WORKSHOP REPORT ON POLARIZED PROTON ION SOURCES

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Résumé - Nous présentons ici le résumé d'un atelier qui a examiné les performances actuelles et les possibilités futures des sources de protons polarisés en mai 1983. Les meilleures sources basées sur l'effet Lamb ont atteint 4 μA mais les perspectives d'accroissement sont limitées par la luminosité de la source. Les sources atomiques ont atteint environ un niveau de 8 μA en H^- et on a proposé des techniques pour accroître leur niveau jusqu'à 1 mA. On décrit des techniques pour réaliser des faisceaux pulsés intenses à partir de sources atomiques ultra-froides. On présente les résultats obtenus avec une source d'ions H^- à pompage optique ainsi que d'autres méthodes pour produit de l'hydrogène atomique polarisé par pompage optique.

Abstract - The results from a workshop, during May 1983, which examined the capabilities and future possibilities of polarized proton sources are summarized. The best Lamb-shift sources have achieved 4 μA but the potential for further increase is limited by the proton source brightness. Atomic sources have reached the $\sim 8 \mu\text{A H}^-$ range and techniques for increasing this to $\sim 1 \text{ mA}$ are proposed. Techniques for achieving intense pulsed beams with ultra cold atomic sources are described. Results from an optically pumped H^- ion source at KEK are given along with alternative schemes for producing polarized atomic hydrogen by optical pumping.

INTRODUCTION

A workshop on high intensity polarized proton ion sources, sponsored by the International Committee for Symposia on High Energy Spin Physics was held at TRIUMF from May 23rd to 28th, 1983. There were forty-two registered participants specializing in the areas of accelerator, ion source, atomic, fusion and nuclear physics reflecting a growing interest in polarized proton sources. The proceedings of the workshop have been published as an AIP conference proceedings /1/. The program was split equally into formal lecture and informal working sessions. Topics covered included Lamb-shift (metastable) sources, atomic (ground state) sources, ultra cold atomic beams and targets, optically pumped sources and ionizers.

The workshop was primarily concerned with improving the performance of polarized proton ion sources. In principle, however, any nucleus with a non-zero spin can be polarized by similar techniques. In existing polarized proton sources, the procedure can be summarized in four basic steps. Initially a high quality atomic beam is formed. The electron spin of the atoms is then aligned through the use of magnetic fields, RF or photon induced transitions, spin exchange or charge exchange. Next the nuclear spin is aligned through the hyperfine interaction using appropriate magnetic fields and/or RF induced transitions. Finally the nuclear-polarized atoms are ionized through either charge exchange or electron stripping. Although the technical details are quite different for each type of source and each has a unique set of problems, there is also a considerable area of common interest in such topics as the choice of the ideal ionizer or the techniques for the formation of an atomic beam of high brightness.

In the Lamb-shift source, metastable (2S) atoms of a particular spin orientation are selectively quenched to the ground state. The remaining metastable atoms, now aligned, are selectively ionized. In the atomic (ground state) source the

unwanted spin alignment is removed from a slow atomic beam through the use of non-uniform magnetic fields (Stern-Gerlach separation). The remaining, polarized, beam is then ionized either directly to form H^- or H^+ or in a two step process first producing H^+ and then H^- by double charge exchange. For the optically pumped source one can either pump the atom directly (He^3 and alkalis) with a suitable laser or pump an alkali and transfer the spin to an atomic or ion beam by either spin or charge exchange. In the ultra cold atomic source the atoms relax at low temperatures in a high magnetic field, first to an electron spin aligned target and eventually to a nuclear spin aligned target. An ionizer and/or extractor is required to form a polarized beam. The workshop addressed the specific problems of each source in separate working sessions. Common concerns such as ionizers were discussed in joint working sessions.

LAMB-SHIFT SOURCES

The physics and technological details of Lamb-shift type polarized ion sources have been thoroughly reviewed [2]. Nevertheless, to remind the non-source specialists of the essential details, a block diagram showing the important processes is given in Fig. 1. In brief outline, protons from an ion source are transported at ~ 550 eV through a cesium vapour to produce a metastable (H_{2S}) atomic beam. Nuclear polarization is achieved through the use of magnetic and/or RF electric fields which cause mixing between metastable $2S_{1/2}$ states of one spin alignment and the short lived $2P_{1/2}$ states. Finally a selective ionizer is used to preferentially ionize only the remaining metastables, now polarized.

Fig. 1

The H^- current from the best sources has increased from that reported two years earlier by 100% to ~ 2 μA per hyperfine state, albeit with slightly less polarization. The working group concluded that the Lamb-shift source technology is mature and further large increases in current will be difficult to achieve. A major difficulty with the Lamb-shift source has been in the metastable beam formation region where space charge forces due to the relatively slow 550 eV protons have limited the useful proton current neutralized in the cesium vapour canal. There have been two approaches to try to reduce the severity of the space charge problem. In the first, the cesium has been placed as close as possible to the proton source, before the 550 eV proton beam has significantly diverged. In the second, the proton beam is expanded and transported up to 30 cm prior to being refocussed through the cesium canal. Both approaches are producing very similar H^- currents. The primary limitation is now the brightness of the proton source. Discussion centred on possible techniques to circumvent this limitation through the use of multi-hole extraction electrodes and unconventional proton sources, such as the electron-cyclotron-resonance type source. It was felt that with carefully optimized designs, a factor of two increase in current might be possible. A further factor of two increase in current would be expected if the cesium vapour could be electronically polarized by laser pumping, removing the need for either the rf spin filter or the diabatic field reversal. It was pointed out that large currents (5 mA!!) of H^+ could be produced if the metastable beam could be efficiently photo-ionized. In conclusion, even though substantial increases in either H^- or D^- current are not expected in the near future, the Lamb-shift source will continue to be used on accelerators for some time yet because of; 1) the good emittance, 2) the ease of choosing either pure vector or pure tensor deuterium states and 3) the suitability (long drift length)

for producing pulsed beam bunches.

ATOMIC BEAM SOURCES

Atomic beam sources have also been thoroughly reviewed in the literature /3,4/. A block diagram outlining the important processes in a source is given in Fig. 2. A

Fig. 2

dissociator, nozzle and skimmer are used to form a slow collimated beam of atom hydrogen (or deuterium). Spin selection is accomplished with Stern-Gerlach style separation magnets and RF induced transitions. Electron ionizers are used to produce H^+ , followed by alkali vapour targets if H^- is desired. Alternatively H^- is also produced directly with the reaction $H^0 + Cs^0 \rightarrow Cs^+ + H^-$. In the two years since the previous workshop the H^- currents have increased from 3 μA to 6 μA dc and to 7.5 μA pulsed. The dc H^+ currents are already at the 125 μA level and do not have the same demands for improvement.

The atomic beam source has the potential for substantially higher currents if the source is optimized. In the atomic beam formation region, for instance, it is important to efficiently cool the beam to less than 20 K as the beam density is proportional to $T^{-1/2}$. It was pointed out that this gain will not be seen unless the surface of the accommodator is coated with a material having a low recombination coefficient in the low temperature regime. Finally, in order to realize the larger currents, it is also necessary to redesign the separation magnets to match the slower velocity beam. The acceptance of the system would be increased since these magnets can be shortened and their vertical aperture increased. Thus the beam density after the separation magnets is also sensitive to the atomic beam velocity and is expected to be proportional to $T^{-3/2}$. It was estimated for an ideally designed beam formation region, the current could be increased a factor of 20 to 30 over existing atomic sources.

Improvements to the ionizers were also considered. For H^+ ions, a modern electron impact ionizer is capable of ionizing 3 to 5% of the H^0 beam. It was felt that an electron-cyclotron-resonance (ECR) ionizer would be much more efficient but might also lead to a loss in polarization. For H^- ions, it was expected that sources using the $H^0 + Cs^0 \rightarrow H^- + Cs^+$ reaction would shortly be achieving $\sim 20 \mu A$ due to improvements made in the cesium beam. A novel suggestion by J. Alessi was

the use of a ring magnetron, shown in Fig. 3, to take advantage of the much larger cross sections in the reaction $\text{H}^0 + \text{D}^- \rightarrow \text{H}^- + \text{D}^0$ /5/. The ring magnetron design should avoid the space charge problems with the D^- beam that led to failure in earlier attempts to use this reaction. At least an order of magnitude increase in H^- current would be expected.

The workshop concluded that the atomic source has a large potential for improvement. The projected gains, if realized, could in the future result in H^+ currents exceeding 2 mA and H^- currents in the 1 mA range.

Fig. 3

ULTRA COLD ATOMIC SOURCES

A thorough discussion on the physics and possibilities of ultra cold atomic sources is the subject of another contribution to this conference /6/. The source has many design variations depending on the application. Figure 4 shows a particular scheme that received a great deal of interest at the Vancouver workshop. Hydrogen atoms are cooled in stages down to ~ 0.3 K and then stored in a confinement cell within an axial magnetic field. Only atoms in the two hyperfine states having the proper electron spin alignment are trapped. These atoms can be extracted by using μ -waves to induce transitions to either one of the two other hyperfine states. Ionization techniques would be similar to those used in conventional atomic sources. The μ -wave extraction technique is particularly convenient for applications requiring intense pulsed beams, such as synchrotrons or linacs since it would be possible to accumulate atoms between pulses. Furthermore the extracted atoms would be both focussed and accelerated by the magnetic field of the solenoid. Laboratory experiments have demonstrated storage densities $\sim 3 \cdot 10^{17}$ atoms/cm³ with input flux $\sim 10^{16}$ atoms/sec. It was estimated that for low-duty cycle accelerators, such as the AGS, it should be possible to reach peak intensities $\sim 2 \cdot 10^{19}$ atoms/sec. However, for applications requiring dc sources there seems to be no advantage, given current technology, over conventional-cooled atomic sources. Development work is in progress with groups at CERN, KEK, and a combined group from the University of Michigan, Brookhaven and MIT.

OPTICALLY PUMPED POLARIZED PROTON SOURCES

Three years ago at the Ann Arbor workshop Anderson reviewed his proposal for an optically pumped polarized proton source /7/. At the Vancouver workshop Mori of KEK described the characteristics of a working source based on the Anderson proposal /8/. The essential details of this scheme are indicated in the block diagram of Fig. 5. Protons, at an energy of ~ 7 keV, passing through a sodium vapour target polarized by optical pumping, have a large probability of picking up electrons to form an electronically polarized atomic beam. Nuclear polarization is obtained with the Sona technique /9/. Charge exchange in a second alkali yields large $\vec{H}^-$ currents. Crucial to the KEK design has been an ECR proton ion source /10/. The ECR source has allowed Mori to circumvent the anticipated problem of emittance blow-up in the first charge exchange canal. The beam polarization was measured at 355 keV

Fig. 4

Fig. 5

as a function of beam current. The initial results are shown in Fig. 6. It is believed that the polarization can be increased with greater laser power. High background gas pressure is also suspected to be responsible for a substantial unpolarized background. The workshop felt that the source has a large potential for improvement over its already impressive performance. It was suggested that potassium instead of sodium would result in higher laser polarization efficiency. Also noted was the fact that since most of the angular momentum was being lost to the walls, a wall coating to reduce this loss rate would also enhance the efficiency. Development work on such sources is being actively pursued at KEK, TRIUMF, and the University of Wisconsin.

Happer of Princeton University proposed a system to make polarized $\bar{n}$ using spin exchange collisions. In this scheme rubidium and hydrogen atoms are combined in a cell. The rubidium is electron-spin polarized by optical pumping, rather than the hydrogen. (Intense lasers are available at wavelengths suitable for the alkalis

Fig. 6

Fig. 7

but not yet at the wavelengths required for hydrogen.) The electronic polarization is transferred by spin exchange to the hydrogen atoms. The reaction $\text{Rb}(+) + \text{H}(+) \rightarrow \text{Rb}(+) + \text{H}(+)$ has a relatively large cross section, $\sigma \approx 2 \times 10^{-14} \text{ cm}^2$. A schematic of a possible experimental setup is shown in Fig. 7. Frequent spin exchange collisions lead to nuclear polarization. The power requirements are about 4 watts of optical power per ampere of protons. The group at Princeton have carried out experiments producing highly polarized ^{129}Xe by spin exchange reactions with optically pumped Rb /11/. The cross section for this reaction is only $\approx 1 \times 10^{-19} \text{ cm}^2$. Consequently one would expect a much higher transfer efficiency when hydrogen is used, if the lower wall relaxation time for H^+ can be increased.

SUMMARY

After many years of effort to reach the 10 μA range, polarized ion source builders are confident that at least two of the existing technologies should be capable of demonstrating dc H^- currents of $\sim 100 \mu\text{A}$ in the near future. Recent calculations and experiments on the ETHZ atomic source /12/ indicate that by cooling the atomic beam to 30 K and by rebuilding the separation magnets the H^- current will increase a factor of 15 from $\sim 6 \mu\text{A}$ to $\sim 90 \mu\text{A}$. At TRIUMF it has been demonstrated that the optical pumping efficiency of sodium can be enhanced by more than a factor of 15 through the use of bi-directional pumping, magnetic field inhomogeneities, and Viton surfaces. This implies that the KEK style polarized source should be capable of at least 100 μA of highly polarized H^- at modest laser power. The high pulsed currents required by some accelerators can probably be attained using the storage features of the ultra cold sources. It is expected that tests currently being carried out at CERN will demonstrate its feasibility /13/.

Finally, for the more distant future, schemes have been proposed which would lead to H^- sources equalling today's unpolarized H^- sources. Anderson et al. in two recent publications /14,15/ calculate that successive spin-dependent charge-transfer collisions can be utilized to produce nuclear-polarized H^- currents by a process they refer to as "collisional pumping". The process requires a spin-polarized target thickness $\sim 10^{17} \text{ atoms/cm}^2$, almost two orders of magnitude thicker than the existing optically-pumped spin-aligned targets. A group at Berkeley is planning to experimentally examine the problems associated with optical pumping at the required target thickness.

The future for polarized proton ion sources is very promising. There are several new groups actively building sources and new ideas are being pursued.

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