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KEK OPTICALLY PUMPED POLARIZED H^- ION SOURCE

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Summary

Optically pumped polarized H^- ion source has been developed at KEK. Various improvements have been made for stably long term operation. Among them, efforts were concentrated to develop a control system for pumping dye lasers with a personal computer and an ECR ion source. We also examine polarizing effect of dissociated hydrogen atoms from H_2^+ ions and show that it could be possible to use H_2^+ ions instead of H^+ ions in this type of polarized ion source.

Introduction

An optically pumped polarized H^- ion source has been developed for acceleration of a polarized beam in the KEK 12 GeV synchrotron[1]. This polarized ion source uses a charge-exchange reaction between fast hydrogen ions extracted from an ECR ion source and electron-spin polarized sodium atoms produced by an optical pumping with dye laser.

A preliminary test for the acceleration of polarized beam in the 500 MeV booster synchrotron has been already made. A beam of 20 μA was extracted from the ion source and accelerated to 750 keV and almost 10 % of the beam could be accelerated to 20 MeV by the linac. This poor transmission was mainly due to the small acceptance of a 750 keV Wien filter and relatively low capture efficiency of the linac. The beam polarization was measured at the exit of the linac with a nuclear reaction of carbon and it was about 40 %. The beam polarization was strongly affected by a polarization of optically pumped sodium atoms and higher polarization could be expected at thinner target thickness of sodium atoms. We have obtained the beam polarization of 50 - 60 %, however, the beam intensity decreased to less than 1 μA at the exit of the linac.

In this preliminary experiment, we have faced several problems on the operation of the polarized ion source. Among them, the stability of the dye laser was most troublesome. We use two sets of single frequency dye lasers. Although each laser has its own feedback system for frequency stabilization, we have been frequently bothered by frequency jumps due to mode hop. We have developed a frequency stabilized feedback system with a personal computer to overcome this problem. Using this system, we could stabilize the frequency of each dye laser within ± 300 MHz for long period operation. Recently, we have also improved the ECR ion source as follows: six pieces of small SmCo permanent magnets forming multicusp magnetic field were introduced into the ECR cavity, the inside of the cavity was convered with quartz to increase the plasma density and the fraction of H^+ components and several extraction electrodes were tested to increase the beam intensity and stability. In order to optimize the magnetic field gradient, a couple of large diameter solenoid coils were installed in the zero-crossing region. These coils were very useful to cancel the stray magnetic field from the ECR solenoid coils.

Recently, very interesting phenomena for this type of polarized ion source has been found in TRIUMF[3] and KEK. Neutral hydrogen atoms, which are generated by dissociative charge exchange reactions of H_2^+ ions with optically pumped sodium atoms, are also polarized. We have made several experiments to confirm these facts and found that, surprisingly, the polarization of hydrogen atoms produced from H_2^+ ions were relatively high and did not decrease so much as that of hydrogen atoms from H^+ ions when the external magnetic field became small. We understand that this polarization effect concerns deeply with the mechanism of the dissociative charge exchange reactions of H_2^+ ions and could be explained well with resonant and non-resonant reaction processes forming the dissociative states of hydrogen molecules. In this paper, we will also decribe these processes to explain the exprimental results.

Improvements of Ion Source

A 16.5 GHz ECR ion source is used as a H^+ ion source. 1 - 2 KW microwave power is fed to the cavity axially through a sapphire window. Six pieces of SmCo permanent magnets are installed into the cavity to produce multicusp magnetic field and they are separated from plasma by a cylindrical quartz tube. Proton ratio of the extracted beam was able to increase to 85 %. Whereas the operating hydrogen pressure decreased 50 % with these improvements. The configuration of the beam extracting system was modified as shown in Fig. 1. It consists of three multigrided electrodes and each electrode has five pieces of 0.1 mm diameter tungsten wires, which are supported at one end to eliminate deformation caused by heavy beam loading. The electrode lifetime becomes longer than that of the previously used electrodes which were made of stainless steel.

Two single frequency dye lasers are used for the optical pumping of sodium atoms. They are adjusted in the resonance band width of 3 GHz of sodium D1 line and have to be stable for long term operation. However, the frequency of the dye laser would be easily fluctuated by mode hop or thermal effect. In order to overcome this problem, we have developed a frequency stabilized feedback system which consists of a personal computer, two wavemeters to measure the frequencies of lasers, two beam position detectors and movable four mirrors. Fig. 2 shows the outputs of the personal computer, one with feedback and the other without feedback. Time scale for each one is about one hour. As can be seen in this figure, fluctuation

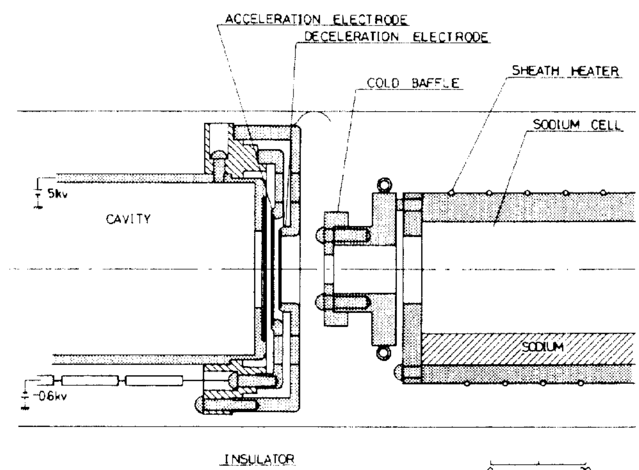

Fig. 1 Configuration of the beam extracting system.

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of the frequency can be suppressed within 0.01 cm^{-1} (= 300 MHz) by this system. We are now able to operate the dye lasers for several ten hours continuously without any particular tunings for them.

Productions of Polarized Hydrogen Atoms by Dissociative Charge Exchange Reactions of H_2^+ Ions

The extracted beam from the ECR ion source contains small amounts of H_2^+ ions except H^+ ions. These H_2^+ ions could dissociate into hydrogen atoms by trapping electrons from polarized sodium atoms. Very recently, it has been found that these dissociated hydrogen atoms are polarized in these reactions. This very interesting phenomena, if it is true, will bring not only a physical attention but open a new phase for the development of this type of polarized ion source.

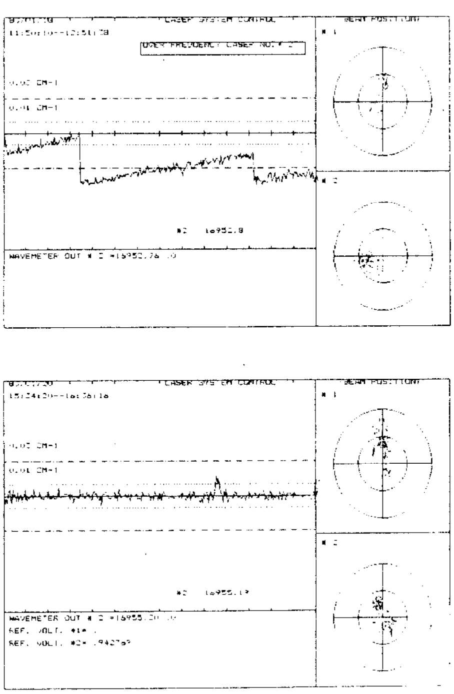
In order to examine this effect experimentally, we have measured the polarization of hydrogen atoms by a simple method proposed by W.D. Cornelius[3]. This method is based on the following principle; Polarized hydrogen atom which is produced by a collision with optically pumped sodium atom would possibly become H^- ion by trapping electron from another polarized sodium atom. Since H^- ion only forms with electronic spin antiparallel, the H^- ion current depends on the polarization of hydrogen atoms and sodium atoms. The difference of H^- ion currents measured by switching the pumping lasers on and off should be related with the polarizations of hydrogen atoms(P_H) and sodium atoms (P_A) as follows.

$$\varepsilon = \frac{I^-(\text{off}) - I^-(\text{on})}{I^-(\text{off})} = P_H \cdot P_A \quad . \qquad (1)$$

Since P_H is proportional to P_A,

$$P_H = \eta P_A \qquad (0 \leq \eta \leq 1) \quad . \qquad (2)$$

Here, η can be written in the following equation by the polarization transfer t_1 from sodium atom to hydrogen atom and the fraction f of unpolarized



without feedback

with feedback

Fig. 2 Outputs of the personal computer.

hydrogen atoms generated by the collisions with residual hydrogen gas molecules.

$$\eta = t_1(1 - f) \quad . \qquad (3)$$

Then, ε becomes,

$$\varepsilon = t_1(1 - f)P_A^2 \quad . \qquad (4)$$

If f is negligibly small, then,

$$t_1 \simeq \frac{\varepsilon}{P_A^2} \quad . \qquad (5)$$

Thus, we could obtain the polarization transfer t_1 in the charge exchange reaction by ε and P_A.

In our practical experiments, we analyzed the H^- ion beam by a small bending magnet, which was placed at the exit of sodium cell, to distinguish H^- ions whether they were produced from H_2^+ ions or H^+ ions. The H^- beam currents were measured by a Faraday cup and averaged to increase a signal to noise ratio because the ECR ion source was operated in a pulse mode. On the other hand, the polarization of the optically pumped sodium atoms was measured by a Faraday rotation method[4]. In order to get a measurable beam intensity and reduce the contributions from unpolarized background hydrogen atoms (f in eq. (3)), the experiments have been performed at relatively thick sodium target, of which thickness was about 8 - 9 × 10^{13} atoms/cm^2.
At this target thickness, the measured polarization was 45 - 50 %.

In Fig. 3, the values of measured polarization transfer t_1 are plotted for each case of H_2^+ ions (open circles in the figure) and H^+ ions (closed circle), separately as a function of a magnetic field strength at the sodium target. In this energy range (∿ 3 - 5 keV) of H^+ ion beam, most of hydrogen atoms are produced in n = 2 state and the polarization transfer t_1 can be estimated theoretically, which is also shown in the figure as a solid line. As can be clearly seen from this figure, the measured polarization transfer of dissociated hydrogen atoms from H_2^+ ions are relatively high and, moreover, it does not change so much as that from H^+ ions when the strength of the magnetic field decreases.

Obviously, these surprising experimental results account that the mechanism of preserving the polarization of dissociated hydrogen atoms should be existed in the dissociation process of H_2^+ ions.

Recently, D.P. de Bruijn et al. have made excellent experiments for the dissociative charge exchange reactions of H_2^+ ions and discussed the dissociation processes in detail[5]. According to their explanations, dissociated hydrogen atoms should be generated by passing a triplet level ($b^3\Sigma_u^+$) of hydrogen molecule after H_2^+ ion captures an valence electron of sodium atom. The $b^3\Sigma_u^+$ state, in which spins of two electrons are parallel, forms a repulsive potential as shown in Fig. 4. In this figure, some other important levels of H_2^+ ion and hydrogen molecule concerned with the dissociative reaction are also shown. de Bruijn et al. found that the following three processes would be dominant in case of sodium atoms before the final dissociative level of $b^3\Sigma_u^+$ is formed:
(a) $a^3\Sigma_g^+$ state, which is an excited level of hydrogen molecule, is formed as a predissociative state and then radiatively decay to $b^3\Sigma_u^+$ state by the molecular transition.
(b) Direct transition from $X^2\Sigma_g^+$ state of H_2^+ ion to the repulsive $b^3\Sigma_u^+$ state, resulting in two ground-state hydrogen atoms.
(c) Predissociative channel via $c^3\Pi_u$ state which couples rotationally with the $b^3\Sigma_u^+$ state.
Since the ionization energy of sodium atom is 5.14 eV, (a) and (c) processes are resonantly occured.

Here, we will consider the polarization of dissociative hydrogen atoms in these three processes when the target sodium atoms are polarized. In process (a), the predissociative $a^3\Sigma_g^+$ state is an asymmetric state for orbital wave function and symmetric for the spin state of two electrons. Thus, the both electron spins are parallel and the polarization of the captured electron should be conserved. In the molecular transition from $a^3\Sigma_g^+$ to $b^3\Sigma_u^+$, the spin state does not change, so that atoms could preserve the same polarization as that of the sodium atoms. The process (b) is a direct transition to the triplet state $b^3\Sigma_u^+$, in which the spin state of two electrons is symmetric (parallel) and therefore the polarization of the dissociated hydrogen atoms could be also conserved. $c^3\Pi_u$ state in the process (c) is the state that becomes H(1S) + H(2P) at $R \to \infty$. Therefore, the electron spin couples with orbital angular momentum and the polarization of electron spin should be varied with a magnetic field strength in the same way of H^+ ions.

If we consider only these three processes in the dissociative charge exchange reactions of H_2^+ ions, the polarization transfer t_2 for H_2^+ ions could be given in the following equation.

$$t_2 = (\gamma_{a+b} + \gamma_c \cdot t_1) \quad , \tag{6}$$

where γ_{a+b} and γ_c represent the fractions of dissociated hydrogen atoms produced by processes of (a) + (b) and (c) respectively. According to the measurements of de Bruijn et al., $\gamma_c \sim \gamma_{a+b} = 0.5$ in case of sodium atoms. Calcurated values of t_2 are shown as a broken line in Fig. 3. t_2 is relatively high and does not decrease so much as t_1 when the strength of the magnetic field becomes small. Experimental values also show good agreements with calculated values. Even at low magnetic field ($\sim$ 2KG), it is expected to conserve more than 70 % and this is a very attractive feature for this type of polarized ion source.

Conclusion

Various improvements for the optically pumped polarized ion source have been made. Especially, frequency stabilized feedback system for pumping lasers using a personal computer has been developed and it works very well for long term operation. A multicusp magnetic field was introduced in the plasma cavity of the ECR ion source and made possible to increase the proton ratio and the beam intensity.

On the other hand, we have measured the polarization of dissociated hydrogen atoms from H_2^+ ions and found it was relatively high. This interesting phenomena could be explained from the dissociation mechanism of hydrogen molecule and the theoretically calculated values show good agreements with the experimental values. We are now believing that this polarization effect could open a new phase for the development of this type of polarized ion source.

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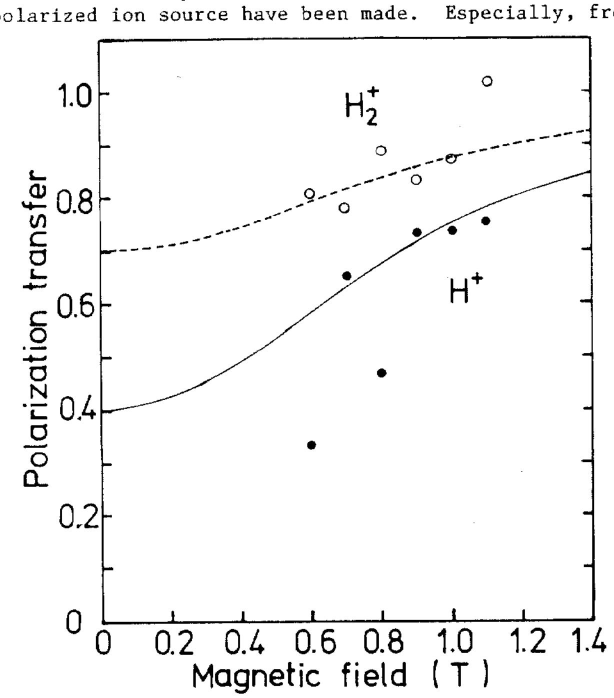

Fig. 3 Polarization transfer from polarized sodium atom to hydrogen atom by charge exchange reaction of H_2^+ ion and H^+ ion.

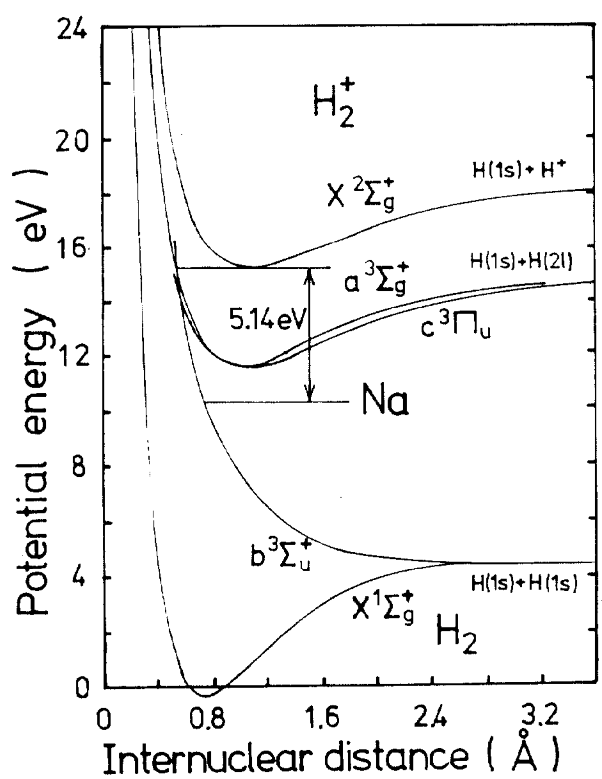

Fig. 4 Potential curves of H_2^+ ion and hydrogen molecule.