PRESENT STATUS AND FUTURE PROSPECTS OF OPTICALLY PUMPED POLARIZED ION SOURCE

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abstract

Present status and future prospect of optically pumped polarized ion source(OPPIS) are described.

1. Introduction

An idea of the optically pumped polarized ion source (OPPIS) for producing polarized negative hydrogen ion source , which is based on electron-capture reactions of negative hydrogen ions from the optically pumped sodium atoms, was originally proposed by Anderson[1]. The first OPPIS based on this idea was successfully developed at KEK in 1983.[2] Since then, OPPIS has been developed at various laboratories, LAMPF,TRIUMF and INR.[3][4][5] Recently, it was found at KEK that, with dual-optically pumped scheme, OPPIS was also able to generate highly polarized negative deuterium ions which have been thought difficult to make so far.[6][7] In order to increase the beam intensity further in future, a new type of OPPIS with spin-exchange scheme is being rigorously investigated. It may not be a dream to generate the same intensity level of polarized ion beams in future by OPPIS compared with that of the unpolarized ion beams.

2. Present status of OPPIS for polarized negative hydrogen ions

A schematic diagram of the optically pumped polarized ion source is shown in Fig. 1. Low-energy (several keV) protons pick up polarized electrons from the optically pumped alkali atoms and form electron-spin polarized hydrogen atoms. In order to avoid depolarization due to a spin-orbital angular momentum coupling in the excited state (2P state) hydrogen atoms, which are formed in electron pick-up reactions in this proton beam energy range, a high magnetic field of more than 1 T is necessary. The effect of the depolarization is calculated as a function of the magnetic field strength by several groups.[8,9] The measured polarization transfer was 10 to 15 % lower than the theoretically expected value. This might be partly due to the unpolarized atomic hydrogen beam which is formed by charge-exchange reactions with residual hydrogen gas molecules flowing from the proton source. The electron-spin polarized hydrogen atoms pass through a zero-crossing magnetic field and the electron-spin polarization transfers to nuclear-spin polarization by a non-adiabatic transition(Sona transition). Ionizing the nuclear-spin polarized hydrogen atoms to negative hydrogen ions can be done by the charge-exchange reaction with another alkali atoms such as sodium.

The optical pumping of the alkali atoms in the neutralizer was previously performed with a dye laser because of its wavelength tunability to match the absorption resonance lines concerning to the optical pumping. However, recently, tunable solid state laser such as Ti-sapphire or Alexandrite laser has been widely used because of its relatively large power and ease for maintenance.

Characteristics and performance of OPPIS at various laboratories are summarized in table 1. The beam intensity from OPPIS reaches more than 100 μ A for polarized negative hydrogen ion beam and 1 mA for polarized proton beam with relatively small beam emittance, respectively, in pulsed mode operation and 25μ A for negative hydrogen ion beam in DC mode operation. The beam polarization depends very much on the external magnetic field strength in electron-capture process. When the magnetic field strength is about 2.5T, the beam polarization of 80 % was realized in TRIUMF.

3. OPPIS for polarized negative deuterium ions

Polarized protons have been successfully accelerated in the KEK 12-GeV proton synchrotron (KEK-PS) since 1985.[10] 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.

Although OPPIS is very useful to generate polarized protons, it has been thought that OPPIS is inadequate for making highly polarized deuterons. In deuterium atoms, because the nuclear spin, I=1, three hyperfine sublevels (I_z=+1,0,-1) exist. High polarization can not be expected if only a Sona transition is used because of the I_z=0 state. The theoretical maximum polarizations, in this case, are +-2/3 for vector polarization (P_z) and -1/3 for tensor polarization (P_{zz}).

To achieve a high polarization, a new scheme which selects a pure nuclear-spin state is necessary. In 1988, Schneider and Clegg[11] proposed a new nuclear-spin state selection scheme. Their idea is as follows: After picking up the polarized electrons from optically pumped alkali atoms, deuterium atoms are electron-spin polarized, for example, in the state of m_j =+1/2. 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 can form negative ions because of the Pauli exclusion principle. This process is shown in Fig.2 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.

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. Radiation trapping is a re-

Table 1 Characterisitcs and performance of OPPIS in the world.

	KEK	LAMPF	TRIUMF	INR
intensity				
H^-	100μA(H)	50μA(2μA)	25μA	400μA
H^+	1mA(H)	-	-	4mA
polarization	.65	.64(.77)	.80	.65
emittance (πmm.mrad)	2.0	1.0	1.0	1.0
duty factor	0.001	0.1	DC	0,0002

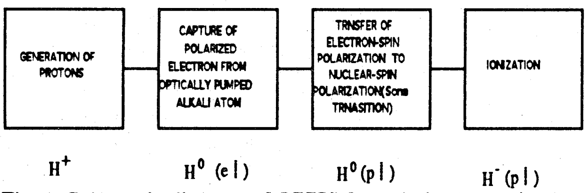


Fig. 1 Schematic diagram of OPPIS for polarized negative hydrogen ions.

absorption process of fluorescence photons in optical pumping and it limits the maximum polarization of the pumped atoms. However, their conclusion was qualitative and they did not estimate quantitatively the effect of xradiation trapping. Recently, 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.[12]

Recently, a preliminary experiment for proving the principle of the dual-pumped scheme has been carried out at KEK. In the preliminary experiment, we obtained P_D= -0.55 +- 0.04. The results of the experiment will be presented in detail in this conference[13], which was almost 70 % of the maximum limiting value. This is very encouraging and it may be said that the dual-optically pumped scheme for producing highly polarized negative deuterium ions has worked in principle.

4. Future of OPPIS with spin-exchange scheme

The principle of the spin-exchange optically pumped polarized hydrogen or deuterium ion source is based on the electron-spin polarization transfer of alkali atoms to the hydrogen or deuterium atoms by spin exchange collision. The way of making nuclear polarization of hydrogen or deuterium atoms by the spin-exchanged collision is as follows;(1) Atomic hydrogen or deuterium beam either which is thermal or energetic(~keV) is generated. (2) Electron-spin polarized alkali atoms are produced by optical pumping. (3) The electron-spin polarization is transferred to hydrogen or deuterium atoms by spin exchange collisions. (4) The electron-spin polarization of hydrogen or deuterium atoms are transferred to the nuclear-spin polarization by hyperfine interaction. (5) The nuclear-spin polarized hydrogen or deuterium atoms are ionized.

In the mutual atomic collision process between hydrogen/deuterium atoms and alkali atoms, the spin-exchange differential cross section can be written by,

$$\frac{d\sigma_{ex}}{d\theta_{cm}} = \frac{|f_t(\theta_{cm}) - f_s(\theta_{cm})|^2}{4} . \qquad (1)$$

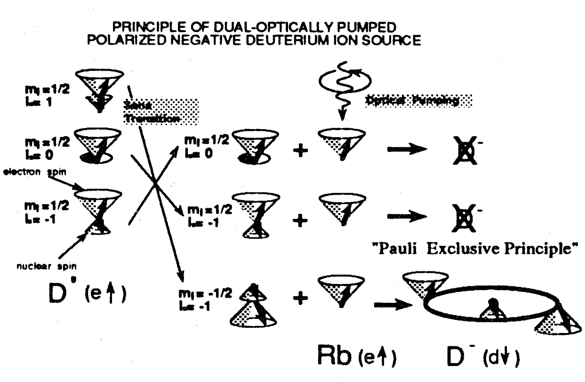


Fig. 2 Principle of OPPIS for polarized negative deuterium ions with dual optical pumping.

Here, f_t and f_s are the scattering amplitudes for the singlet and triplet states of the two atomic molecular system, respectively and each of them can be estimated from the phase shift which is calculated from an electronic potential curve corresponding to each state.

The calculated total spin-exchange cross sections are summarized for thermal H-Na, H-K, H-Rb and H-Cs systems in Table 2. [14]

Table 2 Total spin-exchange cross section for thermal H-Na, H-K, H-Rb and H-Cs systems.

H-Na :	2.2×10^{-15} cm^2
H-K :	2.7×10^{-15} cm^2
H-Rb :	2.9×10^{-15} cm^2
H-Cs :	3.4×10^{-15} cm^2

The spin-exchange cross sections between energetic hydrogen or deuterium atoms of several keV and thermal alkali atoms are calculated by Swenson et al. The calculated cross section for H-Na system is shown in Fig.3 as a function of the incident energy of hydrogen atomic beam. The measurement of the spin-exchange

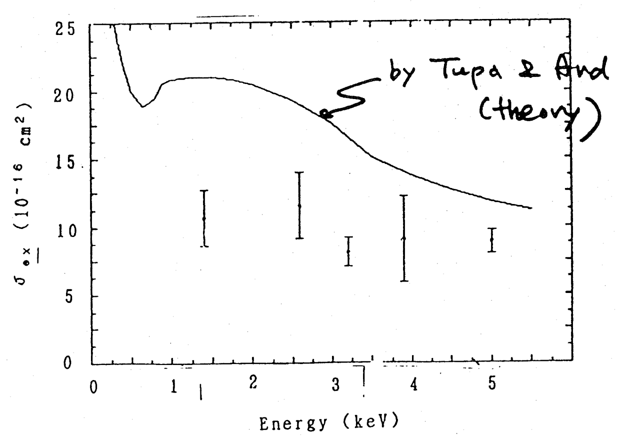


Fig. 3 Spin-exchange cross sections of H-Na system as a function of atomic hydrogen beam energy. The solid line shows the theoretically calculated one and the closed circles presents the experimental results.

cross section for H-Na system was carried out at KEK with modifying their OPPIS. The results are also shown in Fig. 3. The measured values are somewhat smaller than those expected from the calculation, however, still larger than 1×10^{-15} cm^2.

The atomic polarization of thermal hydrogen atoms induced by spin-exchange collisions with optical pumping polarized alkali atoms can be expressed in the following form.

$$P_H = \frac{\gamma_{se} P_A}{\gamma_{se} + \gamma_r}[1 - \exp\{-(\gamma_{se} + \gamma_r) t\}]. \qquad (2)$$

Here, P_A, γ_{se} and γ_r are the atomic polarization, the spin-exchange rate(=$<\sigma_{ex} v> n_A$) and the polarization relaxation time of hydrogen atoms, respectively. Apparently, when $\gamma_{se} > \gamma_r$, eq. (3) becomes,

$$P_H \sim P_A. \qquad (3)$$

In order to get a high polarization of hydrogen atoms, the density of sodium atoms n_A should be more than 10^{13}n/cm^3 and the relaxation rate γ_r should be less than 10^3 s^{-1}.

In optical pumping at a simple three level system, the polarization becomes,

$$P \approx [\ 1 - \frac{2\gamma}{\Phi + 2\gamma}\ ] \qquad (4)$$

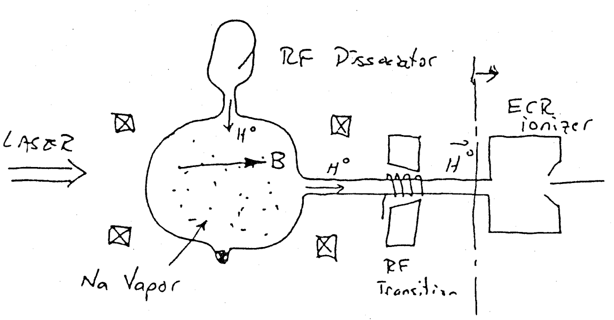
Here, $\Phi = I / h\nu$, where I is a laser power, and γ is the relaxation rate, respectively. When I = 1W, Φ becomes more than 10^7 photons/s. Even if γ is 10^4 s^{-1}, the polarization is still close to 100%. However, when alkali atom density exceeds more than 10^{12} n/ cm^3, an emitting photon in spontaneous decaying of the excited state is re-absorbed by another atom and eventually the polarization should be destroyed. This multiple process is named radiation trapping.

The polarization decrease due to the radiation trapping was calculated theoretically by Tupa and Anderson[15] and their calculations have been clarified experimentally.[16] The polarization can not reach 100% because of radiation trapping when the relaxation time is small. In order to achieve high polarization of more than 90% at the sodium density of about 10^{13} n/cm^3, the relaxation time should be longer than at least 100μsec.

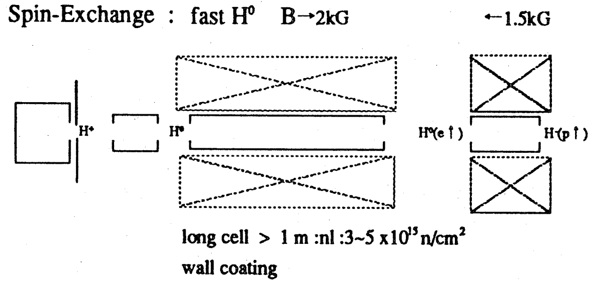
Another important effect induced by radiation trapping is that the polarization of optically pumped alkali atoms are very much affected by the external magnetic field strength. In a weak magnetic field, the hyperfine sublevels for ground and excited states of alkali atom are not well resolved and the absorption line widths for those sublevels are overlapped each other by a Doppler broadening. Therefore, re-absorption probability of emitted photons from the excited state becomes large and the polarization results in decreasing. On the other hand, in a strong magnetic field, the hyperfine sublevels are well resolved and the polarization decrease caused by radiation tapping can be reduced. Of course, electron-spin polarization of hydrogen atoms is realized in a strong magnetic field by spin-exchange collision, therefore RF transition is essential to make nuclear-spin polarization.

Recently, the group led by Holt in Argonne National Laboratory has been carrying on the development works of the spin-exchange type of polarized deuterium gas source for electron storage rings.[17] The obtained polarized deuterium flux was 2.1 x 10^{17} n/s and the electron-spin polarization of deuterium atoms of 73+-3% was achieved in a strong magnetic field of 2.2kG.

A schematic layout of the OPPIS with spin-exchange is shown in Fig. 5. The expected beam intensity reaches more than 10 mA if 30 % of the ionization efficiency in the ECR ionizer, which is a very reasonable value for ordinary ECR ion source, is assumed.



(a) Spin-exchange for thermal hydorgen atoms.



* acceptance : 0.18 mm.mrad(100% normalized)

*multiple sacterign

(b) Spin-exchange for fast hydrogen atomic beam.

Fig. 5 OPPIS with spin-exchange scheme.

5. Conclusion

Present status of OPPIS for polarized negative hydrogen ions are breifely summarized. And a new dual-optically-pumped scheme to obtain a high deuteron-spin polarization in an optically pumped polarized ion source has been examined. The results of the preliminary experiment are very encouraging and it is shown that the new scheme, in principle, has worked.

The spin-exchange optically pumped polarized hydrogen or deuterium gas source looks to have a large potential in future. With further development of this method, many new nuclear and high energy physics experiments will become feasible. We may conclude that OPPIS has a large potential.

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