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Recent Progress in Optically Pumped Polarized Ion Sources

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Recent progress in optically pumped polarized ion sources which have been developed at various laboratories is described. Polarization transfer from optically pumped atom to hydrogen atom at a magnetic field of 1 - 1.5 T shows a consistent value for these laboratories, which is about 60 - 65 %, and 15 % lower than that of the theoretically predicted value. Various schemes for achieving an efficient optical pumping are also shown. Moreover, polarization effect of dissociated hydrogen atom from H_2^+ ions, which has been recently discovered in TRIUMF and KEK, is described and some experimental results are also shown.

§1. Introduction

The first idea of producing a polarized ion by a pick-up reaction of polarized electron from optically pumped alkaline atom was proposed by W. Haeberli in 1966[1]. In 1979, L.W. Anderson examined precisely the possibility of this type of polarized ion source using dye lasers[2]. Recently, several laboratories, TRIUMF[3], Institute for Nuclear Research (Moscow)[4] and KEK[5] have developed the polarized H^- ion sources and obtained encouraging results.

The most important point for this type of polarized ion source is how to make an electron capture in a high magnetic field of more than 1 T from optically pumped alkaline atoms to preserve the polarization. ECR ion source has been adopted for this purpose at KEK and TRIUMF. Another way of using a neutral hydrogen beam was developed in the Institute for Nuclear Research. The experimental results for the polarization transfer from polarized electron to proton are consistent among these laboratories within errors; 60 - 65 % at the magnetic field of 1 - 1.2 T.

In KEK, the recent efforts were concentrated on a stable long period operation, especially on the operation of dye lasers[6]. 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 system. Using this system, we could stabilize the frequency of each dye laser within ± 300 MHz for long period operation.

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 covered 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 have been found at TRIUMF 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.

In a preliminary experiment, we found that hydrogen atoms produced from H_2^+ ions seemed to be polarized and the polarization did not decrease so much as that of hydrogen atoms from H^+ ions when the external magnetic field became small.

§2. Optical Pumping and Developments of Ion Source

This type of polarized ion source can use any type of alkaline atoms, however, sodium has been normally used because the wavelength range of the most efficient dye laser with R6G could cover the sodium D1 resonance line (589.593 nm). Fig. 1 shows the Zeeman splitting sublevels of the sodium atom concerning D1 and D2 resonance lines. Optical pumping is performed between sublevels of 3S (m_j = + 1/2) - 3P (m_j = - 1/2) or 3S (m_j = - 1/2) - 3P (m_j = + 1/2). In order to calculate the efficiency of optical pumping, it is necessary to solve the rate equations for each level including the hyperfine sublevels. However, roughly, we could estimate it by the following equation[7]

$$\dot{N} = \frac{P}{\hbar\omega}\rho - \frac{N}{T}$$

where N is the number of atoms, P an incident laser power and ω an angular frequency of laser. ρ shows a number of atoms which could be pumped by one photon (normally 1/3) and T is a relaxation time. In equilibrium, $\dot{N} = 0$, then,

$$P = \frac{N\hbar\omega}{T\rho}$$

T is determined by wall collision time, D/v (D: diameter of the cell, v: mean velocity of atom). When D = 1 cm and $v = 1 \times 10^5$ cm/sec, $T = 10^{-5}$ sec. For the sodium atom, the photon energy $\hbar\omega$ is 3×10^{-19} J. If the laser power is 1 W, the number of atoms which could be completely oriented is about 1×10^{13} atoms and for 1 cm^2 cross section of laser beam, the sodium target thickness of 1×10^{13} atoms/cm^2 could be completely polarized.

This estimate assumes that the frequency coverage of the pumping laser for the resonance line width would be complete. Actual output of the laser beam has a mode structure, therefore, it is very important to have good coverage of the laser band width for the absorption lines. Several ways have been proposed to realize this situation. In KEK, we have used two single frequency dye lasers for the optical pumping and each frequency of lasers is slightly detuned to the center frequency of the resonance. By using this scheme, about 90 % sodium polarization has been obtained at 1×10^{13} atoms/cm^2. However, it gradually decreased to 60 % at 6×10^{13} atoms/cm^2 and at this target thickness we have obtained polarized H^- current of 25 μ A and the proton polarization measured at 20 MeV was 40 %.

At the target thickness of 1 - 2×10^{13} atoms/cm^2, the sodium polarization is relatively high, however, contributions of the unpolarized background hydrogen atoms become also high. Fig. 2 shows the measured H° beam intensity as a function of sodium target thickness. As can be seen in this figure, 20 - 30 % of the total H° beam

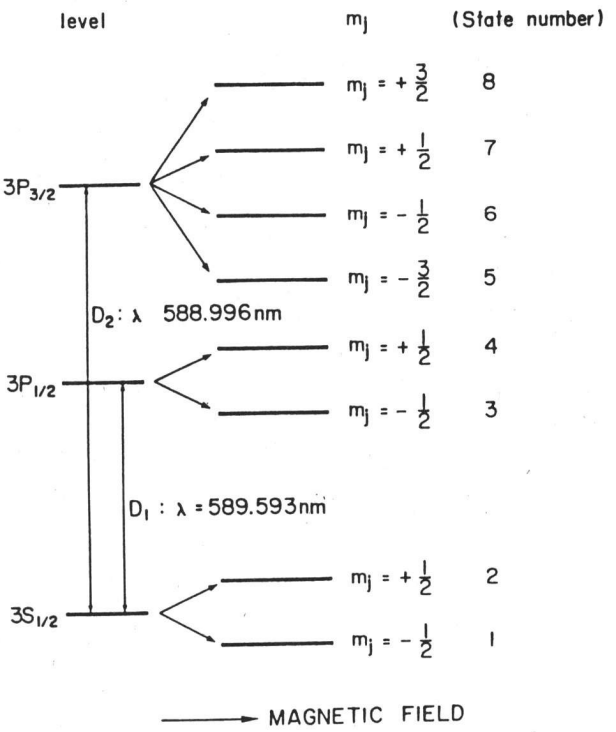

Fig. 1 Zeeman splitting sublevels of sodium atom in a high magnetic field.

intensity was occupied by the unpolarized background beam at 2 × 10^{13} atom/cm^2.

Another way for optical pumping is to use a broad band dye laser and this has been developed at TRIUMF. In a normal broad band dye laser using a birefringement filter, its line width is about 30 - 40 GHz and it was too wide for efficient pumping. In TRIUMF, a thin solid etalon was inserted in the laser cavity to reduce the line width to about 6 GHz and they have succeeded to increase the sodium polarization up to about 60 % at 5 × 10^{13} atoms/cm^2 with only 800 mW laser power. In KEK, we have also made similar experiments for a broad band laser and these preliminary results are shown in Fig. 3. By narrowing the line width, the sodium polarization was increased.

A.N. Zelenskii et al. have used an intese pulsed dye laser, whose output power was more than 100 W and the line width was about 43 GHz (0.5 A). They have obtained H^+ ion current of 1 mA and H^- ion current of 25 μA with the proton polarization of 65 ± 3 %. This scheme might be very useful for a pulsed beam application.

Polarization transfer from sodium atoms to hydrogen atoms during the electron capture reaction were measured at TRIUMF, Moscow and KEK independently. Their results are summarized in Fig. 4. At a magnetic field of more than 1 T, these results show reasonable agreement with a polarization around 60 - 65 %.

The discrepancy for the theoretically predicted value is about 15 %. It is not clear where these differences come from, however, part of them is probably due to the unpolarized background H° components as described before.

§3. Polarization Effect of Dissociated Hydrogen Atoms

The extracted beam from the ECR ion source contains small amounts of H_2^+ ions besides 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 have some polarization effects.

In order to examine these effects experimentally, we have measured the polarization of hydrogen atoms indirectly by a simple method proposed by W.D. Cornelius[8]. This method is based on the following principle; Polarized hydrogen atom which is produced by a collision with an optically pumped sodium atom could

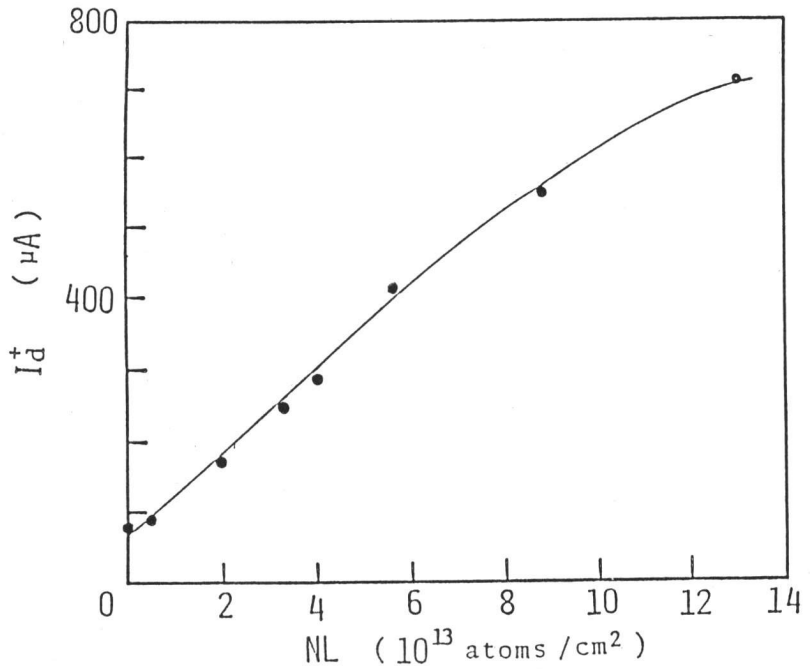

Fig. 2 Measured hydrogen beam intensity as function of the target thickness of sodium atoms.

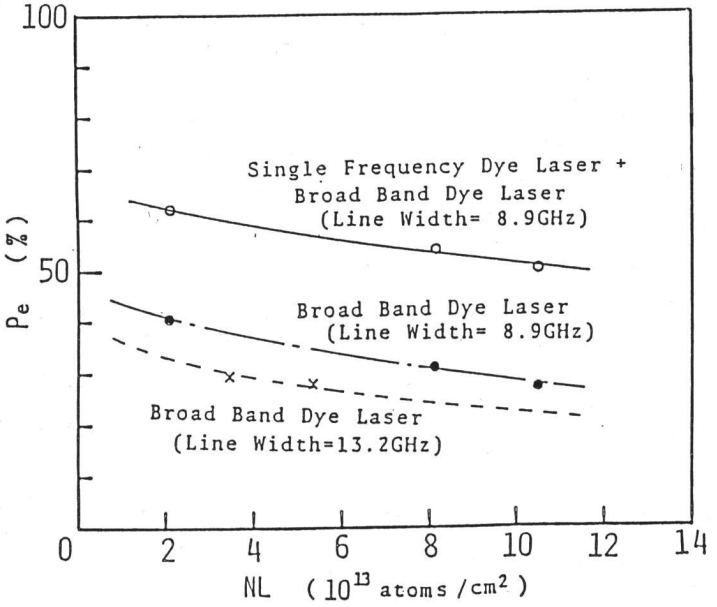

Fig. 3 Sodium polarizations by broad band and/or single frequency dye lasers.

possibly become an H^- ion by trapping an electron from another polarized sodium atom. Since the 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 (PH) and sodium atoms (P_A) as follows.

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

So, by measuring P_A, we could estimate the polarization of hydrogen atom P_H.

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 whether H^- ions were produced from H_2^+ ions or from 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 optically pumped sodium atoms was measured by a Faraday rotation method[9-10]. In order to get a measurable beam intensity and reduce the contributions from unpolarized background hydrogen atoms, the experiments have been performed with a relatively thick sodium target, which thickness about 8 - 9 $\times 10^{13}$ atoms/cm^2. At this target thickness, the measured polarization was 48 %.

In Fig. 5, the values of measured ε are plotted for each case of H_2^+ ions (open circles) and H^+ ions (closed circules), separately as a function of an external magnetic field strength. As can be

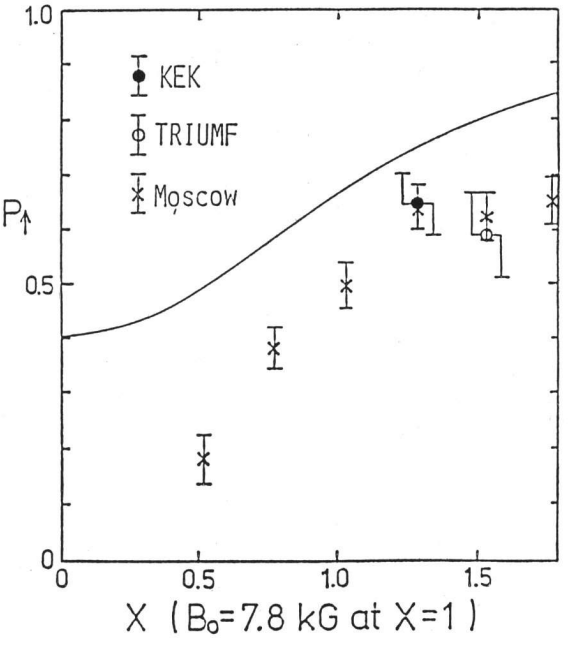

Fig. 4 Polarization transfer from optically pumped sodium atom to hydrogen atom.

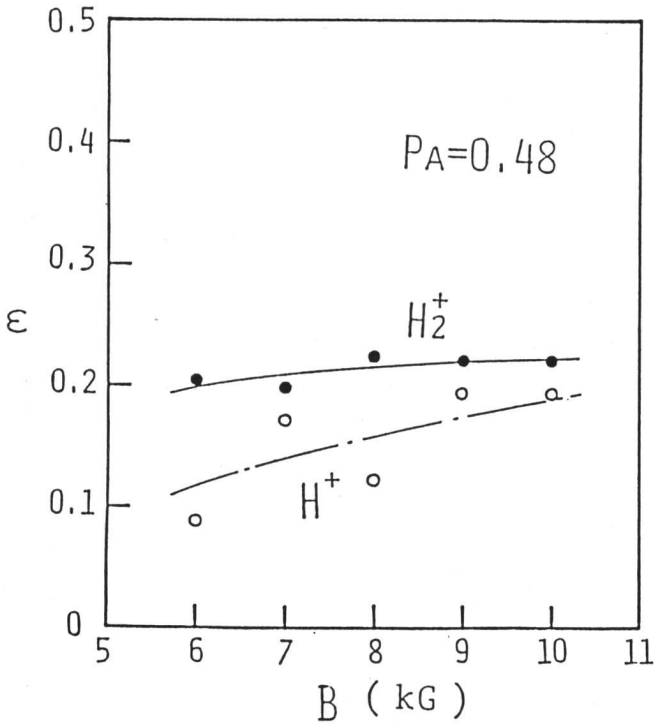

Fig. 5 Measured polarization effects of dissociated hydrogen atoms from H_2^+ ions and hydrogen atoms from H^+ ions.

seen in this figure, there seemed to be a not so small polarization effect for dissociated hydrogen atoms and surprisingly, it did not change so much as that from H^+ ions does when the strength of the magnetic field decreases.

Obviously, these experimental results show that the mechanism of preserving the polarization of dissociated hydrogen atoms should exist in the dissociation process of H_2^+ ions. In normal consideration, the dissociated hydrogen atoms come from a triplet state of the hydrogen molecule. Therefore, if the captured electron is spin polarized, the dissociated hydrogen atom could be polarized and its polarization is estimated to be 2/3. Experiment shows a somewhat larger value than this, however, the fact that the polarization is not affected by the magnetic field strength seems to be interesting.

§4. Conclusion

Recent progress in optically pumped polarized ion sources which have been developed at KEK, TRIUMF and Institute of Nuclear Research (Moscow) was reviewed. KEK and TRIUMF have adopted an ECR ion source as an H^+ ion source to avoid the beam optics problem in a high magnetic field of more than 1 T. In Moscow, they have used another interesting scheme instead of ECR ion source; a neutralized hydrogen beam is stripped by a He gas target and then the H^+ ions capture polarized electrons from optically pumped sodium atoms in a high magnetic field. Polarization transfer from optically pumped sodium atom to hydrogen atom was measured independently in these three laboratories. The results show good agreements at the magnetic field strength of 1 - 1.2 T with a valve of 60 - 65 %. We also described various ways to make an efficient optical pumping; multi-single frequency dye lasers, broad band laser with etalon and intense pulsed dye laser. At the moment, the laser power is not enough to get completely polarized sodium atoms at relatively high target thickness of more than 5×10^{13} atoms/cm^2. In this manner, more powerful laser and/or effective wall coatings to reduce the relaxation is eagerly required.

We also measured the polarization effects of dissociated hydrogen atoms from H_2^+ ions. The results seemed to be relatively higher than values expected from

simple considerations. More information on the dissociation process is necessary. However, the fact that this polarization effect seems not to depend largely on the magnetic field would be very interesting, especially, when it could be applied to a polarized ion source.

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DISCUSSION

FICK: Can you comment a little bit more on the question: narrow line width of laser versus Doppler broadening and hyperfine splitting in the optical pumping process?

MORI: Narrow band (single frequency) laser can not cover an absorption line width completely, however, by a hole-burning effect with its high spectral density, relatively high sodium polarization could be achieved. However, in order to get a complete polarization at the thick target, we really need a high power laser beam whose band width should be well matched to the absorption line width.