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PRODUCTION OF POLAREIZED NEGATIVE DEUTERIUM ION BEAM WITH DUAL OPTICAL PUMPING

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Abstract

To obtain highly vector-spin polarized negative deuterium ion beam, a dual optically pumped polarized negative deuterium ion source has been developed at KEK. It is possible to select a pure nuclear-spin state with this scheme, and negative deuterium ion beam with 100 % nuclear-spin vector polarization can be produced in principle. We have obtained about 70 % of nuclear-spin vector polarized negative deuterium ion beam so far. This result may open up a new possibilities for the optically pumped polarized ion source.

1. INTRODUCTION

An ordinary deuteron beam was successfully accelerated to an energy of 11.2GeV (5.6GeV/u) in the KEK 12 GeV proton synchrotron (KEK-PS), the limiting energy of the ring, in 1992. [1] The beam intensity of the accelerated deuterons reached more than 2 x 10^{12} ppp which was almost the same as that for protons. Following this success, it has been strongly requested to accelerate polarized deuteron beam, and it will be started from this autumn. For this purpose, a polarized deuteron beam with high nuclear-spin vector polarization and large beam intensity is demanded. So we started development of polarized negative deuterium ion source with dual optical pumping.

As for polarized ion source, an optically pumped polarized ion source(OPPIS) has been used for generating nuclear-spin polarized negative hydrogen ion beam 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 ion beam. In 1987, 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 not be 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 optically pumped scheme in detail and found that radiation trapping was not a serious problem and highly nuclear-spin polarized negative deuterium ion beam could be obtained with the dual optically pumped scheme.[8]

In this paper, we report the experimental results which showed that the highly nuclear-spin vector polarized negative deuterium ion beam could be produced by OPPIS with dual optical pumping.

2. DUAL-OPPIS FOR DEUTERON

The principle of a dual optically pumped polarized negative deuterium 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.1. 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.1. 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.1. Therefore, the deuterium atoms with only the hyperfine sub-level of I_z=-1 (state 1' in Fig.1) has an opposite electron-spin state, m_j =-1/2, of the other two sub-levels (2' and 3') after 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. The nuclear-spin state of the negative deuterium ions in this case is I_z=-1, the nuclear-spin vector polarization becomes -1. The nuclear-spin tensor polarization is, in this case, -1. Using a proper rf transition simultaneously, a pure nuclear-spin tensor polarization of -2 may become possible.

3. EXPERIMENTAL APPARATUS

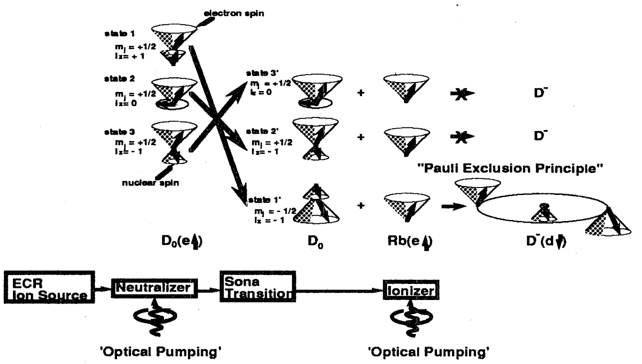


Fig.1 The principle of a dual optically pumped polarized negative deuterium ion source

Schematic of dual-OPPIS

Figure 2 shows a schematic diagram of a dual-optically pumped polarized negative deuterium ion source which has been developed at KEK. There are ECR ion source and neutralizer in the super conducting magnet which makes a high magnetic field of about 2.7 Tesla. A microwave is fed into ECR source from upstream of it. The solenoid has three independent coils which allows control of the magnetic field shape. A deuteron beam is extracted from ECR ion source by an electrode system which accelerates the beam to energy of approximately 6 keV. The deuteron beam enters a electron-spin polarized rubidium vapor cell , where a fraction of the deuterons picks up a polarized electron by charge transfer from rubidium and are thus neutralized. we call this cell neutralizer. The electron-spin polarization is induced by optical pumping with circularly polarized laser tuned to the rubidium D_1 transition at 795 nm. Rubidium is chosen because of its relatively high charge exchange cross section with fast deuteron [9], and the availability of high laser power at the wavelength.

Most of neutralized deuterium is created in the excited *n=2* state. For that reason it is necessary that charge exchange occurs within a high magnetic field which preserves the electron-spin polarization of deuterium atom as the atom decays to the ground state [10]. The ECR cavity extraction electrodes and neutralizer are both contained within the same high magnetic field so as to reduce the effective emittance increase of the deuteron beam as it enters the magnetic field region of the neutralizer. The magnetic field reverses direction in the region between neutralizer and negative ionizer cell, and as the neutral deuterium beam passes through this region, the nuclear-spin polarization is enhanced by means of a Sona transition [11]. This deuterium atom picks up a polarized electron by charge transfer from rubidium in ionizer. The electron-spin polarization is induced by optical pumping. Nuclear-spin vector polarized negative deuterium ion beam is created with this scheme. In the downstream of the ionizer, there are einzel lens, wien filter and Faraday cup for which D^- beam current is measured. In order to pump the rubidium atoms in neutralizer and ionizer, two broad band Ti-sapphire lasers are fed into neutralizer and ionizer from downstream of it respectively. The thickness and electron-spin polarization of rubidium in neutralizer and ionizer are measured by Faraday rotation with linearly polarized laser light tuned to the rubidium D_2 transition at 780 nm. This probe laser fed into neutralizer and ionizer from upstream of this ion source.

ECR Deuteron Source

Figure 3 shows a schematic diagram of ECR deuteron source and extraction electrode system. The ECR cavity is a stainless steel cylinder of 29 cm length and 6 cm inner diameter. It is mounted to an insulating Teflon holder to allow the application of the 6 kV potential for deuteron extraction. The Teflon holder also supports the extraction electrode system. The plasma chamber is made of stainless steel and the inside of it a quartz glass tube contains to evacuate the plasma. External grooves in the stainless steel cylinder hold a Sm-Co hexapole structure to make a good plasma confinement. Microwave is fed into a plasma chamber through a thin vacuum sealed microwave window. Microwave power is generated by a 18 GHz klystron which operates with a long pulse duration (upto 1 msec) and high repetition rate (20 Hz). A maximum power of microwave generated by this klystron is 1 kW.

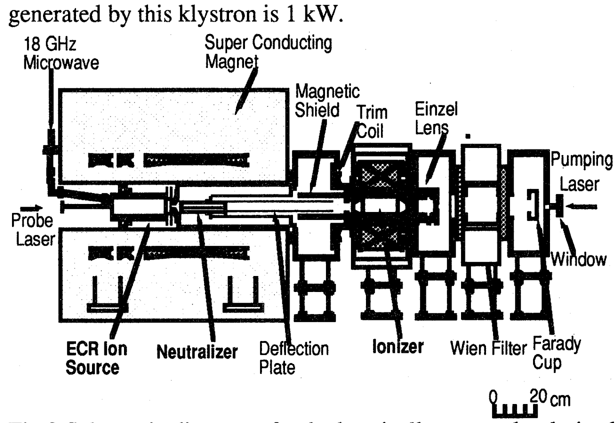


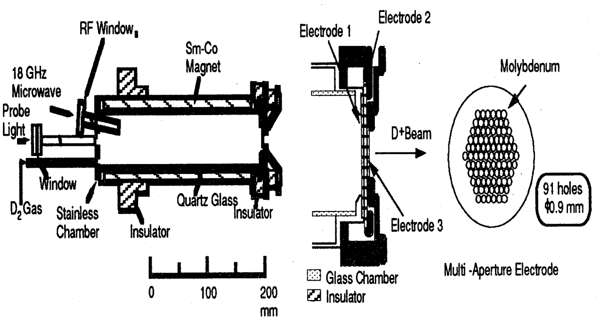
Fig.2 Schematic diagram of a dual optically pumped polarized negative deuterium ion source at KEK

Extraction Electrode System

A three-electrode system consists of 0.5 mm thick molybdenum disks with an hexagonal array of 91 holes 0.9 mm in diameter. The first electrode is integral to ECR cavity. The outer two electrodes are supported by stainless steel holders which are attached to the Teflon insulator. The first electrode and second one are consisted in 1 mm apart, and the distance between second electrode and third one is 1.5 mm. The electrodes are operated in an accel-accel mode with the second electrode set about 1 kV below the cavity potential. The third electrode is kept at ground potential.

4. EXPERIMENTAL RESULTS

In a dual optical pumping scheme, the deuteron polarization can be estimated with an unique method, which is called as "intensity modulation method". One of three hyperfine sublevels is selected to be D^- ions by Pauli exclusion principle.



(a) ECR Deuteron Source (b) Extraction Electrode System

Fig.3 Schematic diagram of ECR deuteron source and the extraction electrode syatem

Beam intensity can be modulated by switching an optical pumping from on to off or changing a electron-spin polarization direction. Deuterium atoms in only one hyperfine sub-level can become negative deuterium ions by picking up polarized electrons from the optically pumped alkali atoms in the ionizer. Thus, the beam intensity of negative deuterium ions depends upon the population of deuterium atoms in each hyperfine sub-level after the Sona transition. This means that the deuteron vector polarization (P_Z) and the electron-spin polarization of optically pumped alkali atoms in the ionizer (P_e^i) affect the beam intensity of negative deuterium ions. These values are related each other as expressed in the following equation.

$$P_Z = -2\,\varepsilon / P_e^i\,(1 - \varepsilon).$$

Here, $\varepsilon = (I_{off} - I_{on}) / I_{off}$, where I_{off} and I_{on} are the beam intensities of negative deuterium ions when the optical pumping of the alkali atoms in the ionizer is turned off and on, respectively. The result of the experiment is shown in Fig.4. The vertical axis in the figure presents the nuclear-spin vector polarization of negative deuterium ions. The horizontal axis shows the relative change of the beam intensity of the negative deuterium ions by switching the optical pumping of the alkali atoms in the ionizer on and off. The solid line in the figure presents the relation between ε and nuclear-spin vector polarization for $P_e^i = 0.95$. In our experiment, the electron polarization of the alkali atoms in ionizer was 95 %. The electron-spin polarization of alkali atoms in the ionizer (P_e^i) was measured by using a Faraday rotation method. The nuclear-spin vector polarization of D^- ions can be estimated from that equation. The triangle plot in the figure shows the experimental result when the magnetic field strength of the neutralizer is 1.2 Tesla, and the circle plot shows the experimental result when the magnetic field is 2.7 Tesla. The errors shown in the figure present the fluctuations of the data taken at different times. In 1.2 Tesla ε value obtain in our experiment was about 0.21. It correspond to nuclear-spin vector polarization of D^- ions of 55 %. In 2.7 Tesla ε was about 0.25 and nuclear-spin vector polarization was 70 %. The magnetic field strength of the neutralizer increased from 1.2 Tesla to 2.7 Tesla, the nuclear-spin vector polarization of D^- ions also increased from 55 % to 70 %. This is because of the spin-orbit coupling in the neutral deuterium atoms, which are created by picking up polarized electrons from the optically pumped rubidium atoms in the neutralizer, reduces the electron-spin polarization at the large magnetic field strength.

5. CONCLUSION

We have been developing at a dual optically pumped polarized negative deuterium ion source for producing deuteron with high nuclear-spin vector polarization. With this source, negative deuterium ion beam with about 70 % nuclear-spin vector polarization was obtained in the present experiment. In order to obtain a large beam intensity, we are optimizing this source.We are now installing this source into the high voltage station for the KEK 12 GeV proton synchrotron (KEK-PS). We hope to get the polarized deuteron beam acceleration in the KEK-PS by the end of this year.

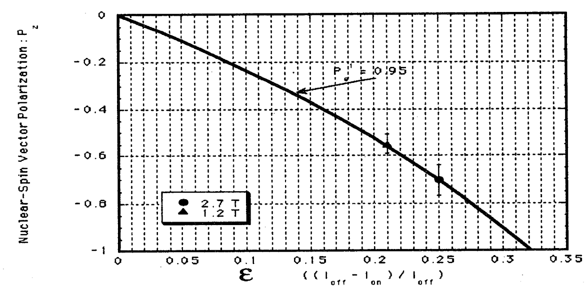


Fig.4 The relation between e and nuclear-spin vector polarization for Pei=0.95. The plots in the figure show the experimental results when the magnetic field strength of neutralizer is 1.2 T and 2.7 T.

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