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PROGRESS IN THE ART OF PRODUCING POLARIZED IONS

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1. Introduction

The purpose of this paper is to give a short review of the progress that has been made during the last two years in the design and construction of polarized-ion sources, and to summarize current research efforts on new types of ion sources. This report is based largely on the papers given at two very recent international symposia, one on "Polarization Phenomena in Nuclear Physics" at Santa Fe (August 1980), the other on "Polarized Beams and Polarized Targets in High Energy Physics" in Lausanne, Switzerland (November 1980). My presentation here will omit a detailed introduction about the basic principles of polarized ion sources based on the atomic-beam principle and on the Lamb-shift. This background material can be found in several review papers, some of which discuss the physical principles in detail.[1]

In the following discussion, the emphasis is on the production of polarized *negative* ions, but positive ions are mentioned because in the conventional atomic-beam ion source, negative ions are obtained by charge exchange of a positive polarized beam. While originally beams of polarized negative ions were developed for tandem accelerators, negative ions have important advantages also for synchrotrons and cyclotrons, because the stripping of H^- to H^+ in a thin foil can be used either for multiturn injection or for ease in extraction.

2. The Conventional Atomic Beam Polarized-Ion Source

The source of the atoms is a RF discharge tube (for H_2 or D_2) or an oven (for alkali atoms). Atoms emerging from the source aperture are collimated and passed through an inhomogeneous magnetic field ("separation magnet", usually a six-pole magnet). In this way only atoms of one electron spin projection ($m_J = 1/2$) are retained in the beam. Nuclear vector or tensor polarization of either sign is obtained by passing the beam of atoms through a set of RF transition units. Typically, about 10^{16} polarized atoms/sec can be produced.

Polarized beams of protons or deuterons are produced by electron bombardment of the atomic beam. A magnetic field of some 1-2 kG is required to decouple nuclear and electronic spin. All current ionizers are based on the electron-bombardment ionizer designed by Glavish et al.[2] but through the years the ionization efficiency has seen continuous improvement (see ref. 3). The present best ionizer is a new type of Glavish-ionizer, developed three years ago jointly between ANAC and CERN. It uses a plasma-discharge, supported by electrons from a filament, inside a solenoid of ~ 40 cm length. The solenoid is wound as a number of separate pancakes so that the field can be contoured. Experiences by Grüebler et al.[4] with a similar home-built ionizer indicates that a DC beam of 100 μA $\vec{H}^+$ or $\vec{D}^+$ can be produced. Similarly, at the ANAC plant, 80 μA $\vec{H}^+$ was readily obtained[5] in a recent routine test of an ionizer prior to shipment.

There is promise that further increases in beam can be obtained from improvements of the atomic-beam apparatus. The ionization efficiency of the ionizer increases with decreasing velocity of the atomic beam, because slower atoms spend more time in the ionizer and thus have a greater chance of being ionized. Recent studies[6,7] suggest that the ion-beam intensity can be approximately doubled by cooling the exit nozzle of the dissociator. Additional gains may be possible by careful shaping of the magnetic field gradients in the separation magnet along the atomic beam trajectory. Initially, the field shaping consisted simply of using a taper on the aperture of the six-pole magnet. Later, the use of a separate second sixpole magnet was proposed[8] to reduce chromatic aberrations ("compressor magnet"). Recently, Mathews[7] described a new atomic-beam apparatus in which the magnet location and taper is specifically adjusted to fit the velocity spectrum of their cooled dissociator. The other novelty of this atomic-beam source is that it is pumped entirely by clean pumps [one turbo pump, two cryopumps]. It is highly probable that about 200 μA $\vec{H}^{+}$ or $\vec{D}^{+}$ can be obtained if one applies the best currently known design criteria.

While the best ionizers for $\vec{H}^{o}$ and $\vec{D}^{o}$ have an ionization efficiency of a few percent, polarized alkali atoms ($\vec{Li}$, $\vec{Na}$) can be almost completely ionized by surface ionization on oxydized tungsten, heated to ~ 1800 K. If the atoms stick to the surface for more than a millisecond or so, they tend to depolarize. This can largely be avoided by operating the ionizer at sufficiently high temperature.[9] Polarized alkali sources based on this principle have been developed at Hamburg and Heidelberg for use on the Heidelberg tandem.[10]

Once a beam of polarized *positive* hydrogen- or alkali-ions is obtained, it can be converted to negative ions in the usual way, i.e. charge exchange in an alkali vapor. Again, a magnetic field needs to be applied, in this case to avoid depolarization during the short time when the positive ion has turned into a neutral atom, but not yet into a negative ion. For hydrogen ions the most successful charge exchange vapor is Na, for which one expects a negative ion yield of about 10% at energies of a few keV. In practice the yield is reduced by the finite aperture of the vapor cell and by scattering in the cell. At ETH, Zürich, a $\vec{H}^{-}$ beam intensity of 3 μA has been achieved by this method.[4] The development of polarized Li^{-} and Na^{-} at Heidelberg has resulted in a beam intensity of 0.1-0.15 μA.

3. Production of Negative Ions by Colliding Beams

In 1968 I proposed a new way to transform $\vec{H}^{o}$ into $\vec{H}^{-}$ without going through $\vec{H}^{+}$ as an intermediate step.[11] The idea is to bombard the $\vec{H}^{o}$ atomic beam with a beam of Cs^{o} atoms or H^{-} (or D^{-}) ions: $\vec{H}^{o} + Cs^{o} \rightarrow \vec{H}^{-} + Cs^{+}$, or $\vec{H}^{o} + H^{-} \rightarrow \vec{H}^{-} + H^{o}$. Typically, for the first process, the Cs^{o} energy should be ~ 20-100 keV, while for the second process the increase of the cross section to low energies favors as low a H^{-} beam energy as possible, say 1 keV or so. The resulting $\vec{H}^{-}$ can readily be distinguished from the incident H^{-} by the difference in energy, but of course D^{-} can be used as the electron donor just as well.

This type of ion source is still in its infancy. A $\vec{H}^{-}$, $\vec{D}^{-}$ source based on charge transfer from a 40 keV Cs^0 beam is in operation on the Wisconsin tandem. An $\vec{H}^-$ and $\vec{D}^-$ beam current of 3 μA has been obtained[12] using a Cs^0 beam of 2-3 mA. The polarization of the beam is very high, due to the fortunate circumstance that bombardment of background gas (including H_2) by Cs^0 produces very few H^- ions. For ionization of $\vec{H}^0$ in a magnetic field of 1 kG, the measured proton polarization after acceleration is (91±1)%, compared to a theoretically expected maximum polarization for this particular magnetic field of 94.6%.

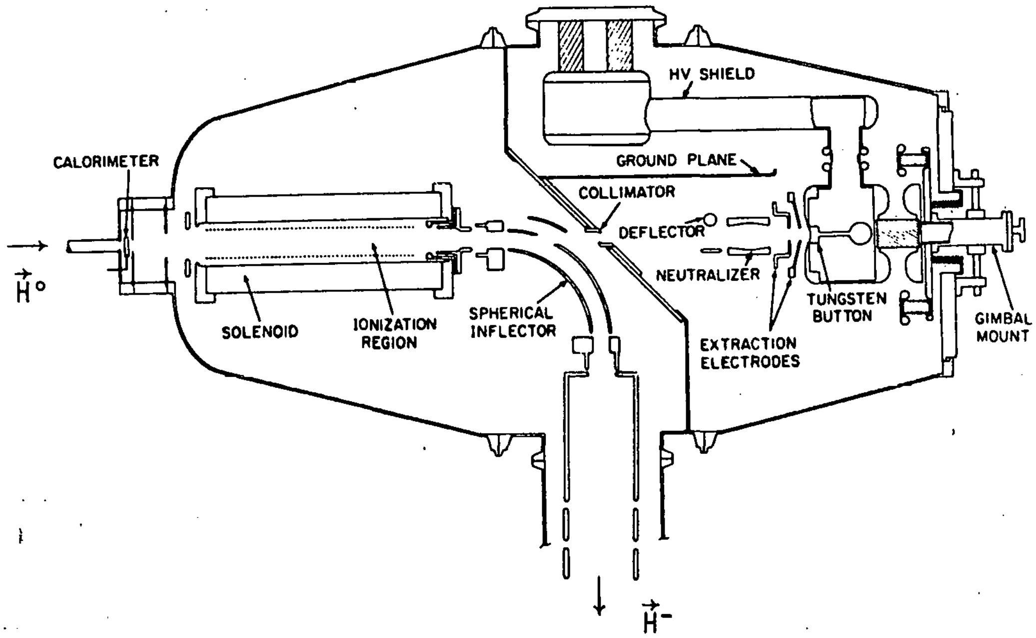

Fig. 1. Colliding-beam source for polarized negative ions. The atomic-beam apparatus is not shown.

Part of the Wisconsin source is shown in Fig. 1. The atomic-beam source and RF transitions are not shown. The calorimeter can be inserted to measure the intensity of the Cs^0 beam. The right-hand compartment contains the Cs^0 source, where Cs vapor is ionized by a hot porous tungsten disk. The Cs^+ beam is accelerated to 40 keV and is then neutralized to 95% in a Cs vapor cell. The remaining Cs^+ beam is deflected out of the way. The output of the source is limited at the moment by the relatively poor focus of the Cs beam, which leads to excessive loading of the electrodes in the ionizer if the Cs beam is increased too far. Since we have neither remote controls for the source nor tandem operators, the experimenters tend not to push the source to high intensity. All we know for certain is that 3.0 μA H^- and D^- can be obtained and that the source runs essentially unattended for 3-5 day runs at the 1 μA level. Construction of a cesium beam test bench is planned to further improve this source. A commercial source[13] based on this principle has a design aim of 10 μA. To reach the design aim will require substantial improvement in the focussing of the Cs gun or the addition of a magnetic focussing element.

The colliding-beam principle is applicable also to the production of alkali heavy ions and ions of other atoms which can be polarized by Stern-Gerlach separation. No experimental work has been done and only a few of the relevant cross sections are known. The cross section for $\vec{Li} + Cs^o \rightarrow \vec{Li}^- + Cs^+$ is largest for a Cs^o energy of about 100 keV where $\sigma \sim 3\times10^{-16}$ cm^2. A colliding-beam source using a polarized Li atomic beam[14] of 1×10^{16} atoms/sec ($v \gtrsim 1700$ m/sec) and 3 mA/cm^2 Cs^o beam would be expected to yield about 1 μA $\vec{Li}^-$ for a 30 cm long ionization region. In view of the fact that the Wisconsin colliding beam source produces the predicted H^- intensity[2], it is likely that this would be the case for operation with Li as well. Nevertheless, it is certainly possible that as much or even more beam could be obtained with the Heidelberg-type source. Even if it should turn out that the colliding beam method for heavy ions does not surpass other schemes for beam intensity, this would seem an attractive method for laboratories requiring both H^- and heavy ion beams since one would only need to replace the dissociator (for H_2) with an oven (for the alkali atoms) to switch from one ion species to the other.

4. Lamb Shift Sources

The Lamb-shift source is not only the most common source of polarized hydrogen ions on tandem accelerators, but is used also to provide polarized proton beams at two medium-energy facilities (TRIUMF,LAMPF). It appears that this type of source is approaching the end of its development as far as beam intensity is concerned. The figure of merit ($P^2 \times$ intensity) has seen no substantial improvement for some time, in spite of several high-quality development programs. While the Lamb-shift source does not provide the highest available beam intensity, it has important advantages. It is at present the only practical source for polarized tritium ions. Another advantage is that deuterium ions can be prepared in single hyperfine states, yielding a tensor polarization $P_{zz} = -2$. It should be noted, however, that this is possible also with atomic-beam sources, if one induces transitions *between* separate sections of the six-pole magnet.

5. Sources Based on Optically Pumped Alkali Vapor

In this section I want to comment briefly on the present state of sources which use optically pumped alkali vapors. We must distinguish clearly between two different types of applications: (a) for sources of polarized Li, Na etc. ions, optical pumping can replace the six-pole separation magnet employed in the conventional atomic-beam source, (b) for sources of polarized hydrogen ions, a beam of unpolarized protons (e.g. 5 keV energy) can be passed through an optically pumped alkali vapor cell. The protons pick up polarized electrons to form a beam of fast (5 keV) $\vec{H}^o$ atoms. These are then ionized to H^+ or H^- in a second charge exchange cell.

(a) The production of a polarized alkali beam by optical pumping has been discussed by Anderson[15]. In its simplest form, the source would consist of an oven containing, for instance, Li or Na. The atomic beam emerging from a small aperture is illuminated by circularly polarized laser light to excite the ground state atoms, e.g. to various $P_{3/2}$ states. As the atoms travel through the laser beam they decay and get excited again several times. In each absorption process the atoms acquire additional angular momentum until they all are in the state of highest total angular momentum, i.e. the state of highest m_F. Another few cm downstream from the oven the atoms impinge on a surface ionizer, just as in the more conventional alkali polarized-ion source. No complete source based on this principle has been built yet, but experiments have been reported very recently[16,17] which show that ^{6}Li and ^{23}Na atomic beams can be polarized by this method.

The advantages of optical pumping over the more conventional atomic beam method arise primarily from the fact that in the conventional method the solid angle of atoms from the oven is much smaller than is possible with the new scheme. Thus one should obtain much more ion beam intensity, or instead, for the same intensity, one can reduce the flux out of the oven and correspondingly reduce build-up of alkali on apertures etc. Another advantage is the improvement in the degree of polarization resulting from pumping all atoms into a single hyperfine component. It should be pointed out, however, that a similar improvement can be gained in the conventional atomic beam source by placing RF transition units between separate six-pole magnets. There is virtually no question that the optically-pumped polarized alkali source can be made to work. However, one should not assume that this new source is necessarily so cheap and simple that the conventional atomic-beam source is obsolete. It is neither cheap nor simple to set up and operate the required tuneable dye lasers.

(b) The application of optically pumped alkali vapor to produce polarized hydrogen ions was suggested a long time ago. The general principle, illustrated very schematically in Fig. 2, goes back to a suggestion by Zavoiskii[18] to have a proton beam of a few keV energy pick up polarized electrons in a first target (he proposed a magnetized iron foil). In a

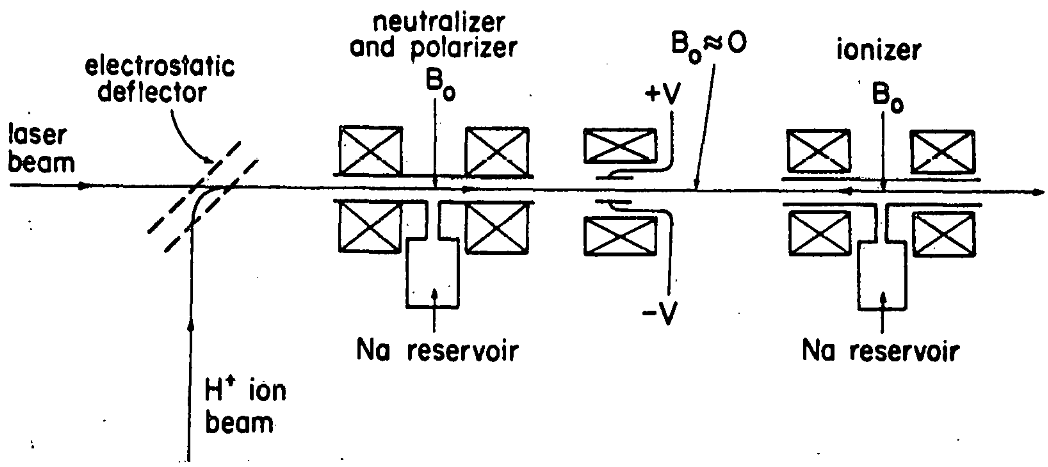

Fig. 2. Proposed production of $\vec{H}^-$ ions by pick-up of polarized electrons in an optically pumped alkali vapor cell [polarizer], followed by charge exchange of the H^o in a second vapor cell [ionizer]. The figure is from ref. 20.

second target the fast polarized $\vec{H}^{0}$ are to be converted to $\vec{H}^{+}$ or $\vec{H}^{-}$. In 1965 I proposed[19] to use as the first target a polarized alkali atomic beam or an optically pumped alkali vapor. Anderson[20] recently discussed this possibility in some detail and showed that considerable $\vec{H}^{-}$ or $\vec{D}^{-}$ intensities might be achieved by this method.

There does not yet exist an operating ion source of this type, but development work is progressing in a number of laboratories. The questions are (i) can one maintain high polarization of the alkali vapor inside a charge exchange tube in spite of depolarization in collisions with the wall? Specifically, how does the polarization of the alkali vapor depend on the intensity of pumping radiation and on the thickness (atoms/cm^2) of the vapor target? (ii) how large is the resulting polarization of the beam, and how does the polarization depend on the magnetic field strength in the optically-pumped cell. Here the question is what fraction of the $\vec{H}^{0}$ is formed in excited states which then lose angular momentum in transitions to the ground state. (iii) what beam intensity can be achieved? This depends in part on the previous question, since depolarization can presumably be avoided by applying a sufficiently strong magnetic field to the vapor cell (~ 10 kG) but this may cause ion-optic problems. Of the above questions, the first has been answered very recently by a group in Japan.[21] They pumped a Na cell with a 1W dye laser and measured the polarization of the Na atoms by deflection in a six-pole magnet. The results show that 70% polarization of the Na vapor is achieved with a density of 3×10^{12} Na atoms/cm^2, in good agreement with Anderson's estimate. The most pressing next problem is to measure the beam polarization. It must be noted that a source of this type, even if all depolarization problems can be overcome, is not particularly suited for tensor-polarized deuterons, because the application of Sona-transitions to ground-state atoms yields a maximum tensor polarization $P_{zz} = 1/3$.

6. Conclusions

Not so many years ago, experimenters had to suffer a big loss in intensity if they wanted to use polarized beams. This has now changed dramatically. One can safely say that $\vec{H}^{+}$ beams of 100 μA and $\vec{H}^{-}$ (or $\vec{D}^{-}$) beams of 3 μA can be expected in routine operation if one designs a source that combines the best presently known technology for the various parts of the source. Until quite recently, a source output of 1.0 μA was a cause for celebration. Now there are available reliable and easy to operate sources which produce above 1 μA source output day after day.

The best current sources make use of the atomic-beam method. Further improvements are very likely, particularly for the colliding-beam method which is still in its infancy. Lamb-shift sources are not likely to compete as far as intensity is concerned, the aficionados claim that the new sources based on optically pumped alkali vapors will yield 100 μA $\vec{H}^{-}$ or more. Whatever the merit of such claims, it should be kept in mind that there is a substantial difference between estimates on paper and operating hardware. It would be a mistake to pursue only this one avenue because of expected large and easy rewards. Other schemes, like the colliding beam source using $\vec{H}^{0}$ + D^{-} should be pursued as well, since the possible rewards in this case are probably even higher. It has been argued that no one can use more than a few μA of beam anyway, so that the interest in even more intense beams may seem misplaced. Nevertheless, it is much more comfortable to work with a source that has a margin of safety. Also, applications to meson factories, to synchrotrons and to "cyclograafs" [cyclotron injecting H^- into a tandem] would make 100 μA $\vec{H}^-$ and $\vec{D}^-$ highly useful.

The most natural application of optically pumped alkali vapor is to the production of polarized alkali ions. Rapid progress has been made in these developments during the last year. Interesting work is also being done in other areas, such as experiments to produce polarized $^3He^-$ ions. The extensive body of interesting new experiments presented at the recent International Symposium on Polarization Phenomena in Nuclear Physics attests to the important role that polarized ion sources now play in nuclear physics.

REFERENCES

1. W. Haeberli, Ann. Rev. Nucl. Sci. 17, 373 (1967).
2. H.F. Glavish, E.R. Collins, B.A. McKinnon, I.J. Walker, Proc. Symp. on Polarization Phenomena of Nucleons (P. Huber and E. Schoepper, eds.) Birkhäuser (Basel) 1966, p. 85.
3. H.F. Glavish, IEEE Trans. Nucl. Sci. 26, 1517 (1979).
4. W. Grüebler and P. Schmelzbach, Proc. Fifth Int. Symp. on Polarization Phenomena in Nuclear Physics (Santa Fe, 1980), to be published: P.A. Schmelzbach, W. Grüebler, V. König and B. Jenny, High Energy Physics with Polarized Beams and Polarized Targets (Lausanne, 1980), contributed paper.
5. H.F. Glavish, (private communication).
6. Y. Wakuta, Y. Koga, H. Hasuyama and H. Yamamoto, Nucl. Instr. Meth. 147, 461 (1977); P.F. Schultz, E.F. Parker and J.J. Madsen, Proc. Fifth Int. Symp. on Polarization Phenomena in Nuclear Physics (Santa Fe, 1980) contributed paper 3.15 (to be published).
7. H.G. Mathews, Ph.D. thesis, University of Bonn (1979).
8. H.F. Glavish, Proc. Fourth Int. Symp. on Polarization Phenomena in Nuclear Reactions (W. Grüebler and V. König, eds.) Birkhäuser (Basel) 1976, p. 844.
9. R. Böttger, B. Bauer, P. Egelhof, K.H. Möbius, Z. Moroz, E. Steffens, G. Tungate, W. Dreves, I. Koenig and D. Fick, Proc. Fifth. Int. Symp. on Polarization Phenomena in Nucl. Phys. (Santa Fe, 1980) paper 3.40, to be published.
10. E. Steffens, Proceedings Fifth Tandem Conference (Catania, Italy, June, 1980); E. Steffens, IEEE Trans. Nucl. Sci. 23, 1145 (1976).
11. W. Haeberli, Nucl. Instr. Meth. 62, 355 (1968).
12. 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, Proc. Fifth Int. Symp. on Polarization Phenomena in Nuclear Physics (Santa Fe, 1980) contributed paper 3.3, (to be published).
13. ANAC, Inc., 3067 Olcutt St., Santa Clara, California 95050.
14. C.A. Gagliardi et al., Proc. Fifth Int. Symp. on Polarization Phenomena in Nuclear Physics (Santa Fe, 1980) contributed paper 3.25, to be published.

15. L.W. Anderson and G.A. Nimmo, Phys. Rev. Lett. 42, 1520 (1979).
16. G. Baum, C.D. Caldwell and W. Schröder, J. Appl. Phys. 21, 121 (1980).
17. W. Dreves et al., Proc. Fifth Int. Symp. on Polarization Phenomena in Nuclear Physics (Santa Fe, 1980) contributed paper 3.20, to be published.
18. E.K. Zavoiskii, Soviet Physics JETP, 5, 378 (1957).
19. W. Haeberli, Proc. Second Int. Symp. on Polarization Phenomena in Nuclear Reactions (P. Huber and H. Schopper, eds.) Birkhäuser (Basel) 1966, p. 64, see also ref. 1.
20. L.W. Anderson, Nucl. Instr. Meth. 167, 363 (1979).
21. Y. Mori, K. Ito, A. Takagi and S. Fukumoto, High Energy Physics with Polarized Beams and Polarized Targets (Lausanne 1980), to be published.