A Dual-Optically-Pumped Polarized Negative Deuterium Ion Source

M. Kinsho*, Y. Mori, K.Ikegami, and A.Takagi
*Graduate University for Advanced Studies
Oho 1-1, Tsukuba-shi, Ibaraki-ken 305, JAPAN
National Laboratory for High Energy Physics (KEK)
Oho 1-1, Tsukuba-shi, Ibaraki-ken 305, JAPAN

(abstract)

An optically pumped polarized H^- source (OPPIS), which is based on the charge exchange between H^+ ions and electron-spin-polarized alkali atoms has been developed at KEK[1]. Just by applying this scheme to a deuteron beam, it is difficult to obtain a highly vector polarized deuteron beam. To obtain highly vector polarized D^- ions, we have developed a "dual optical pumping type" of polarized D^- source. With this scheme, a 100 % vector nuclear-spin polarization for D^- ions is possible in principle. In a preliminary experiment, a 60 % of vector nuclear-spin polarized D^- ions was obtained.

I. INTRODUCTION

Polarized protons have been successfully accelerated in the KEK 12-GeV proton synchrotron (KEK-PS) since 1985. Many experiments have been carried out with polarized proton beams so far. Recently, several proposals for the physics experiments with polarized deuteron beams in the KEK-PS are under discussion.

An OPPIS has been used for acceleration of polarized proton beams in the KEK-PS so far. The idea of this type of polarized ion source was proposed by Anderson[2] and the first operational ion source has been successfully developed at KEK. [3] Afterwards, various institutes have developed an optically pumped polarized ion source (OPPIS) for their accelerators. [4][5][6]

It has been believed that this type of polarized ion source is not useful to produce a highly nuclear-spin polarized(vector and tensor) deuterium ions. In 1988, Schneider and Clegg[7] proposed a new nuclear-spin state selection scheme. In spite of this possibility of making a highly polarized deuteron beam by optical pumping, they concluded eventually in their paper that this dual optical pumping scheme might be not practical because efficient optical pumping of the thick target in the ionizer is difficult due to radiation trapping. However, we have re-examined the dual-pumped scheme in detail and found that radiation trapping was not a serious problem and highly polarized deuterons could be obtained with the dual-pumped scheme.[8]

In this paper, we report the preliminary experimental results which showed that the highly vector polarized negative deuterium ions could be produced by the OPPIS with dual-optically-pumped technique.

II. OPPIS FOR DEUTERONS

A block diagram of the dual-optically-pumped polarized ion source is shown in Fig.1 schematically. The idea of this scheme is as follows: After picking up the polarized electrons from optically pumped alkali atoms, for example, deuterium atoms are electron-spin polarized in the state of $m_j = +1/2$ as shown in Fig.2.

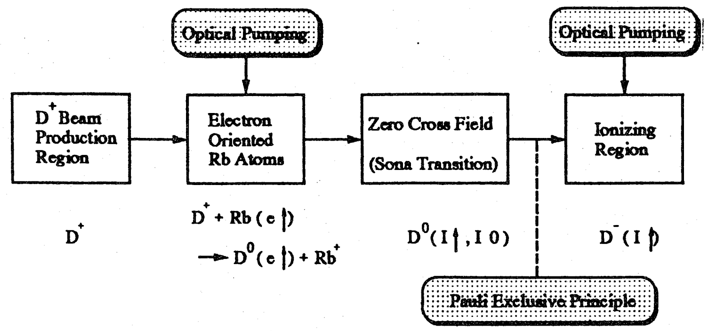

Fig. 1 Block diagram of the dual-optically-pumped polarized ion source.

These electron-spin polarized deuterium atoms equally populate three hyperfine sub-levels I_Z=+1, 0, and -1 in a high magnetic field, which are labeled the states 1, 2, and 3, respectively in Fig.2. Using the Sona transition, the state 1 ($m_j = +1/2$, I_Z=+1) goes to the state 1' ($m_j = -1/2$, I_Z=-1), the state 2 ($m_j = +1/2$, I_Z=0) goes to the state 2' ($m_j = +1/2$, I_Z=-1), and the state 3 goes to the state 3' ($m_j = +1/2$, I_Z=0), respectively as shown in Fig.2. Therefore, the deuterium atoms with only the hyperfine level of I_Z=-1 (state 1' in Fig. 2) has an opposite electron-spin state, $m_j = -1/2$, of the other two sub-levels (2' and 3') after Sona transition.

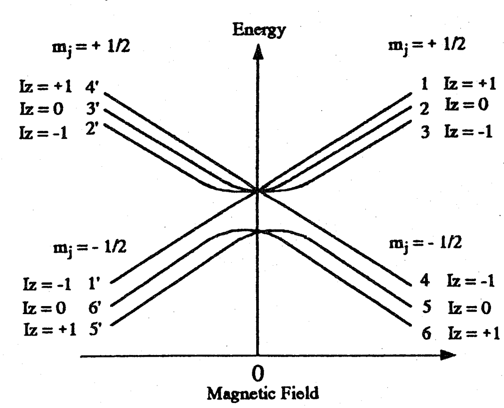

Fig. 2 Hyperfine sub-levels of deuterium atom in Sona transition.

When the alkali atoms in the ionizer are also optically pumped and their electrons are to be spin polarized in the $m_j = +1/2$

state, only deuterium atoms with the electron-spin state of $m_j = -1/2$ (state 1') can form negative ions because of the Pauli exclusion principle. This process is shown in Fig.3 schematically. The nuclear-spin state of the negative deuterium ions in this case is $I_z=-1$, the nuclear vector polarization becomes -1. The nuclear tensor polarization is, in this case, -1. Using a proper rf transition simultaneously, a pure nuclear tensor polarization of -2 may become possible.

III. EXPERIMENT OF DUAL OPTICAL PUMPING

In order to check this dual-pumped scheme experimentally, we have used a following simple method. When the alkali atoms in the ionizer are electron-spin polarized by optical pumping, deuteron atoms which are stayed in the state of $m_j=+1/2$ can be permitted to form negative ions in the charge-exchange reactions with alkali atoms of which electron-spin state is $m_j=-1/2$, from the Pauli exclusion principle. Contribution of the each hyperfine sub-level of deuterium atoms after the Sona transition to the intensity of the negative deuterium ions can be expressed in the following equation.

$$I(1') = \frac{1}{3}\, i_+ \frac{N_0}{2}\,(1+P_{IONZ})\,\sigma_0\, l\,,$$
$$I(2') = \frac{1}{3}\, i_+ \frac{N_0}{2}\,(1-P_{IONZ})\,\sigma_0\, l\,,$$
$$I(3') = \frac{1}{3}\, i_+ \frac{N_0}{2}\,(1-P_{IONZ})\,\sigma_0\, l\,,$$
$$I(4') = \frac{1}{3}\, i_- \frac{N_0}{2}\,(1-P_{IONZ})\,\sigma_0\, l\,, \qquad (1)$$
$$I(5') = \frac{1}{3}\, i_- \frac{N_0}{2}\,(1+P_{IONZ})\,\sigma_0\, l\,,$$
$$\text{and } I(6') = \frac{1}{3}\, i_- \frac{N_0}{2}\,(1+P_{IONZ})\,\sigma_0\, l\,.$$

Here, $I(k')$ $k=1,2...6$ is the negative deuterium ion currents contributed from the each hyperfine sub-level k'of deuterium atoms which is shown in Fig. 2. And, N_0 the density of the alkali atoms in the ionizer, P_{IONZ} the electron-spin polarization of the alkali atoms in the ionizer, σ_0 is the spin independent electron pick-up cross section to form negative deuterium ions and l the ionizer length, respectively. In eq.(1), i_+ and i_- are the intensities of the deuterium atoms with the electron-spin states of $m_j=+1/2$ and $m_j=-1/2$, and these are written as $i_+ = I_{D^0}(1+P_{D^0})$ and $i_- = \frac{I_{D^0}}{2}(1-P_{D^0})$, respectively. Here I_{D^0} is the intensity of electron-spin polarized deuteron atoms in the neutralizer and P_{D^0} the electron-spin polarization of deuteron atoms in the neutralizer. Therefore, the total beam intensity of negative deuterium ions after the ionizer can be written in following equation.

$$I = \frac{I_{D^0} N_0}{6}\,(3 - P_{D^0} P_{IONZ})\,\sigma_0\, l\,. \qquad (2)$$

As can be clearly seen from this equation, the intensity of electron polarized deuteron atoms (I_{D^0}) is determined by both electron-spin polarization of the deuteron atoms after the neutralizer and the alkali atoms in the ionizer.

Here, we define ε as $\varepsilon = (I_{off} - I_{on}) / I_{off}$, where I_{off} and I_{on} are the beam intensities when the pumping laser for the ionizer is off and on, respectively. Thus, from eq.(2) ε can be expressed in the following form.

$$\varepsilon \equiv \frac{I_{off} - I_{on}}{I_{off}} = \frac{1}{3}\, P_{D^0} P_{IONZ}\,. \qquad (3)$$

It is clearly seen from this equation that ε depends only on P_{D^0} and P_{IONZ}. When the electron-spin polarization directions of the alkali atoms in both neutralizer and ionizer are parallel, ε becomes positive. On the other hand, when the electron-spin polarization directions of the alkali atoms in each cell are anti-parallel, ε becomes negative.

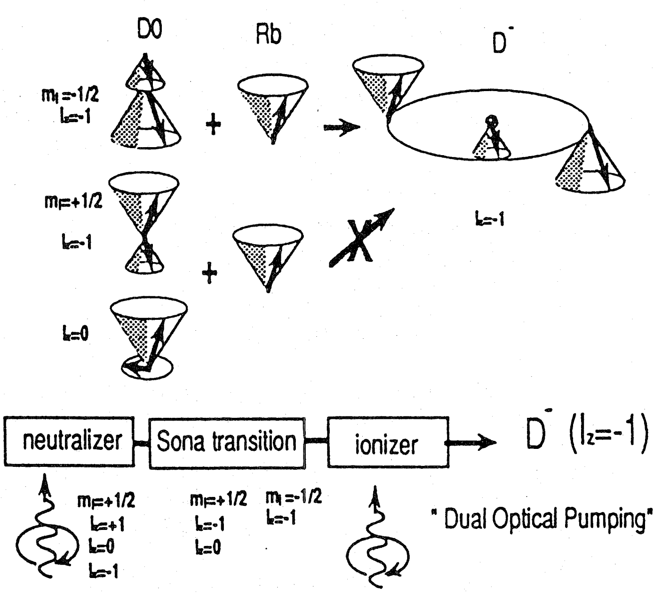

Fig. 3 Principle of the dual-optically-pumped polarized negative deuterium ion source.

Figure 4 shows the changes of the beam intensities of negative deuterium ions in each case that the electron-spin polarization directions of the alkali atoms in the neutralizer and the ionizer are parallel and anti-parallel, respectively. The upper trace shows the beam intensity of negative deuterium ions when the rubidium atoms in the ionizer are electron-spin polarized whose polarization direction is parallel to the polarization direction of the electron-spin polarized deuterium atoms after the neutralizer. The lower one corresponds to that when the polarization directions of rubidium atoms in the ionizer and deuterium atoms after neutralizer are opposite. The middle trace shows the beam intensity when the optical pumping of the ionizer is off. Apparently seen from this figure, the negative deuterium intensity is increased or decreased according to the polarization of rubidium atoms in the ionizer as expected from eq.(3). In this preliminary experiment, the electron polarization of rubidium atoms in ionizer (P_{IONZ}) was 1, therefore, the polarization of deuteron atoms (P_{D^0}) was estimated to be 0.42.

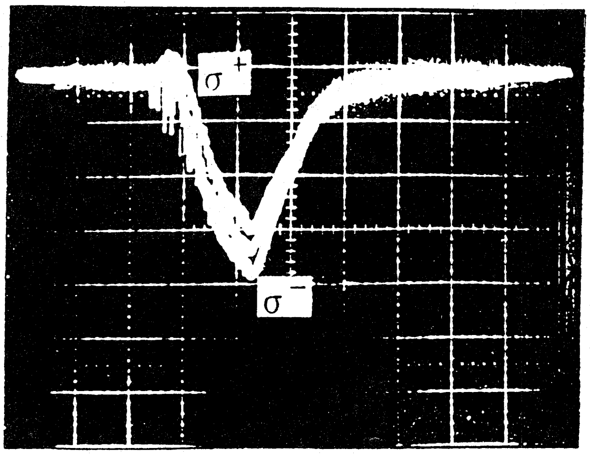

Fig. 4 The changes of the beam intensities of negative deuterium ions.

From these experimental results, it was confirmed that this dual optical pumping scheme for generating a highly polarized negative ion worked well.

Calculation of P_{D^-}

From definition, the deuteron vector polarization (P_{D^-}) is written as follows,

$$P_{D^-} = \frac{I_+ - I_-}{I_+ + I_0 + I_-} \quad . \qquad (4)$$

Here I_+ is the beam fraction of the deuteron nuclear spin component of m_I=+1, I_- the fraction of m_I=-1 and I_0 the fraction of m_I=0, respectively. From eq.(1), numerator and denominator of eq.(4) can be written as,

$$I_+ - I_- = \frac{1}{3} I_{D^o} N_0 P_{D^o} \sigma_0 l,$$

$$\text{and } I_+ + I_0 + I_- = \frac{I_{D^o} N_0}{6}(3 - P_{D^o} P_{IONZ}) \sigma_0 l,$$

respectively. Then, eq.(4) can be rewritten as,

$$P_{D^-} = \frac{-2P_{D^o}}{3 - P_{D^o} P_{IONZ}} . \qquad (5)$$

From eq.(5) and eq.(3), P_{D^-} is given by the following equation

$$P_{D^-} = \frac{-2\varepsilon}{P_{IONZ}(1 - \varepsilon)} \quad . \qquad (6)$$

The relationship between P_{D^-} , P_{IONZ} and ε are shown in Fig. 5. With the measurements of P_{IONZ} and ε , we can estimate the deuteron vector polarization of negative deuterium ions (P_{D^-}) from eq. (6) .

The result of the preliminary experiment is also shown in Fig. 5. The closed circle in the figure shows the experimental result. The electron-spin polarization of alkali atoms in the ionizer (P_{IONZ}) was measured with a Faraday rotation method. The errors shown in the figure present the fluctuations of the data taken at different times. We obtained $P_{D^-} = -0.55 \pm 0.04$ in the preliminary experiment. In the present apparatus where the magnetic field strength at the neutralizer is 1.1T, the theoretical maximum polarization is limited to less than 80%. This is because the spin-orbit coupling in neutral deuterium atoms, which are created by picking up polarized electrons from the optically pumped alkali atoms in the neutralizer, reduces the electron-spin polarization at this magnetic field strength. Thus, the obtained nuclear-spin polarization of negative deuterium ions was almost 70% of the maximum limiting value. This is a very encouraging result and it can be said that the dual-optically pumped scheme for producing highly polarized negative deuterium ions has worked in principle.

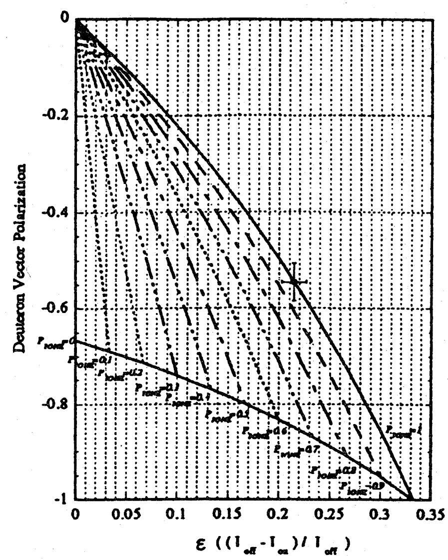

Fig.5 Relation between P_{D^-} and ε. The closed circle in the figure shows the experimental result.

IV. CONCLUSION

A new dual-optically-pumped scheme to obtain a high deuteron-spin polarization in an optically pumped polarized ion source has been examined in detail. The results of the preliminary experiment are very encouraging and it is shown that the new scheme, in principle, has worked. It was previously thought that the optically pumped polarized ion source was not useful for producing highly polarized deuterons. Our results may open up a new possibilities for the optically pumped polarized ion sources.

REFERENCES

[1]Y.Mori et al ; contributions for this conference.

[2] W.L.Anderson: Nucl. Instr. and Meth. 167,363(1979).

[3] Y.Mori, K.Ikegami, Z.Igarashi, A.Takagi,and S.Fukumoto: AIP Proc. 117,New York(1983)123.

[4] R.L.York, O.B. Van Dyck, D.R.Swenson and D.Tupa: Proc. of the Int. Workshop on Polarized Ion Sources and Polarized Gas Jets, KEK Report 90-15(1990),page 142.

[5] L.Buchmann,C.D.P.Levy, M.McDonald, R.Ruegg, and P.W.Schmor: ibid page 161.

[6] A. Zelenskii, S.A.Kokhanovskii, V.G.Polushkin and K.N. Vishnevskii:ibid page 154.

[7] M.B.Schneider and T.B.Clegg: Nucl. Instr. and Meth.,A254,630(1987).

[8]Y.Mori ; submitted to Nucl. Instr. Meth.