond these levels? For the electron-bombardment source, further improvements might be gained by improving the present ~ 3% efficiency of the ionizer but the present ionizers already are highly developed devices and at some point one will start running out of atoms to ionize. By comparison, a much larger gain can in principle be expected for colliding beam sources, because already a current density of 20 mA/cm^2 Cs^o would produce a ten-fold increase to yield above 100 μA of polarized H^- beam. Since the collision partners are neutral one is only concerned with the space charge of the extracted beam. Whether or not the optically pumped alkali source is capable of large polarization remains to be seen. We should remember that a loss in polarization of a factor 2 is equivalent to a factor 4 in beam intensity. The published estimates of beam currents for this source are as high as 120 μA, assuming a Na target thickness near the limit imposed by imprisonment of radiation. Furthermore, we should be careful not to compare beam current estimates based on calculations alone with beam current estimates based on improvements of existing sources.

I am confident that pulsed polarized H^- beam currents of 100 μA can be obtained. What is required, more than rapid construction of ambitious sources, is a systematic approach to source development based on quantitative diagnostic methods on one hand, and simple feasibility tests of new ideas on the other.

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