The 13th Symposium on Accelerator Science and Technology, Suita, Osaka, Japan, October 2001

Development of polarized ^{3}He ion source at RCNP

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A long history is presented on the polarized ^{3}He ion source being developed at RCNP for nuclear physics research at an intermediate energy region. A particular emphasis was placed on how we solved serious problems encountered in each phase of the development by employing delicate nature of atomic physics.

INTRODUCTION

Over the decade ago a development of a polarized ^{3}He ion source started at RCNP, Osaka University primarily for nuclear physics research at an intermediate energy region. We started constructing a device based on a polarized electron capture reaction for a fast $^3He^{2+}$ ion incident on a polarized alkali vapor at first. Though this was a start of painful development, we could finally obtain many fruitful results. In this paper, we will present why we should overcome many difficulties and how we could overcome them.

OPPIS [PHASE 1]

We initiated to develop a polarized ^{3}He ion source based on a polarized electron capture by a fast ion [1] later named, "OPPIS" (Optical Pumping Polarized Ion Source). The reason why we chose this was because the OPPIS revealed great success in producing a polarized proton beam with high intensity and high polarization [2,3] relative to other methods such as an AB (Atomic Beam) or a direct ^{3}He pumping method [4]. The $^3He^+$ OPPIS ion source applied to the ^{3}He polarization uses an electron capture between an incident fast $^3He^{2+}$ ion and a polarized alkali atom optically pumped [5–9]. After completion of a bench test device, we measured the $^3He^+$ nuclear polarization by varying a hepp impact energy for optimization of the ^{3}He OPPIS. The result showed a gentle decrease with an incident $^3He^{2+}$ energy. This behavior was reasonably reproduced by the theory based on the semi-classical impact parameter method [10,11]. Observed absolute values of the ^{3}He nuclear polarization were, on the other hand, greatly reduced relative to the alkali atomic polarization. This was in striking contrast with the proton OPPIS, where almost no proton depolarization was observed with respect to the alkali polarization [3]. The origin of this reduction was understood in terms of an insufficient LS decoupling field for a polarized $^3He^+$ ion; the LS decoupling field needed for hydrogen is only about 2 T, whereas that for $^3He^+$ ion was estimated to be over 30 T [12].

In addition to the above discouraging result, we met another serious problem; an extracted beam intensity from the ^{3}He OPPIS [13] was greatly reduced. This was simply understood in terms of a transversal emittance growth due to fringing fields of the solenoidal coil at both ends [14].

EPPIS [PHASE 2]

This urged us to discover an alternating idea which uses multiple electron capture and stripping collisions between an incident $^3He^+$ ion and a polarized Rb vapor [15]. Since this method uses multiple charge changing collisions between a he atom and $^3He^+$ ion with almost no contribution from a $^3He^{2+}$ ion, the LS decoupling could be accomplished with a practically available magnetic field ($\sim$ a few T). This eventually results in the expectation that most of the alkali polarization would be converted to the ^{3}He nuclear polarization. We named this novel method an "electron pumping" from analogy of the optical pumping. After an enormous effort, we succeeded in experimentally proving validity of the electron pumping [16]. Later, we named this polarized source "EPPIS" (Electron Pumping Polarized Ion Source).

Another principal superiority of the EPPIS over the OPPIS is a suppression of emittance growth since a ^{3}He charge state is the same, i.e., $+1$ when the ion is incident on and emerging out of the solenoid coil. Nevertheless, there may be additional emittance growth induced by the multiple stripping and capture collisions under the strong magnetic field. This may further influence a spatial distribution of the ^{3}He nuclear polarization. To see these effects more closely, we carried out the Monte Carlo simulations. We could find that no sizable emittance growth occurs thanks to the fact that a penetrating ^{3}He spends a substantial time with a ^{3}He atomic state free from a magnetic field [17]. On the other hand, concerning the polarization distribution of the $^3He^+$ beam, a hole having a less polarization the surrounding region was predicted, which was later named a "polarization hole" [18]. These findings would be beneficial not only to design a practical ion source but also to study plasma physics and probably astrophysics.

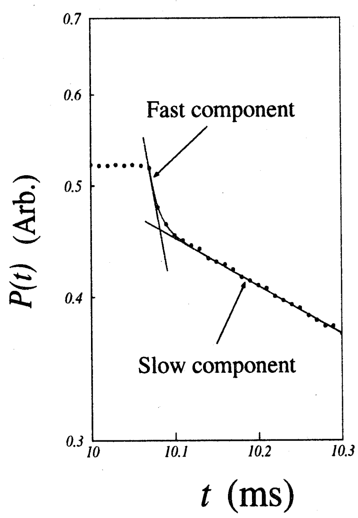

FIG. 1. Rb polarization (arbitrary unit) is observed as a function of time. Pumping laser is switched off at t = 10.07 ms, where an external magnetic field is 4T, and Rb cell temperature is 125 °C.

In spite of great success in the EPPIS, we met a somewhat serious problem. The EPPIS requires a polarized Rb vapor with thickness higher than 10^{14} cm^{-2}, an order of magnitude higher than that required for the OPPIS ion source [15,16]. However, fabrication of highly polarized Rb vapor with such a high thickness is not easy. In addition, no basic study has been systematically done on this subject. In our work, we studied the relaxation mechanism by a time differential measurement with a chopped pumping laser [19]. One of the remarkable results was an obvious presence of a fast decaying component in addition to a well established slow component caused by the wall relaxation, diffusion, effusion and so on as shown in Fig. 1. This new component was understood in terms of formation of a sheath with higher polarization due to a radiation trapping predominated at high vapor thickness. We found that the radiation trapping and absorption of the pumping light make it difficult to attain a highly polarized Rb vapor homogeneously distributed, which is indispensable to the EPPIS.

SEPIS [PHASE 3]

This urged us to devise a new polarization principle which does not use a thick Rb vapor. A new idea which meets the above requirement was proposed after a detailed analysis of our measurement of the electron pumping [21]. In their work, the spin exchange cross section could be deduced from the observed electron pumping effect (a closed circle with an error bar in Fig. 2-(a)). Though they could not theoretically reproduce the experimental result at first, they finall succeeded in reproduction by a sophisticated theory as described in the following:

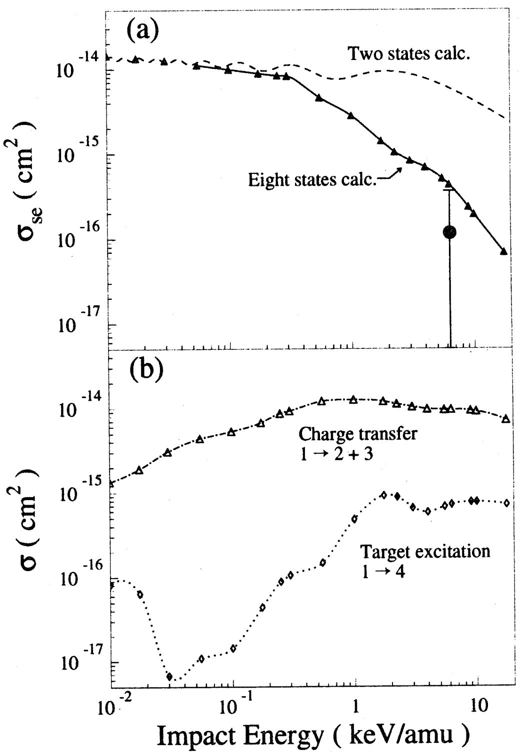

FIG. 2. (a) Calculated spin exchange cross sections plotted as a function of impact energy of $^3He^+$ ion, where the dashed curve is those calculated with the two states, and closed triangles and solid curve are those calculated with the eight states. (b) Calculated cross sections for the charge transfer (open triangles and a dot-dashed curve) and target excitation (open diamonds and a dotted curve) channels. The detail is explained in ref. [20].

The atomic collision theory based on the semi-classical close-coupling method allowing inclusion of the charge exchange and target excitation processes unexpectedly predicted an anomalously large spin-exchange cross section between a $^3He^+$ ion and a polarized Rb atom in particular at a $^3He^+$ impact energy lower than a few 100 eV/amu (a solid curve in Fig. 2-(a)) [20]. This is in striking contrast with the behavior of the hydrogen spin-exchange cross section. Since our new method uses an enhanced spin-exchange cross section at a low $^3He^+$ incident energy, we named it SEPIS (Spin Exchange Polarized Ion Source). Since the SEPIS requires neither an un-practically large magnetic field nor an extremely thick Rb vapor, the ^3He ion SEPIS will hopefully be one of the most practical polarized ^3He ion sources in the next generation.

CONCLUSION AND FUTURE PROSPECT

After a long journey we have reached the concept of the SEPIS. We believe that the SEPIS is one of the most promising polarized ^{3}He ion source ever proposed. An application of the SEPIS should not be restricted in nuclear physics regime but must be extended to particle physics such as RHIC or DESY. In Fig. 4, a schematic view of a practical polarized ^{3}He ion source based on the SEPIS is illustrated.

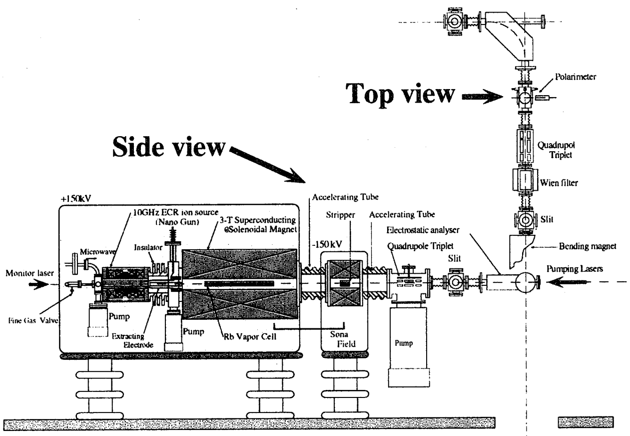

FIG. 3. A schematic view of the SEPIS ion source

Since the SEPIS ion source requires neither an unpractically large magnetic field nor an extremely thick Rb vapor, the ^{3}He ion SEPIS will hopefully be one of the most practical polarized ^{3}He ion sources in the next generation.

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